A&A 660, A45 (2022)
https://doi.org/10.1051/0004-6361/202142439

Astronomy & Astrophysics

Eruptions from coronal bright points: A spectroscopic view by IRIS of a mini-filament eruption, QSL reconnection, and reconnection-driven outflows★

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Received 14 October 2021 / Accepted 1 February 2022

ABSTRACT

Context. Our study investigates a mini-filament eruption associated with cancelling magnetic fluxes. The eruption originates from a small-scale loop complex commonly known as a coronal bright point (CBP). The event is uniquely recorded in both the imaging and spectroscopic data taken with the Interface Region Imaging Spectrograph (IRIS).

Aims. The investigation aims to gain a better understanding of the physical processes driving these ubiquitous small-scale eruptions.

Methods. We analysed IRIS spectroscopic and slit-jaw imaging observations as well as images taken in the extreme-ultraviolet channels of the Atmospheric Imaging Assembly (AIA) and line-of-sight magnetic-field data from the Helioseismic Magnetic Imager (HMI) on board the Solar Dynamics Observatory. As the observations can only indicate the possible physical processes at play, we also employed a non-linear force-free field (NLFFF) relaxation approach based on the HMI magnetogram time series. This allowed us to further investigate the evolution of the magnetic-field structures involved in the eruption process.

Results. We identified a strong small-scale brightening as a micro-flare in a CBP, recorded in emission from chromospheric to flaring plasmas. The mini-eruption is manifested via the ejection of hot (CBP loops) and cool (mini-filament) plasma recorded in both the imaging and spectroscopic data. The micro-flare is preceded by the appearance of an elongated bright feature in the IRIS slit-jaw 1400 Å images, located above the polarity inversion line. The micro-flare starts with an IRIS pixel size brightening and propagates bi-directionally along the elongated feature. We detected, in both the spectral and imaging IRIS data and AIA data, strong flows along and at the edges of the elongated feature; we believe that these represent reconnection outflows. Both edges of the elongated feature that wrap around the edges of the erupting MF evolve into a J-type shape, creating a sigmoid appearance. A quasi-separatrix layer (QSL) is identified in the vicinity of the polarity inversion line by computing the squashing factor, Q, in different horizontal planes of the NLFFF model.

Conclusions. This CBP spectro-imaging study provides further evidence that CBPs represent downscaled active regions and, as such, they may make a significant contribution to the mass and energy balance of the solar atmosphere. They are the sources of all range of typical active-region features, including magnetic reconnection along QSLs, (mini-)filament eruptions, (micro-)flaring, reconnection outflows, etc. The QSL reconnection site has the same spectral appearance as the so-called explosive events identified by strong blue- and red-shifted emission, thus providing an answer to an outstanding question regarding the true nature of this spectral phenomenon.

Key words. Sun: filaments, prominences – Sun: activity – Sun: chromosphere – Sun: corona – methods: data analysis – methods: numerical

1. Introduction

Over the past few years, we reported three studies on eruptions from small-scale loop systems known as coronal bright points (CBPs) by Mou et al. (2018, hereafter Paper I), Galsgaard et al. (2018, hereafter Paper II), and Madjarska et al. (2018, hereafter Paper III). These eruptions have been labelled as jets in extreme-ultraviolet (EUV) and X-ray data (e.g. Madjarska et al. 2020, and references therein) when detected in coronal holes and mini coronal mass ejections (mini-CMEs, Innes et al. 2009; Mou et al. 2018) observed in the quiet Sun. The term mini-CME is used to describe the observation of small-scale eruptions that do not evolve as collimated flows, namely, as jets that are typically ejected from CBPs in coronal holes. Rather, these events develop as expanding bubbles due to the closed magnetic-field structure of the quiet Sun. Whether these eruptions are fully confined or some of the ejected material reaches the interplanetary space remains an open question. We refer hereafter to this phenomenon simply as 'mini-eruptions'. The CBPs are composed of a set of small-scale coronal loops seen with enhanced emission in EUV and X-rays linking photospheric magnetic-flux concentrations of opposite polarity (for review see Madjarska 2019).

Here, we briefly review the main results on the eruptions from Papers I, II, and III. Firstly, Paper I shows that 76% of the analysed CBPs (31 out of 42) were the source region of one or more eruptions. The eruptions generally occurred during the late stage in the life of the CBPs, which is when magnetic-flux convergence and cancellation are typically occurring. The CBP eruptions commonly evolve with the ejection of cool and hot plasma. The cool plasma appears in absorption in the coronal

★ Movies associated to Figs. A.1 and A.2 are available at https://www.aanda.org

A&A 656, A86 (2021)
https://doi.org/10.1051/0004-6361/202141500

Astronomy & Astrophysics

Investigation of the subsurface structure of a sunspot based on the spatial distribution of oscillation centers inferred from umbral flashes★

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Received 9 June 2021 / Accepted 13 September 2021

ABSTRACT

The subsurface structure of a solar sunspot is important for the stability of the sunspot and the energy transport therein. Two subsurface structure models have been proposed, the monolithic and cluster models, but no clear observational evidence supporting a particular model has been found to date. To obtain clues about the subsurface structure of sunspots, we analyzed umbral flashes in merging sunspots registered by IRIS Mg II 2796 Å slit-jaw images. Umbral flashes are regarded as an observational manifestation of magnetohydrodynamic shock waves originating from convection cells below the photosphere. By tracking the motion of individual umbral flashes, we determined the position of the convection cells that are the oscillation centers located below the umbra. We found that the oscillation centers are preferentially located at dark nuclei in the umbral cores rather than in bright regions such as light bridges or umbral dots. Moreover, the oscillation centers tend to deviate from the convergent interface of the merging sunspots where vigorous convection is expected to occur. We also found that the inferred depths of the convection cells have no noticeable regional dependence. These results suggest that the subsurface of the umbra is an environment where convection can occur more easily than the convergent interface, and hence support the cluster model. For more concrete results, further studies based on umbral velocity oscillations in the lower atmosphere are required.

Key words. sunspots – Sun: chromosphere – Sun: oscillations – Sun: helioseismology

1. Introduction

The subsurface structure of sunspots is an important topic in solar physics. This veiled structure situated below the photosphere should be interacting with convective flows, playing a key role in the formation, evolution, and dissipation of the sunspots. The subsurface structure of sunspots is also important in thermal energy transfer. It determines the intensity of the umbrae and gives an indication of the formation mechanism of the inhomogeneous small-scale structures inside sunspots (Borrero & Ichimoto 2011).

Previous studies have proposed two representative models of the sunspot subsurface structure: the monolithic model (Hoyle 1949) and the cluster model (Parker 1979). The monolithic model treats a sunspot as a single magnetic flux tube. By contrast, in the cluster model, also known as the jellyfish or spaghetti model, a sunspot is considered to be an assembly of small flux tubes. There are several observational and theoretical works to verify each model, but they remain inconclusive.

The early magnetic field measurements of sunspots seemed to support the monolithic model. It is well known that a sunspot has a systematic magnetic field structure (Hoyle 1949) that is characterized by monotonically decreasing field strength and increasing field inclination from the sunspot center toward its boundary; this favors the monolithic model. However, it is reported that the power of the magnetic field strength oscillations has isolated multiple peaks inside sunspots (Rueedi et al. 1998; Balthasar 1999). Each penumbral fibril regarded as a magnetic flux tube shows independent behavior, which is referred to as uncombed penumbra (Thomas & Weiss 2004). These findings hint toward the cluster model rather than the monolithic model.

High resolution observations revealed the existence of subarcsecond structures inside sunspot umbrae that are represented by umbral dots and light bridges. These structures are closely related to convective motions (Ortiz et al. 2010; Watanabe et al. 2012). Initially, it was suggested that they cannot be formed in the strong magnetic field environment due to the inhibition of horizontal motions in plasma convection. They were naturally regarded as a tip of the field-free hot gases between magnetic flux tubes in the cluster models (Parker 1979; Choudhuri 1986). Contrary to this expectation, recent magnetohydrodynamic (MHD) simulations based on the monolithic model have successfully reproduced realistic umbral dots (Schüssler & Vögler 2006) or even the sunspots' overall fine structures (Rempel 2011). It implies that the magneto-convection, which is the convection of magnetized plasma, can produce tiny field-free regions inside large flux tubes. Accordingly, it still remains debatable whether these small-scale structures are intrusions between small magnetic flux tubes or internal structures of large flux tubes caused by magneto-convection (see Borrero & Ichimoto 2011 and references therein).

Local helioseismology provides information about the physical quantities below the photosphere. One of these quantities is the subsurface converging flow, which is required for the

★ Movie is available at https://www.aanda.org

The Astrophysical Journal, 918:21 (18pp), 2021 September 1 https://doi.org/10.3847/1538-4357/ac090a

Coronal Hole Detection and Open Magnetic Flux

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Received 2021 March 9; revised 2021 May 21; accepted 2021 June 6; published 2021 August 31

Abstract

Many scientists use coronal hole (CH) detections to infer open magnetic flux. Detection techniques differ in the areas that they assign as open, and may obtain different values for the open magnetic flux. We characterize the uncertainties of these methods, by applying six different detection methods to deduce the area and open flux of a near-disk center CH observed on 2010 September 19, and applying a single method to five different EUV filtergrams for this CH. Open flux was calculated using five different magnetic maps. The standard deviation (interpreted as the uncertainty) in the open flux estimate for this CH ≈ 26%. However, including the variability of different magnetic data sources, this uncertainty almost doubles to 45%. We use two of the methods to characterize the area and open flux for all CHs in this time period. We find that the open flux is greatly underestimated compared to values inferred from in situ measurements (by 2.2–4 times). We also test our detection techniques on simulated emission images from a thermodynamic MHD model of the solar corona. We find that the methods overestimate the area and open flux in the simulated CH, but the average error in the flux is only about 7%. The full-Sun detections on the simulated corona underestimate the model open flux, but by factors well below what is needed to account for the missing flux in the observations. Under-detection of open flux in coronal holes likely contributes to the recognized deficit in solar open flux, but is unlikely to resolve it.

Unified Astronomy Thesaurus concepts: Solar coronal holes (1484); Solar magnetic fields (1503); Interplanetary magnetic fields (824)

1. Introduction

The solar wind is a magnetized plasma that expands outward from the solar corona to fill the interplanetary space. It plays a key role in heliophysics, providing the medium by which solar-originating space weather-driving phenomena, such as coronal mass ejections and solar energetic particles, produce effects/impacts on Earth and on the surrounding space environment. The solar wind is approximately structured into two types: slow and fast with different sources (Schwenn et al. 1981). Fast solar wind streams are associated with recurrent geomagnetic activity (Neupert & Pizzo 1974) and are therefore of increased research interest. They have been identified to originate from deep within coronal holes (Krieger et al. 1973), where the predominantly open magnetic field allows plasma to escape easily (Altschuler et al. 1972). Along these open magnetic field lines, the density and temperature of the outflowing plasma falls rapidly with height, causing a relatively low intensity emission of coronal holes (hereafter, CHs) in EUV and X-ray images, or correspondingly bright in He I 10830 absorption (Bohlin 1977). The bulk of the Sun's open magnetic flux that is measured in interplanetary space is therefore expected to originate from CH regions. However, recent investigations have shown that the open magnetic flux identified in CHs underestimates the open magnetic flux in the heliosphere deduced from in situ measurements by a factor of two or more, referred to as the "Open Flux Problem" (Linker et al. 2017; Lowder et al. 2017; Wallace et al. 2019). While the fast wind is associated with the CHs themselves, the more variable slow solar wind is associated with the CH boundaries. In one class of theories, the slow wind arises quasi-statically from regions of large expansion factor near the boundaries (Wang & Sheeley 1990; Cranmer et al. 2007). Interchange reconnection (reconnection between open and closed fields; Crooker et al. 2002) has been suggested as the source of a dynamic slow solar wind (Fisk et al. 1998; Antiochos et al. 2011) and would most easily occur near CH boundaries. Fisk & Kasper (2020) argue that recent measurements from Parker Solar Probe (PSP; Fox et al. 2016) show that open magnetic flux is transported by interchange

The Astrophysical Journal, 909:202 (10pp), 2021 March 10 https://doi.org/10.3847/1538-4357/abdfd5

On the Nature of Propagating Intensity Disturbances in Polar Plumes during the 2017 Total Solar Eclipse

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Received 2020 October 15; revised 2021 January 22; accepted 2021 January 24; published 2021 March 18

Abstract

The propagating intensity disturbances (PIDs) in plumes are still poorly understood, and their identity (magnetoacoustic waves or flows) remains an open question. We investigate PIDs in five plumes located in the northern polar coronal hole observed during the 2017 total solar eclipse. Three plumes are associated with coronal bright points, jets, and macrospicules at their base (active plumes), and the other two plumes are not (quiet plumes). The electron temperature at the base of the plumes is obtained from the filter ratio of images taken with the X-ray Telescope on board Hinode and the passband ratio around 400 nm from an eclipse instrument, the Diagnostic Coronagraph Experiment. The phase speed (v_r), frequency (ω), and wavenumber (k) of the PIDs in the plumes are obtained by applying a Fourier transformation to the spacetime ($r - t$ plane) plots in images taken with the Atmospheric Imaging Assembly (AIA) in three different wavelength channels (171, 193, and 211 Å). We found that the PIDs in the higher-temperature AIA channels, 193 and 211 Å, are faster than that of the cooler AIA 171 Å channel. This tendency is more significant for the active plumes than the quiet ones. The observed speed ratio (∼1.3) between the AIA 171 and 193 Å channels is similar to the theoretical value (1.25) of a slow magnetoacoustic wave. Our results support the idea that PIDs in plumes represent a superposition of slow magnetoacoustic waves and plasma outflows that consist of dense cool flows and hot coronal jets.

Unified Astronomy Thesaurus concepts: Solar coronal waves (1995); Solar coronal plumes (2039); X-ray bright point (1812); Solar eclipses (1489); Fast solar wind (1872); Solar coronal holes (1484); Solar coronal heating (1989)

Supporting material: animation

1. Introduction

Polar plumes are long-lasting, dense, raylike, and relatively bright solar corona structures, usually observed in the extreme UV (EUV), X-ray, and white light. They are magnetically open linear structures extending from the Sun's surface to about 30 $R_\odot$ and known to be a source of the fast solar wind (Poletto 2015; Zangrilli & Giordano 2020, and references therein). Raouafi et al. (2008) suggested that low-rate magnetic reconnection is responsible for the formation and sustainability of plumes. Plumes are thought to be associated with coronal bright points (CBPs; Madjarska 2019) that form at the boundaries of supergranulation cells. Several observations support the idea that polar plumes are associated with CBPs, X-ray jets, or EUV jets in the network regions (Raouafi & Stenborg 2014). Wang & Sheeley (1995) suggested that the properties of a few hours' long and hazy plume structure can be adequately explained by the quasi-static upward evaporation of material heated by conduction during magnetic reconnection at the boundary of the supergranular cells. This suggestion was supported by the observations of a particularly bright plume taken with the Solar Heliospheric Observatory/Coronal Diagnostic Spectrometer (SOHO/CDS). Young et al. (1999) investigated a plume above the limb and the plume base visible on the solar disk. They reported that the temperature of the plume above the limb is about 1 MK, and the temperature remains constant with height. They found a strong brightening lying directly below the plume's main body with a high temperature of 2 MK, i.e., a CBP. They suggested that the footpoint morphology is similar to an emerging bipole in a region of unipolar magnetic flux, which is typical for CBPs (Madjarska 2019).

Due to the open magnetic configuration in polar coronal holes, polar plumes could be waveguides for magnetohydrodynamic (MHD) waves (e.g., Nakariakov 2006; Poletto 2015). The existence of waves in plumes has been demonstrated by observations taken with the UltraViolet Coronagraph Spectrometer (Ofman et al. 1997), Extreme ultraviolet Imaging Telescope (DeForest & Gurman 1998), CDS (Banerjee et al. 2000), Solar Ultraviolet Measurements of Emitted Radiation (Gupta et al. 2012) on board SOHO, and a theoretical model for the propagation of magnetoacoustic waves in polar plumes by Ofman et al. (1999).

Propagating intensity disturbances (PIDs) in plumes have been interpreted as compressible magnetoacoustic waves, as their intensity enhancement coincides with the blueshift of the O V 629 Å line profile taken with CDS (Banerjee et al. 2000). Banerjee et al. (2009) observed intensity oscillations with a period of 10–30 minutes and propagation velocity from 75 to 125 km s^{-1}, depending on the line formation temperature. They concluded that the most likely cause for PIDs is slow magnetoacoustic waves. This conclusion was supported by

A&A 646, A107 (2021)
https://doi.org/10.1051/0004-6361/202039329

Astronomy & Astrophysics

The chromospheric component of coronal bright points

Coronal and chromospheric responses to magnetic-flux emergence*

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Received 3 September 2020 / Accepted 4 December 2020

ABSTRACT

Context. We investigate the chromospheric counterpart of small-scale coronal loops constituting a coronal bright point (CBP) and its response to a photospheric magnetic-flux increase accompanied by co-temporal CBP heating.

Aims. The aim of this study is to simultaneously investigate the chromospheric and coronal layers associated with a CBP, and in so doing, provide further understanding on the heating of plasmas confined in small-scale loops.

Methods. We used co-observations from the Atmospheric Imaging Assembly and Helioseismic Magnetic Imager on board the Solar Dynamics Observatory, together with data from the Fast Imaging Solar Spectrograph taken in the Hα and Ca II 8542.1 Å lines. We also employed both linear force-free and potential field extrapolation models to investigate the magnetic topology of the CBP loops and the overlying corona, respectively. We used a new multi-layer spectral inversion technique to derive the temporal variations of the temperature of the Hα loops (HLs).

Results. We find that the counterpart of the CBP, as seen at chromospheric temperatures, is composed of a bundle of dark elongated features named in this work Hα loops, which constitute an integral part of the CBP loop magnetic structure. An increase in the photospheric magnetic flux due to flux emergence is accompanied by a rise of the coronal emission of the CBP loops, that is a heating episode. We also observe enhanced chromospheric activity associated with the occurrence of new HLs and mottles. While the coronal emission and magnetic flux increases appear to be co-temporal, the response of the Hα counterpart of the CBP occurs with a small delay of less than 3 min. A sharp temperature increase is found in one of the HLs and in one of the CBP footpoints estimated at 46% and 55% with respect to the pre-event values, also starting with a delay of less than 3 min following the coronal heating episode. The low-lying CBP loop structure remains non-potential for the entire observing period. The magnetic topological analysis of the overlying corona reveals the presence of a coronal null point at the beginning and towards the end of the heating episode.

Conclusions. The delay in the response of the chromospheric counterpart of the CBP suggests that the heating may have occurred at coronal heights.

Key words. Sun: chromosphere – Sun: corona – Sun: activity – Sun: magnetic fields – methods: observational – methods: data analysis

1. Introduction

Coronal bright points (CBPs) have been intensively studied for almost five decades. The CBPs are constituted by a set of small-scale coronal loops with an average height of 6500 km that connect photospheric magnetic-flux concentrations of opposite polarity. As the plasma confined in these loops is heated to a million degrees, they are seen with enhanced emission in the extreme-ultraviolet (EUV) and X-ray wavelengths. The CBPs are found to be uniformly distributed in the quiet Sun and coronal holes and also appear in the vicinity of active regions. For a review of CBPs, see Madjarska (2019).

The CBP emission throughout EUV and X-ray wavelengths shows conspicuous spatial and temporal variabilities (for a review, see Sect. 5.1 in Madjarska 2019). The first simultaneous observations of CBPs in spectral lines formed at chromospheric, transition region, and coronal temperatures were reported by Habbal & Withbroe (1981). The study revealed that the EUV emission from CBPs varies dynamically on short timescales. The emission enhancements in coronal lines were found to have a counter-response in chromospheric and transition-region lines. The analysed spectroheliograms were taken with the Harvard EUV experiment on Skylab/ATM at a 5″ spatial resolution and 5.5 min cadence in the C II 1335 Å, Ly-α 1216 Å, O IV 554 Å, O VI 1032 Å, C III 977 Å, and Mg X 625 Å lines.

* Movies are available at https://www.aanda.org

The Astrophysical Journal, 904:84 (14pp), 2020 December 1 https://doi.org/10.3847/1538-4357/abc1e0

Detection of Opposite Magnetic Polarity in a Light Bridge: Its Emergence and Cancellation in Association with LB Fan-shaped Jets

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Received 2020 August 28; revised 2020 October 13; accepted 2020 October 14; published 2020 November 24

Abstract

Light bridges (LBs) are relatively bright structures that divide sunspot umbrae into two or more parts. Chromospheric LBs are known to be associated with various activities including fan-shaped jet-like ejections and brightenings. Although magnetic reconnection is frequently suggested to be responsible for such activities, not many studies present firm evidence to support the scenario. We carry out magnetic field measurements and imaging spectroscopy of an LB where fan-shaped jet-like ejections occur with co-spatial brightenings at their footpoints. We study LB fine structure and magnetic field changes using TiO images, Near-InfraRed Imaging Spectropolarimeter, and Hα data taken by the 1.6 m Goode Solar Telescope. We detect magnetic flux emergence in the LB that is of opposite polarity to that of the sunspot. The new magnetic flux cancels with the pre-existing flux at a rate of 5.6×10^{18} Mx hr^{-1}. Both the recurrent jet-like ejections and their base brightenings are initiated at the vicinity of the magnetic flux cancellation, and show apparent horizontal extension along the LB at a projected speed of up to 18.4 km s^{-1} to form a fan-shaped appearance. Based on these observations, we suggest that the fan-shaped ejections may have resulted from slipping reconnection between the new flux emerging in the LB and the ambient sunspot field.

Unified Astronomy Thesaurus concepts: Solar activity (1475); Solar photosphere (1518); Solar chromosphere (1479); Solar magnetic fields (1503)

Supporting material: animations

1. Introduction

Sunspot light bridges (LBs) are relatively bright and elongated structures that either protrude from one side of the penumbra into the umbra or completely divide a sunspot umbra into two or more parts. They are formed by the coalescence of umbrae in complex active regions or during the final stage of the active region evolution (Bray & Loughhead 1964; García de la Rosa 1987). Among various ways to classify LBs, their brightness and morphological properties are often used to separate LBs into two categories, strong or faint LBs. Strong LBs fully separate umbral cores and have brightness comparable to that of the penumbra (Sobotka et al. 1993, 1994; Jurčák et al. 2006; Rimmele 2008). They very often display a granular structure with granules that are slightly smaller than the quiet-Sun granules (Sobotka et al. 1994), and their formation is closely related to the sunspot decay (Vázquez 1974). Faint LBs, composed of elongated bright grains, penetrate the umbra (Lites et al. 1991; Sobotka et al. 1993). The size of these grains is comparable to those of umbral dots. Strong LBs can be further classified into two types: (i) penumbral LBs that show a fine filamentary structure and (ii) photospheric or granular LBs that show a fine structure similar to the photospheric granulation (Rimmele 1997; Lagg et al. 2014).

Compared to the magnetic field of the surrounding umbra, magnetic fields in LBs were found to be of the same polarity as the host umbra but of lower strength and more inclined (Beckers & Schröter 1969; Lites & Skumanich 1990; Lites et al. 1991; Rueedi et al. 1995; Leka 1997; Jurčák et al. 2006; Toriumi et al. 2015b), supporting the idea of the field-free plasma intrusion into the sunspot umbra (Spruit & Scharmer 2006). The azimuth of the LB magnetic field shows a tendency to be aligned with the LB orientation (Jurčák et al. 2006; Leka 1997). Leka (1997) suggested a magnetic canopy structure above an LB based on the analysis of inverted vector magnetograms. Later, Jurčák et al. (2006) reported a stratification of the magnetic field strength and temperature above LBs, which is consistent with the idea of magnetic canopy.

The presence of inclined LB magnetic fields embedded in more a vertical umbral field provides a favorable environment for magnetic reconnection to proceed at locations of strong discontinuity of the magnetic field. High resolution observations of strong LBs carried out by Berger & Berdyugina (2003) revealed an enhanced brightness in TRACE 1600 Å images, which indicates a magnetically heated LB chromosphere. The detection of persistent or transient brightness enhancements in the chromosphere above LBs suggests chromospheric heating in the LBs (Louis et al. 2008, 2009; Toriumi et al. 2015b).

In addition to brightness enhancement, several studies reported jet-like plasma ejections of LBs seen in various chromospheric (Roy 1973; Asai et al. 2001; Shimizu et al. 2009; Robustini et al. 2016) and UV spectral lines (Toriumi et al. 2015b; Tian et al. 2018). A typical property of the LB ejections is their intermittency. Asai et al. (2001) reported the repetitive occurrence of Hα surges with a mean lifetime of about 10 minutes. The surges showed a maximum apparent length of 20 Mm and a projection-corrected mean velocity of 40 km s^{-1}. LB jets often display a fan-shaped appearance and their tips follow a parabolic trajectory indicating an impulsive

A&A 643, A19 (2020)
https://doi.org/10.1051/0004-6361/202038287

Astronomy & Astrophysics

Eruptions from coronal hole bright points: Observations and non-potential modelling⋆

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Received 29 April 2020 / Accepted 3 September 2020

ABSTRACT

Context. We report on the third part of a series of studies on eruptions associated with small-scale loop complexes named coronal bright points (CBPs).

Aims. A single case study of a CBP in an equatorial coronal hole with an exceptionally large size is investigated to expand on our understanding of the formation of mini-filaments, their destabilisation, and the origin of the eruption triggering the formation of jet-like features recorded in extreme ultraviolet (EUV) and X-ray emission. We aim to explore the nature of the so-called micro-flares in CBPs associated with jets in coronal holes and mini coronal mass ejections in the quiet Sun.

Methods. Co-observations from the Atmospheric Imaging Assembly (AIA) and Helioseismic Magnetic Imager (HMI) on board the Solar Dynamics Observatory as well as GONG Hα images are used together with a non-linear force free field (NLFFF) relaxation approach, where the latter is based on a time series of HMI line-of-sight magnetograms.

Results. A mini-filament (MF) that formed beneath the CBP arcade about 3−4 h before the eruption is seen in the Hα and EUV AIA images to lift up and erupt triggering the formation of an X-ray jet. No significant photospheric magnetic flux concentration displacement (convergence) is observed and neither is magnetic flux cancellation between the two main magnetic polarities forming the CBP in the time period leading to MF lift-off. The CBP micro-flare is associated with three flare kernels that formed shortly after the MF lift-off. No observational signature is found for magnetic reconnection beneath the erupting MF. The applied NLFFF modelling successfully reproduces both the CBP loop complex as well as the magnetic flux rope that hosts the MF during the build-up to the eruption.

Conclusions. The applied NLFFF modelling is able to clearly show that an initial potential field can be evolved into a non-potential magnetic field configuration that contains free magnetic energy in the region that observationally hosts the eruption. The comparison of the magnetic field structure shows that the magnetic NLFFF model contains many of the features that can explain the different observational signatures found in the evolution and eruption of the CBP. In the future, it may eventually indicate the location of destabilisation that results in the eruptions of flux ropes.

Key words. Sun: activity – Sun: corona – Sun: filaments, prominences – Sun: magnetic fields – methods: numerical – methods: observational

1. Introduction

Coronal bright points (CBPs) have been intensively studied for almost five decades. They represent a set of small-scale coronal loops that connect magnetic flux concentrations of an opposite polarity. As the plasma confined in these loops is heated to over a million degrees, they are seen with enhanced emission in the extreme ultraviolet (EUV) and X-ray. CBPs are found to be uniformly distributed in the solar corona of the quiet Sun, coronal holes, and in the vicinity of active regions. This paper is the third of a series of studies that investigate the eruptive behaviour of CBPs. Mou et al. (2018, hereafter Paper I) explored the morphological and dynamical evolution of eruptions associated with CBPs in the context of their full lifetime evolution. The follow-up study by Galsgaard et al. (2019, hereafter Paper II) employed data-driven modelling based on a non-linear force-free field (NLFFF) relaxation code in order to reproduce the time evolution of the magnetic field of these eruptions; additionally, they provide insight into the possible causes for destabilisation and eruption. An overview of the observational findings and modelling of CBPs and related phenomena are given in Papers I and II. Madjarska (2019) provides a detailed review on CBPs.

Here, we briefly summarise the main findings on the eruptions from quiet Sun CBPs from Papers I and II. Paper I reports that 76% of the studied CBPs (31 out of 42) hosted at least one eruption during their lifetime. The study then explored the observational properties of 21 eruptions associated with 11 quiet Sun CBPs. The eruptions occurred, on average, ∼17 h after the CBP formation, where the typical lifetime of CBPs in images taken with the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) in the Fe XII 193 Å channel (hereafter AIA 193) was found to be ∼21 h. Convergence and

⋆ Movies associated to Figs. 9 and B.2 are available at https://www.aanda.org

A&A 642, A154 (2020)
https://doi.org/10.1051/0004-6361/202038288

Astronomy & Astrophysics

Impulsive wave excitation by rapidly changing granules⋆

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Received 29 April 2020 / Accepted 19 August 2020

ABSTRACT

It is not yet fully understood how magnetohydrodynamic waves in the interior and atmosphere of the Sun are excited. Traditionally, turbulent convection in the interior is considered to be the source of wave excitation in the quiet Sun. Over the last few decades, acoustic events observed in the intergranular lanes in the photosphere have emerged as a strong candidate for a wave excitation source. Here we report our observations of wave excitation by a new type of event: rapidly changing granules. Our observations were carried out with the Fast Imaging Solar Spectrograph in the Hα and Ca II 8542 Å lines and the TiO 7057 Å broadband filter imager of the 1.6 m *Goode* Solar Telescope at the Big Bear Solar Observatory. We identify granules in the internetwork region that undergo rapid dynamic changes such as collapse (event 1), fragmentation (event 2), or submergence (event 3). In the photospheric images, these granules become significantly darker than neighboring granules. Following the granules' rapid changes, transient oscillations are detected in the photospheric and chromospheric layers. In the case of event 1, the dominant period of the oscillations is close to 4.2 min in the photosphere and 3.8 min in the chromosphere. Moreover, in the Ca II–0.5 Å raster image, we observe repetitive brightenings in the location of the rapidly changing granules that are considered the manifestation of shock waves. Based on our results, we suggest that dynamic changes of granules can generate upward-propagating acoustic waves in the quiet Sun that ultimately develop into shocks.

Key words. Sun: photosphere – Sun: chromosphere – Sun: oscillations – methods: observational

1. Introduction

A wide range of observations have revealed that oscillations and waves are abundant in the solar atmosphere. They are clearly observed in the umbral and penumbral regions of sunspots (e.g., Beckers & Schultz 1972) and the network and internetwork regions of the quiet Sun (e.g., Orrall 1966; Deubner & Fleck 1990). It is not yet known how waves are generated in the solar atmosphere. Theoretical studies suggest that solar acoustic waves can be produced by impulsive disturbances in a gravitationally stratified medium (Kalkofen et al. 1994; Chae & Goode 2015). Chae & Goode (2015) report that when a region is disturbed by an impulsive event, acoustic waves with an acoustic cutoff frequency naturally arise in a medium. In terms of global p-mode oscillations, it is now generally accepted that p-modes are excited by turbulent convection (Goldreich & Kumar 1990). Nigam & Kosovichev (1999) found that a wave excitation source is located at a depth of 75 ± 25 km below the photosphere by comparing theoretical and observed p-mode power spectra. Since turbulent convection occurs ubiquitously, the observed oscillations show the superposition of oscillation signals coming from different sources. In this regard, investigating an individual wave excitation event that is well-separated in time and space could facilitate the establishment of the wave excitation process.

The wave excitation process appears to be related to localized disturbances below the photosphere. Using one-dimensional simulations, Goode et al. (1992) showed that acoustic waves are excited by individual wave excitation events occurring less than 200 km below the base of the photosphere. Rimmele et al. (1995) found a spatially localized transient wave energy flux that arises due to the excitation of waves beneath the photosphere. These phenomena are termed acoustic events and they are generally found in the intergranular lanes (Rimmele et al. 1995; Bello González et al. 2010). On a much larger scale, they are found in intergranular lanes located in or near the boundaries of regions with predominant downward vertical motions and horizontal converging flows on a mesogranular scale (Malherbe et al. 2015). Before the acoustic events occur, darkening of intergranular lanes is observed at the photospheric level, and the darkening is interpreted as catastrophic cooling that occurs in the intergranular lanes below the photosphere (Rimmele et al. 1995). Similarly, theoretical studies suggest that localized cooling events and subsequent downflows could be related to a wave excitation process (Rast 1999; Skartlien et al. 2000).

Furthermore, the waves generated beneath the photosphere propagate upward and affect the upper atmosphere. In the internetwork region, small intermittent brightenings have been observed in Ca II H and K filtergrams and time series of spectra (e.g., Bappu & Sivaraman 1971; Zirin 1974; Cram & Dame 1983). These brightenings are called Ca II bright grains or internetwork grains, and several studies have suggested that they are closely related to wave phenomena due to their recurrent behavior (for a review, see Rutten & Uitenbroek 1991). Based on one-dimensional non-local thermodynamic equilibrium (non-LTE) radiation-hydrodynamic simulations, Carlsson & Stein (1997) asserted that the bright grains are produced by waves coming from below the photosphere that subsequently develop into acoustic shocks in the mid-chromosphere (~1 Mm above

⋆ Movie attached to Fig. A.1 is available at https://www.aanda.org

A&A 640, A45 (2020)
https://doi.org/10.1051/0004-6361/202038141

Astronomy & Astrophysics

Inference of chromospheric plasma parameters on the Sun

Multilayer spectral inversion of strong absorption lines

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Received 10 April 2020 / Accepted 9 June 2020

ABSTRACT

The solar chromosphere can be observed well through strong absorption lines. We infer the physical parameters of chromospheric plasmas from these lines using a multilayer spectral inversion. This is a new technique of spectral inversion. We assume that the atmosphere consists of a finite number of layers. In each layer the absorption profile is constant and the source function varies with optical depth with a constant gradient. Specifically, we consider a three-layer model of radiative transfer where the lowest layer is identified with the photosphere and the two upper layers are identified with the chromosphere. The absorption profile in the photosphere is described by a Voigt function, and the profile in the chromosphere by a Gaussian function. This three-layer model is fully specified by 13 parameters. Four parameters can be fixed to prescribed values, and one parameter can be determined from the analysis of a satellite photospheric line. The remaining 8 parameters are determined from a constrained least-squares fitting. We applied the multilayer spectral inversion to the spectral data of the Hα and the Ca II 854.21 nm lines taken in a quiet region by the Fast Imaging Solar Spectrograph (FISS) of the Goode Solar Telescope (GST). We find that our model successfully fits most of the observed profiles and produces regular maps of the model parameters. The combination of the inferred Doppler widths of the two lines yields reasonable estimates of temperature and nonthermal speed in the chromosphere. We conclude that our multilayer inversion is useful to infer chromospheric plasma parameters on the Sun.

Key words. Sun: atmosphere – Sun: photosphere – Sun: chromosphere – methods: data analysis – radiative transfer – line: profiles

1. Introduction

Strong absorption lines in the visible and infrared wavelengths are important spectral windows into the solar chromosphere. These lines are observable from the ground and contain useful information of chromospheric plasmas. The Hα line of hydrogen has been the most popular of these windows. This line is favored because it is strong, and broad enough for filtergraph observations. The Hα filter images of solar regions display a great variety of intensity structures (Rutten 2008; Leenaarts et al. 2012). Even though the image data of the intensity directly provide much useful (mostly morphological) information of the underlying plasma structures, they do not provide estimates of plasma parameters, which are crucial for understanding the physical conditions. The inference of plasma parameters requires the spectral data of the strong absorption lines and a successful spectral inversion.

Spectral inversion is the process of inferring the plasma parameters from the observed profile of a spectral line. Two types of spectral inversion have been popular in solar observations that assume the constancy of physical parameters. One is the Milne-Eddington inversion, and the other is the cloud model inversion (Beckers 1964). The Milne-Eddington inversion is based on the assumption that the spectral line is formed in a plasma layer of infinite optical thickness where the absorption profile is constant over optical depth and the source function varies with a constant gradient. This inversion has been used mainly to model spectral lines formed in the photosphere and to infer the magnetic fields from their Stokes profiles (Unno 1956; Skumanich & Lites 1987).

The cloud model inversion, on the other hand, assumes that the line is formed in a plasma layer of finite optical depth where the source function as well as the absorption profile is constant over optical depth. This model has been used mostly to infer the physical parameters of cloud-like features lying far above the solar surface (Tziotziou 2007), as was well illustrated in Fig. 1 of Heinzel et al. (1999). A number of variants have been proposed to generalize the original cloud model of Beckers (1964) by incorporating the varying source function (Mein et al. 1996; Heinzel et al. 1999; Tsiropoula et al. 1999), the presence of multiple clouds (Gu et al. 1996), the concept of the embedded cloud (Steinitz et al. 1977; Chae 2014), etc. Despite these variants, the usage of the cloud model inversion is still limited, and is often hampered by the difficulty of choosing the incident intensity profile. Because the incident intensity below the feature of interest cannot be determined from observations, it has to be assumed to be the same as that in its neighborhood, for instance.

Here we present a multilayer inversion for modeling the spectral profiles of strong absorption lines. This represents a combined generalization of the two types of spectral inversion. A strong line is formed over a wide height range of the atmosphere from the photosphere to the chromosphere. The formation of the line in the photosphere can be modeled by the Milne-Eddington model, and the formation in the chromosphere can be modeled by the cloud model inversion. When the source function is allowed to vary with optical depth, there is no fundamental difference between the two types of inversion. Thus we expect that the formation of a strong line can be modeled by the radiative transfer across a finite number of layers in each of

Living Reviews in Solar Physics (2019) 16:2
https://doi.org/10.1007/s41116-019-0018-8

REVIEW ARTICLE

Coronal bright points

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Received: 9 August 2018 / Accepted: 11 February 2019 / Published online: 15 March 2019

Abstract

Coronal bright points (CBPs) are a fundamental class of solar activity. They represent a set of low-corona small-scale loops with enhanced emission in the extreme-ultraviolet and X-ray spectrum that connect magnetic flux concentrations of opposite polarities. CBPs are one of the main building blocks of the solar atmosphere outside active regions uniformly populating the solar atmosphere including active region latitudes and coronal holes. Their plasma properties classify them as downscaled active regions. Most importantly, their simple structure and short lifetimes of less than 20 h that allow to follow their full lifetime evolution present a unique opportunity to investigate outstanding questions in solar physics including coronal heating. The present Living Review is the first review of this essential class of solar phenomena and aims to give an overview of the current knowledge about the CBP general, plasma and magnetic properties. Several transient dynamic phenomena associated with CBPs are also briefly introduced. The observationally derived energetics and the theoretical modelling that aims at explaining the CBP formation and eruptive behaviour are reviewed.

Keywords Sun: coronal loops · Sun: activity · Sun: corona

Contents

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A&A 623, A78 (2019)
https://doi.org/10.1051/0004-6361/201834329

Astronomy & Astrophysics

Eruptions from quiet Sun coronal bright points

II. Non-potential modelling⋆

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Received 27 September 2018 / Accepted 28 January 2019

ABSTRACT

Context. Our recent observational study shows that the majority of coronal bright points (CBPs) in the quiet Sun are sources of one or more eruptions during their lifetime.

Aims. Here, we investigate the non-potential time-dependent structure of the magnetic field of the CBP regions with special emphasis on the time-evolving magnetic structure at the spatial locations where the eruptions are initiated.

Methods. The magnetic structure is evolved in time using a non-linear force-free field (NLFFF) relaxation approach based on a time series of helioseismic and magnetic imager (HMI) longitudinal magnetograms. This results in a continuous time series of NLFFFs. The time series is initiated with a potential field extrapolation based on a magnetogram taken well before the time of the eruptions. This initial field is then evolved in time in response to the observed changes in the magnetic field distribution at the photosphere. The local and global magnetic field structures from the time series of NLFFF field solutions are analysed in the vicinity of the eruption sites at the approximate times of the eruptions.

Results. The analysis shows that many of the CBP eruptions reported in a recent publication contain a twisted flux tube located at the sites of eruptions. The presence of flux ropes at these locations provides in many cases a direct link between the magnetic field structure, their eruption, and the observation of mini coronal mass ejections (mini-CMEs). It is found that all repetitive eruptions are homologous.

Conclusions. The NLFFF simulations show that twisted magnetic field structures are created at the locations hosting eruptions in CBPs. These twisted structures are produced by footpoint motions imposed by changes in the photospheric magnetic field observations. The true nature of the micro-flares remains unknown. Further 3D data-driven magnetohydrodynamic modelling is required to show how these twisted regions become unstable and erupt.

Key words. magnetic fields – methods: numerical – Sun: magnetic fields – magnetohydrodynamics (MHD) – Sun: activity

1. Introduction

The solar corona consists of a large selection of different phenomena that manifest themselves in X-ray and extreme-ultraviolet (EUV) observations over a variety of length and time scales. Generally, the main focus of interest is on the large-scale active regions (ARs) with all their complexity and highly time-dependent evolution. This however has a clear disadvantage. The high complexity of ARs is significantly challenging since their dynamical evolution is influenced by many different phenomena that act over a variety of length and time scales. At the other end of the size spectrum, the so-called coronal bright points (CBPs) represent one of the most typical omnipresent small-scale phenomenon in the solar corona. They are found in the quiet Sun, coronal holes, and in the vicinity of ARs. The plasma properties of CBPs indicate that they represent a scaled-down version of ARs (for more details see Madjarska 2019). Coronal bright points have a much simpler magnetic structure (≤60″ in diameter) and shorter lifespans (in EUV – ≤20 h, ≤12 h in X-rays), which permits us to follow their full lifecycle (e.g. Golub et al. 1974; Harvey et al. 1993; Mou et al. 2018). These properties of CBPs provide a unique opportunity to reach a better understanding of the basic physical mechanisms of coronal heating and dynamics.

The first paper of this study (Mou et al. 2018, hereafter Paper I) showed that more than two thirds (31 out of 42 or 76%) of CBPs host at least one eruption during their lifetime. The study explored the observational properties of 11 quiet-Sun CBPs and 21 eruptions associated with them. These eruptions took place ∼17 h after the CBP formation where the average lifetime of the CBPs in data taken in the 193 Å channel of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) was ∼21 h. They occurred during the convergence and cancellation phase of the bipole evolution of the CBPs. The CBP eruptions presented an expulsion of chromospheric material either as an elongated filamentary structure (mini-filament, MF) or a volume of cool material (cool plasma cloud, CPC). This was accompanied by the ejection of the CBP or higher overlying hot loops. In some cases, coronal waves were

⋆ Movies associated to Figs. 1–5 are available at https://www.aanda.org

⋆⋆ The name of this author was wrongly spelled in Mou et al. (2018, Paper I) as Chauzhou Mou.

Space Sci Rev (2018) 214:120
https://doi.org/10.1007/s11214-018-0551-0

Solar Ultraviolet Bursts

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Received: 27 April 2018 / Accepted: 5 October 2018 / Published online: 6 November 2018

Abstract The term "ultraviolet (UV) burst" is introduced to describe small, intense, transient brightenings in ultraviolet images of solar active regions. We inventorize their properties and provide a definition based on image sequences in transition-region lines. Coronal signatures are rare, and most bursts are associated with small-scale, canceling opposite-polarity fields in the photosphere that occur in emerging flux regions, moving magnetic features in sunspot moats, and sunspot light bridges. We also compare UV bursts with similar transition-region phenomena found previously in solar ultraviolet spectrometry and with similar phenomena at optical wavelengths, in particular Ellerman bombs. Akin to the lat-

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11214-018-0551-0) contains supplementary material, which is available to authorized users.

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A&A 619, A55 (2018)
https://doi.org/10.1051/0004-6361/201833243

Astronomy & Astrophysics

Eruptions from quiet Sun coronal bright points

I. Observations*

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Received 17 April 2018 / Accepted 13 August 2018

ABSTRACT

Context. Eruptions from coronal bright points (CBPs) are investigated in a two-part study.
Aims. The present study aims to explore in full detail the morphological and dynamical evolution of these eruptions in the context of the full lifetime evolution of CBPs. A follow-up study employs data-driven modelling based on a relaxation code to reproduce the time evolution of the magnetic field of these eruptive CBPs, and provide insight into the possible causes for destabilisation and eruption.
Methods. Observations of the full lifetime of CBPs in data taken with the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory in four passbands, He II 304 Å, Fe IX/X 171 Å, Fe XII 193 Å, and Fe XVIII 94 Å are investigated for the occurrence of plasma ejections, micro-flaring, mini-filament eruptions, and mini coronal-mass ejections (mini-CMEs). Data from the Helioseismic and Magnetic Imager are analysed to study the longitudinal photospheric magnetic field evolution associated with the CBPs and related eruptions.
Results. First and foremost, our study shows that the majority (76%) of quiet Sun CBPs (31 out of 42 CBPs) produce at least one eruption during their lifetime. From 21 eruptions in 11 CBPs, 18 of them occur, on average, ∼17 h after the CBP formation. The average lifetime of the CBPs in AIA 193 Å is ∼21 h. The time delay in the eruption occurrence coincides in each CBP with the convergence and cancellation phase of the CBP bipole evolution during which the CBPs become smaller until they fully disappear. The remaining three eruptions happen 4–6 h after the CBP formation. In 16 out of the 21 eruptions, the magnetic convergence and cancellation involve the CBP main bipoles, while in three eruptions, one of the BP magnetic fragments and a pre-existing fragment of opposite polarity converge and cancel. In one BP with two eruptions, cancellation was not observed. The CBP eruptions involve in most cases the expulsion of chromospheric material either as an elongated filamentary structure (mini-filament, MF) or a volume of cool material (cool plasma cloud, CPC), together with the CBP or higher overlying hot loops. Coronal waves were identified during three eruptions. A micro-flaring is observed beneath all erupting MFs/CPCs. Whether the destabilised MF causes the micro-flaring or the destabilisation and eruption of the MF is triggered by reconnection beneath the filament remains uncertain. In most eruptions, the cool erupting plasma either partially or fully obscures the micro-flare until the erupting material moves away from the CBP. From 21 eruptions, 11 are found to produce mini-CMEs. The dimming regions associated with the CMEs are found to be occupied by both the "dark" cool plasma and areas of weakened coronal emission caused by the depleted plasma density.
Conclusions. The present study demonstrates that the small-scale loop structures in the quiet Sun, the evolution of which is determined by their magnetic footpoint motions and/or ambient field topology, evolve into an eruptive phase that triggers the ejection of cool and hot plasma in the corona.

Key words. methods: observational – Sun: activity – Sun: corona – Sun: coronal mass ejections (CMEs)

1. Introduction

Coronal bright points (CBPs) are among the most typical small-scale phenomena in the solar corona. The earliest discovery of CBPs was in X-rays which initially led to the introduction of the term "X-ray BP" (Vaiana et al. 1970). X-ray BPs were seen in rocket mission observations as point-like structures with typical sizes ranging from 10″ to 50″ that form a bright core of ∼10″ (Golub et al. 1974). Their lifetimes differ when observed in different imaging channels, that is, when observed at different temperatures. Coronal bright points were found to have a lifetime in X-rays from 2 to 48 h with an average lifespan of 8 h (Golub et al. 1976). Later, using data from the Yohkoh X-ray telescope, Harvey et al. (1993) studied the lifetimes of 514 X-ray BPs and established that coronal hole BPs (34% of the total) have an average existence of 12 h 36 min, the quiet Sun (QS) BPs (60%) 13 h and 11 h for active-region CBPs (6%). Studies based on extreme-ultraviolet (EUV) observations (e.g. Habbal & Withbroe 1981; Zhang et al. 2001) show that the lifetimes of BPs in EUV range from a few minutes to a few days with an average value of 20 h (Zhang et al. 2001). For a review of the observational properties of CBPs and their modelling see (Madjarska 2018).

High-resolution spectroheliograms in Fe XIV 284 Å taken with the EUV spectrograph on the Apollo Telescope Mount on board *Skylab* first revealed that CBPs consist of small-scale

* The movies associated to Figs 1, 3, 4, 6 are available at https://www.aanda.org

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **478,** 1884–1892 (2018)
Advance Access publication 2018 May 11
doi:10.1093/mnras/sty1211

Helium abundance and speed difference between helium ions and protons in the solar wind from coronal holes, active regions, and quiet Sun

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Accepted 2018 May 4. Received 2018 May 2; in original form 2018 February 6

ABSTRACT

Two main models have been developed to explain the mechanisms of release, heating, and acceleration of the nascent solar wind, the wave-turbulence-driven (WTD) models and reconnection-loop-opening (RLO) models, in which the plasma release processes are fundamentally different. Given that the statistical observational properties of helium ions produced in magnetically diverse solar regions could provide valuable information for the solar wind modelling, we examine the statistical properties of the helium abundance ($A_{\rm He}$) and the speed difference between helium ions and protons ($v_{\alpha p}$) for coronal holes (CHs), active regions (ARs), and the quiet Sun (QS). We find bimodal distributions in the space of $A_{\rm He}$ and $v_{\alpha p}/v_{\rm A}$ (where $v_{\rm A}$ is the local Alfvén speed) for the solar wind as a whole. The CH wind measurements are concentrated at higher $A_{\rm He}$ and $v_{\alpha p}/v_{\rm A}$ values with a smaller $A_{\rm He}$ distribution range, while the AR and QS wind is associated with lower $A_{\rm He}$ and $v_{\alpha p}/v_{\rm A}$, and a larger $A_{\rm He}$ distribution range. The magnetic diversity of the source regions and the physical processes related to it are possibly responsible for the different properties of $A_{\rm He}$ and $v_{\alpha p}/v_{\rm A}$. The statistical results suggest that the two solar wind generation mechanisms, WTD and RLO, work in parallel in all solar wind source regions. In CH regions WTD plays a major role, whereas the RLO mechanism is more important in AR and QS.

Key words: methods: observational – Sun: abundances – Sun: activity – solar wind.

1 INTRODUCTION

Helium is ranked as the second most abundant element in the Sun and in the solar wind (SW), and it is an important tool in exploring the nature of the solar wind. In particular, the difference in the helium ion and proton properties can help us understand the mechanisms for the release, heating, and acceleration of the nascent solar wind (e.g. Marsch et al. 1982a; Neugebauer et al. 1996; Steinberg et al. 1996; Reisenfeld et al. 2001; Kasper et al. 2007, 2012). The abundance of helium ($A_{\rm He}$) and the speed difference between helium ions and protons ($v_{\alpha p}$) in the solar wind were extensively studied in the past. The abundance of helium is about 8.5 per cent in the photosphere (e.g. Grevesse & Sauval 1998; Asplund et al. 2009). Measurements of the corona above polar coronal holes and surrounding quiet Sun areas showed that $A_{\rm He}$ is in the range 4–5 per cent (Laming & Feldman 2001, 2003). The $A_{\rm He}$ is usually below 5 per cent in the solar wind and changes with the solar activity (Ogilvie & Hirshberg 1974; Feldman et al. 1978). Using data obtained by *Wind*, Aellig, Lazarus & Steinberg (2001) confirmed this finding and also established that this tendency is more clear for the slow SW. By dividing the solar wind into 25 speed intervals, Kasper et al. (2007, 2012) examined the relationship between the helium abundance and the speed of the solar wind for a whole solar activity cycle, and found a strong correlation between $A_{\rm He}$ and sunspot numbers for the slowest solar wind.

The speeds of helium ions are usually larger than the proton speeds in the solar wind, although helium ions are heavier than protons. Using data obtained by Helios, Marsch et al. (1982a) analysed the speed difference between helium ions and protons, and found that $v_{\alpha p}$ increases with the solar wind speed. While $v_{\alpha p}$ is close to the local Alfvén wave speed in the fast SW, the average $v_{\alpha p}$ for the slow SW is close to zero, and $v_{\alpha p}$ in the fast SW decreases with the increase of the heliocentric distances at almost the same rate as of $v_{\rm A}$. Consequently, these results were confirmed from observations made by *Ulysses* (Neugebauer et al. 1996; Reisenfeld et al. 2001), *Wind* (Steinberg et al. 1996), and *ACE* (Berger, Wimmer-Schweingruber & Gloeckler 2011).

The plasma release, heating, and acceleration mechanisms of the nascent solar wind are a fundamental problem in solar and space physics. Two classes of models, the wave-turbulence-driven (WTD) models (Hollweg 1986; Wang & Sheeley 1991; Cranmer, van

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A&A 615, A47 (2018)
https://doi.org/10.1051/0004-6361/201629304

Astronomy & Astrophysics

Energetics of Hi-C EUV brightenings

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Received 13 July 2016 / Accepted 23 March 2018

ABSTRACT

We study the thermal structure and energetics of the point-like extreme ultraviolet (EUV) brightenings within a system of fan loops observed in the active region AR 11520. These brightenings were simultaneously observed on 2012 July 11 by the High-resolution Coronal (Hi-C) imager and the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). We identified 27 brightenings by automatically determining intensity enhancements in both Hi-C and AIA 193 Å light curves. The energetics of these brightenings were studied using the Differential Emission Measure (DEM) diagnostics. The DEM weighted temperatures of these transients are in the range $\log T(K) = 6.2-6.6$ with radiative energies $\approx 10^{24-25}$ ergs and densities approximately equal to a few times 10^9 cm^{-3}. To the best of our knowledge, these are the smallest brightenings in EUV ever detected. We used these results to determine the mechanism of energy loss in these brightenings. Our analysis reveals that the dominant mechanism of energy loss for all the identified brightenings is conduction rather than radiation.

Key words. Sun: atmosphere – Sun: corona – Sun: UV radiation – Sun: transition region – Sun: activity

1. Introduction

One of the most important unsolved problems in solar and heliospheric physics is that of determining the mechanism by which the corona is heated. It is clear now that coronal heating and magnetic fields are correlated, but the actual mechanism of how magnetic energy is transferred to coronal thermal energy is not well understood (see Klimchuk 2006, for a review). Parker (1988) suggested a heating mechanism wherein the energy that is built-up due to highly turbulent convective motions in the photosphere, in the form of twisting and tangling of magnetic field lines, is transferred to the upper layers and released through magnetic reconnection processes. This process is inherently impulsive in nature and is often referred to as the nanoflare model of coronal heating. It was envisioned by Parker (1988) that these impulsive events may have an energy content of $\approx 10^{24}$ ergs, approximately nine orders of magnitude lower than standard solar flares. However, there has been no direct observation of individual nanoflares, possibly because they occur at scales unresolvable by the currently available instruments. Therefore, their existence has always been questioned.

Numerous small scale energetic events have been observed in the solar atmosphere with length-scales ranging from a few arcseconds to tens of arcseconds and lifetimes ranging from a few minutes to hours. Some examples are explosive events (e.g. Dere et al. 1989; Gupta & Tripathi 2015; Huang et al. 2017, and the references therein), extreme ultraviolet (EUV) blinkers (e.g. Harrison 1997; Subramanian et al. 2012, and the references therein), spicules (e.g. Roberts 1945; Tsiropoula et al. 2012, and the references therein), macrospicules (e.g. Bohlin et al. 1975; Moore et al. 1977; Kayshap et al. 2013, and the references therein) and X-ray & EUV jets (e.g. Shibata et al. 1992; Chifor et al. 2008; Subramanian et al. 2010; Chandra et al. 2015; Mulay et al. 2016, and the references therein). These events are omnipresent in the solar atmosphere. However, their contribution to coronal heating is still inconclusive.

Spatial resolution plays a crucial role in the interpretation of observed coronal plasma. So far, the space-borne EUV and X-ray observations have not achieved the resolutions, which would allow us to observe the individual strands that are presumed to make up coronal loops. The High-resolution Coronal (Hi-C; Cirtain et al. 2013) rocket flight has recorded the best-resolution images of the solar corona. These observations have provided us with a spectacular trove of data of a group of active regions (ARs) and have unraveled interesting transient features in the moss (Testa et al. 2013) and inter-moss regions (Winebarger et al. 2013), as well as at the footpoints of a fan loop system associated with AR 11520 (EUV bright dots; Régnier et al. 2014). These brightenings were classified as nanoflare-like brightenings by the respective authors.

The study presented in this paper is focussed on the transients EUV brightenings seen in fan loop systems associated with AR 11520. These brightenings appear as tiny dot-like intensity enhancements. A sample of eight such events was studied by Régnier et al. (2014). These events were characterised in four different categories based on their light curve characteristics, as single intensity peak events, double intensity peak events, long duration events, and bursty events with multiple intensity peaks. They have length scales of $\sim 1''$ and lifetime of ~ 25 s. These scales are either comparable to or much shorter than the resolvable limits of the best available EUV full-disk imager, the

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A&A 606, A46 (2017)
DOI: 10.1051/0004-6361/201731041

Astronomy & Astrophysics

Magnetic topological analysis of coronal bright points*

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Received 25 April 2017 / Accepted 11 July 2017

ABSTRACT

Context. We report on the first of a series of studies on coronal bright points which investigate the physical mechanism that generates these phenomena.

Aims. The aim of this paper is to understand the magnetic-field structure that hosts the bright points.

Methods. We use longitudinal magnetograms taken by the Solar Optical Telescope with the Narrowband Filter Imager. For a single case, magnetograms from the Helioseismic and Magnetic Imager were added to the analysis. The longitudinal magnetic field component is used to derive the potential magnetic fields of the large regions around the bright points. A magneto-static field extrapolation method is tested to verify the accuracy of the potential field modelling. The three dimensional magnetic fields are investigated for the presence of magnetic null points and their influence on the local magnetic domain.

Results. In nine out of ten cases the bright point resides in areas where the coronal magnetic field contains an opposite polarity intrusion defining a magnetic null point above it. We find that X-ray bright points reside, in these nine cases, in a limited part of the projected fan-dome area, either fully inside the dome or expanding over a limited area below which typically a dominant flux concentration resides. The tenth bright point is located in a bipolar loop system without an overlying null point.

Conclusions. All bright points in coronal holes and two out of three bright points in quiet Sun regions are seen to reside in regions containing a magnetic null point. An as yet unidentified process(es) generates the brigh points in specific regions of the fan-dome structure.

Key words. Sun: atmosphere – Sun: corona – Sun: magnetic fields – methods: numerical – methods: observational

1. Introduction

The term "coronal bright point" (BP) describes a phenomenon in the solar atmosphere that appears in extreme-ultraviolet (EUV) and X-ray images as a small-scale multi-loop system of enhanced coronal emission that is associated with magnetic bipolar features (e.g. Golub et al. 1977; Webb et al. 1993; Brown et al. 2001; Mou et al. 2016). BPs were detected for the first time in soft X-ray photographs taken during rocket missions in 1968–1973 (Vaiana et al. 1973) and later were analysed in great detail during the *Skylab* mission (Golub et al. 1976a,b; Habbal 1992, and the references therein). Habbal et al. (1990) found that BPs show no difference in their properties in coronal holes (CH) and the quiet Sun (QS), which led the authors to conclude that they do not depend on the structure of the surrounding background corona.

BPs have sizes in the range 10″–50″. Their average lifetime derived from observations taken with the Fe XII 195 Å filter of the Extreme-ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SoHO) is 20 h (Zhang et al. 2001), while recently Mou et al. (2016) reported a lifetime ranging from 2.7 to 58.8 h from a study of 70 BPs observed with the Fe XII 193 Å filter of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO). In X-rays, BPs have lifetimes of only eight hours (Golub et al. 1974). Zhang et al. (2001) concluded that the temperatures of BPs are generally below 2×10^6 K, which also explains their smaller size and shorter lifetime in X-rays compared to lower temperature observations. Habbal et al. (1990) found that simultaneously measured peaks of emission in six different lines (with a large range of formation temperatures from chromospheric to coronal) were not always co-spatial, implying that the BPs may consist of a complex of small-scale loops at different temperatures and heights. Kwon et al. (2012) investigated the multi-thermal nature of EUV BPs using the coronal 171, 193, and 284 Å, and the 304 Å (chromosphere – transition region) filter images from observations with the Extreme-UltraViolet Imager (EUVI) on board the twin Solar Terrestrial Relations Observatory (STEREO) satellites. The correlation coefficient between the different channels made the authors conclude that BPs at 171, 195, and 284 Å belong to the same loop system, while the BP emission in 304 Å can be interpreted as coming from cool legs of the loops.

The coronal emission evolution of BPs strongly correlates with the variation of the total unsigned photospheric magnetic flux of the associated magnetic bipolar features (MBFs; e.g. Preś & Phillips 1999; Madjarska et al. 2003; Ugarte-Urra et al. 2004). Mou et al. (2016) concluded that the formation of the

* The movies are available at http://www.aanda.org

The Astrophysical Journal, 842:38 (16pp), 2017 June 10 https://doi.org/10.3847/1538-4357/aa7415

The Plasma Parameters and Geometry of Cool and Warm Active Region Loops

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Received 2016 October 25; revised 2017 May 2; accepted 2017 May 4; published 2017 June 12

Abstract

How the solar corona is heated to high temperatures remains an unsolved mystery in solar physics. In the present study we analyze observations of 50 whole active region loops taken with the Extreme-ultraviolet Imaging Spectrometer on board the *Hinode* satellite. Eleven loops were classified as cool loops (<1 MK) and 39 as warm loops (1–2 MK). We study their plasma parameters, such as densities, temperatures, filling factors, nonthermal velocities, and Doppler velocities. We combine spectroscopic analysis with linear force-free magnetic field extrapolation to derive the 3D structure and positioning of the loops, their lengths and heights, and the magnetic field strength along the loops. We use density-sensitive line pairs from Fe XII, Fe XIII, Si X, and Mg VII ions to obtain electron densities by taking special care of intensity background subtraction. The emission measure loci method is used to obtain the loop temperatures. We find that the loops are nearly isothermal along the line of sight. Their filling factors are between 8% and 89%. We also compare the observed parameters with the theoretical Rosner–Tucker–Vaiana (RTV) scaling law. We find that most of the loops are in an overpressure state relative to the RTV predictions. In a follow-up study, we will report a heating model of a parallel-cascade-based mechanism and will compare the model parameters with the loop plasma and structural parameters derived here.

Key words: methods: observational – Sun: corona – techniques: spectroscopic

1. Introduction

Loops are one of the main building blocks of the solar atmosphere. Understanding their heating, however, remains a huge challenge (Klimchuk 2006). Particularly, the question whether the plasma is heated by steady or impulsive, uniform or localized mechanism(s) is still open (Susino et al. 2010). Priest et al. (1998) noted that the physical parameter (e.g., temperature and density) profiles along a coronal loop are highly sensitive to the heating mechanisms. Accordingly, theoretical heating models require accurate measurements of the plasma parameters along coronal loops, e.g., temperature, density, filling factor, velocity, magnetic field, etc.

A number of authors have used imaging or spectral data to investigate the physical properties of coronal loops. Based on observations, loops are divided into cool, warm, and hot loops. Cool loops are those typically detected in ultraviolet (UV)/extreme-ultraviolet (EUV) lines with formation temperatures between 0.1 and 1 MK (e.g., Reale 2014; Gupta et al. 2015). The temperature range of warm loops is 1–2 MK (e.g., Lenz et al. 1999). Hot loops are usually observed in soft X-rays. They are located in active regions (ARs) and have temperatures higher than 2 MK (e.g., Yoshida et al. 1995).

Warm loops are reported in several comprehensive studies based on spectral data taken with the Coronal Diagnostic Spectrometer (CDS) on board the *Solar and Heliospheric Observatory* (*SOHO*; e.g., Schmelz et al. 2001; Del Zanna & Mason 2003; Scott et al. 2008) and Extreme-ultraviolet Imaging Spectrometer (EIS) on board the *Hinode* satellite (e.g., Warren et al. 2008; Tripathi et al. 2009; Scott et al. 2012; Gupta et al. 2015). There are also a number of studies on warm loops using imaging observations (e.g., Lenz et al. 1999; Aschwanden et al. 2008).

Lenz et al. (1999) reported the temperature and emission measure along segments of four warm loops using imaging data from the *Transition Region and Coronal Explorer* satellite and compared the observed loop structure with theoretical isothermal and nonisothermal static loop models. They found that the loop temperature profile is near constant and incompatible with the theoretical results. Schmelz et al. (2001) studied an AR warm loop in CDS data and concluded that the temperature distribution is "inconsistent with isothermal plasma along either the line of sight (LOS) or the length of the loop." The authors suggested that both radiative and conductive losses are important in the case of their loop. Tripathi et al. (2009) obtained the physical parameters along a segment from an AR loop using EIS data and obtained temperatures of 0.8–1.5 MK, electron densities in the range of 10^{9}–$10^{8.5}$ cm^{-3}, and filling factors from 0.02 to 4 as the loop height increased. They also concluded that the loop is close to isothermal for each position along the loop after accounting for the background emission (see also similar results by Del Zanna 2003; Del Zanna & Mason 2003).

There are also reports on the physical parameters along the whole length of a loop. For example, Priest et al. (1998) analyzed a whole loop using *Yohkoh* Soft X-ray Telescope (SXT) data and concluded that the uniform heating model can fit well the loop observational temperature distribution. More importantly, it was found that the "observed variation in temperature along a loop is highly sensitive to the spatial distribution of the heating." Landi & Landini (2004) made use of spectral data from CDS and compared them with a 1D, time-independent, nonstatic model. They found no agreement between the model predictions and the observations for the whole loop. Aschwanden et al. (2008) used a triangulation method to obtain the 3D reconstructions of 30 coronal loops in an AR observed simultaneously with the Extreme-Ultraviolet Imaging (EUVI) telescopes on the *STEREO A* and *B* spacecraft and adopted an emission measure method from triple-filter images to derive the densities and temperatures of the loops. They compared the obtained pressure of all loops with the

The Astrophysical Journal, 836:169 (9pp), 2017 February 20 https://doi.org/10.3847/1538-4357/aa5cba

Charge States and FIP Bias of the Solar Wind from Coronal Holes, Active Regions, and Quiet Sun

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Received 2016 September 13; revised 2017 January 22; accepted 2017 January 25; published 2017 February 17

Abstract

Connecting in situ measured solar-wind plasma properties with typical regions on the Sun can provide an effective constraint and test to various solar wind models. We examine the statistical characteristics of the solar wind with an origin in different types of source regions. We find that the speed distribution of coronal-hole (CH) wind is bimodal with the slow wind peaking at $\sim$400 km s^{-1} and the fast at $\sim$600 km s^{-1}. An anti-correlation between the solar wind speeds and the O^{7+}/O^{6+} ion ratio remains valid in all three types of solar wind as well during the three studied solar cycle activity phases, i.e., solar maximum, decline, and minimum. The N_{Fe}/N_O range and its average values all decrease with the increasing solar wind speed in different types of solar wind. The N_{Fe}/N_O range (0.06–0.40, first ionization potential (FIP) bias range 1–7) for active region wind is wider than for CH wind (0.06–0.20, FIP bias range 1–3), while the minimum value of N_{Fe}/N_O ($\sim$ 0.06) does not change with the variation of speed, and it is similar for all source regions. The two-peak distribution of CH wind and the anti-correlation between the speed and O^{7+}/O^{6+} in all three types of solar wind can be explained qualitatively by both the wave-turbulence-driven and reconnection-loop-opening (RLO) models, whereas the distribution features of N_{Fe}/N_O in different source regions of solar wind can be explained more reasonably by the RLO models.

Key words: solar wind – Sun: abundances – Sun: activity – Sun: corona – Sun: magnetic fields

1. Introduction

It is common knowledge that the in situ solar wind has two basic components: a steady fast ($\sim$800 km s^{-1}) and a variable slow ($\sim$400 km s^{-1}) component (e.g., Schwenn 2006, and the references therein). While it is widely accepted that fast solar wind (FSW) originates in coronal holes (CHs; Krieger et al. 1973; Zirker 1977; Gosling & Pizzo 1999), the source regions of slow solar wind (SSW) are still poorly understood. One of the sources of the SSW has been linked to sources at the edges of active regions (ARs; e.g., Kojima et al. 1999; Sakao et al. 2007; Culhane et al. 2014, etc.) and it is also believed that SSW originates in the quiet Sun (QS; e.g., Woo & Habbal 2000; Feldman et al. 2005; Fu et al. 2015).

Intuitively, identification of wind sources can be done by tracing wind parcels back to the Sun. By applying a potential-field-source-surface (PFSS) model, Luhmann et al. (2002) mapped a low-latitude solar wind back to the photosphere for nearly three solar activity cycles. They showed, for instance, that polar CHs contribute to the solar wind only over about half the solar cycle, while for the rest of the time the low-latitude solar wind originates from "isolated low-latitude and mid-latitude CHs or polar CH extensions that have a flow character distinct from that of the large polar hole flows." Using a standard two-step mapping procedure, Neugebauer et al. (2002) traced solar wind parcels back to the solar surface for four Carrington rotations during a solar maximum phase. The solar wind was divided into two categories, CH and AR wind, and their statistical parameters were analyzed separately. The authors reported that the O^{7+}/O^{6+} ion ratio is lower for the coronal-hole wind in comparison to the AR wind. Fu et al. (2015) traced the solar wind back to its sources and classified the solar wind by the type of the source region, i.e., AR, QS, and CH wind. They found that the fractions occupied by each type of solar wind change with the solar cycle activity and established that the QS regions are an important source of the solar wind during the solar minimum phase.

Alternatively, wind sources can be determined by examining in situ charge states and elemental abundances. For the former, the charge states of species such as oxygen and carbon are regarded as a telltale signature of the solar wind sources. For example, the density ratio of $n(O^{7+})$ to $n(O^{6+})$ (i.e., ionic charge state ratio, hereafter O^{7+}/O^{6+}) does not vary with the distance beyond several solar radii above the solar surface, and, therefore, it reflects the electron temperature in the coronal sources (Owocki et al. 1983; Buergi & Geiss 1986). As the temperatures in different source regions are different, therefore, the source regions can be identified by the charge states detected in situ (Zhao et al. 2009; Landi et al. 2012). The first ionization potential (FIP) effect describes the element anomalies in the upper solar atmosphere and the solar wind (especially in the SSW), i.e., the abundance increase of elements with a FIP of less than 10 eV (e.g., Mg, Si, and Fe) to those with a higher FIP (e.g., O, Ne, and He). The in situ measured FIP bias is usually represented by N_{Fe}/N_O and it can be expressed as

$$\text{FIP bias} = \frac{(N_{Fe}/N_O)_{\text{solar wind}}}{(N_{Fe}/N_O)_{\text{photosphere}}}, \quad (1)$$

where N_{Fe}/N_O is the abundance ratio of iron (Fe) and oxygen (O). In the slow wind the FIP bias is $\sim$3, while in the fast streams it is found to be smaller but still above 1 (von Steiger et al. 2000). As the FIP bias in CHs, the QS, and ARs has significant differences, the solar wind detected in situ can be linked to those source regions (e.g., Feldman et al. 2005; Laming 2015, and the references therein). In the present study, we only present the in situ measurements of N_{Fe}/N_O that can

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **464**, 1753–1761 (2017) doi:10.1093/mnras/stw2469
Advance Access publication 2016 September 28

Explosive events in active region observed by IRIS and SST/CRISP

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Accepted 2016 September 27. Received 2016 September 26; in original form 2016 June 28

ABSTRACT

Transition-region explosive events (EEs) are characterized by non-Gaussian line profiles with enhanced wings at Doppler velocities of 50–150 km s^{-1}. They are believed to be the signature of solar phenomena that are one of the main contributors to coronal heating. The aim of this study is to investigate the link of EEs to dynamic phenomena in the transition region and chromosphere in an active region. We analyse observations simultaneously taken by the Interface Region Imaging Spectrograph (IRIS) in the Si IV 1394 Å line and the slit-jaw (SJ) 1400 Å images, and the Swedish 1-m Solar Telescope in the Hα line. In total 24 events were found. They are associated with small-scale loop brightenings in SJ 1400 Å images. Only four events show a counterpart in the Hα−35 km s^{-1} and Hα+35 km s^{-1} images. Two of them represent brightenings in the conjunction region of several loops that are also related to a bright region (granular lane) in the Hα−35 km s^{-1} and Hα+35 km s^{-1} images. 16 are general loop brightenings that do not show any discernible response in the Hα images. Six EEs appear as propagating loop brightenings, from which two are associated with dark jet-like features clearly seen in the Hα−35 km s^{-1} images. We found that chromospheric events with jet-like appearance seen in the wings of the Hα line can trigger EEs in the transition region and in this case the IRIS Si IV 1394 Å line profiles are seeded with absorption components resulting from Fe II and Ni II. Our study indicates that EEs occurring in active regions have mostly upper-chromosphere/transition-region origin. We suggest that magnetic reconnection resulting from the braidings of small-scale transition region loops is one of the possible mechanisms of energy release that are responsible for the EEs reported in this paper.

Key words: methods: observational – techniques: spectroscopic – Sun: activity – Sun: chromosphere – Sun: transition region.

1 INTRODUCTION

Explosive events (EEs) are small-scale transients (duration <600 s, size <5 arcsec) observed in the solar transition region, and describe non-Gaussian line profiles with enhanced wings at Doppler velocities of 50–150 km s^{-1} (Brueckner & Bartoe 1983; Dere, Bartoe & Brueckner 1989). The physical nature of EEs is under investigation for more than two decades. EEs were first suggested to be the spectral footprint of bidirectional jets caused by magnetic reconnection (Dere et al. 1991; Innes et al. 1997). Later, chromospheric upflow events (Chae et al. 1998b), siphon flows in small-scale loops (Teriaca et al. 2004), surges (Madjarska, Doyle & de Pontieu 2009) and transient brightenings, and X-ray jets (Madjarska et al. 2012) have been associated with EEs.

Porter & Dere (1991) reported that EEs occur in the solar magnetic network lanes. This has been later confirmed by many further studies (e.g. Madjarska & Doyle 2003; Ning, Innes & Solanki 2004; Teriaca et al. 2004; Muglach 2008, etc.). Chae et al. (1998a) established that the majority of EEs are associated with the cancellation of photospheric magnetic flux, which was recently confirmed by Huang et al. (2014) and Gupta & Tripathi (2015). EEs were modelled by Innes & Tóth (1999), Roussev & Galsgaard (2002), Roussev et al. (2001c), Roussev et al. (2001b), Roussev et al. (2001a), and Innes et al. (2015) in 2D numerical simulations as the product of magnetic reconnection.

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The Astrophysical Journal Letters, 829:L30 (7pp), 2016 October 1 doi:10.3847/2041-8205/829/2/L30

NARROW-LINE-WIDTH UV BURSTS IN THE TRANSITION REGION ABOVE SUNSPOTS OBSERVED BY IRIS

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Received 2016 July 5; revised 2016 August 16; accepted 2016 August 16; published 2016 September 29

ABSTRACT

Various small-scale structures abound in the solar atmosphere above active regions, playing an important role in the dynamics and evolution therein. We report on a new class of small-scale transition region structures in active regions, characterized by strong emissions but extremely narrow Si IV line profiles as found in observations taken with the Interface Region Imaging Spectrograph (IRIS). Tentatively named as narrow-line-width UV bursts (NUBs), these structures are located above sunspots and comprise one or multiple compact bright cores at sub-arcsecond scales. We found six NUBs in two data sets (a raster and a sit-and-stare data set). Among these, four events are short-lived with a duration of ∼10 minutes, while two last for more than 36 minutes. All NUBs have Doppler shifts of 15–18 km s^{-1}, while the NUB found in sit-and-stare data possesses an additional component at ∼50 km s^{-1} found only in the C II and Mg II lines. Given that these events are found to play a role in the local dynamics, it is important to further investigate the physical mechanisms that generate these phenomena and their role in the mass transport in sunspots.

Key words: line: profiles – methods: observational – Sun: atmosphere – Sun: transition region – sunspots

Supporting material: animations

1. INTRODUCTION

Small-scale structures and activities abound in solar active regions (ARs), including explosive events (Dere et al. 1989; Innes et al. 1997; Huang et al. 2014), blinkers (Harrison et al. 1999; Parnell et al. 2002), small-scale loops (Huang et al. 2015), spicules and fibrils (Wilhelm 2000; Tsiropoula et al. 2012; Pereira et al. 2014; Rouppe van der Voort et al. 2015), to name a few. Thanks to recent high-resolution observations of ARs, activities have been seen on even finer scales. For example, observations made with the High-resolution Coronal Imager (Hi-C; Kobayashi et al. 2014) have indicated signatures of magnetic braids with scales of ∼0.″2 in AR loops (Cirtain et al. 2013), heating events with a similar size in both moss (Testa et al. 2013) and inter-moss loops (Winebarger et al. 2013), as well as fine loops at sub-arcsecond scales (Peter et al. 2013). Using Hi-C observations, Régnier et al. (2014) reported on the discovery of small-scale brightenings named "EUV bright dots" (EUV BDs) found at the base of large-scale loops rooted at the edge of ARs with a characteristic duration of 25 s and a typical length of $\lesssim 1''$. More recently, the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) has discovered very broad Si IV emission profiles blended by strong absorption lines in small-scale (∼1″) compact brightenings in ARs (Peter et al. 2014). These brightenings, named "hot bombs," were suggested to be signatures of hot plasmas in the photosphere generated by magnetic reconnections. In addition, Tian et al. (2014) reported on sub-arcsecond BDs implicating heating events in the transition region (TR) above umbrae and penumbrae of sunspots underlying ARs. Deng et al. (2016) found that these BDs do not have a chromospheric response and suggested their TR formation. Similarly, BDs in sunspots were also recently reported in Hi-C observations (Alpert et al. 2016). In sunspot umbrae and penumbrae, Kleint et al. (2014) presented IRIS observations of small-scale brightenings associated with supersonic downflows, which were suggested to play a role in heating the TR above sunspots. Penumbral jets have been investigated with IRIS data and were found to be heated to TR temperature (Vissers et al. 2015).

In the present work, we report on a new class of fine-scale structures in ARs, characterized by very bright emissions but extremely narrow profiles in the Si IV line in the TR above sunspots as observed by IRIS. In what follows, we present our observations in Section 2, describe the results in Section 3, and summarize our findings in Section 4 where some discussions are also offered.

2. OBSERVATIONS

The IRIS observations analyzed in this study include two data sets. The first (DATA1) is a raster data set taken on 2014 February 16 from 20:19 UT to 21:04 UT when IRIS was targeting AR 11974 and scanned the same area twice with a 0.″35 wide slit and an exposure time of 2 s. The spectral slit scanned a 140″ × 175″ field of view (FOV) with a step size of 0.″35 and an along-slit pixel size of 0.″17, in which several sunspots and their surrounding plages were observed (see Figures 1(b)–(d)).

The second data set (DATA2) was taken on 2014 March 10 from 04:10 UT to 10:26 UT, when IRIS targeted NOAA 11998 in a sit-and-stare mode with an exposure time of 15 s. In both data sets, we analyzed the spectral data taken in the Si IV 1394 Å and 1403 Å, C II 1334 Å and 1336 Å, Mg II k 2796 Å and Mg II h 2803 Å lines as well as the continuum around 2832 Å. In both data sets, the slit-jaw (SJ) data with a spatial resolution of 0.″34 taken in the 1330 Å and

Solar Phys (2016) 291:2441–2456
DOI 10.1007/s11207-016-0979-x

Sources of the Slow Solar Wind During the Solar Cycle 23/24 Minimum

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Received: 1 April 2016 / Accepted: 17 August 2016 / Published online: 22 September 2016

Abstract We investigate the characteristics and the sources of the slow ($< 450\ \mathrm{km\,s^{-1}}$) solar wind during the four years (2006 – 2009) of low solar activity between Solar Cycles 23 and 24. We used a comprehensive set of *in-situ* observations in the near-Earth solar wind (*Wind* and ACE) and removed the periods when large-scale interplanetary coronal mass ejections were present. The investigated period features significant variations in the global coronal structure, including the frequent presence of low-latitude active regions in 2006 – 2007, long-lived low- and mid-latitude coronal holes in 2006 – mid-2008 and mostly the quiet Sun in 2009. We examined Carrington rotation averages of selected solar plasma, charge state, and compositional parameters and distributions of these parameters related to the quiet Sun, active region Sun, and the coronal hole Sun. While some of the investigated parameters (*e.g.* speed, the C^{+6}/C^{+4} and He/H ratios) show clear variations over our study period and with solar wind source type, some (Fe/O) exhibit very little changes. Our results highlight the difficulty of distinguishing between the slow solar wind sources based on the inspection of solar wind conditions.

Keywords Solar wind · Corona · Modelling

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New Astronomy 48 (2016) 66–73

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Homologous prominence non-radial eruptions: A case study

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HIGHLIGHTS

- A sequence of four homologous prominence eruptions of confined type is analysed.
- Homologous behaviour during the pre-eruptive phase is found in 17 GHz radio data.
- A new (fourth) criterion for homology is defined.
- Maximum height increase of each consecutive eruption-an important homology feature.

ARTICLE INFO

Article history:
Received 13 January 2016
Revised 27 April 2016
Accepted 4 May 2016
Available online 10 May 2016

Keywords:
Solar prominences
Eruption
Initiation
Propagation
Reformation
Radio emission
Microwave
Radio burst
Type III

ABSTRACT

The present study provides important details on homologous eruptions of a solar prominence that occurred in active region NOAA 10904 on 2006 August 22. We report on the pre-eruptive phase of the homologous feature as well as the kinematics and the morphology of a forth from a series of prominence eruptions that is critical in defining the nature of the previous consecutive eruptions. The evolution of the overlying coronal field during homologous eruptions is discussed and a new observational criterion for homologous eruptions is provided. We find a distinctive sequence of three activation periods each of them containing pre-eruptive precursors such as a brightening and enlarging of the prominence body followed by small surge-like ejections from its southern end observed in the radio 17 GHz. We analyse a fourth eruption that clearly indicates a full reformation of the prominence after the third eruption. The fourth eruption although occurring 11 h later has an identical morphology, the same angle of propagation with respect to the radial direction, as well as similar kinematic evolution as the previous three eruptions. We find an important feature of the homologous eruptive prominence sequence that is the maximum height increase of each consecutive eruption. The present analysis establishes that all four eruptions observed in Hα are of confined type with the third eruption undergoing a thermal disappearance during its eruptive phase. We suggest that the observation of the same direction of the magnetic flux rope (MFR) ejections can be consider as an additional observational criterion for MFR homology. This observational indication for homologous eruptions is important, especially in the case of events of typical or poorly distinguishable morphology of eruptive solar phenomena.

1. Introduction

The relationship between eruptive prominences (EPs) and other eruptive solar phenomena such as CMEs and flares (e.g. St. Cyr and Webb, 1991; Subramanian and Dere, 2001; Schrijver et al., 2008; Chandra et al., 2010) suggests that the three eruptive events often occur in the same large-scale coronal magnetic field configuration (e.g. Forbes, 2000) in which the EP occupies a limited volume at its base. It is commonly accepted that solar prominence (filament) eruptions frequently accompany coronal mass ejections (CMEs). Thus, studying the pre-eruption phase, origin and evolution of EPs gives additional information relevant to CMEs' launch and propagation.

The observations and studies of early stages of prominence eruptions, i.e. prominence pre-eruptive activation, are crucial for the understanding of the signatures and pre-cursors of forthcoming solar eruptions. The observations of prominence motions before and near the eruption onset can provide information for the coronal magnetic field evolution during the pre-eruptive stages (e.g. Sterling et al., 2012). Multi-wavelength studies of the precursor signatures for eruptions, such as pre-eruptive brightenings in microwave, extreme ultraviolet (EUV), and X-ray emission changes are necessary to reveal the processes involved in the prominence destabilisation. In particular, microwave observations can show the full temporal and spatial prominence (filament)

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http://dx.doi.org/10.1016/j.newast.2016.05.001

The Astrophysical Journal Letters, 821:L30 (6pp), 2016 April 20 doi:10.3847/2041-8205/821/2/L30

OSCILLATORY RESPONSE OF THE SOLAR CHROMOSPHERE TO A STRONG DOWNFLOW EVENT ABOVE A SUNSPOT

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Received 2016 February 1; revised 2016 April 5; accepted 2016 April 5; published 2016 April 20

ABSTRACT

We report three-minute oscillations in the solar chromosphere driven by a strong downflow event in a sunspot. We used the Fast Imaging Solar Spectrograph of the 1.6 m New Solar Telescope and the Interface Region Imaging Spectrograph (IRIS). The strong downflow event is identified in the chromospheric and transition region lines above the sunspot umbra. After the event, oscillations occur at the same region. The amplitude of the Doppler velocity oscillations is 2 km s^{-1} and gradually decreases with time. In addition, the period of the oscillations gradually increases from 2.7 to 3.3 minutes. In the IRIS 1330 Å slit-jaw images, we identify a transient brightening near the footpoint of the downflow detected in the Hα+0.5 Å image. The characteristics of the downflowing material are consistent with those of sunspot plumes. Based on our findings, we suggest that the gravitationally stratified atmosphere came to oscillate with a three-minute period in response to the impulsive downflow event as was theoretically investigated by Chae & Goode.

Key words: Sun: atmosphere – Sun: chromosphere – Sun: oscillations

1. INTRODUCTION

Ever since discovery of three-minute umbral oscillations (Beckers & Tallant 1969; Beckers & Schultz 1972; Giovanelli 1972), they have been studied for several decades by numerous authors (for reviews, see Staude 1999; Bogdan & Judge 2006; Khomenko & Collados 2015). The oscillations are detected in the multiple layers of the solar atmosphere above sunspot umbrae (e.g., Lites & Thomas 1985; Thomas et al. 1987; Maltby et al. 1999; O'Shea et al. 2002). They are generally manifested as periodic fluctuations of intensity and velocity. The oscillations are commonly regarded as slow magnetoacoustic waves upwardly propagating in the gravitationally stratified medium, as the oscillations in the higher atmosphere lag behind those in the lower atmosphere (Brynildsen et al. 1999, 2004; Tian et al. 2014). It is believed that the power of the three-minute oscillations may mostly come from the photosphere or below it. Two specific processes are currently considered as the major candidates for the driver of the oscillations: *p*-mode absorption of global solar oscillations and magnetoconvection inside sunspots (see the review by Khomenko & Collados 2015 and references therein).

Theory predicts that the three-minute umbral oscillations can be excited by impulsive disturbances inside the atmosphere as well. Early studies by Lamb (1909) and Kalkofen et al. (1994) showed that the atmosphere disturbed by an impulsive disturbance at a point begins to oscillate with frequency asymptotically approaching the acoustic cutoff frequency. The recent study of Chae & Goode (2015) found that the necessary condition for the cutoff frequency oscillations to have enough power is the occurrence of the impulsive disturbance of large vertical extent. Since there are many activities in the chromosphere, we expect that impulsive disturbances that produce the three-minute oscillations occur even though they may not be the major driver of such oscillations. Despite this expectation, so far there has been no observational report of such three-minute oscillations generated by impulsive events in the chromosphere above sunspots. This is in contrast with the common findings of oscillations and waves in the corona driven by the strongest impulsive events such as flares (Aschwanden et al. 1999; Nakariakov et al. 1999; Schrijver et al. 2002), lower coronal eruptions/ejections (Zimovets & Nakariakov 2015), and filament destabilizations (Schrijver et al. 2002). Strong X-class flares even affect the solar interior and cause sunquakes which are acoustic waves produced in the photosphere (Kosovichev & Zharkova 1998; Kosovichev 2006). Probably, the impulsive events leading to three-minute oscillations in the chromosphere may be too small and too weak to be detected.

In this Letter, for the first time we report on the occurrence of the three-minute oscillations driven by an impulsive disturbance in the chromosphere. In this specific study, the disturbance was caused by a strong downflow event detected in the chromospheric and transition region (TR) lines above a sunspot umbra. It is important to understand the properties of the oscillations and waves in order to estimate physical quantities of the medium for further study. We analyze multi-wavelength data acquired by the Fast Imaging Solar Spectrograph (FISS; Chae et al. 2013) installed at the 1.6 m New Solar Telescope (NST) of Big Bear Solar Observatory and Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014).

2. OBSERVATIONS AND DATA ANALYSIS

We observed a small sunspot in NOAA active region 12172 on 2014 September 27. It was located between a leading main sunspot and a trailing main sunspot. The region of our interest was so variable that the morphology of the small sunspot kept changing within several hours, and the sunspot finally disappeared the day after our observation period. The FISS is a dual-band Echélle spectrograph that records the Hα band and the Ca II 8542 Å band simultaneously with imaging capability. Imaging is done by fast scanning of a slit over the field of view (FOV), and the step size is 0.″16. With this instrument, we acquired data for an hour from 17:03:40 to 18:00:50 UT with

The Astrophysical Journal, 818:9 (13pp), 2016 February 10 doi:10.3847/0004-637X/818/1/9

MAGNETIC FLUX SUPPLEMENT TO CORONAL BRIGHT POINTS

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Received 2015 May 10; accepted 2015 November 20; published 2016 February 2

ABSTRACT

Coronal bright points (BPs) are associated with magnetic bipolar features (MBFs) and magnetic cancellation. Here we investigate how BP-associated MBFs form and how the consequent magnetic cancellation occurs. We analyze longitudinal magnetograms from the Helioseismic and Magnetic Imager to investigate the photospheric magnetic flux evolution of 70 BPs. From images taken in the 193 Å passband of the Atmospheric Imaging Assembly (AIA) we dermine that the BPs' lifetimes vary from 2.7 to 58.8 hr. The formation of the BP MBFs is found to involve three processes, namely, emergence, convergence, and local coalescence of the magnetic fluxes. The formation of an MBF can involve more than one of these processes. Out of the 70 cases, flux emergence is the main process of an MBF buildup of 52 BPs, mainly convergence is seen in 28, and 14 cases are associated with local coalescence. For MBFs formed by bipolar emergence, the time difference between the flux emergence and the BP appearance in the AIA 193 Å passband varies from 0.1 to 3.2 hr with an average of 1.3 hr. While magnetic cancellation is found in all 70 BPs, it can occur in three different ways: (I) between an MBF and small weak magnetic features (in 33 BPs); (II) within an MBF with the two polarities moving toward each other from a large distance (34 BPs); (III) within an MBF whose two main polarities emerge in the same place simultaneously (3 BPs). While an MBF builds up the skeleton of a BP, we find that the magnetic activities responsible for the BP heating may involve small weak fields.

Key words: methods: observational – Sun: activity – Sun: corona – Sun: magnetic fields

Supporting material: animations

1. INTRODUCTION

Coronal bright points (BPs) are small (on average 20″–30″) and short-lived (from a few minutes to a few tens of hours) bright structures, ubiquitously found in the solar corona. They are believed to be the signature of a direct energy deposition in the upper solar atmosphere (Webb et al. 1993; McIntosh 2007). Coronal BPs were first identified in X-ray images and were named X-ray bright points (XBPs) in the 1970s (Vaiana et al. 1970). They have an average lifetime of 8 hr in X-rays (Timothy et al. 1974; Golub et al. 1976a, 1976b). When observed in extreme-ultraviolet (EUV) (e.g., Habbal & Withbroe 1981; Habbal et al. 1988; Zhang et al. 2001; Madjarska et al. 2012), they are found to have a lifetime that varies from a few minutes to a few days with an average of 20 hr (Zhang et al. 2001). BPs consist of multiple small-scale (a few arcseconds) and rapidly evolving (a few minutes) loops (e.g., Sheeley & Golub 1979; Habbal et al. 1990; Ugarte-Urra & Doyle 2004).

Many studies (e.g., Krieger et al. 1971; Golub et al. 1975a, 1975b, 1976a, 1977; Webb et al. 1993; Brown et al. 2001; Madjarska et al. 2003; Huang et al. 2012; Chandrashekhar et al. 2013) have revealed that BPs are associated with magnetic bipolar features (MBFs). An MBF is a pair of opposite-polarity magnetic features observed in magnetogram data. The relationship between magnetic flux emergence and BPs has been studied in the past, but only limited case studies were reported during the *Solar and Heliospheric Observatory* (*SOHO*) era. Golub et al. (1977) compared BPs observed in X-rays with ephemeral active regions (i.e., emerging bipolar regions) and found a weak correlation. Martin & Harvey (1979) argued that the discrepancy can be explained if the BPs are associated with short-lived ephemeral active regions that might not have been detected in the low temporal resolution data. BPs are also strongly associated with magnetic cancellation (e.g., Webb et al. 1993; Brown et al. 2001; Madjarska et al. 2003; Huang et al. 2012). A study by Webb et al. (1993) found that 18 of 25 BPs were associated with magnetic cancellation. They also found that BPs have a stronger connection with magnetic cancellation rather than flux emergence. From high-resolution Solar Optical Telescope (SOT) magnetograms, Huang et al. (2012) detemined that all 28 BPs were associated with flux emergence followed by magnetic field cancellation.

The strong connection between BPs and magnetic field cancellation has been considered as evidence of magnetic reconnection occurring in BPs. Preś & Phillips (1999) suggested that all the energy losses of a BP are in fact replenished by magnetic energy. Magnetic reconnection in BPs has also been supported by a magnetic field dynamic reconfiguration of BPs (Pérez-Suárez et al. 2008; Alexander et al. 2011; Zhang et al. 2012). Recently, Zhang et al. (2014) suggested that interchange reconnection might occur between two close chambers of a BP. Priest et al. (1994) proposed a scenario where the reconnection results from the converging motion of magnetic polarities. According to this model, the interaction distance has to be less than a certain value in order to trigger the appearance of a BP. This model was also further developed by Parnell et al. (1994) and von Rekowski et al. (2006a, 2006b), and it was linked to various observations (e.g., Brown et al. 2001; Madjarska et al. 2003; Huang et al. 2012; Zhang et al. 2012).

A&A 584, A39 (2015)
DOI: 10.1051/0004-6361/201526339

Astronomy & Astrophysics

Active region upflows

II. Data driven magnetohydrodynamic modelling*

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Received 17 April 2015 / Accepted 17 September 2015

ABSTRACT

Context. Observations of many active regions show a slow systematic outflow/upflow from their edges lasting from hours to days. At present no physical explanation has been proven, while several suggestions have been put forward.

Aims. This paper investigates one possible method for maintaining these upflows assuming, that convective motions drive the magnetic field to initiate them through magnetic reconnection.

Methods. We use Helioseismic and Magnetic Imager (HMI) data to provide an initial potential 3D magnetic field of the active region NOAA 11123 on 2010 November 13 where the characteristic upflow velocities are observed. A simple 1D hydrostatic atmospheric model covering the region from the photosphere to the corona is derived. Local correlation tracking of the magnetic features in the HMI data is used to derive a proxy for the time dependent velocity field. The time dependent evolution of the system is solved using a resistive 3D magnetohydrodynamic code.

Results. The magnetic field contains several null points located well above the photosphere, with their fan planes dividing the magnetic field into independent open and closed flux domains. The stressing of the interfaces between the different flux domains is expected to provide locations where magnetic reconnection can take place and drive systematic flows. In this case, the region between the closed and open flux is identified as the region where observations find the systematic upflows.

Conclusions. In the present experiment, the driving only initiates magneto-acoustic waves without driving any systematic upflows at any of the flux interfaces.

Key words. Sun: corona – Sun: activity – Sun: magnetic fields – methods: numerical

1. Introduction

The Extreme ultraviolet Imaging Spectrometer (EIS) on board Hinode provides detailed observations of active regions, showing the existence of localised regions with systematic, relative low velocity upflows, that last from hours to days. However, neither the source region nor the mechanism which drives these upflows have been identified yet, although several theories have been put forward. There has been a general consensus to use the expression "outflows" for the phenomenon, with the indirect assumption, that these flows are related to open field lines, that allow the upflows to contribute directly to the slow solar wind. As most models have been based on local field extrapolations, it is not certain these field lines are really open and allow the plasma to escape the sun; therefore, we refer to these flows as upflows in this paper. For a detailed review of the observational contributions to this field see Vanninathan et al. (2015, hereafter Paper I).

Over time different theories have been suggested to explain the mechanisms, that drive the upflows. It has been suggested, that three- and five-minutes oscillations can drive upflows (Del Zanna 2008; Marsch et al. 2004). These oscillations have been identified in the upflow regions by Guo et al. (2010) and Ugarte-Urra & Warren (2011), who propose the underlying processes to be sporadic in both space and time. From a potential magnetic field extrapolation, Harra et al. (2008) found, that reconnection on one side of the investigated active region generated long loops which connect across the region. They concluded, that the observed upflows were the result of an expansion of the newly formed loops as they move up toward a new equilibrium.

In a different investigation Marsch et al. (2008) identified circulation of plasma through magnetic funnels and closed loops as a natural state of the plasma, that is continuously in motion. They suggested photospheric convection as the ultimate driving mechanism of the plasma motions in the corona. Using potential field extrapolations of a region containing two active regions Boutry et al. (2012) found, that about 18% of the mass upflow from one region was accounted for as downflow in the neighbouring region. Del Zanna et al. (2011) found a relation between radio noise storms and coronal upflows, indicating, that magnetic reconnection may be initiating the process. From magnetic field extrapolations they find magnetic null points and associated separatrices in the corona which could be associated with magnetic reconnection. A study of an active region-coronal hole (AR-CH) boundary by Van Driel-Gesztelyi et al. (2012) supports

* Movie is available in electronic form at http://www.aanda.org

A&A 584, A38 (2015)
DOI: 10.1051/0004-6361/201526340

Astronomy & Astrophysics

Active region upflows

I. Multi-instrument observations*

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Received 17 April 2015 / Accepted 17 September 2015

ABSTRACT

Context. We study upflows at the edges of active regions, called AR outflows, using multi-instrument observations.

Aims. This study intends to provide the first direct observational evidence of whether chromospheric jets play an important role in furnishing mass that could sustain coronal upflows. The evolution of the photospheric magnetic field, associated with the footpoints of the upflow region and the plasma properties of active region upflows is investigated with the aim of providing information for benchmarking data-driven modelling of this solar feature.

Methods. We spatially and temporally combine multi-instrument observations obtained with the Extreme-ultraviolet Imaging Spectrometer on board the Hinode, the Atmospheric Imaging Assembly and the Helioseismic Magnetic Imager instruments on board the Solar Dynamics Observatory and the Interferometric BI-dimensional Spectro-polarimeter installed at the National Solar Observatory, Sac Peak, to study the plasma parameters of the upflows and the impact of the chromosphere on active region upflows.

Results. Our analysis shows that the studied active region upflow presents similarly to those studied previously, i.e. it displays blueshifted emission of 5–20 km s^{-1} in Fe XII and Fe XIII and its average electron density is 1.8×10^9 cm^{-3} at 1 MK. The time variation of the density is obtained showing no significant change (in a 3σ error). The plasma density along a single loop is calculated revealing a drop of 50% over a distance of ~20 000 km along the loop. We find a second velocity component in the blue wing of the Fe XII and Fe XIII lines at 105 km s^{-1} reported only once before. For the first time we study the time evolution of this component at high cadence and find that it is persistent during the whole observing period of 3.5 h with variations of only ±15 km s^{-1}. We also, for the first time, study the evolution of the photospheric magnetic field at high cadence and find that magnetic flux diffusion is responsible for the formation of the upflow region. High cadence Hα observations are used to study the chromosphere at the footpoints of the upflow region. We find no significant jet-like (spicule/rapid blue excursion) activity to account for several hours/days of plasma upflow. The jet-like activity in this region is not continuous and blueward asymmetries are a bare minimum. Using an image enhancement technique for imaging and spectral data, we show that the coronal structures seen in the AIA 193 Å channel are comparable to the EIS Fe XII images, while images in the AIA 171 Å channel reveal additional loops that are a result of contribution from cooler emission to this channel.

Conclusions. Our results suggest that at chromospheric heights there are no signatures that support the possible contribution of spicules to active region upflows. We suggest that magnetic flux diffusion is responsible for the formation of the coronal upflows. The existence of two velocity components possibly indicates the presence of two different flows, which are produced by two different physical mechanisms, e.g. magnetic reconnection and pressure-driven jets.

Key words. Sun: chromosphere – sun: corona – methods: observational – line: profiles

1. Introduction

The possible contribution of the surroundings of active regions (ARs) to the slow solar wind was first pointed out by Kojima et al. (1999). By comparing velocity distributions at 2.5 $R_\odot$ and potential field extrapolations based on Kitt Peak magnetograms, Kojima et al. (1999) found that compact low-speed wind regions are associated with large magnetic flux expansions adjacent to ARs. The first identification of continuous intermittent flows with velocities from 5 to 20 km s^{-1} at the periphery of an AR was made by Winebarger et al. (2001) using Transition Region And Coronal Explorer (TRACE) 171 Å data. By comparing their data with a quasi-static model, the authors suggested that this can only be explained by plasma flow from the chromosphere to the corona. The identification of AR outflows was difficult because of the lack of suitable observations (spectral temperature coverage), until the launch of Hinode. Sakao et al. (2007) "asserted that these observations are possibly the first identification of outflowing solar wind material" in the vicinity of ARs. They analysed images from the X-ray Telescope (XRT) on board Hinode and measured upward Doppler velocities of ~50 km s^{-1} using the Extreme-ultraviolet Imaging Spectrometer (EIS) in a Fe XII line (no wavelength is given in the paper). Del Zanna (2008) gave a detailed report on AR upflows (blueshifted emission). The author found Doppler velocities of 5–10 km s^{-1} in the EIS Fe XII 195.12 Å line and 10–30 km s^{-1} in the Fe XV 284.16 Å line, occurring in areas of weak emission "in a sharp boundary between low-lying hot 3 MK loops

* Movies associated to Figs. A.1–A.3 are available in electronic form at http://www.aanda.org

The Astrophysical Journal, 812:173 (11pp), 2015 October 20 doi:10.1088/0004-637X/812/2/173

CORONAL RESPONSE TO AN EUV WAVE FROM DEM ANALYSIS

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Received 2015 February 2; accepted 2015 September 18; published 2015 October 20

ABSTRACT

Extreme-Ultraviolet (EUV) waves are globally propagating disturbances that have been observed since the era of the *Solar and Heliospheric Observatory*/Exteme-ultraviolet Imaging Telescope instrument. Although the kinematics of the wave front and secondary wave components have been widely studied, there is not much known about the generation and plasma properties of the wave. In this paper we discuss the effect of an EUV wave on the local plasma as it passes through the corona. We studied the EUV wave, generated during the 2011 February 15 X-class flare/coronal mass ejection event, using Differential Emission Measure diagnostics. We analyzed regions on the path of the EUV wave and investigated the local density and temperature changes. From our study we have quantitatively confirmed previous results that during wave passage the plasma visible in the Atmospheric Imaging Assembly (AIA) 171 Å channel is getting heated to higher temperatures corresponding to AIA 193 and 211 Å channels. We have calculated an increase of 6%–9% in density and 5%–6% in temperature during the passage of the EUV wave. We have compared the variation in temperature with the adiabatic relationship and have quantitatively demonstrated the phenomenon of heating due to adiabatic compression at the wave front. However, the cooling phase does not follow adiabatic relaxation but shows slow decay indicating slow energy release being triggered by the wave passage. We have also identified that heating is taking place at the front of the wave pulse rather than at the rear. Our results provide support for the case that the event under study here is a compressive fast-mode wave or a shock.

Key words: Sun: corona – Sun: evolution – waves

1. INTRODUCTION

Globally propagating disturbances in the solar atmosphere have been known since they were first detected by Moreton & Ramsey (1960) in Hα images during flare observations, the so-called Moreton waves. Such phenomena were modeled by Uchida (1968) as the chromospheric imprint of fast mode magnetohydrodynamic (MHD) waves in the corona. Though, it was not until the launch of the Extreme-ultraviolet Imaging Telescope (EIT, Delaboudinière et al. 1995) on board the *Solar and Heliospheric Observatory* (SOHO, Domingo et al. 1995) that the proposed coronal counterparts were identified (Moses et al. 1997; Thompson et al. 1998). These transient events have since been termed as "EIT waves" after the instrument used to discover them. However, due to the debate regarding the true nature of these transients and to incorporate observations made from different instruments, several authors refer to these events by other names such as "coronal bright fronts" (Gallagher & Long 2011), "coronal propagating fronts" (Schrijver et al. 2011), "global Extreme-Ultraviolet (EUV) waves" (Patsourakos & Vourlidas 2012), and "large-scale coronal propagating fronts" (Nitta et al. 2013). In this paper we will refer to them with a generic name such as EUV waves.

Inconsistencies in speeds between Moreton and EUV waves (Klassen et al. 2000), as well as the observation of stationary fronts (Delannée & Aulanier 1999) led to alternate interpretations and models for the observed wave-like signatures. There are two main opposing theories, waves and non-waves, to explain the visible features of EUV waves. In the non-wave models, these transient phenomena are interpreted as ground tracks of successive restructuring of magnetic field lines during the eruption of a coronal mass ejection (CME, Delannée & Aulanier 1999; Chen et al. 2002; Attrill et al. 2007). The wave models treat them as fast-mode shock waves or large amplitude waves (Thompson et al. 1998; Mann et al. 1999; Warmuth et al. 2001). A third hybrid model tries to bridge the gap by recognizing the existence of two bright fronts: one consistent with the wave model and the other with the non-wave model (Zhukov & Auchère 2004). In recent years, this theory has gained support through observations (Liu et al. 2010) and MHD simulations (Cohen et al. 2009; Downs et al. 2012).

The average speed of EUV waves was measured to be in the range of 200–400 km s^{-1} in the EIT data (Thompson & Myers 2009) and the *Solar Terrestrial Relations Observatory* (*STEREO*) data (Muhr et al. 2014) and updated to 600 km s^{-1} from the Atmospheric Imaging Assembly (AIA) data (Nitta et al. 2013). Fast EUV waves typically decelerate during propagation, which has been interpreted as the nonlinear evolution of large-amplitude fast magnetosonic waves (Vršnak et al. 2006; Long et al. 2008; Veronig et al. 2008; Warmuth & Mann 2011; Muhr et al. 2014). Taking advantage of the quadrature configuration of the *STEREO* satellites, many authors were able to study the 3D structure and evolution of EUV waves (Kienreich et al. 2009; Ma et al. 2009; Patsourakos et al. 2009; Veronig et al. 2010; Temmer et al. 2011). It was estimated that most of the EUV wave emission is coming from heights of 80–100 Mm above the photosphere (Kienreich et al. 2009; Patsourakos et al. 2009) which is comparable to 1–2 coronal scale heights (distance from the photosphere over which the pressure scales as a factor of $1/e$).

The high cadence and resolution of AIA has helped in improving the knowledge of kinematics of wave fronts and to identify secondary wave components. With regard to solar atmospheric research and plasma physics in general, it is

ADAHELI+: exploring the fast, dynamic Sun in the x-ray, optical, and near-infrared

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Abstract. Advanced Astronomy for Heliophysics Plus (ADAHELI+) is a project concept for a small solar and space weather mission with a budget compatible with an European Space Agency (ESA) S-class mission, including launch, and a fast development cycle. ADAHELI+ was submitted to the European Space Agency by a European-wide consortium of solar physics research institutes in response to the “Call for a small mission opportunity for a launch in 2017,” of March 9, 2012. The ADAHELI+ project builds on the heritage of the former ADAHELI mission, which had successfully completed its phase-A study under the Italian Space Agency 2007 Small Mission Programme, thus proving the soundness and feasibility of its innovative low-budget design. ADAHELI+ is a solar space mission with two main instruments: ISODY+: an imager, based on Fabry–Pérot interferometers, whose design is optimized to the acquisition of highest cadence, long-duration, multiline spectropolarimetric images in the visible/near-infrared region of the solar spectrum. XSPO: an x-ray polarimeter for solar flares in x-rays with energies in the 15 to 35 keV range. ADAHELI+ is capable of performing observations that cannot be addressed by other currently planned solar space missions, due to their limited telemetry, or by ground-based facilities, due to the problematic effect of the terrestrial atmosphere. [DOI: 10.1117/1.JATIS.1.4.044006]

Keywords: Sun; satellites; infrared spectroscopy; Fabry–Pérot; x-rays; polarimetry.

Paper 15065 received Jul. 27, 2015; accepted for publication Nov. 6, 2015; published online Dec. 11, 2015.

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The Astrophysical Journal, 810:46 (11pp), 2015 September 1 doi:10.1088/0004-637X/810/1/46

COOL TRANSITION REGION LOOPS OBSERVED BY THE INTERFACE REGION IMAGING SPECTROGRAPH

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Received 2015 May 21; accepted 2015 July 27; published 2015 August 27

ABSTRACT

We report on the first *Interface Region Imaging Spectrograph* (*IRIS*) study of cool transition region loops, a class of loops that has received little attention in the literature. A cluster of such loops was observed on the solar disk in active region NOAA11934, in the Si IV 1402.8 Å spectral raster and 1400 Å slit-jaw images. We divide the loops into three groups and study their dynamics. The first group comprises relatively stable loops, with 382–626 km cross-sections. Observed Doppler velocities are suggestive of siphon flows, gradually changing from $-10\ \mathrm{km\,s^{-1}}$ at one end to $20\ \mathrm{km\,s^{-1}}$ at the other end of the loops. Nonthermal velocities of $15 \sim 25\ \mathrm{km\,s^{-1}}$ were determined. Magnetic cancellation with a rate of $10^{15}\ \mathrm{Mx\,s^{-1}}$ is found at the blueshifted footpoints. These physical properties suggest that these loops are impulsively heated by magnetic reconnection, and the siphon flows play an important role in the energy redistribution. The second group corresponds to two footpoints rooted in mixed-magnetic-polarity regions, where magnetic cancellation with a rate of $10^{15}\ \mathrm{Mx\,s^{-1}}$ and explosive-event line profiles with enhanced wings of up to $200\ \mathrm{km\,s^{-1}}$ were observed. In the third group, interaction between two cool loop systems is observed. Evidence for magnetic reconnection between the two loop systems is reflected in the explosive-event line profiles and magnetic cancellation with a rate of $3 \times 10^{15}\ \mathrm{Mx\,s^{-1}}$ observed in the corresponding area. The *IRIS* has provided opportunity for in-depth investigations of cool transition region loops. Further numerical experiments are crucial for understanding their physics and their roles in the coronal heating processes.

Key words: methods: observational – Sun: chromosphere – Sun: transition region – techniques: spectroscopic

Supporting material: animations

1. INTRODUCTION

The magnetized solar upper atmosphere is structured by numerous types of loops (Del Zanna & Mason 2003; Fletcher et al. 2014). Based on their temperatures, they are categorized into cool (10^5–10^6 K), warm (1–2×10^6 K) and hot ($\geqslant 2 \times 10^6$ K) loops (Reale 2014). Loops cooler than 10^5 K were also suggested to have a major contribution to the EUV output of the solar transition region (Feldman 1983, 1987, 1998; Dowdy et al. 1986; Dowdy 1993; Feldman et al. 2001; Sasso et al. 2012). They were also observed in CDS and SUMER off-limb observations (Brekke et al. 1997b; Chae et al. 2000). Hotter and cooler loops tend not to be co-spatial (e.g., Fludra et al. 1997; Spadaro et al. 2000), though there are exceptions (e.g., Kjeldseth-Moe & Brekke 1998).

Loop heating is a major part of the great coronal heating problem that still remains an unresolved puzzle (Klimchuk 2006; Reale 2014). Two mechanisms have been proposed (for details, see Klimchuk 2006). The first mechanism is the so-called "steady heating" and means that loops are heated continuously. The second suggested mechanism is the "impulsive heating" where loops are heated by low-frequency events, e.g., nanoflare storms or resonant wave absorption (Klimchuk 2006, and references therein). Plasma velocity is a key parameter that can help determine which heating mechanism is in operation (Klimchuk 2006; Winebarger et al. 2013; Reale 2014). Uniform, steady heating results in a stationary temperature distribution and a balance between heat flux and radiation losses, therefore no strong flows would exist in the loop. In the cases of non-uniform steady heating and impulsive heating, stronger plasma flows along the loop can be found due to imbalance of plasma pressure between the two loop footpoints. Which one of these heating mechanisms is at work mainly depends on the plasma and magnetic properties of the loops. It is widely accepted that warm loops are heated by impulsive processes (Winebarger et al. 2002b; Warren et al. 2003; Cargill & Klimchuk 2004; Winebarger & Warren 2005; Klimchuk 2006, 2009; Tripathi et al. 2009; Ugarte-Urra et al. 2009). However, for hot loops, both impulsive (Tripathi et al. 2010; Cadavid et al. 2014; Ugarte-Urra & Warren 2014; Viall & Klimchuk 2011) and steady heating (Warren et al. 2010; Winebarger et al. 2011) have been suggested.

There exist only a limited number of studies on cool loops mainly due to instrumental limitations. By comparing observations and simulations, Doyle et al. (2006) suggested that cool loops are heated by nonlinear heating pulses, i.e., transient events. As discussed above, flow properties can be used to infer the heating mechanism in a loop. They are mainly based on Doppler shift measurements that can only be derived from spectral data. Doppler shifts, however, carry only line-of-sight (LOS) information and may cancel out in data with insufficient resolution, especially in cases of anti-parallel flows in close-by loop strands (e.g., Alexander et al. 2013). Cool loops are difficult to identify in on-disk observations because of the strong background emission and/or LOS contamination by other features. Di Giorgio et al. (2003) studied a loop-like bright feature observed in CDS on board the *Solar and Heliospheric Observatory*, and found $21\ \mathrm{km\,s^{-1}}$ blueshifted flow in the O V lines ($T = 2.5 \times 10^5$ K) after correcting for the projection effect. By combining TRACE images and SUMER spectral observations, Doyle et al. (2006) found a $\sim 20\ \mathrm{km\,s^{-1}}$ redshifted velocity in a footpoint of a cool loop in the SUMER N V line ($T = 2 \times 10^5$ K). Brekke et al. (1997b) reported

A&A 575, A39 (2015)
DOI: 10.1051/0004-6361/201424754

Astronomy & Astrophysics

A coronal wave and an asymmetric eruptive filament in SUMER, CDS, EIT, and TRACE co-observations★

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Received 5 August 2014 / Accepted 31 October 2014

ABSTRACT

Context. The investigation covers the complex subject of coronal waves and the phenomena contributing to and/or causing their formation.

Aims. The objectives of the present study is to provide a better physical understanding of the complex inter-relation and evolution of several solar coronal features comprising a double-peak flare, a coronal dimming caused by a coronal mass ejection (CME), a CME-driven compression, and a fast-mode wave. For the first time, the evolution of an asymmetric eruptive filament is analysed in simultaneous Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectroscopic and Transition Region and Coronal Explorer (TRACE) and Extreme-ultraviolet Imaging Telescope (EIT) imaging data.

Methods. We use imaging observations from EIT and TRACE in the 195 Å channel and spectroscopic observations from the Coronal Diagnostic Spectrometer (CDS) in a rastering and SUMER in a sit-and-stare observing mode. The SUMER spectra cover spectral lines with formation temperatures from log $T(K) \sim 4.0$ to 6.1.

Results. Although the event was already analysed in two previous studies, our analysis brings a wealth of new information on the dynamics and physical properties of the observed phenomena. We found that the dynamic event is related to a complex flare with two distinct impulsive peaks, one according to the Geostationary Operational Environmental Satellite (GOES) classification as C1.1 and the second – C1.9. The first energy release triggers a fast-mode wave and a CME with a clear CME driven compression ahead of it. This activity is related to, or possibly caused, by an asymmetric filament eruption. The filament is observed to rise with its leading edge moving at a speed of ~300 km s^{-1} detected both in the SUMER and CDS data. The rest of the filament body moves at only ~150 km s^{-1} while untwisting. No signature is found of the fast-mode wave in the SUMER data, suggesting that the plasma disturbed by the wave had temperatures above 600 000 K. The erupting filament material is found to emit only in spectral lines at transition region temperatures. Earlier identification of a coronal response detected in the Mg X 609.79 Å line is found to be caused by a blend from the O IV 609.83 Å line.

Conclusions. We present a unique analysis of the complex phenomenon called "EIT/coronal wave", confirming its bimodal nature. We suggest that the disintegration of the dimming/CME and the CME-driven compression are either caused by a CME-CME interaction taking place in the low solar atmosphere or by an impulsive CME cavity overexpansion in the low solar atmosphere.

Key words. Sun: corona – Sun: transition region – Sun: activity – methods: observational – line: profiles

1. Introduction

Coronal waves (CWs), also known as extreme-ultraviolet (EUV) and Extreme-ultraviolet Imaging Telescope (EIT) waves (hereafter coronal waves), are large-scale coronal transients observed in the form of a diffuse brightening that were first detected in observations taken by EIT (Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (SoHO, Thompson et al. 1998). These waves are usually observed as moving, bright quasi-circular rings of increased emission in EUV wavelengths, mainly in the 195 Å imaging channels (1.6 MK) with a typical velocity of 200−400 km s^{-1}. In 171 Å channels the CWs are seen as emission reduction with respect to the surrounding coronal emission, which is caused by heating and thus the ionization of Fe IX/X to higher ionisation states. Coronal waves are caused by the shock produced from the sudden energy release in active regions and are associated with coronal mass ejections (CMEs) rather than flares (Biesecker et al. 2002). Not all CMEs, however, are found to generate coronal waves (Biesecker et al. 2002). Moreton waves (i.e. a chromospheric wave, first reported by Moreton (1960) in Hα observations propagating with 1000 km s^{-1}) are believed to be the chromospheric counterpart of coronal waves, with both waves showing similar behaviour (Veronig et al. 2006, and the references therein). Asai et al. (2012) reported on the first simultaneous co-spatial detection of a Moreton and a coronal wave.

Thanks to the high-cadence images from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO), it was found that CWs show deceleration which is a typical characteristic of large-amplitude waves (Warmuth et al. 2004; Long et al. 2008; Veronig et al. 2008). Coronal wave fronts are reported to be anisotropic and non-homogeneous (Thompson et al. 1999). From observations with the Extreme Ultraviolet Imager (EUVI) on board STEREO-B, Veronig et al. (2010) found that coronal waves are dome shaped with erupting CME loops inside the dome. The CW properties can be found tabulated in Gallagher & Long (2011).

The nature of the phenomenon "coronal wave" is strongly disputed. The interpretations include fast-mode waves (Wills-Davey & Thompson 1999; Warmuth et al. 2001; Schmidt & Ofman 2010), slow-mode waves or solitons (Wills-Davey et al. 2007), and non-waves related to a current shell (Delannée et al. 2008) or successively reconnecting magnetic field lines at a

★ A movie associated to Fig. A.1 is available in electronic form at http://www.aanda.org

The Astrophysical Journal, 797:88 (14pp), 2014 December 20 doi:10.1088/0004-637X/797/2/88

EXPLOSIVE EVENTS ON A SUBARCSECOND SCALE IN *IRIS* OBSERVATIONS: A CASE STUDY

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Received 2014 July 4; accepted 2014 September 22; published 2014 December 3

ABSTRACT

We present a study of a typical explosive event (EE) at subarcsecond scale witnessed by strong non-Gaussian profiles with blue- and redshifted emission of up to 150 km s^{-1} seen in the transition region Si IV 1402.8 Å, and the chromospheric Mg II k 2796.4 Å and C II 1334.5 Å observed by the *Interface Region Imaging Spectrograph* (*IRIS*) at unprecedented spatial and spectral resolution. For the first time an EE is found to be associated with very small-scale (∼120 km wide) plasma ejection followed by retraction in the chromosphere. These small-scale jets originate from a compact bright-point-like structure of ∼1.″5 size as seen in the *IRIS* 1330 Å images. *SDO*/AIA and *SDO*/HMI co-observations show that the EE lies in the footpoint of a complex loop-like brightening system. The EE is detected in the higher temperature channels of AIA 171 Å, 193 Å, and 131 Å, suggesting that it reaches a higher temperature of log $T = 5.36 \pm 0.06$ (K). Brightenings observed in the AIA channels with durations 90–120 s are probably caused by the plasma ejections seen in the chromosphere. The wings of the C II line behave in a similar manner to the Si IV's, indicating close formation temperatures, while the Mg II k wings show additional Doppler-shifted emission. Magnetic convergence or emergence followed by cancellation at a rate of 5×10^{14} Mx s^{-1} is associated with the EE region. The combined changes of the locations and the flux of different magnetic patches suggest that magnetic reconnection must have taken place. Our results challenge several theories put forward in the past to explain non-Gaussian line profiles, i.e., EEs. Our case study on its own, however, cannot reject these theories; thus, further in-depth studies on the phenomena producing EEs are required.

Key words: methods: observational – Sun: activity – Sun: chromosphere – Sun: transition region – techniques: spectroscopic

Online-only material: animations, color figures

1. INTRODUCTION

The solar transition region is the interface between the chromosphere and the corona within which the temperature rapidly rises from 25,000 K to 1 MK. Plasma in the solar transition region appears to be very dynamic, as evidenced by the so-called "explosive events" (EEs). The term "explosive event" describes non-Gaussian (mostly transition region) line profiles showing Doppler velocities of 50–150 km s^{-1} (Brueckner & Bartoe 1983). On average the EE size as determined along a spectrometer slit is about 2″–5″ with a lifetime of up to 600 s (Dere et al. 1989). From 82 EEs observed by HRTS, Dere et al. (1989) found only one case in which there was evidence for apparent velocities. This result suggests that the velocities of events associated with EEs are non-isotropic, and (some or all) EEs are possibly the spectral signature of jets. EEs are often observed in bursts lasting up to 30 minutes (Innes et al. 1997a; Doyle et al. 2006).

EEs are usually found along the magnetic network at the boundaries of the super-granulation cells (Dere et al. 1989; Porter & Dere 1991; Madjarska & Doyle 2003). They are associated with regions of weak and mixed polarity fluxes (Brueckner et al. 1988; Dere et al. 1991; Chae et al. 1998a; Teriaca et al. 2004; Muglach 2008). Chae et al. (1998a) studied the magnetic field of 163 EEs identified in Solar Ultraviolet Measurement of Emitted Radiation (SUMER) observations and Big Bear Solar Observatory (BBSO) magnetograms, and found that 103 of these were associated with magnetic flux cancellations. However, the connection between EEs and magnetic cancellation is still under debate. Muglach (2008) found that only 7 out of 37 EEs were associated with magnetic cancellation sites while the magnetic flux for 62% of EEs did not change during their lifetime, though it is possible that this is due to instrumental limitations. Magnetic reconnection is proposed as the possible mechanism that produces opposite directed jets generating the EE's blue- and redshifted emission (see, e.g., Dere et al. 1991; Innes et al. 1997b; Chae et al. 1998a; Ryutova & Tarbell 2000; Lee et al. 2000).

The true nature of the events associated with EEs remains unknown as these "events" actually carry only the spectral signature about the observed phenomena. EEs were suggested to be the signature of siphon flows in small-scale loops (Teriaca et al. 2004). They are also believed to be produced by spicules and macrospicules (Wilhelm 2000), and were found to be associated with chromospheric upflow events (Chae et al. 1998b). EEs were found in transient brightenings and X-ray jets (Madjarska et al. 2012). Madjarska et al. (2009) showed that EEs can result from up- and down-flows in a surge. Curdt & Tian (2011) put forward the idea that EEs are produced by swirling jets where a helical motion would be mostly responsible for the blue- and redshifted emission (the Si III 1206.51 Å line was used in this study).

EEs are typically observed in transition region emission lines with formation temperatures ranging from 2×10^4 K to 5×10^5 K (Brueckner & Bartoe 1983). Dere (1992) reports from HRTS spectra that less than 1% of the EEs observed in transition region lines are also seen in C I 1561 Å (1×10^4 K) while they are weakly seen in C II 1335 Å (1.6×10^4 K). SUMER observations showed that EEs also appear in lower temperature lines such as O I (1×10^4 K), Lyman 6 to Lyman 11 (1.2×10^4 K; Madjarska & Doyle 2002), and Lyman β (1.2×10^4 K;

A&A 566, A148 (2014)
DOI: 10.1051/0004-6361/201323097

Astronomy & Astrophysics

Hα spectroscopy and multiwavelength imaging of a solar flare caused by filament eruption*

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Received 21 November 2013 / Accepted 6 May 2014

ABSTRACT

Context. We study a sequence of eruptive events including filament eruption, a GOES C4.3 flare, and a coronal mass ejection.

Aims. We aim to identify the possible trigger(s) and precursor(s) of the filament destabilisation, investigate flare kernel characteristics, flare ribbons/kernels formation and evolution, study the interrelation of the filament-eruption/flare/coronal-mass-ejection phenomena as part of the integral active-region magnetic field configuration, and determine Hα line profile evolution during the eruptive phenomena.

Methods. Multi-instrument observations are analysed including Hα line profiles, speckle images at Hα – 0.8 Å and Hα + 0.8 Å from IBIS at DST/NSO, EUV images and magnetograms from the SDO, coronagraph images from STEREO, and the X-ray flux observations from *Fermi* and GOES.

Results. We establish that the filament destabilisation and eruption are the main triggers for the flaring activity. A surge-like event with a circular ribbon in one of the filament footpoints is determined as the possible trigger of the filament destabilisation. Plasma draining in this footpoint is identified as the precursor for the filament eruption. A magnetic flux emergence prior to the filament destabilisation followed by a high rate of flux cancellation of 1.34×10^{16} Mx s^{-1} is found during the flare activity. The flare X-ray lightcurves reveal three phases that are found to be associated with three different ribbons occurring consecutively. A kernel from each ribbon is selected and analysed. The kernel lightcurves and Hα line profiles reveal that the emission increase in the line centre is stronger than that in the line wings. A delay of around 5–6 min is found between the increase in the line centre and the occurrence of red asymmetry. Only red asymmetry is observed in the ribbons during the impulsive phases. Blue asymmetry is only associated with the dynamic filament.

Key words. Sun: activity – Sun: flares – Sun: filaments, prominences – line: profiles

1. Introduction

Solar flares are powerful solar phenomena that are believed to be driven by magnetic reconnection resulting in plasma heating and particle acceleration. They can be observed as emission enhancements across the entire electromagnetic spectrum, from radio to γ-ray wavelengths. Flares are considered as phenomena initiated in the corona since radio and hard X-ray emission at flaring sites were discovered (Shibata & Magara 2011, and the references therein). For decades, the chromospheric response to flares has been investigated by using Hα filtergrams. Flaring sites observed in Hα show spectacular phenomena such as filament (prominence) eruptions and flare ribbons (bright regions in the chromosphere along the magnetic neutral line); Hα kernels, which are very bright and compact Hα emission sources embedded in flare ribbons, are also common features appearing during a flare. They are believed to be the locations of high-energetic particle precipitation. More details about solar flares can be found in several reviews (e.g. Hudson 2007; Benz 2008; Shibata & Magara 2011; Fletcher et al. 2011).

Although flares have been observed at chromospheric temperature since the Hα filter was invented in the 1930s, the precise mechanism(s) by which energy release in the corona drives chromospheric emission bursts, called ribbons or kernels, has not been well established. A two-dimensional magnetic reconnection model called CSHKP (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), suggests that the plasma surrounding a null point in the corona is heated such that high coronal pressure, thermal conduction, and non-thermal particles (mostly electrons) can efficiently carry energy from the magnetic reconnection site in the corona to the lower solar atmosphere along the magnetic field lines (Magara et al. 1996). Thermal radiation from soft X-rays, EUV, and UV can also contribute to this process, but this contribution was found to be very small (Allred et al. 2005). Other more recent works have raised questions about the viability of this mechanism in the light of recent observations (Fletcher & Hudson 2008) and suggested Alfvén wave propagation as an alternate energy transport mechanism from the corona to chromosphere during flares (Russell & Fletcher 2013).

Although Hα filtergrams provide a wealth of information on the dynamic morphological evolution of the flare in the chromosphere (Hudson 2007, and references therein), full Hα line profiles have powerful diagnostic potential for understanding the physical mechanism driving solar flares. Based on a static model, Canfield et al. (1984) calculated Hα profiles of flare chromospheres produced by different mechanisms (see the previous

* Appendix A and movie associated to Fig. A.4 are available in electronic form at http://www.aanda.org

The Astrophysical Journal Letters, 784:L39 (4pp), 2014 April 1 doi:10.1088/2041-8205/784/2/L39

INTENSITY ENHANCEMENT OF O VI ULTRAVIOLET EMISSION LINES IN SOLAR SPECTRA DUE TO OPACITY

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Received 2014 January 14; accepted 2014 March 5; published 2014 March 19

ABSTRACT

Opacity is a property of many plasmas. It is normally expected that if an emission line in a plasma becomes optically thick, then its intensity ratio to that of another transition that remains optically thin should decrease. However, radiative transfer calculations undertaken both by ourselves and others predict that under certain conditions the intensity ratio of an optically thick to an optically thin line can show an increase over the optically thin value, indicating an enhancement in the former. These conditions include the geometry of the emitting plasma and its orientation to the observer. A similar effect can take place between lines of differing optical depths. While previous observational studies have focused on stellar point sources, here we investigate the spatially resolved solar atmosphere using measurements of the $I(1032\,\text{Å})/I(1038\,\text{Å})$ intensity ratio of O VI in several regions obtained with the Solar Ultraviolet Measurements of Emitted Radiation instrument on board the *Solar and Heliospheric Observatory* satellite. We find several $I(1032\,\text{Å})/I(1038\,\text{Å})$ ratios observed on the disk to be significantly larger than the optically thin value of 2.0, providing the first detection (to our knowledge) of intensity enhancement in the ratio arising from opacity effects in the solar atmosphere. The agreement between observation and theory is excellent and confirms that the O VI emission originates from a slab-like geometry in the solar atmosphere, rather than from cylindrical structures.

Key words: opacity – radiative transfer – Sun: transition region – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Opacity is a common property of many astrophysical and laboratory plasmas. In most circumstances, one would expect that opacity in an emission line would lead to a reduction in its intensity compared to the optically thin value. However, theoretical work by Bhatia and co-workers (Bhatia & Kastner 1999; Bhatia & Saba 2001; Kastner & Bhatia 2001), using the escape factor method, indicated that in certain circumstances the intensity of an emission line could be enhanced over its optically thin value due to the effects of opacity. Their research did not explain how this (apparently counter-intuitive) result came about, and the answer had to await the more sophisticated calculations of Kerr et al. (2004), who determined the radiation transport in the plasma using the CRETIN code (Scott 2001). The CRETIN results provided the origin of the line enhancement effect, namely, that the ion in an upper state of a transition can be pumped in the optically thick case by photons traversing the plasma at many different angles. As a consequence, the line intensity enhancement effect, and its apparent magnitude, is very dependent both on the geometry of the plasma and the orientation of the observer (i.e., the line of sight to the plasma by which it is viewed). Subsequently, Kerr et al. (2005) extended this work by using an analytical approach to consider several different geometries. They found that the detection of line intensity enhancement could, in theory, discriminate between different plasma geometries and the orientation of the observer. This would in principle provide a powerful new diagnostic for astrophysical sources, many of which are spatially unresolved.

Observationally, searches have been undertaken for line intensity enhancements in stellar spectra using the ratio of lines of differing optical depths. Rose et al. (2008) found some evidence of this effect in the $I(15.01\,\text{Å})/I(16.78\,\text{Å})$ ratio of Fe XVII in the active cool dwarf EV Lac, with a measured value of 2.50 ± 0.50 from *XMM-Newton* satellite observations compared to a theoretical optically thin result of $\leqslant 1.93$. More recently, Keenan et al. (2011) analyzed *Far-Ultraviolet Spectroscopic Explorer* satellite spectra of the active late-type stars ϵ Eri, II Peg and Prox Cen, and measured several $I(1032\,\text{Å})/I(1038\,\text{Å})$ ratios of O VI that were larger (by up to 30%) than the optically thin value of 2.0.

Although we are confident that the above detections are secure, they are very limited in number, and additionally are restricted to spatially unresolved (distant stellar) objects. In the present Letter, we therefore extend the work to search for O VI line intensity enhancements in a spatially resolved source, namely, the Sun, and also build on our previous theoretical research for O VI (Keenan et al. 2011) to calculate O VI models for cylindrical, as well as slab and spherical, geometries.

2. OBSERVATIONS

Observations were obtained with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument (Wilhelm

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The Astrophysical Journal, 779:125 (10pp), 2013 December 20 doi:10.1088/0004-637X/779/2/125

ELLERMAN BOMBS—EVIDENCE FOR MAGNETIC RECONNECTION IN THE LOWER SOLAR ATMOSPHERE

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Received 2013 May 23; accepted 2013 October 28; published 2013 December 2

ABSTRACT

The presence of photospheric magnetic reconnection has long been thought to give rise to short and impulsive events, such as Ellerman bombs (EBs) and Type II spicules. In this article, we combine high-resolution, high-cadence observations from the Interferometric BIdimensional Spectrometer and Rapid Oscillations in the Solar Atmosphere instruments at the Dunn Solar Telescope, National Solar Observatory, New Mexico, with co-aligned *Solar Dynamics Observatory* Atmospheric Imaging Assembly and *Hinode* Solar Optical Telescope (SOT) data to observe small-scale events situated within an active region. These data are then compared with state-of-the-art numerical simulations of the lower atmosphere made using the MURaM code. It is found that brightenings, in both the observations and the simulations, of the wings of the Hα line profile, interpreted as EBs, are often spatially correlated with increases in the intensity of the Fe I λ6302.5 line core. Bipolar regions inferred from *Hinode*/SOT magnetic field data show evidence of flux cancellation associated, co-spatially, with these EBs, suggesting that magnetic reconnection could be a driver of these high-energy events. Through the analysis of similar events in the simulated lower atmosphere, we are able to infer that line profiles analogous to the observations occur co-spatially with regions of strong opposite-polarity magnetic flux. These observed events and their simulated counterparts are interpreted as evidence of photospheric magnetic reconnection at scales observable using current observational instrumentation.

Key words: Sun: atmosphere – Sun: chromosphere – Sun: magnetic fields – Sun: photosphere

Online-only material: color figures

1. INTRODUCTION

Ellerman bombs (EBs) were first observed by Ellerman (1917) and are small-scale (1″ or less), short-lived (2–15 minutes), impulsive events detected in the lower solar atmosphere (see, e.g., Zachariadis et al. 1987; Georgoulis et al. 2002; Watanabe et al. 2011; Nelson et al. 2013). It has been widely suggested that a link exists between EBs and photospheric vertical magnetic fields; Pariat et al. (2004, 2007) presented co-aligned magnetograms and observations showing the formation of EBs in the plage region trailing an emerging active region (AR). More recently, Nelson et al. (2013) found that strong Hα line wing enhancements, identified as small-scale EBs, almost ubiquitously surrounded a complex penumbral structure in an emerging AR and are linked to strong magnetic fields and *G*-band magnetic bright points (MBPs). Due to the link between EBs and strong photospheric magnetic fields, it has often been asserted that EBs arise as a result of magnetic reconnection in the photosphere. Georgoulis et al. (2002) suggested three cartoon topologies that could excite magnetic reconnection in the photosphere, including the partial sinking of a flux tube due to intergranular downflows, flux loops emerging in a *serpentine* manner, and complex unipolar magnetic fields. Within any AR, many examples of cancellation can be observed by magnetogram data, implying the rapid change of magnetic field configuration within the photosphere, potentially consistent with the topologies suggested by Georgoulis et al. (2002). In this article, we address any potential links between EBs and cancellation events around the lead sunspot of a stable AR.

In a recent review, Rutten et al. (2013) suggested that certain brightenings in the wings of the Hα line often regarded as EBs could, in fact, be formed due to the influence of high magnetic field concentrations on the Hα profile. It was suggested that classical EBs, where energy release leads to increased intensity in the Hα line wings, may often be confused with pseudo-EBs, where the line wings of the Hα profile outline strong magnetic fields in the lower photosphere. The definitions of these two forms of brightenings advance the work of Watanabe et al. (2011), who suggested that an event must show "flaring," rapid and small-scale topological variations associated with high energy, to be classified as an EB. Due to the sparseness of high-resolution magnetogram data, however, it has so far proved difficult to identify whether certain topologies lead to the classical EB form, i.e., whether only bipolar regions lead to "flaring" events.

Strong observational evidence supporting a photospheric magnetic reconnection model has, so far, proved difficult to establish. The spatial and temporal resolutions of modern magnetogram data are low compared to hypothesized reconnection events (such as EBs), as well as events within the simulated photosphere (see, e.g., Shelyag et al. 2007), meaning that unequivocal inferences about observed magnetic topologies and evolution are rare. In recent years, however, the possible importance of reconnection in the photosphere has been highlighted by the suggestion that such high-energy events could be driving mass into the chromosphere through the excitation of, for example, Type II spicules (De Pontieu et al. 2007), as well as, potentially, providing energy for heating. This, in turn, has highlighted the need for an analysis of the lower solar atmosphere

A&A 557, L9 (2013)
DOI: 10.1051/0004-6361/201321902

Astronomy & Astrophysics

Letter to the Editor

Diagnosing transient ionization in dynamic events

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Received 16 May 2013 / Accepted 15 July 2013

ABSTRACT

Aims. The present study aims to provide a diagnostic line ratio that will enable the observer to determine whether a plasma is in a state of transient ionization.

Methods. We use the Atomic Data and Analysis Structure (ADAS) to calculate line contribution functions for two lines, Si IV 1394 Å and O IV 1401 Å, formed in the solar transition region. The generalized collisional-radiative theory is used. It includes all radiative and electron collisional processes, except for photon-induced processes. State-resolved direct ionization and recombination to and from the next ionization stage are also taken into account.

Results. For dynamic bursts with a decay time of a few seconds, the Si IV 1394 Å line can be enhanced by a factor of 2–4 in the first fraction of a second with the peak in the line contribution function occurring initially at a higher electron temperature due to transient ionization compared to ionization equilibrium conditions. On the other hand, the O IV 1401 Å does not show such any enhancement. Thus the ratio of these two lines, which can be observed with the Interface Region Imaging Spectrograph, can be used as a diagnostic of transient ionization.

Conclusions. We show that simultaneous high-cadence observations of two lines formed in the solar transition region may be used as a direct diagnostic of whether the observed plasma is in transient ionization. The ratio of these two lines can change by a factor of four in a few seconds owing to transient ionization alone.

Key words. Sun: corona – Sun: transition region – line: formation – atomic processes – line: profiles

1. Introduction

All spectral lines have encoded information that allows the observer to diagnose important physical parameters of the underlying plasma. For example, forbidden or inter-system lines allow an evaluation of the plasma's electron density, while resonance lines allow the observer to diagnose the electron temperature. With sufficient spectral resolution, all spectral lines can be used to give the observer information on plasma flows and/or turbulent motions. To diagnose a plasma's state of ionization, however, requires both high-cadence data and suitable spectral lines.

Various authors have presented simulated spectra based on transient ionization (Mewe & Schrijver 1980; Reale & Orlando 2008) for comparison with observational data. In a recent paper, Doyle et al. (2012) discussed the diagnostic potential of high-cadence ultraviolet spectral data when transient ionization is considered. The above paper used high-cadence spectral line data from the Solar Maximum Mission (SMM) observed in O V 1371 Å which allowed the authors to measure electron densities and temperatures during the early stages of a feature's evolution, something that is not currently possible. The high cadence UV spectrometer on SMM allowed observations of selected spectral lines with a subsecond cadence.

The forthcoming observations from the Interface Region Imaging Spectrograph[1] will once again enable high quality observations of lines formed in the solar transition region. What we would like to have is a simple line ratio consisting of one line that shows a response to transient ionization and another line that is not responsive to transient ionization. Then, provided we can monitor these lines with sufficient cadence, any fast (≈0.5 s) increase in the ratio must be due to non-equilibrium conditions. Here, we look at the response of two such lines, Si IV 1394 Å and O IV 1401 Å. The Si IV 1394 Å line is in the ground spin system (3s $^2S_{1/2}$–3p $^2P_{3/2}$). The character of the excitation cross-sections (dipole and non-spin change) and access to higher n-shell/cascade will result in a line enhancement. However, the O IV 1401 line, by contrast, has an upper state in the quartet spin system ($2s^22p$ $^2P_{3/2}$–$2s2p^2$ $^4P_{5/2}$) which means that access to this spin system is driven by cross-sections that decrease with temperature, hence little or no line enhancement, therefore, transient ionization under-fills the population structure of the alternate spin systems from the ground. By contrast, the ground spin system population structure gets enhanced (due to the exponential factor in the rate coefficient) with increasing electron temperature.

2. Transient ionization

The atomic structure of atoms and ions is in principle an infinite assembly of levels with an infinite number of reactions between them, however, simplifying assumptions about the nature of the plasma, its dynamic character and the relative importance of

[1] http://iris.lmsal.com/

Solar Phys (2013) 283:307–323
DOI 10.1007/s11207-012-0222-3

Statistical Analysis of Small Ellerman Bomb Events

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Received: 1 August 2012 / Accepted: 28 December 2012 / Published online: 30 January 2013

Abstract The properties of Ellerman bombs (EBs), small-scale brightenings in the Hα line wings, have proved difficult to establish because their size is close to the spatial resolution of even the most advanced telescopes. Here, we aim to infer the size and lifetime of EBs using high-resolution data of an emerging active region collected using the *Interferometric BIdimensional Spectrometer* (IBIS) and *Rapid Oscillations of the Solar Atmosphere* (ROSA) instruments as well as the *Helioseismic and Magnetic Imager* (HMI) onboard the *Solar Dynamics Observatory* (SDO). We develop an algorithm to track EBs through their evolution, finding that EBs can often be much smaller (around 0.3″) and shorter-lived (less than one minute) than previous estimates. A correlation between G-band magnetic bright points and EBs is also found. Combining SDO/HMI and G-band data gives a good proxy of the polarity for the vertical magnetic field. It is found that EBs often occur both over regions of opposite polarity flux and strong unipolar fields, possibly hinting at magnetic reconnection as a driver of these events.The energetics of EB events is found to follow a power-law distribution in the range of a nanoflare (10^{22-25} ergs).

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Solar Phys (2013) 282:67–86
DOI 10.1007/s11207-012-0146-y

Nature of Quiet Sun Oscillations Using Data from the *Hinode*, TRACE, and SOHO Spacecraft

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Received: 29 March 2011 / Accepted: 24 September 2012 / Published online: 17 October 2012

Abstract We study the nature of quiet-Sun oscillations using multi-wavelength observations from TRACE, *Hinode*, and SOHO. The aim is to investigate the existence of propagating waves in the solar chromosphere and the transition region by analyzing the statistical distribution of power in different locations, *e.g.* in bright magnetic (network), bright non-magnetic and dark non-magnetic (inter-network) regions, separately. We use Fourier power and phase-difference techniques combined with a wavelet analysis. Two-dimensional Fourier power maps were constructed in the period bands 2 – 4 minutes, 4 – 6 minutes, 6 – 15 minutes, and beyond 15 minutes. We detect the presence of long-period oscillations with periods between 15 and 30 minutes in bright magnetic regions. These oscillations were detected from the chromosphere to the transition region. The Fourier power maps show that short-period powers are mainly concentrated in dark regions whereas long-period powers are concentrated in bright magnetic regions. This is the first report of long-period waves in quiet-Sun network regions. We suggest that the observed propagating oscillations are due to magnetoacoustic waves, which can be important for the heating of the solar atmosphere.

Keywords Chromosphere, quiet · Transition region · Oscillations · MHD waves

Electronic supplementary material The online version of this article (doi:10.1007/s11207-012-0146-y) contains supplementary material, which is available to authorized users.

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Solar Phys (2012) 280:425–434
DOI 10.1007/s11207-012-9986-8

ADVANCES IN EUROPEAN SOLAR PHYSICS

Off-limb (Spicule) DEM Distribution from SoHO/SUMER Observations

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Received: 29 November 2011 / Accepted: 17 March 2012 / Published online: 19 April 2012

Abstract In the present work we derive a Differential Emission Measure (DEM) distribution from a region dominated by spicules. We use spectral data from the *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER) spectrometer on-board the *Solar Heliospheric Observatory* (SoHO) covering the entire SUMER wavelength range taken off-limb in the Northern polar coronal hole to construct this DEM distribution using the CHIANTI atomic database. This distribution is then used to study the thermal properties of the emission contributing to the 171 Å channel in the *Atmospheric Imaging Assembly* (AIA) on-board the *Solar Dynamics Observatory* (SDO). From our off-limb DEM we found that the radiance in the AIA 171 Å channel is dominated by emission from the Fe IX 171.07 Å line and has sparingly little contribution from other lines. The product of the Fe IX 171.07 Å line contribution function with the off-limb DEM was found to have a maximum at $\log T_{\mathrm{max}}$ (K) $= 5.8$ indicating that during spicule observations the emission in this line comes from plasma at transition region temperatures rather than coronal. For comparison, the same product with a quiet Sun and prominence DEM were found to have a maximum at $\log T_{\mathrm{max}}$ (K) $= 5.9$ and $\log T_{\mathrm{max}}$ (K) $= 5.7$, respectively. We point out that the interpretation of data obtained from the AIA 171 Å filter should be done with foreknowledge of the thermal nature of the observed phenomenon. For example, with an off-limb DEM we find that only 3.6 % of the plasma is above a million degrees, whereas using a quiet Sun DEM, this contribution rises to 15 %.

Advances in European Solar Physics
Guest Editors: Valery M. Nakariakov, Manolis K. Georgoulis, and Stefaan Poedts

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A&A 545, A67 (2012)
DOI: 10.1051/0004-6361/201219516

Astronomy & Astrophysics

Coronal hole boundaries evolution at small scales

III. EIS and SUMER views★

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Received 1 May 2012 / Accepted 29 June 2012

ABSTRACT

Context. We report on the plasma properties of small-scale transient events identified in the quiet Sun, coronal holes and their boundaries.

Aims. We aim at deriving the physical characteristics of events that were identified as small-scale transient brightenings in XRT images.

Methods. We used spectroscopic co-observations from SUMER/SoHO and EIS/Hinode combined with high-cadence imaging data from XRT/Hinode. We measured Doppler shifts using single and multiple Gaussian fits of the transition region and coronal lines as well as electron densities and temperatures. We combined co-temporal imaging and spectroscopy to separate brightening expansions from plasma flows.

Results. The transient brightening events in coronal holes and their boundaries were found to be very dynamical, producing high-density outflows at high speeds. Most of these events represent X-ray jets from pre-existing or newly emerging coronal bright points at X-ray temperatures. The average electron density of the jets is $\log_{10} N_e \approx 8.76$ cm^{-3} while in the flaring site it is $\log_{10} N_e \approx 9.51$ cm^{-3}. The jet temperatures reach a maximum of 2.5 MK but in the majority of the cases the temperatures do not exceed 1.6 MK. The footpoints of jets have maximum temperatures of 2.5 MK, though in a single event scanned a minute after the flaring the measured temperature was 12 MK. The jets are produced by multiple microflaring in the transition region and corona. Chromospheric emission was only detected in their footpoints and was only associated with downflows. The Doppler shift measurements in the quiet Sun transient brightenings confirmed that these events do not produce jet-like phenomena. The plasma flows in these phenomena remain trapped in closed loops.

Conclusions. We can conclude that the dynamic day-by-day and even hour-by-hour small-scale evolution of coronal hole boundaries reported in Paper I is indeed related to coronal bright points. The XRT observations reported in Paper II revealed that these changes are associated with the dynamic evolution of coronal bright points producing multiple jets during their lifetime until their full disappearance. We demonstrate here through spectroscopic EIS and SUMER co-observations combined with high-cadence imaging information that the co-existence of open and closed magnetic fields results in multiple energy depositions, which propel high-density plasma along open magnetic field lines. We conclude from the physical characteristics obtained in this study that X-ray jets are important candidates for the source of the slow solar wind. This, however, does not exclude the possibility that these jets are also the microstreams observed in the fast solar wind, as recently suggested.

Key words. Sun: corona – Sun: transition region – line: profiles – methods: observational

1. Introduction

Coronal holes (CHs) are regions on the Sun dominated by open magnetic fields. They are seen with reduced emission in spectral lines formed at coronal temperatures and are identified as the source regions of the fast solar wind with velocities of ~800 km s^{-1} (Krieger et al. 1973). The CHs form in both polar and equatorial regions. The latter are often connected with the polar CHs with a channel of open magnetic field and are called equatorial extensions of polar coronal holes (EECHs). These exhibit a more rigid rotation (Timothy et al. 1975) with respect to the typical differential rotation at photospheric levels. Therefore, it is believed that interchange magnetic reconnection happens between the open (coronal hole's) and closed (quiet Sun) magnetic field lines. This was suggested to play an important role in the generation of the slow solar wind flow (Wang et al. 1998b; Woo et al. 2004). Evidence of dynamic processes taking place at coronal hole boundary (CHB) regions was first provided from spectroscopic observations by Madjarska et al. (2004). It has been found that events described by non-Gaussian profiles of transition region spectral lines, e.g. in N IV 765.15 Å and Ne VIII 770.43 Å, were abundant along the boundary of an EECH. Similar results were found at a polar coronal hole boundary by Doyle et al. (2006) in O VI 1031.93 Å. More details on the background of CHs and coronal hole boundaries can be found in Madjarska & Wiegelmann (2009, hereafter Paper I) and Subramanian et al. (2010, hereafter Paper II).

Madjarska & Wiegelmann (2009) showed that although isolated equatorial CHs and EECHs maintain their general shape during several solar rotations, a closer look at their day-by-day and hour-by-hour evolution demonstrates significant dynamics. Using the Extreme-ultraviolet Imaging Telescope (EIT)/SoHO 195 Å and TRACE 171 Å observations, they found that evolution of small-scale loops, i.e. coronal bright

★ Figures A.1, A.2, and movies are available in electronic form at http://www.aanda.org

Solar Phys (2012) 280:111–124
DOI 10.1007/s11207-012-0025-6

The Diagnostic Potential of Transition Region Lines Undergoing Transient Ionization in Dynamic Events

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Received: 12 January 2012 / Accepted: 4 May 2012 / Published online: 6 June 2012

Abstract We discuss the diagnostic potential of high cadence UV spectral data when transient ionization is considered. For this we use high cadence UV spectra taken during the impulsive phase of a solar flare (observed with instruments on-board the *Solar Maximum Mission*) which showed excellent correspondence with hard X-ray pulses. The ionization fraction of the transition region ion O V and, in particular, the contribution function for the O V 1371 Å line are computed within the Atomic Data and Analysis Structure, which is a collection of fundamental and derived atomic data and codes to manipulate them. Due to transient ionization, the O V 1371 Å line is enhanced in the first fraction of a second with the peak in the line contribution function occurring initially at a higher electron temperature than in ionization equilibrium. The rise time and enhancement factor depend mostly on the electron density. The fractional increase in the O V 1371 Å emissivity due to transient ionization can reach a factor of two–four and can explain the fast response in the line flux of transition regions ions during the impulsive phase of flares solely as a result of transient ionization. This technique can be used to diagnose the electron temperature and density of solar flares observed with the forthcoming Interface Region Imaging Spectrograph.

Keywords Atomic processes · Line: formation · Sun: activity · Sun: atmosphere

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Space Sci Rev (2012) 169:181–244
DOI 10.1007/s11214-012-9920-2

Solar Fine-Scale Structures. I. Spicules and Other Small-Scale, Jet-Like Events at the Chromospheric Level: Observations and Physical Parameters

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Received: 1 February 2012 / Accepted: 10 July 2012 / Published online: 24 July 2012

Abstract Over the last two decades the uninterrupted, high resolution observations of the Sun, from the excellent range of telescopes aboard many spacecraft complemented with observations from sophisticated ground-based telescopes have opened up a new world producing significantly more complete information on the physical conditions of the solar atmosphere than before. The interface between the lower solar atmosphere where energy is generated by subsurface convection and the corona comprises the chromosphere, which is dominated by jet-like, dynamic structures, called mottles when found in quiet regions, fibrils when found in active regions and spicules when observed at the solar limb. Recently, space observations with Hinode have led to the suggestion that there should exist two different types of spicules called Type I and Type II which have different properties. Ground-based observations in the Ca II H and K filtergrams reveal the existence of long, thin emission features called straws in observations close to the limb, and a class of short-lived events called rapid blue-shifted excursions characterized by large Doppler shifts that appear only in the blue wing of the Ca II infrared line. It has been suggested that the key to understanding how the solar plasma is accelerated and heated may well be found in the studies of these jet-like, dynamic events. However, while these structures are observed and studied for more than 130 years in the visible, but also in the UV and EUV emission lines and continua, there are still many questions to be answered. Thus, despite their importance and a multitude of observations performed and theoretical models proposed, questions regarding their

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A&A 540, A127 (2012)
DOI: 10.1051/0004-6361/201118588

Astronomy & Astrophysics

Kinematics and helicity evolution of a loop-like eruptive prominence⋆

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Received 5 December 2011 / Accepted 12 February 2012

ABSTRACT

Aims. We aim at investigating the morphology as well as kinematic and helicity evolution of a loop-like prominence during its eruption.

Methods. We used multi-instrument observations from AIA/SDO, EUVI/STEREO and LASCO/SoHO. The kinematic, morphological, geometrical, and helicity evolution of a loop-like eruptive prominence were studied in the context of the magnetic flux rope model of solar prominences.

Results. The prominence eruption evolved as a height-expanding twisted loop with both legs anchored in the chromosphere of a plage area. The eruption process consisted of a prominence activation, acceleration, and a phase of constant velocity. The prominence body was composed of counter-clockwise twisted threads around the main prominence axis. The twist during the eruption was estimated at 6π (3 turns). The prominence reached a maximum height of 526 Mm before contracting to its primary location and was partially reformed in the same place two days after the eruption. This ejection, however, triggered a coronal mass ejection (CME) observed in LASCO C2. The prominence was located in the northern periphery of the CME magnetic field configuration and, therefore, the background magnetic field was asymmetric with respect to the filament position. The physical conditions of the falling plasma blobs were analysed with respect to the prominence kinematics.

Conclusions. The same sign of the prominence body twist and writhe, as well as the amount of twisting above the critical value of 2π after the activation phase indicate that possibly conditions for kink instability were present. No signature of magnetic reconnection was observed anywhere in the prominence body and its surroundings. The filament/prominence descent following the eruption and its partial reformation at the same place two days later suggest a confined type of eruption. The asymmetric background magnetic field possibly played an important role in the failed eruption.

Key words. Sun: activity – Sun: filaments, prominences – magnetic fields

1. Introduction

Prominence eruptions are large-scale eruptive phenomena that occur in the low solar atmosphere. Observations show that prominences display a wide range of eruptive activity. There are three types of prominence (filament) eruptions according to the observational definitions of Gilbert et al. (2007) based on the relation between the filament mass and corresponding supporting magnetic structure: full, partial, and failed (confined), of which the partial ones are the most complex. A full eruption occurs when the entire magnetic structure and the pre-eruptive prominence material are expelled into the heliosphere. If neither the filament mass, nor the supporting magnetic structure escape the solar gravitational field, it is a failed eruption. Partial eruptions can be divided into two subcategories: i) when the entire magnetic structure erupts, with the eruption containing either part or none of its supported pre-eruptive prominence material; and ii) when the magnetic structure itself partially escapes with either some or none of the filament mass (Gilbert et al. 2007). One important observational consequence concerning partial and failed eruptions is the re-formation of the filament at the pre-eruptive location.

Sterling & Moore (2004a,b) unveiled a common pattern of prominence eruptions: an initial slow-rise phase (with very low acceleration), during which the filament gradually ascends, followed by a sharp change to a phase of fast acceleration. There are three types of prominence eruption after the fast-rise phase: i) an eruptive prominence can continue to rise with acceleration; ii) the fast rise can be followed by a constant velocity phase; or iii) the constant velocity phase of an eruptive prominence can be followed by a deceleration phase (Vršnak 1998).

Eruptive prominences (EPs) (or filaments, if observed on the solar disk) are frequently associated with and physically related to coronal mass ejections (CMEs) and flares (Tandberg-Hanssen 1995; Webb et al. 1976; Munro et al. 1979; Webb & Hundhausen 1987; St. Cyr & Webb 1991). Usually, all three eruptive events occur in the same large-scale coronal magnetic field, in which the EP only occupies a limited volume at its

⋆ Movies showing the temporal evolution are available in electronic form at http://www.aanda.org

A&A 538, A50 (2012)
DOI: 10.1051/0004-6361/201117877

Astronomy & Astrophysics

What is the true nature of blinkers?

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Received 12 August 2011 / Accepted 5 November 2011

ABSTRACT

Aims. The aim of this work is to identify the true nature of the transient EUV brightenings, called blinkers.
Methods. Co-spatial and co-temporal multi-instrument data, including imaging (EUVI/STEREO, XRT and SOT/Hinode), spectroscopic (CDS/SoHO and EIS/Hinode) and magnetogram (SOT/Hinode) data, of an isolated equatorial coronal hole were used. An automatic program for identifying transient brightenings in CDS O v 629 Å, EUVI 171 Å and XRT was applied.
Results. We identified 28 blinker groups in the CDS O v 629 Å raster images. All CDS O v 629 Å blinkers showed counterparts in EUVI 171 Å and 304 Å images. We classified these blinkers into two categories, one associated with coronal counterparts and other with no coronal counterparts as seen in XRT images and EIS Fe xii 195.12 Å raster images. Around two-thirds of the blinkers show coronal counterparts and correspond to various events like EUV/X-ray jets, brightenings in coronal bright points or foot-point brightenings of larger loops. These brightenings occur repetitively and have a lifetime of around 40 min at transition region temperatures. The remaining blinker groups with no coronal counterpart in XRT and EIS Fe xii 195.12 Å appear as point-like brightenings and have chromospheric/transition region origin. They take place only once and have a lifetime of around 20 min. In general, lifetimes of blinkers are different at different wavelengths, i.e. different temperatures, decreasing from the chromosphere to the corona.
Conclusions. This work shows that the term blinker covers a range of phenomena. Blinkers are the EUV response of various transient events originating at coronal, transition region and chromospheric heights. Hence, events associated with blinkers contribute to the formation and maintenance of the temperature gradient in the transition region and the corona.

Key words. Sun: atmosphere – Sun: corona – methods: observational – methods: data analysis – sun: transition region

1. Introduction

The quasi-steady mechanism(s) that sustains the heating of the outer solar atmosphere and the solar wind is currently under intensive investigation using state-of-the-art ground- and space-based instrumentation. These observations show that small-scale salt and pepper like bipolar network magnetic fields constantly reconfigure themselves on time scales of minutes-to-hours, resulting in a complicated and dynamically evolving solar atmosphere. It is believed that magnetic reconnection and subsequent energy release is the major mechanism which can relax these constantly evolving magnetic field structures. Such small-scale energy releases seen as sudden brightenings (blinkers or extreme-ultraviolet (EUV) brightenings), fast plasma ejections (spicules or EUV/X-ray jets), etc., are omnipresent and have been reported at different heights in the solar atmosphere. It is crucial to establish links between these different events as they potentially connect the lower and upper solar atmosphere and, hence, could contribute to the transfer of mass and energy in the atmosphere (Parker 1988; Schrijver et al. 1997, 1998; Moore et al. 1999; Winebarger et al. 2002; Yamauchi et al. 2005).

EUV brightenings, also called blinkers, were first reported by Harrison (1997) in the quiet Sun, at transition region (TR) temperatures, using the Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995) onboard SoHO spacecraft. They show intensity enhancements of a factor of 2–3 (Harrison 1997; Bewsher et al. 2002) and Doppler velocities of 25–30 km s^{-1} (Bewsher et al. 2003) in TR lines like O v 629.77 Å ($T \approx 2.4 \times 10^5$ K). The average lifetime of these EUV brightenings is 16 min ranging from 6 to 40 min (Bewsher et al. 2002). They have also been observed in active regions (Walsh et al. 1997; Parnell et al. 2002; Bewsher et al. 2003), with slightly higher Doppler velocities of 20–40 km s^{-1} (Bewsher et al. 2003). Corresponding signatures of blinkers were found in chromospheric lines (Brković et al. 2001; Brković & Peter 2003; Brooks et al. 2004; Brooks & Kurokawa 2004). Harrison et al. (1999) derived an average intensity increase of 4% and 7% in the coronal Mg ix 368.9 Å and Mg x 624.9 Å lines, respectively, for these events. Bewsher et al. (2002) also detected a weak response of blinkers in these lines and concluded "that blinkers have no coronal signatures", although "it may be simply that these lines are too weak to detect anything in". Priest et al. (2002) suggested from simple physical models that blinkers can be produced by five different physical mechanisms, namely: the heating of cool spicular material; the containment of plasma in low-lying loops in the network; the thermal linking of cool and hot plasma at the feet of coronal loops; the heating and evaporation of chromospheric plasma in response to a coronal heating event; and the cooling and draining of hot coronal plasma when coronal heating is switched off.

Coronal jets are dynamic features which are observed as collimated ejections of plasma on small scales. They were first observed with the solar X-ray telescope onboard the Yohkoh satellite (Shibata et al. 1992) and are believed to be the result of magnetic reconnection (Yokoyama & Shibata 1995). The X-ray Telescope (XRT; Golub et al. 2007) onboard Hinode opened a new era for studying X-ray features in tens-of-second detail, revealing the association of some jets with the expansion and eruption of coronal bright point loops

A&A 548, A62 (2012)
DOI: 10.1051/0004-6361/201220079

Astronomy & Astrophysics

Coronal hole boundaries at small scales

IV. SOT view. Magnetic field properties of small-scale transient brightenings in coronal holes*

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Received 23 July 2012 / Accepted 5 October 2012

ABSTRACT

Context. We study the magnetic properties of small-scale transients in coronal holes and a few in the quiet Sun identified in X-ray observations and spectroscopic data in two previous papers.
Aims. We aim to investigate the role of small-scale transients in the evolution of the magnetic field in an equatorial coronal hole.
Methods. Two sets of observations of an equatorial coronal hole and another two in quiet-Sun regions were analysed using longitudinal magnetograms taken by the Solar Optical Telescope. An automatic feature tracking program, SWAMIS, was used to identify and track the magnetic features. Each event was then visually analysed in detail.
Results. In both coronal holes and quiet-Sun regions, all brightening events are associated with bipolar regions and are caused by magnetic flux emergence followed by cancellation with the pre-existing and/or newly emerging magnetic flux. In the coronal hole, 19 of 22 events have a single stable polarity which does not change its position in time. In eleven cases this is the dominant polarity. In the coronal hole, the magnetic features with the largest flux are those of the dominant polarity, while the opposite polarity is distributed in weaker features. The number of magnetic features of the dominant polarity is four times grater than the opposite polarity. The supergranulation configuration appears to preserve its general shape during approximately nine hours of observations although the large concentrations (the dominant polarity) in the network did evolve and/or were slightly displaced, and their strength either increased or decreased. The emission fluctuations/radiance oscillations seen in the X-ray bright points are associated with recurring magnetic cancellation in the footpoints. Unique observations of an X-ray jet reveal similar magnetic behaviour in the footpoints, i.e. cancellation of the opposite polarity magnetic flux. We find that the magnetic flux cancellation rate during the jet is much higher than in bright points. Not all magnetic cancellations result in an X-ray enhancement, suggesting that there is a threshold of the amount of magnetic flux involved in a cancellation above which brightening would occur at X-ray temperatures.
Conclusions. Our study demonstrates that the magnetic flux in coronal holes is continuously processed through magnetic reconnection which is responsible for the formation of numerous small-scale transient events. The open magnetic flux forming the coronal-hole phenomenon is largely involved in these transient features. The question of whether this open flux is transported as a result of the formation and evolution of these transient events, however, still remains open.

Key words. Sun: corona – Sun: chromosphere – Sun: evolution – magnetic fields – methods: observational

1. Introduction

Coronal holes (CHs) are regions on the Sun where the emission of coronal lines is significantly reduced. CHs are found to be the main source regions of the fast solar wind (Krieger et al. 1973) while coronal hole boundaries are believed to be the regions where the slow solar wind originates (Hundhausen 1977). We first studied the small-scale evolution of CHs and their boundaries using spectroscopic observations from SUMER (Madjarska et al. 2004). This was followed by three studies. The first one investigated dynamic phenomena at the coronal hole boundaries (CHBs) using TRACE (The Transition Region And Coronal Explorer) and EIT (Extreme-ultraviolet Imaging Telescope) onboard SoHO (Madjarska & Wiegelmann 2009, hereafter Paper I). The second study by Subramanian et al. (2010, hereafter Paper II) automatically identified X-ray transient brightenings in CHs and the quiet-Sun regions in observations from XRT (The X-Ray Telescope) onboard the Hinode satellite. Next, Madjarska et al. (2012, hereafter Paper III) analysed the plasma properties of all the events which were identified in Paper II having simultaneous spectral observations taken with the EIS (Extreme-ultraviolet Imaging Spectrometer) and SUMER (Solar Ultraviolet Measurements of Emitted Radiation) instruments onboard Hinode and SoHO, respectively. By studying tens of events, the authors found that events in the CHs and quiet-Sun regions reached similar temperatures and electron densities, but events in CHs and their boundaries were more dynamic than events in the quiet Sun. Background information on

* Three movies and Appendix A are available in electronic form at http://www.aanda.org

A&A 532, L1 (2011)
DOI: 10.1051/0004-6361/201116735

Astronomy & Astrophysics

Letter to the Editor

Can coronal hole spicules reach coronal temperatures?*

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Received 16 February 2011 / Accepted 11 May 2011

ABSTRACT

Aims. The present study aims to provide observational evidence of whether coronal hole spicules reach coronal temperatures.

Methods. We combine multi-instrument co-observations obtained with the SUMER/SoHO and with the EIS/SOT/XRT/Hinode.

Results. The analysed three large spicules were found to be comprised of numerous thin spicules that rise, rotate, and descend simultaneously forming a bush-like feature. Their rotation resembles the untwisting of a large flux rope. They show velocities ranging from 50 to 250 km s^{-1}. We clearly associated the red- and blue-shifted emissions in transition region lines not only with rotating but also with rising and descending plasmas. Our main result is that these spicules although very large and dynamic, are not present in the spectral lines formed at temperatures above 300 000 K.

Conclusions. In this paper we present the analysis of three Ca II H large spicules that are composed of numerous dynamic thin spicules but appear as macrospicules in lower resolution EUV images. We found no coronal counterpart of these and smaller spicules. We believe that the identification of phenomena that have very different origins as macrospicules is due to the interpretation of the transition region emission, and especially the He II emission, wherein both chromospheric large spicules and coronal X-ray jets are present. We suggest that the recent observation of spicules in the coronal AIA/SDO 171 Å and 211 Å channels probably comes from the existence of transition region emission there.

Key words. Sun: corona – Sun: transition region – line: profiles – methods: observational

1. Introduction

The term spicule refers to jet-like features expelled from the chromosphere as seen at the solar limb. They were first observed by Secchi (1877) and called "spicules" by Roberts (1945). Spicules are best viewed at the solar limb as bright features against the dark background of the solar corona in Hα and Ca II images. Several studies report that these phenomena fall back along the same trajectory or fade out (Beckers 1972; Suematsu 1998). Many on-disk filament-like features were identified as the counterpart of the limb spicules due to the similarities in their properties (Christopoulou et al. 2001; Rouppe van der Voort et al. 2007), and some were named "mottles" (Tsiropoula & Schmieder 1997). Coronal hole spicules are found to be taller than quiet Sun spicules, probably owing to the different configuration of the magnetic field of the two regions (Beckers 1972). Spicules/mottles have been observed at temperatures between 5000 K and 300 000 K. However, De Pontieu et al. (2011) report that a small but sufficient fraction of spicules, including coronal hole spicules, are heated to temperatures above 1 MK based on observations from the Atmospheric Imaging Assembly (AIA) instrument onboard the Solar Dynamic Observatory (SDO) taken with the 171 Å filter. Transient events like spicules/mottles are of prime importance as they intermittently connect the chromosphere with the corona and possibly sustain the mass balance in the solar atmosphere (Tsiropoula & Tziotziou 2004). However, the downflow observed in transition region lines may be the result of the mottle/spicule plasma returning to the solar surface (Pneuman & Kopp 1978; Withbroe 1983; Tsiropoula & Tziotziou 2004). If all the material that is sent up through spicules/mottles is returned to the solar surface, then their contribution to coronal heating will be minimal, dismissing the possibility of spicules directly contributing to coronal heating (Withbroe 1983). Moreover, there are speculations that spicules may be capable of transporting energy high into the upper chromosphere and even up to the corona (Pneuman & Kopp 1978; Athay & Holzer 1982) so they can be possibly responsible for coronal heating (Athay 2000; De Pontieu et al. 2011).

Bohlin et al. (1975) revealed the existence of jet-like features found in images taken with the slitless NRL spectrograph during the Skylab mission. The events were called macrospicules because they resembled Hα spicules, but were much larger and had longer lifetimes. They appear increasingly inclined away from the pole as a function of increasing position angle measured from the pole, which makes them comparable to Hα spicules. They were first seen in He II 304 Å and only rarely in Ne VII 465 Å (5.7 K) (Bohlin et al. 1975). We would like to note here that the formation temperature of He II ranges from 5 to 12×10^4 K with a maximum at 8×10^4 K, corresponding to a low transition region temperature or the uppermost chromosphere (Jordan 1974). Because of the anomalous behaviour of the He I and II lines (Andretta et al. 2003), observation of transient events in these lines does not tell where in the solar atmosphere these events originate. Therefore, to link chromospheric features, such as spicules, with phenomena seen at temperatures describing the transition region and corona, is not a trivial task and requires the use of suitable data.

Spectral and imaging macrospicule analysis were reported in several papers (Pike & Harrison 1997; Parenti et al. 2002; Pike & Mason 2002; Kamio et al. 2010). In SoHO/CDS data, they were registered in spectral lines with formation temperatures from 20 000 K to 1 MK (Pike & Harrison 1997), although Pike & Mason (2002) find no Mg IX (1 MK) emission in the region where macrospicules were detected in He I (20 000 K) and O V (250 000 K). Recently, Kamio et al. (2010) have

* Movie is available in electronic form at http://www.aanda.org

A&A 535, A95 (2011)
DOI: 10.1051/0004-6361/201117515

Astronomy & Astrophysics

Magnetic reconnection resulting from flux emergence: implications for jet formation in the lower solar atmosphere?

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Received 17 June 2011 / Accepted 26 September 2011

ABSTRACT

Aims. We aim at investigating the formation of jet-like features in the lower solar atmosphere, e.g. chromosphere and transition region, as a result of magnetic reconnection.

Methods. Magnetic reconnection as occurring at chromospheric and transition regions densities and triggered by magnetic flux emergence is studied using a 2.5D MHD code. The initial atmosphere is static and isothermal, with a temperature of 2×10^4 K. The initial magnetic field is uniform and vertical. Two physical environments with different magnetic field strength (25 G and 50 G) are presented. In each case, two sub-cases are discussed, where the environments have different initial mass density.

Results. In the case where we have a weaker magnetic field (25 G) and higher plasma density ($N_e = 2\times 10^{11}$ cm^{-3}), valid for the typical quiet Sun chromosphere, a plasma jet would be observed with a temperature of 2–3 $\times 10^4$ K and a velocity as high as 40 km s^{-1}. The opposite case of a medium with a lower electron density ($N_e = 2 \times 10^{10}$ cm^{-3}), i.e. more typical for the transition region, and a stronger magnetic field of 50 G, up-flows with line-of-sight velocities as high as ~90 km s^{-1} and temperatures of 6×10^5 K, i.e. upper transition region – low coronal temperatures, are produced. Only in the latter case, the low corona Fe ix 171 Å shows a response in the jet which is comparable to the O v increase.

Conclusions. The results show that magnetic reconnection can be an efficient mechanism to drive plasma outflows in the chromosphere and transition region. The model can reproduce characteristics, such as temperature and velocity for a range of jet features like a fibril, a spicule, a hot X-ray jet or a transition region jet by changing either the magnetic field strength or the electron density, i.e. where in the atmosphere the reconnection occurs.

Key words. Sun: corona – Sun: transition region – Sun: chromosphere – Sun: magnetic topology

1. Introduction

A variety of jet-like features such as spicules, fibrils, surges, Ellerman bombs, EUV/X-ray jets etc., as seen in various atmospheric regions, are observed in the solar atmosphere. Spicules are relatively thin, elongated jet-like structures best viewed at the solar limb in Hα or Ca II images as bright features against a dark background. The close correlation between observed properties of limb spicules and other on-disk features such as mottles, fibrils and straws has prompted many authors to suggest that these may be counterparts of each other (Tsiropoula & Schmieder 1997). As viewed in the optical, the classical spicule is observed to reach heights of 6500–15 000 km (Beckers 1968; Withbroe 1983) with an average lifetime of 5 min and average plasma velocities of 25 km s^{-1}. Recently, using high-resolution observations in Ca ii H (3968 Å) from the Solar Optical Telescope (SOT) on Hinode, De Pontieu et al. (2007) suggested at least two types of spicules, the classical spicule and a more dynamic one.

Tavabi et al. (2011) suggested four types of spicules based on their diameter, ranging from 0.3″ (220 km), 0.5″ (360 km), 0.75″ (550 km) to 1.15″ (850 km). Typically, they show a succession of upward and downward motions. The more dynamic spicule develop and disappear on timescales of 10–60 s, with velocities sometimes exceeding 100 km s^{-1}.

Spicules are also seen in UV and EUV lines (Dere et al. 1989) and thus reach at least to transition region temperatures. Cook et al. (1984) using HRTS observations taken in C iv 1550 Å showed that these structures show tilted features which was interpreted as rotational velocities of approximately 50 km s^{-1}. In a more recent paper, Madjarska et al. (2011a) showed that this may be better interpreted as a multi-strand structure with up-flows and down-flows.

Several authors have looked at magnetic reconnection as a driving mechanism for hot jets (Jin et al. 1996; Innes & Tóth 1999; Galsgaard et al. 2005; Nishizuka et al. 2008; Patsourakos et al. 2008; Murray et al. 2009; Rosdahl & Galsgaard 2010; Pariat et al. 2010, and references therein). Roussev et al. (2001a,b,c) performed 2D Magneto-hydrodynamic (MHD) simulations of transition region jets deriving blue-shifts of the order of 100 km s^{-1}. Several initial physical environments were studied. However, the plasma β on the current sheet was the same in all the cases with the maximum velocity of the blue-shifted jets eventually reaching almost the same value in all cases, although they were different at the beginning of the experiments.

Various authors have suggested that spicules can be driven by waves (magnetoacoustic or Alfvén) (Hansteen et al. 2006; De Pontieu et al. 2007; Heggland et al. 2007), while Sterling et al. (1993), Karpen et al. (1995), and Heggland et al. (2009) have considered magnetic reconnection as a plausible candidate for driving chromospheric jets. In all the models mentioned above, spicules are produced but their velocities are small (~25 km s^{-1}). Martínez-Sykora et al. (2011b) explored 3D

A&A 526, A19 (2011)
DOI: 10.1051/0004-6361/201015269

Astronomy & Astrophysics

Dynamics and plasma properties of an X-ray jet from SUMER, EIS, XRT, and EUVI A & B simultaneous observations*

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Received 24 June 2010 / Accepted 27 October 2010

ABSTRACT

Context. Small-scale transient phenomena in the quiet Sun are believed to play an important role in coronal heating and solar wind generation. One of them, called "X-ray jet", is the subject of our study.

Aims. We intend to investigate the dynamics, evolution, and physical properties of this phenomenon.

Methods. We combine multi-instrument observations obtained simultaneously with the SUMER spectrometer onboard SoHO, with EIS and XRT onboard Hinode, and with EUVI/SECCHI onboard the Ahead and Behind STEREO spacecrafts. We derive plasma parameters such as temperatures and densities as well as dynamics by using spectral lines formed in the temperature range from 10 000 K to 12 MK. We also use an image difference technique to investigate the evolution of the complex structure of the studied phenomenon.

Results. With the available unique combination of data we were able to establish that the formation of a jet-like event is triggered by not one, but several energy depositions, which are most probably originating from magnetic reconnection. Each energy deposition is followed by the expulsion of pre-existing or newly reconnected loops and/or collimated flow along open magnetic field lines. We derived in great detail the dynamic process of X-ray jet formation and evolution. For the first time we also found spectroscopically a temperature of 12 MK (Fe XXIII 263.76 Å) and density of 4×10^{10} cm^{-3} in the quiet Sun, obtained from a pair of Fe XII lines with a maximum formation temperature of 1.3×10^6 K, in an energy deposition region. We point out a problem concerning an uncertainty in using the SUMER Mg X 624.9 Å line for coronal diagnostics. We clearly identified two types of up-flow: one collimated up-flow along open magnetic field lines and a plasma cloud formed from the expelled BP loops. We also report a cooler down-flow along closed magnetic field lines. A comparison is made with a model developed by Moreno-Insertis et al. (2008).

Key words. Sun: corona – Sun: transition region – line: profiles – methods: observational

1. Introduction

X-ray jets in the solar atmosphere were first seen in images from the Soft X-ray Telescope (Tsuneta et al. 1991, SXT) onboard the Yohkoh satellite. They appear as collimated flows originating from coronal bright points (BPs) or active regions and are always associated with transient brightenings called microflares. We will review here only the very recent studies on these phenomena. Shimojo et al. (2007, and the references therein) resolved the fine structure of a X-ray jet and reported that a loop appeared near the footpoint of the jet when a footpoint brightening was observed. They also found that the X-ray jet appears after the loop breaks. They observed thread-like structures along the jet. Culhane et al. (2007b) found from Extreme-ultraviolet Imaging Spectrometer (EIS) 40″ slot observations of a polar coronal hole that jet temperatures range from 0.4 MK to 5.0 MK. The jet velocities had values that are less than the escape solar velocity (≈ 618 km s^{-1}). They interpreted the increase of the radiance in the cooler spectral lines as emitted from the falling back plasma of the cooling down jet. Nishizuka et al. (2008) reported on simultaneous cool emission (~10^4 K) in Ca II H images from the Solar Optical Telescope (SOT) onboard Hinode and hot emission (1.3×10^6 K) in Fe XII 195 Å images from the Extreme-ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SoHO) as well as in X-ray Telescope (XRT) images (Al_poly filter with a temperature response with a maximum at 5×10^6 K) from a "giant" jet. From their observations of a current-sheet-like structure seen in all three instruments, they concluded that magnetic reconnection is occurring in the transition region or upper chromosphere. Cirtain et al. (2007) found that X-ray jets have two distinct velocities: one near the Alfvén speed (~800 km s^{-1}) and another near the sound speed (200 km s^{-1}). Patsourakos et al. (2008) discussed the first stereoscopic observations of polar coronal jets made by the Extreme-ultraviolet imagers (EUVI) of the SECCHI instruments onboard the twin STEREO spacecrafts. The authors depicted a helical structure of a jet, which showed signs of untwisting with the jet initially ascending slowly with ≈10–20 km s^{-1} and then suddenly accelerating to velocities higher than 300 km s^{-1}. Helical structures in jets have also been reported by Shimojo et al. (1996), Jiang et al. (2007), and Nisticò et al. (2009). Kamio et al. (2010) studied the relation of so-called macrospicules in He II 304 Å and an X-ray jet. The Doppler shifts of the jet and the inclination angle of the jet were "attributed to a rotating motion of the macrospicule rather than a radial flow or an expansion". The authors concluded that the macrospicule is driven by the unfolding motion of a twisted magnetic flux rope, while the associated X-ray jet is a radial outflow.

It is believed that the majority of the jet-like phenomena in the solar atmosphere are produced by magnetic reconnection.

* Figures 10–16 and movie are only available in electronic form at http://www.aanda.org

A&A 510, A111 (2010)
DOI: 10.1051/0004-6361/200913101

Astronomy & Astrophysics

Chromospheric magnetic reconnection caused by photospheric flux emergence: implications for jet-like events formation

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Received 10 August 2009 / Accepted 17 December 2009

ABSTRACT

Magnetic reconnection in the low atmosphere, e.g. chromosphere, is investigated in various physical environments. Its implications for the origination of explosive events (small-scale jets) are discussed. A 2.5-dimensional resistive magnetohydrodynamic (MHD) model in Cartesian coordinates is used. It is found that the temperature and velocity of the outflow jets as a result of magnetic reconnection are strongly dependent on the physical environments, e.g. the magnitude of the magnetic field strength and the plasma density. If the magnetic field strength is weak and the density is high, the temperature of the jets is very low ($\sim 10^4$ K) as well as its velocity (~ 40 km s^{-1}). However, if environments with stronger magnetic field strength (40 G) and smaller density (electron density $N_e = 2 \times 10^{10}$ cm^{-3}) are considered, the outflow jets reach higher temperatures of up to 6×10^5 K and a line-of-sight velocity of up to 130 km s^{-1} which is comparable with the observational values of jet-like events.

Key words. magnetohydrodynamics (MHD) – Sun: chromosphere – Sun: transition region – Sun: UV radiation – magnetic fields

1. Introduction

Jet-like events, first reported by Brueckner & Bartoe (1983), are characterised by non-Gaussian spectral line profiles. Dere et al. (1991) suggested that they are produced by bi-directional jets as a result of magnetic reconnection. To date, these jet-like events (often called explosive events) are mainly observed in spectral lines formed at transition region temperatures (Dere 1994; Chae et al. 1998; Innes et al. 2001; Madjarska & Doyle 2003), although observations of explosive events in chromospheric lines are also reported. For example, Madjarska & Doyle (2002) presented the temporal evolution of different temperature plasma using high cadence (10 s) observations obtained with the solar ultraviolet measurement of emitted radiation (SUMER) spectrometer, and found a time delay in the response of the S VI 933 Å (2×10^5 K) line with respect to Ly 6 (2×10^4 K), with the Ly 6 line responding earlier. They concluded that the jet-like events may first appear at chromospheric temperatures. In follow-up work, Doyle et al. (2005) reported on a joint SUMER, coronal diagnostic spectrometer (CDS) on board the Solar Heliospheric Observatory and TRACE imager study, confirming the possibility that some jet-like events originate in the chromosphere. They further suggested that jet-like events could be divided into two types: one formed in the chromosphere and the other formed in the transition region. Some of the observed features are the result of spicules and/or macrospicules (Madjarska & Doyle 2003; Madjarska et al. 2006), while others are the result of high velocity flows in small loops (Teriaca et al. 2004). In more recent work, Madjarska et al. (2009) presented observational data relating explosive events to a surge and demonstrated that the division of small-scale transient events into a number of different subgroups, for instance explosive events, blinkers, spicules, surges or just brightenings, is ambiguous, implying that the definition of a feature based only on either spectroscopic or imaging characteristics as well as insufficient spectral and spatial resolution can be incomplete.

Several numerical models were developed to study jet-like events. Sarro et al. (1999) used a 1D magnetic flux-tube model to simulate the temporal evolution of UV emission line profiles, e.g. C IV 1548.2 Å, in response to energy perturbations located below the transition-region. The maximum blue-shifts they obtained reach values of the order of 100 km s^{-1}. Innes & Tóth (1999) presented a 2D MHD study on jet-like events with different initial conditions, representative of different regions in which the reconnection occurs, e.g. the corona and chromosphere. Their conclusion was that high-velocity components in the profiles of lines formed around 10^5 K can be obtained in both cases, irrespective of the initial conditions. However, heat conduction was not included, and no brightening was found at the zero velocity position of the spectral line. In their model, the initial equilibrium state consists of two regions of oppositely directed magnetic field lines, with a narrow current sheet between the two regions. Magnetic reconnection at the current sheet is initiated by introducing localized anomalous resistivity. Roussev et al. (2001a) carried out 2D MHD simulations, where jet-like events are formed during the process of magnetic reconnection. In their model, the initial magnetic field is parallel to the y-axis (vertical), and there is a thin current concentration formed along the y-axis. Magnetic reconnection is initiated by a localized increase of the magnetic diffusivity in the current concentration. Blue-shifts of the order of 100 km s^{-1} were obtained. By using the same model, they further extended the work and performed simulations under different physical conditions (Roussev et al. 2001b,c).

Yokoyama & Shibata (1995, 1996) performed 2D magnetic reconnection to study coronal X-ray jets using both oblique and

A&A 516, A50 (2010)
DOI: 10.1051/0004-6361/200913624

Astronomy & Astrophysics

Coronal hole boundaries evolution at small scales

II. XRT view. Can small-scale outflows at CHBs be a source of the slow solar wind?★

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Received 8 November 2009 / Accepted 12 April 2010

ABSTRACT

Aims. We aim to further explore the small-scale evolution of coronal hole boundaries using X-ray high-resolution and high-cadence images. We intend to determine the fine structure and dynamics of the events causing changes of coronal hole boundaries and to explore the possibility that these events are the source of the slow solar wind.

Methods. We developed an automated procedure for the identification of transient brightenings in images from the X-ray telescope on-board Hinode taken with an Al Poly filter in the equatorial coronal holes, polar coronal holes, and the quiet Sun with and without transient coronal holes.

Results. We found that in comparison to the quiet Sun, the boundaries of coronal holes are abundant with brightening events including areas inside the coronal holes where closed magnetic field structures are present. The visual analysis of these brightenings revealed that around 70% of them in equatorial, polar and transient coronal holes and their boundaries show expanding loop structures and/or collimated outflows. In the quiet Sun only 30% of the brightenings show flows with most of them appearing to be contained in the solar corona by closed magnetic field lines. This strongly suggests that magnetic reconnection of co-spatial open and closed magnetic field lines creates the necessary conditions for plasma outflows to large distances. The ejected plasma always originates from pre-existing or newly emerging (at X-ray temperatures) bright points.

Conclusions. The present study confirms our findings that the evolution of loop structures known as coronal bright points is associated with the small-scale changes of coronal hole boundaries. The loop structures show an expansion and eruption with the trapped plasma consequently escaping along the "quasi" open magnetic field lines. These ejections appear to be triggered by magnetic reconnection, e.g. the so-called interchange reconnection between the closed magnetic field lines (BPs) and the open magnetic field lines of the coronal holes. We suggest that these plasma outflows are possibly one of the sources of the slow solar wind.

Key words. Sun: atmosphere – Sun: corona – methods: observational – methods: data analysis

1. Introduction

Coronal holes (CHs) are regions of predominantly unipolar coronal magnetic fields with a significant component of the magnetic field open into the heliosphere. They are visible in spectral lines emitting at coronal temperatures as dark areas when compared to the quiet Sun, while in the chromospheric He I 10830 Å line they appear bright. For detailed introduction on coronal holes see Madjarska & Wiegelmann (2009, hereafter Paper I). CHs are identified as the source of the fast solar wind with velocities of up to ≈800 km s^{-1} (Krieger et al. 1973). In contrast, the slow wind has velocities around 400 km s^{-1} and is more dense, and variable in nature when compared to the fast solar wind. von Steiger (1996) found from Ulysses satellite data that the elemental composition of the fast wind is similar to the elemental composition of the photosphere. The slow solar wind is enriched with low first ionization potential (FIP) elements by a factor of 3–5 greater than in the photosphere (with respect to hydrogen) while higher FIP elements were found at solar surface abundances. The FIP effect describes the element abundance anomalies (the enhancement of elements with low FIP such as Fe, Mg and Si over those with high FIP like Ne and Ar) in the upper solar atmosphere and solar wind, and can give a clue on the origin of both the fast and the slow solar winds. von Steiger (1996) concluded that the fast and slow solar winds not only differ in their kinetics but also in their composition of elements.

Woo et al. (2004) suggested that the release of trapped plasma in closed loop structures by magnetic reconnection could play a significant role in the solar wind flow. Such reconnection between the open and closed magnetic field lines presumably happens continuously at coronal hole boundaries. Wang et al. (1998) investigated the ejection of plasma blobs from the streamer belt linked to the slow wind and concluded that magnetic reconnection between the distended streamer loops and the open magnetic field lines might be behind the plasma ejection. They also suggested that this ejection cannot account for all the slow solar wind and a major component should, therefore, originate outside the helmet streamers, i.e. from inside the coronal holes. Madjarska et al. (2004) found non-Gaussian profiles along the boundaries of an equatorial extension of a polar CH in the mid- and high-transition region lines N IV 765 Å and Ne VIII 770 Å, respectively, recorded with the Solar Measurement of Emitted Radiation (SUMER) spectrometer on-board the Solar and Heliospheric Observatory (SoHO). The authors suggested that these profiles are the signature of magnetic reconnection occurring between the closed magnetic

★ 4 movies are only available in electronic form at http://www.aanda.org

A&A 503, 991–997 (2009)
DOI: 10.1051/0004-6361/200912066

Astronomy & Astrophysics

Coronal hole boundaries evolution at small scales

I. EIT 195 Å and TRACE 171 Å view⋆

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Received 13 March 2009 / Accepted 4 June 2009

ABSTRACT

Aims. We aim to study the small-scale evolution at the boundaries of an equatorial coronal hole connected with a channel of open magnetic flux to the polar region and an "isolated" one in the extreme-ultraviolet spectral range. We determine the spatial and temporal scale of these changes.

Methods. Imager data from TRACE in the Fe IX/X 171 Å passband and EIT on-board Solar and Heliospheric Observatory in the Fe XII 195 Å passband were analysed.

Results. We found that small-scale loops known as bright points play an essential role in coronal hole boundary evolution at small scales. Their emergence and disappearance continuously expand or contract coronal holes. The changes appear to be random on a time scale comparable to the lifetime of the loops seen at these temperatures. No signature was found for a major energy release during the evolution of the loops.

Conclusions. Although coronal holes seem to maintain their general shape during a few solar rotations, a closer look at their day-by-day and even hour-by-hour evolution demonstrates significant dynamics. The small-scale loops (10″–40″ and smaller) which are abundant along coronal hole boundaries contribute to the small-scale evolution of coronal holes. Continuous magnetic reconnection of the open magnetic field lines of the coronal hole and the closed field lines of the loops in the quiet Sun is more likely to take place.

Key words. Sun: atmosphere – Sun: corona – methods: observational – methods: data analysis

1. Introduction

Coronal holes (CHs) are large regions on the Sun that are magnetically open. They are identified as the source of the fast solar wind (~800 km s^{-1}) (Krieger et al. 1973) and are visible in coronal lines (formed at temperatures above 6×10^5 K) as regions with a reduced emission relative to the quiet Sun (Wilhelm 2000; Stucki et al. 2002). There are two types of coronal holes: polar and mid-latitude CHs. During the minimum of solar activity, the solar atmosphere is dominated by two large CHs situated at both polar regions. The mid-latitude CHs can be either "isolated" or connected with a channel of open magnetic flux to a polar CH. The latter are called equatorial extensions of polar CHs (EECHs). The isolated coronal holes have an occurrence rate that follows the solar activity cycle and are usually connected with an active region (Insley et al. 1995).

Huber et al. (1974) compared the appearance and physical parameters of the different layers of the solar atmosphere in and outside coronal holes (e.g. the quiet Sun) using the Apollo Telescope mount on Skylab. Their measurements of the height of emission of various ions at different ionisation stages (different formation temperatures) at the polar limb indicated an increase of the thickness of the transition region underlying coronal holes. Hence, they found a difference between quiet Sun and coronal holes already pronounced at transition region temperatures.

Feldman et al. (1999) studied the morphology of the upper solar atmosphere using high-resolution data (1″–2″) taken by the transition region and corona explorer (TRACE), solar ultraviolet measurements of emitted radiation spectrometer (SUMER) on-board SOHO and the Naval Research Laboratory spectrometer on Skylab. The authors found that in the temperature range 4×10^4 K $\leq T_e \leq 1.4 \times 10^6$ K, the upper solar atmosphere is filled with loops of different sizes with hotter and longer loops overlying the cooler and shorter loops (Dowdy et al. 1986). At heights above 2.5×10^4 km in the upper solar atmosphere of the quiet Sun, only loops at temperatures $T_e \sim 1.4 \times 10^6$ K exist. No distinction was found between quiet Sun and coronal hole morphology at $5 \times 10^4 \leq T_e \leq 2.6 \times 10^5$ K. This suggests that both regions are filled with structures of similar sizes which are emitting at similar temperatures. These structures do not exceed a height of 7 Mm and have lengths ≤21 Mm. Feldman et al. (1999) also investigated the coronal hole boundaries concluding that they are seeded with small-scale loops (<7 Mm). There coexist, however, long loops at temperatures above $T \sim 1.4 \times 10^6$ K which generally originate from the same location but close to faraway locations.

Wiegelmann & Solanki (2004) made a further step by reconstructing the magnetic field in coronal holes and the quiet Sun with the help of a potential field model. They found that the CH loops are on average shorter, lower and flatter than in the QS. High and long closed loops are extremely rare in CHs, whereas short and low loops are almost as abundant as in the

⋆ Movies are only available in electronic form at http://www.aanda.org

Article published by EDP Sciences

The Astrophysical Journal, 701:253–259, 2009 August 10 doi:10.1088/0004-637X/701/1/253

EXPLOSIVE EVENTS ASSOCIATED WITH A SURGE

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Received 2009 February 25; accepted 2009 June 12; published 2009 July 21

ABSTRACT

The solar atmosphere contains a wide variety of small-scale transient features. Here, we explore the interrelation between some of them such as surges, explosive events, and blinkers via simultaneous spectral and imaging data taken with the *TRACE* imager, the SUMER and Coronal Diagnostics Spectrometer (CDS) on board *SOHO*, and Swedish Vacuum Solar Telescope La Palma. The features were observed in spectral lines with formation temperatures from 10,000 K to 1 MK and with the *TRACE* Fe IX/X 171 Å filter. The Hα filtergrams were taken in the wings of the Hα 6365 Å line at ±700 mÅ and ±350 mÅ. The alignment of all data in both time and solar XY shows that SUMER line profiles, which are attributed to explosive events, are due to a surge phenomenon. The surge's up- and downflows, which often appear simultaneously, correspond to the blue- and redshifted emission of the transition region N V 1238.82 Å and O V 629.77 Å lines as well as radiance increases of the C I, S I, and S II and Si II chromospheric lines. Some parts of the surge are also visible in the *TRACE* 171 Å images which could suggest heating to coronal temperatures. The surge is triggered, most probably, by one or more Elerman bombs which are best visible in Hα ± 350 Å but were also registered by *TRACE* Fe IX/X 171 Å and correspond to a strong radiance increase in the CDS Mg IX 368.07 Å line. With the present study, we demonstrate that the division of small-scale transient events into a number of different subgroups, for instance explosive events, blinkers, spicules, surges or just brightenings, is ambiguous, implying that the definition of a feature based only on either spectroscopic or imaging characteristics as well as insufficient spectral and spatial resolution can be incomplete.

Key words: Sun: activity – Sun: chromosphere – Sun: corona – Sun: transition region – Sun: UV radiation

Online-only material: mp4 animation

1. INTRODUCTION

Over the last decades, the increased use of space observatories such as the *Solar and Heliospheric Observatory* (*SOHO*), the *Transition Region Coronal Explorer* (*TRACE*), and presently *Hinode*, coupled with ground-based observations, has brought many new features on the Sun to light. What is, however, more important is that the combination of different types of observations, i.e., spectroscopic and imaging, covering a wide wavelength range and having a similar cadence and spatial resolution, provides crucial information on the nature and the physical characteristics of these phenomena.

We now know that the solar atmosphere contains different kinds of small-scale transient events. A particular transient phenomenon, however, is often associated with a specific instrument or a type of instrument, either a spectrometer or an imager. Explosive events (EEs), registered by the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectrometer and the high-resolution telescope and spectrometer (HRTS), for instance, were found to be restricted to transition region temperatures from 2×10^4 K to 5×10^5 K. They were first discovered by Brueckner & Bartoe (1983) in C IV 1548.21 Å data taken with HRTS. They are characterized as short-lived (60–350 s) small-scale (3″–5″ along a spectrometer slit) events identified by Doppler shifts of up to 200 km s^{-1}. It has been suggested that they result from the production of high-velocity bidirectional plasma jets during magnetic reconnection (Dere 1994). They often occur in areas with weak fluxes of mixed polarity or on the border of regions with large concentration of magnetic flux (Chae et al. 1998) and are often observed in bursts lasting up to 30 minutes in regions undergoing magnetic cancellation (Dere 1994; Chae et al. 1998; Pérez et al. 1999; Doyle et al. 2006). Another term often associated with them is bidirectional jets (Innes et al. 1997).

Surges mainly observed in Hα (10^4 K) and Ca II K & H (6×10^3 K) as well as extreme-ultraviolet (EUV) and X-ray jets are also assumed to result from the same physical mechanism. Solar surges are associated with active regions and represent an ejection of dense chromospheric material ($N_e \approx 10^{11}$ cm^{-3}) in the shape of straight or arch-shaped collimated streamers seen dark or bright in the Hα line (Roy 1973). The upflows often return to the solar surface along the same trajectory. Their occurrence is associated with Ellerman bombs (Ellerman 1917) in their footpoints.

The term "blinker" was first used by Harrison (1997) to describe a small-scale (on average 8″ × 8″) brightening in EUV lines observed with the Coronal Diagnostics Spectrometer (CDS) onboard *SOHO*. They last on average 17 minutes and are preferentially located in the network boundaries (Bewsher et al. 2002). It has been suggested that they represent an observational signature of increased filling factor rather than electron density. Several physical mechanisms have been put forward by Priest et al. (2002), Doyle et al. (2004), and Marik & Erdélyi (2002).

There have been attempts to unify some of these terminologies, e.g., blinkers have been suggested as a generic term for EUV network and cell brightenings (Harrison et al. 2003). Chae et al. (2000) stated that blinkers and EEs were the same phenomenon, while Madjarska & Doyle (2003) found them to be two separate unrelated events, as did a statistical study by Brković & Peter (2004). Madjarska & Doyle (2003) also speculated that blinkers may simply be the on-disk signature of spicules. Their work later led to the suggested notion that some

A&A 492, 575–583 (2008)
DOI: 10.1051/0004-6361:200809507

Astronomy & Astrophysics

The structure and dynamics of a bright point as seen with Hinode, SoHO and TRACE

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Received 4 February 2008 / Accepted 6 September 2008

ABSTRACT

Context. Solar coronal bright points have been studied for more than three decades, but some fundamental questions about their formation and evolution still remain unanswered.

Aims. Our aim is to determine the plasma properties of a coronal bright point and compare its magnetic topology extrapolated from magnetogram data with its appearance in X-ray images.

Methods. We analyse spectroscopic data obtained with EIS/Hinode, Ca II H and G-band images from SOT/Hinode, UV images from TRACE, X-ray images from XRT/Hinode and high-resolution/high-cadence magnetogram data from MDI/SoHO.

Results. The BP comprises several coronal loops as seen in the X-ray images, while the chromospheric structure consists of tens of small bright points as seen in Ca II H. An excellent correlation exists between the Ca II H bright points and increases in the magnetic field strength, implying that the Ca II H passband is a good indicator for the concentration of magnetic flux. Furthermore, some of the Ca II H bright points are the locations of the loop foot-points as determined from a comparison between the extrapolated magnetic field configuration and the X-ray images. Doppler velocities between 6 and 15 km s^{-1} are derived from the Fe XII and Fe XIII lines for the bright point region, while for Fe XIV and Si VII they are in the range from -15 to $+15$ km s^{-1}. The coronal electron density is 3.7×10^9 cm^{-3}. An excellent correlation is found between the positive magnetic flux and the X-ray light-curves.

Conclusions. The remarkable agreement between the extrapolated magnetic field configuration and some of the loops composing the bright point as seen in the X-ray images suggests that a large fraction of the magnetic field in the bright point is close to potential. However, some loops in the X-ray images do not have a counterpart in the extrapolated magnetic field configuration implying a non-potential component. The close correlation between the positive magnetic flux and the X-ray emission suggests that energy released by magnetic reconnection is stimulated by flux emergence or cancellation.

Key words. Sun: activity – Sun: magnetic fields – Sun: corona – Sun: chromosphere – line: profiles

1. Introduction

Coronal X-ray bright points (BPs) were first observed in rocket images in 1969 (Vaiana et al. 1973) and were seen as diffuse clouds with a bright core, although when viewed at higher spatial resolution, small loops are resolvable (Sheeley & Golub 1979). BPs are coronal structures smaller than 60″ that are associated with the interaction of photospheric bipolar magnetic features. Up to two third of them are related to cancellation of pre-existing magnetic features rather than to the emergence of new magnetic flux (Webb et al. 1993). McIntosh & Gurman (2005) recently reported on bright point statistics showing that 100 times more BPs were observable in EIT 171 Å than in the 284 Å filter. They speculated that there is a temperature dependence in the generation mechanism. The lifetime of an individual BP can be up to ≈40 h (Golub et al. 1974).

Habbal & Withbroe (1981) used Skylab data to show that BPs exhibit large variations in their emission in chromospheric, transition region and coronal lines. This work was followed up more recently by Madjarska et al. (2003), Ugarte-Urra et al. (2004) and Ugarte-Urra et al. (2005) who studied BPs at transition region temperatures and derived their plasma characteristics such as electron density variability, Doppler shifts and intensity oscillations. The magnetic structure of BPs has been modelled by various authors (Parnell et al. 1994; Longcope et al. 2001; Brown et al. 2001; von Rekowski et al. 2006a). The general view is that these features result from magnetic reconnection, although identifying the specific type of reconnection involved is still a challenge. Coronal reconnection begins when opposite polarity magnetic fragments approach one another, with the resulting release of energy into the corona leading to the formation of a BP.

With the launch of Hinode (Kosugi et al. 2007), new frontiers have opened for studying coronal BPs in combination with data from the Solar & Heliospheric Observatory (SoHO; Domingo et al. 1995) and the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999). Here we present the results of a multi-spacecraft/multi-instrument study of a BP. We use the EUV Imaging Spectrometer (EIS/Hinode; Culhane et al. 2007) together with Ca II H and G-band images from the Solar Optical Telescope (SOT/Hinode; Tsuneta et al. 2007), EUV images from TRACE and the Extreme ultraviolet Imaging Telescope (EIT/SoHO; Delaboudinière et al. 1995), and X-ray images from the X-ray Telescope (XRT/Hinode; Golub et al. 2007; Kano et al. 2007) as well as high-resolution/high-cadence magnetograms from the Michelson Doppler Imager (MDI/SoHO; Scherrer et al. 1995).

With the high-cadence magnetic field data coupled with images from XRT plus Ca II H and G-band data, we look at the structure of the bright point at photospheric, chromospheric and

Solar Phys (2008) 252: 283–292
DOI 10.1007/s11207-008-9271-z

EIS/*Hinode* Observations of Doppler Flow Seen through the 40-Arcsec Wide-Slit

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Received: 19 March 2008 / Accepted: 10 September 2008 / Published online: 10 October 2008

Abstract The Extreme ultraviolet Imaging Spectrometer (EIS) onboard *Hinode* is the first solar telescope to obtain wide-slit spectral images that can be used for detecting Doppler flows in transition region and coronal lines on the Sun and to relate them to their surrounding small-scale dynamics. We select EIS lines covering the temperature range 6×10^4 to 2×10^6 K that give spectrally pure images of the Sun with the 40-arcsec slit. In these images Doppler shifts are seen as horizontal brightenings. Inside the image it is difficult to distinguish shifts from horizontal structures but emission beyond the image edge can be unambiguously identified as a line shift in several lines separated from others on their blue or red side by more than the width of the spectrometer slit (40 pixels). In the blue wing of He II, we find a large number of events with properties (size and lifetime) similar to the well-studied explosive events seen in the ultraviolet spectral range. Comparison with X-Ray Telescope (XRT) images shows many Doppler shift events at the footpoints of small X-ray loops. The most spectacular event observed showed a strong blue shift in the transition region and lower corona lines from a small X-ray spot that lasted less than 7 min. The emission appears to be near a cool coronal loop connecting an X-ray bright point to an adjacent region of quiet Sun. The width of the emission implies a line-of-sight velocity of 220 $\mathrm{km\,s^{-1}}$. In addition, we show an example of an Fe XV shift with a velocity of about 120 $\mathrm{km\,s^{-1}}$, coming from what looks like a narrow loop leg connecting a small X-ray brightening to a larger region of X-ray emission.

Keywords Corona: quiet · Jets · Transition region

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A&A 490, 345–352 (2008)
DOI: 10.1051/0004-6361:200809975

Astronomy & Astrophysics

On the relation between DC current locations and an EUV bright point: A case study

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Received 14 April 2008 / Accepted 20 August 2008

ABSTRACT

Context. Motion of the photospheric plasma forces the footpoints of magnetic flux tubes to move. This can give rise to electric currents in the solar atmosphere. The dissipation of these electric currents and the consequent heating of the solar plasma may be responsible for the formation of Extreme-UltraViolet (EUV) and X-ray bright points. Earlier bright point models usually consider either the emergence or the canceling of photospheric magnetic features as being responsible for reconnection causing the bright point.
Aims. We investigate the consequences of different patterns of horizontal photospheric plasma motion for the generation of electric currents in the solar atmosphere and locate them with respect to an observed EUV bright point. The goal is to find out whether these currents might be responsible for the heating of bright points.
Methods. To perform this study we use a "data driven" three dimensional magnetohydrodynamic model. The model solves an appropriate set of magnetohydrodynamic equations and uses, as initial condition, the magnetic field extrapolated from the line-of-sight component of the photospheric magnetic field observed by MDI/SoHO and the height-stratified, equilibrium density and temperature of the solar corona. We apply different patterns of horizontal photospheric plasma motion, derived from the temporal evolution of the photospheric magnetic structures in the course of the bright point lifetime, as boundary conditions of the model.
Results. All applied patterns of horizontal photospheric plasma motion (shearing, convergence and fragmentation) lead to the formation of electric currents in the chromosphere, transition region and corona. Currents do not develop everywhere in the region where the motion is applied but in specific places where the magnetic field connectivity changes significantly. An important result is that the position where the electric currents develop is independent of the motion pattern used as boundary condition of the model. A comparison with data obtained by TRACE in the 1550 Å channel and by the EIT in the 195 Å channel shows that the region where the strongest current concentrations are formed coincides with the region where the EUV bright point appears.

Key words. Sun: atmosphere – Sun: magnetic fields – Sun: activity – magnetohydrodynamics (MHD) – methods: numerical

1. Introduction

Extreme-UltraViolet (EUV) and X-ray Bright Points (BPs) (Golub 1980; Webb 1986; Habbal 1992) provide a specific example of solar corona heating. The two main groups of models used to explain coronal heating attribute the heating of the solar plasma either to the dissipation of waves (Alfvén 1947) or electric currents (Parker 1972) in the solar atmosphere. In both cases the energy source is kinetic energy associated with photospheric plasma motion.

In this sense, an important feature that can help to understand the nature of the heating is the fact that BPs often are associated with moving bipolar magnetic features. Previous models (Tur & Priest 1976; Priest et al. 1994; Parnell et al. 1994; Longcope 1998) already took into account this characteristics to try to explain BPs. However, the models consider that the moving bipolar magnetic features have a single motion pattern (emerging or canceling) only and they also do not consider plasma motion through regions of strongly diverging magnetic fields. During the evolution of one BP, Brown et al. (2001) found different patterns of motion of the magnetic structures in the solar photosphere. The patterns of motion, coalescence, fragmentation, rotation and translation, were associated with different stages of the evolution of the BP: pre-brightening stage, the initial brightening, the sigmoid phase and the π-phase, respectively. Such motions could generate currents that cannot be easily dissipated in the corona through conventional joule heating (Parker 1972), but by means of an anomalous resistivity (Birn & Priest 2007; Büchner & Elkina 2005, 2006).

The development of electric currents due to horizontal plasma motion in the photosphere and chromosphere was already investigated by Büchner et al. (2004a,b), Büchner (2006) and Santos & Büchner (2007) for different BP cases. They showed that horizontal plasma motion in the photosphere and chromosphere causes the formation of electric currents below the corona at the position of the EUV BP. It was suggested that the enhanced current flow can make the current sheet resistive and allows stress relaxation by current dissipation which powers the BP. However, these models considered a single motion pattern for the magnetic structures associated with the BP.

Here we use a 'data driven' three-dimensional (3D) magnetohydrodynamic (MHD) model (Büchner et al. 2004a) to study the evolution of plasma and magnetic field in an EUV BP region observed on 2006 January 19 in dependence on different kinds of photospheric plasma motion. A preliminary study of the evolution of electric currents in the solar atmosphere due to

A&A 488, 323–329 (2008)
DOI: 10.1051/0004-6361:20079315

Astronomy & Astrophysics

Magnetic topology of blinkers★

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Received 21 December 2007 / Accepted 17 June 2008

ABSTRACT

Context. Co-spatial and co-temporal spectroscopic, imaging and magnetogram data enable us to better understand various solar transient phenomena. Here, we study brightening events in the transition region of the quiet Sun, also called "blinkers".
Aims. We aim to investigate the physical mechanism responsible for blinkers.
Methods. An automated blinker identification procedure (BLIP) is used to identify blinker events in SoHO/CDS data. The 3D magnetic topology of the magnetic field in the blinker region is reconstructed based on SoHO/MDI magnetogram data.
Results. During 3 h of SoHO/CDS observations on 2006 January 18, 66 blinkers were identified in the O v 629 Å emission line. Out of them, a group comprising of 16 events were modelled here. They were found to be associated with the emergence of magnetic flux which gave rise to the appearance of, and multiple magnetic reconnection events across, an upper atmosphere (coronal) magnetic null point, along with a loop structure as observed with TRACE.
Conclusions. This blinker group results from the release of energy that was accumulated during flux emergence, although whether all blinkers follow the same formation scenario requires further investigation using additional multi-instrument/multi-mission studies.

Key words. Sun: activity – Sun: UV radiation – Sun: transition region – Sun: atmosphere – Sun: corona – Sun: magnetic fields

1. Introduction

Over the last decade, the field of solar physics has seen a tremendous improvement in its data acquisition capabilities. The increased use of space observatories such as the Solar and Heliospheric Observatory (SoHO) and the Transition Region and Coronal Explorer (TRACE), has brought many new features on the Sun to light. One of these new features, known as *blinkers*, represents Extreme-UltraViolet (EUV) brightenings, first reported by Harrison (1997) using the SoHO/Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995). They are most readily identified in the O v 629 Å transition region line ($T_{\rm max} \approx 2 \times 10^5$ K), but significant enhancements can also be seen in chromospheric lines like He I 584 Å ($T_{\rm max} \approx 5 \times 10^4$ K). Berghmans et al. (1998) identified many brightenings in EIT He II 304 Å having characteristics completely compatible with CDS blinkers, and suggested that they were reconnection events of low-lying quiet Sun (QS) loops.

Lightcurves of blinkers are separated into two distinct classes: simple blinkers with a smooth increase in intensity having only one significant peak; and complex blinkers with multiple significant peaks (Brković & Peter 2004). Table 1 shows the properties of blinkers derived from CDS and SUMER observations by Brković et al. (2001); Bewsher et al. (2002); Parnell et al. (2002); Madjarska & Doyle (2003); Bewsher et al. (2003); Tomasz et al. (2003).

Blinkers are located above regions of enhanced emission, such as network boundaries in the quiet Sun (Bewsher et al. 2002). Most blinkers were also found to be preferentially located near regions of prominent unipolar magnetic field in both the QS and active regions (Bewsher et al. 2002; Parnell et al. 2002). Doyle et al. (2004) showed an example of a blinker that was caused by the emergence of new magnetic flux.

Chae et al. (2000), Madjarska & Doyle (2003) and Bewsher et al. (2005) identified blinkers in SUMER and CDS simultaneous observations. They found that CDS blinkers consist of many small-scale, short-lived SUMER brightenings lasting 2–3 min and having a typical size of 3″–5″. Chae et al. (2000) suggested that these brightenings are produced by small-scale reconnections of network threads.

A number of theoretical models have been suggested to explain the mechanism responsible for creating blinkers. Harrison et al. (1999) proposed a model which consists of merging of closed loops. Tarbell et al. (1999) put forward a model where reconnection of intense magnetic flux tubes of opposite polarity, in a photospheric environment that is otherwise free of magnetic field, results in a sling-shot effect generating pure acoustic waves. These waves can steepen and create shocks. Depending on the geometry of the collision of the flux tubes, the energy may be converted into either heat or jets, or indeed both.

According to Priest et al. (2002), blinkers may be formed by one of five different mechanisms: (i) the heating of cool spicular material; (ii) the containment of the plasma in the low lying loops in the network; (iii) thermal linking of hot and cold plasma at the feet of coronal loops; (iv) heating and evaporation of chromospheric plasma driven by granular compression; and (v) the cooling and draining of hot coronal plasma when coronal heating is switched off.

Peter & Brković (2003) studied blinkers with SUMER and showed that their decreasing line-width corresponded to an

★ 2 movies are only available in electronic form at http://star.arm.ac.uk/preprints/ and http://www.aanda.org
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A&A 482, 273–278 (2008)
DOI: 10.1051/0004-6361:200809349

Astronomy & Astrophysics

Small-scale flows in SUMER and TRACE high-cadence co-observations*

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Received 3 January 2008 / Accepted 14 February 2008

ABSTRACT

Context. We report on the physical properties of small-scale transient flows observed simultaneously at high cadence with the SUMER spectrometer and the TRACE imager in the plage area of an active region.
Aims. Our major objective is to provide a better understanding of the nature of transient phenomena in the solar atmosphere by using high-cadence imager and spectrometer co-observations at similar spatial and temporal resolution.
Methods. A sequence of TRACE Fe IX/X λ171 Å and high-resolution MDI images were analysed together with simultaneously obtained SUMER observations in spectral lines covering a temperature range from 10 000 K to 1 MK.
Results. We reveal the existence of numerous transient flows in small-scale loops (up to 30 Mm) observed in the plage area of an active region. These flows have temperatures from 10 000 K (the low temperature limit of our observations) to 250 000 K. The coronal response of these features is uncertain due to a blending of the observed coronal line Mg X λ624.85 Å. The duration of the events ranges from 60 s to 19 min depending on the loop size. Some of the flows reach supersonic velocities.
Conclusions. The Doppler shifts often associated with explosive events or bi-directional jets can actually be identified with flows (some of them reaching supersonic velocities) in small-scale loops. Additionally, we demonstrate how a line-of-sight effect can give misleading information on the nature of the observed phenomena if only either an imager or a spectrometer is used.

Key words. Sun: corona – Sun: transition region – line: profiles – methods: observational

1. Introduction

The solar atmosphere is highly dynamic on all scales seen both in spectroscopic and imager data. The dynamics is usually witnessed by non-Gaussian spectral line profiles, a strong radiance increase or proper motion of bright features (dark when seen in absorption). These events are commonly named transient phenomena due to their short duration. They have already been intensively studied for almost three decades during the High-Resolution Telescope and Spectrometer (HRTS), Yohkoh, Solar and Heliospheric Observatory (SoHO) and Transition Region And Coronal Explorer (TRACE) missions and it is strongly believed that they may contribute to both the coronal heating and solar wind generation. However, it is often difficult or even impossible to derive their spatial scale and even to identify their true nature because of the limitations of the existing instruments. Either high-cadence spectroscopic rastering, faster than the lifetime of these phenomena, or lower cadence rastering and simultaneous imaging can provide their correct identification and better understanding of the physical mechanisms involved.

Transient flows were studied since the Skylab mission (Mariska & Dowdy 1992) and later during the SoHO mission (for a recent overview see Doyle et al. 2006). Only recently a transient flow in a small-scale quiet-Sun loop was reported by Teriaca et al. (2004) detected in Solar Ultraviolet Measurement of Emitted Radiation (SUMER) data. The observations were taken in a very high-cadence rastering mode with 3 s exposure time which permitted a "snapshot" of the area to be obtained. Transient flows in loops can be created by heating or pressure imbalance between the footpoints of a loop or by asymmetry in the footpoint areas (Boris & Mariska 1982; Spadaro et al. 1991; Orlando et al. 1995a,b). The heat deposition is believed to be located at the footpoints of the loop (Spadaro et al. 2006).

The phenomena which have all the characteristics of a transient feature are the so-called explosive events also known as bi-directional jets. They were seen both in the quiet Sun and active regions and were first observed with HRTS by Brueckner & Bartoe (1983) and later during the SoHO mission in SUMER observations (Innes et al. 1997). They are identified by their non-Gaussian profiles and were registered in spectral lines with formation temperatures from 4×10^4 K up to 6×10^5 K. No response was found so far at coronal temperatures (Teriaca et al. 2002). Their spatial size estimated from the appearance along a spectrometer slit is 3″–5″. Their lifetime ranges from 60 s to 300 s. Explosive events are mostly known from their spectral characteristics. Observations showing them simultaneously in imager and spectrometer data are very limited. Winebarger et al. (2001) used simultaneous TRACE and SUMER active region observations and found that short-term (≤5 min) intensity fluctuations in TRACE λ171 Å data are on average 2.2 times larger in regions of reconnection than in a non-event region. The regions of reconnection were identified as the regions in which explosive event(s) were observed. The cadence of the TRACE observations was 50 s which is far too low to identify any proper motion if present. Innes (2001) made a detailed analysis of simultaneous SUMER Si IV λ1393 Å line profiles, TRACE λ1550 Å, λ1700 Å

* An animation of the TRACE λ171 Å images is only available in electronic form at http://www.aanda.org

Article published by EDP Sciences

The Astrophysical Journal, 670: L57–L60, 2007 November 20

JETS OR HIGH-VELOCITY FLOWS REVEALED IN HIGH-CADENCE SPECTROMETER AND IMAGER CO-OBSERVATIONS?

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Received 2007 August 17; accepted 2007 September 28; published 2007 October 17

ABSTRACT

We report on active region EUV dynamic events observed simultaneously at high cadence with *SOHO* SUMER and *TRACE*. Although the features appear in the *TRACE* Fe IX/X 171 Å images as jets seen in projection on the solar disk, the SUMER spectral line profiles suggest that the plasma has been driven along a curved large-scale magnetic structure, a preexisting loop. The SUMER observations were carried out in spectral lines covering a large temperature range from 10^4 to 10^6 K. The spectral analysis revealed that a sudden heating from an energy deposition is followed by a high-velocity plasma flow. The Doppler velocities were found to be in the range from 90 to 160 km s^{-1}. The heating process has a duration which is below the SUMER exposure time of 25 s while the lifetime of the events is from 5 to 15 minutes. The additional check on soft X-ray *Yohkoh* images shows that the features most probably reach 3 MK (X-ray) temperatures. The spectroscopic analysis showed no existence of cold material during the events.

Subject headings: line: profiles — methods: observational — Sun: corona — Sun: transition region

Online material: color figures

1. INTRODUCTION

A large variety of jetlike phenomena are often observed in the solar atmosphere, such as surges, spicules, sprays, extreme-ultraviolet (EUV), and X-ray jets. X-ray jets (Shibata et al. 1992) were first identified in data obtained with the Soft X-ray Telescope (SXT) on *Yohkoh* (Tsuneta et al. 1991). They represent X-ray enhancements with an apparent collimated motion and were found to have a typical size of 5×10^3 to 4×10^5 km and an apparent velocity of 30–300 km s^{-1}. Their kinetic energy is estimated to be 10^{25}–10^{28} ergs. Most of the jets were associated with small flares in large X-ray bright points or active regions. Shimojo & Shibata (2000) derived the physical parameters of X-ray jets and found temperatures from 3 to 8 MK (determined by using *Yohkoh* filter ratios) and densities of $(0.7–4.0) \times 10^9$ cm^{-3}. It is strongly believed that they are produced by magnetic reconnection and represent the evaporation flow resulting from the reconnection heating.

EUV jets were studied by Brekke (1999) in off-limb data from the Coronal Diagnostics Spectrometer (CDS) and the Extreme-ultraviolet Imaging Telescope (EIT). From the CDS data it was found that the jet was emitting only at transition region temperatures showing Doppler shifts in the O V 629.73 Å line up to −75 km s^{-1}. The event was also seen in the EIT Fe XII 195 Å passband propagating with an apparent velocity of 180 km s^{-1}. The plasma seemed to be ejected along a large looped magnetic structure. Jets were also analyzed in on-disk data from the *Transition Region and Coronal Explorer* (*TRACE*) taken in the 171 and 1216 Å passbands by Alexander & Fletcher (1999). In the 171 Å channel the ejected plasma was seen both in emission and absorption, which suggests that simultaneously highly collimated hot and cold material was ejected along the magnetic field lines. An EUV jet from a new emerging active region (a large bright point) was analyzed in simultaneous *TRACE*, EIT, and CDS data by Lin et al. (2006). The authors found the plasma jet to emit in a wide temperature range from 10,000 K (He I) to 2.5 MK (Fe XVI, the upper temperature limit of their observations).

Hα surges are often associated with EUV and X-ray emissions showing the coexistence of cool (Hα) and hot ejections of plasma (Jiang et al. 2007 and references therein). Only recently, however, have the spatial and temporal relation of these emissions been studied in detail (Jiang et al. 2007) during surge events in the plage area of an active region. The authors first observed the bright structures in *TRACE* 171 Å followed by the cooler Hα jet which they interpret as cooling of the hot plasma with a cooling time lasting about 6–15 minutes.

2. OBSERVATIONS

The events discussed here occurred in the active region NOAA 8558 on 1999 June 2. No flares were registered during the events. Simultaneous Solar Ultraviolet Measurements of Emitted Radiation (SUMER) telescope and *TRACE* observations were taken during several hours. The field of view (FOV) of the two instruments is shown in Figure 1. EIT Fe XII 195 Å single images for some of the events are also available, as well as a few SXT images. In the present Letter only *TRACE* and SUMER data are shown.

The SUMER spectrometer (Wilhelm et al. 1995; Lemaire et al. 1997) data were taken on 1999 June 2 starting at 09:17 UT and ending at 11:02 UT. A slit with a size of $0.3'' \times 120''$ was used with an exposure time of 25 s pointed at the plage area of the active region between two sunspots (Fig. 1). Four spectral windows were telemetered, each with a size of 120 spatial × 50 spectral pixels. The spectral line readouts are shown in Table 1. At the start of the observations the spectrometer was pointed at solar disk coordinates xcen $= -217''$ (at 09:17 UT) and ycen $= 257''$. Subsequently, the observations were compensated for the solar rotation. The spectral analysis was made in respect to a reference spectrum obtained by averaging over the entire data set.

The *TRACE* (Handy et al. 1999) data were obtained in the Fe IX/X 171 and 1600 Å passbands starting at 09:00 UT and finishing at 11:30 UT on 1999 June 2. The integration time was 2.9 s for the 171 Å passband and 0.3 s for 1600 Å. The

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A&A 452, 1075–1082 (2006)
DOI: 10.1051/0004-6361:20054506

Astronomy & Astrophysics

Study of a transient siphon flow in a cold loop

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Received 10 November 2005 / Accepted 26 February 2006

ABSTRACT

Context. The nature of loops is still a matter of debate with several explanations having been put forward. Simultaneous spectral and imaging data have the capacity to provide a new insight into mass motions, dynamics and energetics of loops.
Aims. We report on spectral data taken with the Solar Ultraviolet Measurements of Emitted Radiation spectrograph (SUMER) and imaging data from the Transition Region and Coronal Explorer (TRACE) of a transient event which occurred in a cold loop, lasting a few minutes.
Methods. A sequence of TRACE images in the 1550 Å and 171 Å filters show a disturbance which originated at one foot-point and propagates along the loop. The SUMER slit was placed at the other foot-point of the loop. In order to interpret the results, numerical simulations were performed with the results then converted into observable quantities and compared with the data.
Results. During the event a radiance increase and a relative red shift of $\approx$20 km s^{-1} was detected in the N V 1238.82 Å line. 1D numerical simulations are performed and observable quantities derived from the results of the simulations. The observed dynamic behaviour of the N V 1238.82 Å line profiles was recovered.
Conclusions. The results suggest that the observations could be interpreted in terms of a short-lived siphon flow reaching a speed of 120 km s^{-1} and driven by a nonlinear heating pulse. The energies required to drive the observed red-shifts are estimated to be about 10^{25} erg. The absence of a significant blue-shift caused by the return flow is explained.

Key words. Sun: corona – Sun: transition region – line: profiles – methods: observational – methods: numerical – hydrodynamics

1. Introduction

Highly dynamic loops have been observed at transition region and coronal temperatures since Skylab observations. Mariska & Dowdy (1992), in their search for Doppler shifts in the Ne VIII 465 Å emission line, reported on down-flow velocities of up to 70 km s^{-1} in active regions while no significant flows were found in a quiet sun region. The Solar Heliospheric Observatory (SoHO) measurements with the Coronal Diagnostic Spectrometer (CDS) in O V 629 Å by Brekke et al. (1997) showed the presence of blue-shifts greater than 50 km s^{-1} in an active region loop with the shift extending over a large fraction of the loop. Winebarger et al. (2001) presented an analysis of continuous intermittent outflow in a bundle of active region coronal loops seen in TRACE data. The measured flow speeds were between 5 and 20 km s^{-1}. In a follow-up study, Winebarger et al. (2002) found line-of-sight flows along active region loops of up to 40 km s^{-1} by analyzing co-aligned data from TRACE and SUMER. More recently Teriaca et al. (2004) detected a supersonic siphon-like flow of 130 km s^{-1} in a small quiet sun loop in O VI 1032 Å using SUMER.

The main difficulty in detecting flows in coronal loops with spectrometers (SUMER, CDS) is related to the fact that the Doppler shift can only be measured along the line-of-sight and may cancel out in data with insufficient spatial resolution. On the other hand, if high resolution images (e.g. TRACE) are used, then only inhomogeneous flow structures can be detected, whereas loops with steady-state flows appear similar to static loops (Aschwanden 2004). This is why the nature of these loops is still a matter of debate with several explanations having been put forward. Flows can be driven by asymmetries (such as heating or pressure imbalances) between the two legs of the loop (e.g. Boris & Mariska 1982; Spadaro et al. 1991; Robb & Cally 1992; Orlando et al. 1995) or by radiatively-cooling condensations (Reale et al. 1996; Müller et al. 2003).

Previous theoretical studies of siphon flows in coronal loops have mainly dealt with steady-state flows. The subject of the present paper is the study of a transient event in a cold loop which lasted for a few minutes. The observations which were carried out with TRACE and SUMER are presented in the first part of the paper. In the second part, a theoretical model for the study of the observed dynamic loop is presented. The evolution of the hydrodynamic quantities inside the loop is examined. Theoretical line profiles are synthesized and the results are compared with the observations. The study allows us to interpret the observations, understand the origin of the transient event and to estimate the energies involved.

2. Observational data

2.1. SUMER

The SUMER spectrograph (Wilhelm et al. 1995; Lemaire et al. 1997) onboard SoHO was designed to provide line profile

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A&A 452, L11–L14 (2006)
DOI: 10.1051/0004-6361:200600024

Astronomy & Astrophysics

Letter to the Editor

Macrospicules and blinkers as seen in Shutterless EIT 304 Å

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Received 20 December 2005 / Accepted 20 April 2006

ABSTRACT

Aims. Small-scale transient phenomena in the solar atmosphere are believed to play a crucial role in the coronal heating and solar wind generation. This study aims at providing new observational evidence on blinkers and macrospicules appearance in imager data and in doing so, establish the long disputed relationship between these phenomena.

Methods. We analyse unique high-cadence images in the transition region He ii 304 Å line obtained in a shutterless mode of the Extreme-ultraviolet Imaging Telescope on board the Solar and Heliospheric Observatory. The data have a cadence of approximately 68 s and a pixel size of 2.62 arcsec. The events are identified through an automatic brightenings identification procedure. Features showing a jet-like structure seen in projection on the disk were selected and their light-curve further analysed.

Results. The temporal evolution of the intensity in three events is shown, two of them seen on-disk as jet-like features and one above the limb. The flux increase, size and duration derived from the light-curve of the on-disk events show an identity with the blinker phenomenon.

Conclusions. The light curves of these events suggest that the off-limb and on-disk features are in fact one and the same phenomenon and therefore that some blinkers are the on-disk counterparts of macrospicules.

Key words. Sun: atmosphere – Sun: transition region – methods: observational – methods: data analysis

1. What do we know about blinkers and macrospicules and their interrelation?

Revealing the nature of various transient small-scale phenomena such as spicules, macrospicules, blinkers, bi-directional jets (also known as explosive events), Extreme-ultraviolet (EUV) network and cell brightenings and nanoflares in the solar atmosphere is of great importance for understanding the fundamental processes such as coronal heating and solar wind generation (for reviews see Walsh & Ireland 2003; Feldman et al. 2005). To achieve this we first have to understand whether the large variety of features is real, or whether we actually observe the same phenomenon but assign it a different name when observed in a particular way, with a particular instrument, or at a particular wavelength (Madjarska & Doyle 2003; Harrison et al. 2003; Brković & Peter 2004; Doyle & Madjarska 2004). After identifying blinkers in SUMER (Solar Ultraviolet Measurements of Emitted Radiation) data, Madjarska & Doyle (2003) concluded that there is no relationship between blinkers and bi-directional jets suggesting that blinkers could be the on-disk signature of EUV spicules. Harrison et al. (2003) unified some of these phenomena considering the different instrumental limitations and the properties of the different transient small-scale phenomena known so far. They found that a number of events such as blinkers, network and cell EUV brightenings can be classified as the same type of phenomenon.

Blinkers represent an enhancement in the intensity of transition region lines and were first identified using Coronal Diagnostic Spectrometer (CDS) observations. They were intensively studied by several authors such as Harrison (1997), Harrison et al. (1999), Bewsher et al. (2002, 2003, 2005), Parnell et al. (2002), Madjarska & Doyle (2003), Doyle et al. (2004), Brooks & Kurokawa (2004) and Brooks et al. (2004). Blinkers occur at the network boundaries, but some were also seen in the intranetwork. They have an average size of about $8'' \times 8''$ and an average lifetime of 16 min. Brković et al. (2001) using observations which permitted a better detection of shorter and longer lived brightenings, determined a lifetime in the range of 3−110 min, with an average duration of 23 min in He i, 16 min in O v and 12 min in Mg ix. The average intensity enhancement found by Harrison et al. (1999) in O v and O iv was 1.48 and 1.43, respectively. The intensity increase was 1.04 for Mg ix and 1.08 for He i, while Brković et al. (2001) found slightly higher values of 1.09 and 1.22, respectively, which could be due to the different method of threshold determination. Blinkers were also studied in detail both in the quiet Sun and active regions by Bewsher et al. (2002) and Parnell et al. (2002). Their analysis of the magnetic fragments in the quiet Sun showed that blinkers preferentially occur above regions of large or strong magnetic fragments with 75% occurring in regions where one polarity dominates. Madjarska & Doyle (2003) using Big Bear Solar Observatory (BBSO) magnetogram observations found that a magnetic flux increase plays a crucial role in the blinker generation. Blinkers show Doppler velocities from −5 to 30 km s^{-1} predominantly red-shifted (Madjarska & Doyle 2003; Bewsher et al. 2003).

Priest et al. (2002) suggested four different mechanisms which could explain the blinker appearance: heating of cool

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A&A 451, L35–L38 (2006)
DOI: 10.1051/0004-6361:20065031

Astronomy & Astrophysics

Letter to the Editor

Dynamic features in the solar atmosphere with unusual spectral line enhancements and Doppler-shifts★

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Received 16 February 2006 / Accepted 26 March 2006

ABSTRACT

Context. The solar atmosphere contains a wide variety of transient features, here, we discuss data relating to one such feature.
Aims. To explore via simultaneous spectral and imaging data the nature of high-velocity flow events in the solar transition region.
Methods. High spectral and temporal resolution data from SUMER/SoHO plus high resolution images from TRACE are used.
Results. In the transient feature discussed, we see a factor of two enhancement in N v 1238, coupled with a factor of two decrease in O v 629 visible over 3″–4″ along the slit. Furthermore, the O v line shows a secondary component with a down-flow of ≈75 km s^{-1}, while the N v line shows only a small additional broadening of the line.
Conclusions. Inclusion of an electron density dependent ionization calculation will increase the N v radiance over that of O v at large electron densities. We suggest this feature can be explained via a highly focused jet at the O v/O vi formation temperature resulting from reconnection. Also, we believe that this event is not unique but that their detection depends on the availability of simultaneous spectral and imaging data of comparable spatial and temporal resolution.

Key words. Sun: activity – Sun: UV radiation – Sun: transition region – Sun: atmosphere – Sun: coronae – atomic processes

1. Introduction

Over the last decade the uninterrupted, high resolution coverage of the Sun both from the excellent range of telescopes aboard many spacecraft and from ground-based instruments has led to a wealth of observations of small-scale dynamic events observed from the chromosphere to the transition region and corona. Over the past few years, many complicated and dynamic fine structures have been reported in association with the network boundaries, e.g., bi-directional jets (sometimes called "explosive events"), blinkers, network flares and bright points. However, their interpretation, interrelationship and relationship to the underlying photospheric magnetic concentrations remains ambiguous, because the same feature has a different appearance when observed in different spectral lines and with different instruments. For example, evidence has been presented by O'Shea et al. (2005) and Madjarska et al. (2006) showing that macro-spicules and blinkers may be the same feature. Harrison et al. (2003) in an attempt to unify some of these phenomena found that a number of events such as blinkers, network and cell brightenings and EUV brightenings can be classified as the same type of phenomenon.

Doyle et al. (2005) presented data of a feature which showed a large line-shift in the N v 1238 Å line, while it was practically absent in O v 629 Å despite the fact that both lines have over-lapping formation temperatures, with the peak formation temperature separated by log T_e = 0.08–0.12 (depending on the assumed atomic model).

In an effort to better understand the range of dynamic features in the solar atmosphere, we re-visit the above work, in particular to explore further multi-wavelength datasets.

Table 1. A summary of the spectral lines observed.

Spectral line	Comment
N v 1238.82 Å	
N v 1242.80 Å	
C i 1249.41 Å + Si x/2 624.78 Å	blend
Mg x/2 624.95 Å + Si ii 1250.09 Å	blend
Si ii 1250.41 Å + C i 1250.42 Å + S ii 1250.58 Å	blend
Si ii 1251.16 Å + C i 1251.17 Å	blend
O v/2 629.73 Å	

2. Data reduction

For the present study, the observations were made with the SUMER spectrograph (Wilhelm et al. 1995; Lemaire et al. 1997) onboard SoHO. SUMER is designed in such a way that it enables line profile measurements at a spatial pixel size of 1″ and a spectral pixel size of 0.042–0.045 Å.

The present dataset was taken within an active region on June 3, 1999 from 09:17:17 UT to 11:08:02 UT. Slit 0.3″ × 120″ was used, exposing for 25 s on the bottom part of detector B (see Table 1 for the list of spectral lines observed). The temporal sequences (28 s cadence) has five spectral windows

★ A movie is available in electronic form at http://www.edpsciences.org

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A&A 444, 593–603 (2005)
DOI: 10.1051/0004-6361:20053708

Astronomy & Astrophysics

Optical and EUV observations of solar flare kernels

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Received 28 June 2005 / Accepted 23 August 2005

ABSTRACT

We present high-resolution spectral observations, covering the entire optical region (3800−9000 Å), of a solar flare observed during a multi-wavelength campaign. The flare, recorded on 2002 January 11, was a medium solar flare event (GOES class C7.5). The spectral observations were carried out using the Hamilton echelle spectrograph on the coudé auxiliary telescope at Lick Observatory and with the Coronal Diagnostic Spectrometer (CDS) on board SoHO. The high signal-to-noise optical spectra are analysed using the same techniques as we applied to stellar flare data. Hα images obtained at Big Bear Solar Observatory (BBSO), plus magnetograms obtained with the Michelson Doppler Imager (MDI) on board SoHO and Transition Region And Coronal Explorer (TRACE) 1600 Å were used in the flare analysis. We observe stellar-like behaviour in the main solar chromospheric activity indicators, which show either filling-in or emission during the flare. We find that the Balmer and Ca II lines show asymmetric profiles, with red-shifted wings and blue-shifted cores. This behaviour could be explained by material expanding. During the flare, the Mg I and Fe I lines show a filling-in of the line profile indicating that the flare affected the lower atmosphere. There is some evidence for pre-flare heating as seen in Fe XIX 592 Å. Furthermore, O V 629 Å shows an increase in flux some 10 min. before the coronal lines, perhaps indicating particle beam heating in the initial stages of the flare. We have also determined the main physical parameters at flare maximum. The electron densities and electron temperatures found for the flare imply that the Balmer emitting plasma originates in the chromosphere. The physical parameters obtained for the modelled flare are consistent with previously derived values for solar flares.

Key words. Sun: activity – Sun: photosphere – Sun: flares – Sun: chromosphere – line: formation – line: profiles

1. Introduction

Flares are events where a large amount of energy is released in a short interval of time, radiating at almost all frequencies in the electromagnetic spectrum. Flares (both solar and stellar) are believed to result when reconnection in the corona rapidly releases magnetic energy stored in the coronal fields (see reviews by Mirzoyan 1984; Haisch et al. 1991; Garcia Alvarez 2000). Many types of cool stars produce flares (Pettersen 1989), sometimes at levels several orders of magnitude more energetic than their solar counterparts. The exact mechanism(s) leading to the energy release and subsequent excitation of various emission features (X-ray, microwave, UV, and optical lines and continua) remains poorly understood. Solar flares are generally observed to have an impulsive phase marked by hard X-ray bursts (Dennis 1985) and microwave radio emission on time scales of seconds to minutes, indicating the presence of accelerated non-thermal particles (Lin 1974; Foukal 1990). In some cases, optical continuum radiation is also observed (Neidig 1989). The impulsive phase is usually followed by a gradual phase, lasting minutes to hours. The impulsive phase shows continuing enhancement of chromospheric and coronal emission followed by a slow decay during the gradual phase (Svestka 1976; Tandberg-Hanssen & Emslie 1988; Dennis & Schwartz 1989).

The Sun, due to its proximity, allows both high spatial and spectral resolution observations of flares. Satellites such as SoHO, TRACE and recently RHESSI, are continuously monitoring high-energy radiation, and magnetograms of the surface are routinely available. Ground-based sites, such as Big Bear Solar Observatory (BBSO) and Sacramento Peak Observatory routinely monitor Hα, Ca II H and K, and take magnetograms. Simultaneous observations in different wavelength ranges (e.g. optical, X-rays, etc.) make it possible for the same flare to be studied at all levels in the solar atmosphere.

Despite the huge number of solar flare observations only a few experiments have studied the full optical spectrum during solar flares (Acampa et al. 1982; Donati-Falchi et al. 1984; Mauas 1990; Mauas et al. 1990). Johns-Krull et al. (1997)

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A&A 439, 351–359 (2005)
DOI: 10.1051/0004-6361:20042560

Astronomy & Astrophysics

Electron density along a coronal loop observed with CDS/SOHO

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Received 17 December 2004 / Accepted 21 April 2005

Abstract. The analysis of a coronal loop observed by CDS and EIT on board SOHO is presented. The loop was situated above the North-East limb at a latitude of $\sim 48°$, being clearly visible in the hottest lines of the dataset, Fe XVI 360.76 Å, i.e. greater than 2 000 000 K. The cooler lines in the sample (i.e. O V 629.73 Å and He I 584.35 Å) showed only a brightening at the footpoints location. Based on the Fe XIV 353.84/334.17 line ratio, the electron density along the loop was determined following three different approaches for the background subtraction. No differences, within the error bars, can be found between the three methods. At the apex, the density is 0.9×10^9 cm^{-3}, while at the footpoint it is 50% greater, i.e. 1.4×10^9 cm^{-3}. The inferred filling factor values along the loop, at the formation temperature of the lines, are in the range 0.2–0.9.
One dimensional hydrodynamic modelling of the loop along a given field line, gravity neglected, was performed. A minimum χ^2 analysis results in a best fit case where the total energy input is directed preferentially to the loop footpoint (the heating rate is three times larger at the base than at the apex). An isochoric solution can not be ruled out completely. The exercise illustrates the necessity of accurate spectral diagnostics in order to derive definite conclusions from theoretical models and suggests the need for simultaneous density and temperature diagnostics.

Key words. Sun: corona – plasmas – hydrodynamics

1. Introduction

Coronal loops extend over a vast range of size and brightness, making the solar corona highly structured. The extent of this structuring has been known since the Skylab era, however, the detail contained within recent SOHO (Solar and Heliospheric Observatory) observations with the Extreme ultraviolet Imaging Telescope (EIT) and the Coronal Diagnostic Spectrometer (CDS) and TRACE (Transition Region And Coronal Explorer) has resulted in many investigations regarding whether these structures are dominated by footpoint heating, uniform heating, asymmetric heating, variable heating, exponential decay heating, apex heating, etc (Reale et al. 2000; Priest et al. 2000; Walsh & Galtier 2000, and references therein). The confirmation that the localization of the heating deposition is as controversial as its nature is demonstrated by the fact that an observational case has been made for each of them, including an example where the same dataset has been interpreted in terms of uniform, footpoint and apex heating (Priest et al. 1998; Aschwanden 2001; Reale 2002). Some of the works have determined temperature profiles along the loops using filter ratios of YOHKOH and TRACE data. These temperature profiles are in turn used to deduce the form of heating and thus the most likely heating mechanism. Some authors, (e.g. Martens et al. 2002; Schmelz et al. 2003; Del Zanna & Mason 2003) have questioned the use of filter ratios and have shown that the temperatures obtained do not describe the state of the loops plasma. Instead, broad-band filter ratios provide at best an average temperature and one should use an emission measure type analysis. These works have insisted on the necessity to complement the high resolution images with a spectroscopic analysis that provides the necessary plasma diagnostics.

In this paper we make use of the spectral capabilities of CDS to determine the electron density along an off-limb coronal loop using the line ratio technique, investigating the problems and uncertainties introduced by several background subtraction methods. Filling factors are also inferred. As a final step, a comparison with a hydrodynamic loop model is presented and the limitations of its conclusions discussed under the observational uncertainties.

In Sect. 2 we outline the present observational data, while Sect. 3 discusses the data reduction including the important point of background subtraction, the loop geometry, electron density and filling factor determination. Section 4 discusses the

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A&A 431, L17–L20 (2005)
DOI: 10.1051/0004-6361:200400137

Astronomy & Astrophysics

Line broadening of EUV lines across the Solar limb: A spicule contribution?

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Received 20 December 2004 / Accepted 28 December 2004

Abstract. Spectral lines formed in the solar transition region show an increase in the line width, peaking at ≈10 000 km above the limb. Looking at a region off-limb with no obvious spicules, the non-spicule region has a significantly smaller line width above 6000 km compared those taken in a spicule region. We suggest that this increase in line broadening is not due to small scale random motions but rather to unresolved line shifts due to spicules and/or macro-spicules activity.

Key words. Sun: atmosphere – transition region – off-limb – line broadening – spicules

1. Introduction

Line width measurements can provide important details on small-scale mass motions and ion temperatures, and if coronal lines are used, informations on coronal heating may be obtained. Several authors have searched for disk center to limb changes (Chae et al. 1998; Erdelyi et al. 1998; Doyle et al. 2000) finding a small variation. In off-limb data, Banerjee et al. (1998), Doyle et al. (1999), Harrison et al. (2002) and O'Shea et al. (2003) have all used data relating to lines formed in the corona, finding a small increase in the line width before reaching a turn-over point. The data of Harrison et al. showed a significant narrowing of a coronal line above 50 000 km. which the authors suggested was related to the dissipation of wave energy. However, O'Shea et al. (2005) has shown that the line widths start to show a decrease in their values at exactly the same location where the dominant excitation changes from being collisionally to radiatively dominant. For lines formed around 100 000 to 300 000 K, several authors, e.g. Mariska et al. (1979), Peter & Vocks (2003), have noted an increase in the line width at 10 to 15″ above the limb. Mariska et al. suggested that this broadening was unlikely to be simply due to an increase in the wave flux above the limb and proposed that inhomogeneous structures could be the cause. More recently, Peter & Vocks (2003) interpreted the increase as evidence of a large increase in the ion temperature to more than 3×10^6 K just above the limb. Here, we look at raster and time series data from lines formed around 200 000 K, suggesting an explanation in terms of spicules. In Sect. 2 we discuss the observational data which consists of both rasters and a time series, with the results presented in Sect. 3.

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2. Observational data

2.1. Rasters

We used a raster sequence of the north solar limb (PCH) taken by the spectrometer SUMER on-board the SoHO satellite. The capabilities and specifications of the SUMER instrument were described by Wilhelm et al. (1995, 1997) and Lemaire et al. (1997). The observation was performed on 1996 August 10 from 00:03 to 16:09 UT. The target was the north polar coronal hole region with a constant SoHO solar Y at 950″ and SoHO solar X moving from –699″ to 721″. The exposure time was 60 s using slit 2 (i.e. 1″ × 300″ centered) with a step size of 1.″5. Detector A was used for producing the four 50 spectral pixel windows at the wavelengths corresponding to the 2nd order spectral lines: Mg X 624.94 Å, O V 629.73 Å and to the 1st order: N V 1238.82 Å, Fe XII 1242.01 Å. Here, we select only the O V ($T \approx 250\,000$ K) transition region line.

We used the standard SUMER data reduction procedures to apply all the corrections needed for the data. These corrections are dead time and local gain correction, flat field subtraction, and a correction for geometrical distortion. Since our interest in this study was focused on the line widths we did not perform a wavelength calibration. Additionally a correction for the spectral line shift caused by thermal deformations of the optical bench of SUMER was applied (Dammasch et al. 1999).

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:200400137

A&A 427, 1065–1074 (2004)
DOI: 10.1051/0004-6361:20040503

Astronomy & Astrophysics

Transition region small-scale dynamics as seen by SUMER on SOHO

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Received 24 March 2004 / Accepted 10 August 2004

Abstract. High spectral, spatial and temporal resolution UV observations of the quiet Sun transition region show a highly structured and dynamical environment where transient supersonic flows are commonly observed. Strongly non-Gaussian line profiles are the spectral signatures of these flows and are known in the literature as explosive events. In this paper we present a high spatial resolution ($\approx 1''$) spectroheliogram of a $273'' \times 291''$ area of the quiet Sun acquired with SUMER/SOHO in the O VI spectral line at λ103.193 nm. The extremely high quality of these observations allows us to identify tens of explosive events from which we estimate an average size of 1800 km and a birthrate of 2500 s^{-1} over the entire Sun. Estimates of the kinetic and enthalpy fluxes associated with these events show that explosive events are not important as far as solar coronal heating is concerned. The relationship with the underlying photospheric magnetic field is also studied, revealing that explosive events generally occur in regions with weak (and, very likely, mixed polarity) magnetic flux. By studying the structure of upward and downward flows exceeding those associated to average quiet Sun profiles, we find a clear correlation between the "excess" flows and the magnetic network. However, although explosive events are always associated with flow patterns often covering areas larger than the explosive event itself, the contrary is not true. In particular, almost all flows associated with the stronger concentrations of photospheric magnetic flux do not show non-Gaussian line profiles. In some cases, non-Gaussian line profiles are associated with supersonic flows in small magnetic loops. The case of a small loop showing a supersonic siphon-like flow of $\approx$130 km s^{-1} is studied in detail. This is, to our knowledge, the first detection of a supersonic siphon-like flow in a quiet Sun loop. In other cases, the flow patterns associated with explosive events may suggest a relation with UV spicules.

Key words. Sun: transition region – Sun: UV radiation – line: profiles

1. Introduction

Extreme-UltraViolet (EUV) spectroscopy of plasmas at Transition Region (TR) temperatures reveals the existence of different kinds of transient phenomena. Highly non-Gaussian line profiles showing strong Doppler shifts are frequently observed in quiet Sun areas and within coronal holes in lines formed between 6×10^4 K and 7×10^5 K. First observed by Brueckner & Bartoe (1983) in HRTS spectra, they are known as UV explosive events (EEs). Their birthrate on the quiet Sun was estimated to be around 1×10^{-16} m^{-2} s^{-1} by Dere et al. (1989). EEs are characterised by spatial scales of $\approx$1600 km, average lifetime of about 60 s and line profiles showing Doppler shifts up to 225 km s^{-1} (Dere et al. 1989). EEs are generally observed along the magnetic network at the boundaries of the super-granulation cells but away from the larger flux concentrations (Porter & Dere 1991), in regions with weak and mixed polarity fluxes (Chae et al. 1998) and in association with episodes of photospheric magnetic flux cancellation (Dere et al. 1991; Chae et al. 1998; Ryutova & Tarbell 2000). Furthermore, the spectral signature of EEs shows enhancements in both the red and blue wings of the profile, implying high velocity flows similar to a bi-directional jet associated with magnetic reconnection (Innes et al. 1997). Hence, EEs are believed to be the product of magnetic reconnection, a magnetic cancellation of the photospheric fields with emerging flux (Dere et al. 1991) or the interaction between separate flux elements driven together by convective motions (Porter & Dere 1991). The large velocities associated with EEs suggest that kinetic and enthalpy flows could be relevant to the coronal energy budget. Winebarger et al. (2002) estimated the global energy

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CORONAL RESPONSE OF BI-DIRECTIONAL JETS

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(Received 19 December 2003; accepted 26 January 2004)

Abstract. EUV bi-directional jets are a prominent class of phenomena characterizing the solar transition region. Using simultaneously obtained SUMER observations in the chromospheric Si II 1251.16 Å and C I 1251.17 Å, transition region N V 1238.8 Å and coronal Mg X 625 Å lines we show an example of a bi-directional jet observed in the chromospheric and the transition region lines but not showing any detectable signature in the coronal line. The phenomenon, however, was also clearly detected by the TRACE imager with the 171 Å filter. This discrepancy is explained here with a non-Maxwellian electron distribution which makes a significant fraction of the plasma in the TRACE 171 Å pass-band to be derived from temperatures around $\approx 300\,000$ K, as opposed to $\approx 800\,000$ K. This could have implications for other phenomena observed in the TRACE pass-bands, including the transition region 'moss' and the 3- and 5-min oscillations.

1. Introduction

The location and importance of ultraviolet bi-directional jets, often called 'explosive events', within the wider frame-work of the upper solar atmosphere is still uncertain. These dynamic events were first detected to occur in the transition region with a birthrate over the whole Sun of between 600 s^{-1} (Dere, Bartoe, and Brueckner, 1989) and 3300 s^{-1} (Ryutova and Tarbell, 2000). They are characterized by spatial scales of ≈ 2000 km, average lifetime of about 200 s and have highly non-Gaussian line profiles with Doppler shifts up to 250 km s^{-1} (Dere, Bartoe, and Brueckner, 1989) and often appear in bursts lasting several minutes (Innes *et al.*, 1997; Chae *et al.*, 1998; Pérez *et al.*, 1999).

Madjarska and Doyle (2002) provided evidence that bi-directional jets also appear in chromospheric lines such as O I and the optically thick H I Ly 6, 7, 8, 9, and 10 lines. The results of an attempt to observe the coronal counterparts to bi-directional jets were presented by Dere (1994), Moses and Cook (1994) and Teriaca, Madjarska, and Doyle (2002). The latter authors obtained high spectral resolution data for a large event in the transition region line N V 1238 Å and the coronal line Mg X 625 Å. These authors concluded that the event observed in N V showed a small enhancement in Mg X which is however caused by the presence of a close-by blend from a Si II line (see Teriaca, Madjarska, and Doyle, 2002, for further details on this blend).

Solar Physics **221:** 51–64, 2004.

A&A 418, 313–324 (2004)
DOI: 10.1051/0004-6361:20035666

Astronomy & Astrophysics

Signature of oscillations in coronal bright points

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Received 12 November 2003 / Accepted 23 January 2004

Abstract. A detailed study of two consecutive bright points observed simultaneously with the Coronal Diagnostic Spectrometer (CDS), the Extreme ultraviolet Imaging Telescope (EIT) and the Michelson Doppler Imager (MDI) onboard the Solar and Heliospheric Observatory (SOHO) is presented. The analysis of the evolution of the photospheric magnetic features and their coronal counterpart shows that there is a linear dependence between the EIT Fe XII 195 Å flux and the total magnetic flux of the photospheric bipolarity. The appearance of the coronal emission is associated with the emergence of new magnetic flux and the disappearance of coronal emission is associated with the cancellation of one of the polarities. In one of the cases the disappearance takes place ~3–4 h before the full cancellation of the weakest polarity.
The spectral data obtained with CDS show that one of the bright points experienced short time variations in the flux on a time scale of 420–650 s, correlated in the transition region lines (O V 629.73 Å and O III 599.60 Å) and also the He I 584.34 Å line. The coronal line (Mg IX 368.07 Å) undergoes changes as well, but on a longer scale. The wavelet analysis of the temporal series reveals that many of these events appear in a random fashion and sometimes after periods of quietness. However, we have found two cases of an oscillatory behaviour. A sub-section of the O V temporal series of the second bright point shows a damped oscillation of five cycles peaking in the wavelet spectrum at 546 s, but showing in the latter few cycles a lengthening of that period. The period compares well with that detected in the S VI 933.40 Å oscillations seen in another bright point observed with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer, which has a period of 491 s. The derived electron density in the transition region was 3×10^{10} cm^{-3} with some small variability, while the coronal electron density was 5×10^{8} cm^{-3}.

Key words. Sun: oscillations – Sun: corona – Sun: transition region – Sun: UV radiation – Sun: magnetic fields

1. Introduction

Coronal EUV/X-ray bright points (hereafter BPs) are small (20–30 Mm) coronal features of enhanced emission most easily observed in the quiet Sun and coronal hole regions. They were first observed and studied in soft X-ray rocket images (Vaiana et al. 1970; Nolte et al. 1979) where they present an average lifetime of ~8 h (Golub et al. 1974). However, they have also been observed in radio (Marsh et al. 1980) and EUV (Habbal & Withbroe 1981) where the emission has an average lifetime of ~20 h (Zhang et al. 2001). The appearance and hence their description is subject to the spatial resolution of the instrument, so they are commonly presented as diffuse clouds with a central bright core of ~10 Mm as seen in Skylab X-rays (Golub et al. 1974) or SOHO/EIT extreme-ultraviolet images. High spatial resolution images (1″–2″) have shown that BPs consist of several miniature loops (Sheeley & Golub 1979) and have a morphology similar to larger scale coronal structures (Frank & Slater 2002).

BPs are associated with photospheric bipolar magnetic features (Krieger et al. 1971), with up to 2/3 of them being associated with chance encounter and cancellation of pre-existing magnetic features rather than the emergence of new magnetic flux (Harvey 1985, 1993; Webb et al. 1993; Longcope et al. 2001). This process normally takes place at the network boundaries of super-granular cells (Egamberdiev 1983; Habbal et al. 1990; Madjarska et al. 2003).

One of the main characteristics of BPs is their intensity variability, as several studies in EUV spectral lines have shown. Sheeley & Golub (1979) found that the constituent loops could evolve on a time scale of ~6 min. Habbal & Withbroe (1981) and Habbal et al. (1990) using the Harvard experiment aboard Skylab showed that they exhibit large variations in the emission of chromospheric, transition region and coronal lines, and no regular periodicity or obvious correlation between the different temperatures was found. The time scales of these variations were as short as the temporal resolution of the observations

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A&A 418, L9–L12 (2004)
DOI: 10.1051/0004-6361:20040104

Astronomy & Astrophysics

New insight into the blinker phenomenon and the dynamics of the solar transition region

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Received 21 January 2004 / Accepted 4 March 2004

Abstract. We present, for the first time, blinker phenomena being associated with brightenings in pre-existing coronal loops registered by the Extreme-ultraviolet Imaging Telescope (EIT) in Fe XII 195 Å. The brightenings occur during the emergence of new magnetic flux as registered by the Big Bear Solar Observatory (BBSO) magnetograph. The blinkers were identified using simultaneous observations obtained with the Coronal Diagnostic Spectrometer (CDS) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrograph. In light of the new observational results, we present one possible theoretical interpretation of the blinker phenomenon. We suggest that the blinker activity we observe is triggered by interchange reconnection, serving to provide topological connectivity between newly emerging flux and pre-existing flux. The EIT images show the existence of loop structures prior to the onset of the blinker activity. Based on the available spatial resolution the blinker occurs within, or nearby, an existing coronal loop. The temperature interfaces created in the reconnection process between the cool plasma of the newly emerging loop and the hot plasma of the existing loop are what we suggest to causes the observed activity seen in both the SUMER and CDS data. As the temperature interfaces propagate with the characteristic speed of a conduction front, they heat up the cool chromospheric plasma to coronal temperatures, an increasing volume of which brightens at transition region temperatures. We believe this new interpretation gives further qualitative understanding about the evolution of newly emerging flux on the Sun. This also provides new insight into the dynamic nature of the solar transition region.

Key words. Sun: atmosphere – transition region – evolution – magnetic fields – UV radiation

1. Introduction

Based on data obtained by the Coronal Diagnostic Spectrometer (CDS) on board SoHO, Harrison (1997) discussed a class of transient phenomenon, which he termed blinkers. These brightenings were associated with enhanced emission in transition region (TR) lines, such as O III 599 Å, O IV 554 Å, and O V 629 Å (these lines have formation temperatures in the range 1.0–2.5 × 10^5 K), involving a typical size of ≈8″ × 8″, and having an average duration of approximately 17 min (Harrison et al. 1999; Bewsher et al. 2002). In a recent survey, Brković et al. (2001) reported lifetimes of blinker events in the range 3–110 min, based on observations that enabled better detection of short- and long-lived CDS brightenings. Spectral line ratio analysis suggested that the intensity enhancements associated with blinkers were consistent with an interpretation involving either an increase in mass density or *filling factor* rather than temperature (Harrison et al. 1999; Teriaca et al. 2001). Based on SUMER data, Madjarska & Doyle (2003) reported Doppler shifts that ranged from –5 to 25 km s^{-1}, but were predominantly red-shifted. A transition from blue to red-shifted emission, in the course of the 200–300 s observations, was observed for one case. Bewsher et al. (2003), using CDS observations, derived Doppler shifts of 25–30 km s^{-1} in O V 629 Å. As reported by Harrison et al. (1999) and Bewsher et al. (2002), blinkers occur predominantly in the network lanes. This usually involves regions of large or strong magnetic fragments; in 75% of the cases one polarity is dominant (see Parnell et al. 2002).

Until recently, it has being highly debated in the community why bi-directional jets (more often called explosive events), yet another transient phenomenon observed in transition region lines, do not have a counterpart in the CDS data. It was also questioned whether blinkers and bi-directional jets were the same transient phenomenon seen differently due to the different spectral and spatial capabilities of the CDS and SUMER instruments. This question remained open until simultaneous observations were made and reported by Chae et al. (2000) and Madjarska & Doyle (2003). Blinkers were identified in the relevant SUMER data as a series of short-lived, small-scale brightenings lasting about 2–3 min, and having a typical size of about 3″–5″. In a recent numerical study,

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THE ASTROPHYSICAL JOURNAL, 603:L57–L59, 2004 March 1

EVIDENCE OF MAGNETIC RECONNECTION ALONG CORONAL HOLE BOUNDARIES

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Received 2003 December 11; accepted 2004 January 20; published 2004 February 12

ABSTRACT

The present study reveals for the first time the existence of bidirectional jets, which are a signature of magnetic reconnection, occurring along coronal hole boundaries. The Solar Ultraviolet Measurement of Emitted Radiation spectrometer observations obtained in the N IV 765.15 Å (1.3×10^5 K) and Ne VIII 770.42 Å (6×10^5 K) emission lines in an equatorial extension of a polar coronal hole, known as the "Elephant's Trunk" coronal hole, show small regions of a few arcseconds size with strong blue- and redshifted emission reaching Doppler shifts of up to 150 km s^{-1}, i.e., bidirectional jets. The jets' number density along coronal hole boundaries was found to be about 4–5 times higher with respect to the quiet Sun.

Subject headings: solar wind — Sun: corona — Sun: transition region

1. INTRODUCTION

Coronal holes (CHs) are large regions on the Sun that are magnetically open and were identified as the source of the fast solar wind (~800 km s^{-1}; Krieger, Timothy, & Roelof 1973). They are visible in coronal lines as regions with a reduced emission relative to the quiet Sun. There are two types of coronal holes: polar and midlatitude. During the minimum of solar activity, the solar atmosphere is dominated by two large CHs situated at both polar regions. The midlatitude CHs can be either "isolated" or connected with a CH channel to a polar CH. The latter CHs are called equatorial extensions of polar CHs (EECHs).

A distinctive feature of EECHs is their nearly rigid rotation in contrast to the typical differential rotation at photospheric level (Timothy, Krieger, & Vaiana 1975). Kahler & Hudson (2002) give a detailed overview of the different mechanisms suggested to maintain the quasi-rigid rotation of the coronal holes. Because of these different rotation profiles at the coronal and photospheric level and the fact that CH boundaries (CHBs) separate two topologically different (open and closed) magnetic field configurations, CHBs are presumably the regions where an opening and closing of magnetic field lines take place.

This reconfiguration is believed to happen through magnetic reconnection between the open and closed magnetic field lines of the CH and the surrounding quiet Sun. Despite numerous attempts at identifying any phenomenon that could be associated with magnetic reconnection along CHBs, no direct evidence has been found so far (Kahler & Hudson 2002). Kahler & Moses (1990) studied *Skylab* X-ray images of CH boundaries with a time resolution of 90 minutes and found that X-ray bright points play an important role in both the expansion and the contraction of a CH. Zhao, Hoeksema, & Scherrer (1999) studied the rotational characteristics of the "Elephant's Trunk" CH (1996; the subject of our study). They found that the CH showed nearly rigid rotation with a rate of $13.^{\circ}25$ day^{-1} ($14.^{\circ}6$ day^{-1} for leader sunspots). They also observed day-to-day variations of the CHBs. Bromage et al. (2000) reported that small-scale changes of the boundaries of the same CH appeared on timescales of a few hours in observations with the Extreme-ultraviolet Imaging Telescope (EIT) on board the *Solar and Heliographic Observatory* (*SOHO*) in Fe XII 195 Å.

Besides their importance for the evolution of CHs, it has also been suggested that CHBs are the main source of the slow solar wind. The first observational evidence that streamer stalks, fine rays representing the filamentary structure of the streamer belt, are the source of the slow solar wind was provided by Woo & Martin (1997). From the Large Angle and Spectrometric Coronagraph Experiment (LASCO) observations of outward-moving density inhomogeneities of denser plasma, called blobs, Wang et al. (1998) suggested that the slow solar wind (<500 km s^{-1}) originates in helmet streamer loops but with a major component originating outside the helmet streamers, i.e., from inside the CHs near the boundaries.

For the present study, a search was carried out for spectroscopic observations that could potentially reveal signatures of magnetic reconnection. Equatorial coronal holes are the best candidates for such a study because of the most favorable line of sight. We also looked for data obtained in a sit-and-stare mode, which means that the slit is pointed over a certain solar region long enough to detect any velocity event propagating along the line of sight. The objective of this Letter is to present the very first evidence for the existence of magnetic reconnection along CH boundaries as revealed by observations obtained with the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectrometer on board *SOHO*.

2. OBSERVATIONAL MATERIAL

The data used in this work were obtained on 1996 October 19 and 20 in an EECH (Fig. 1). The observations were simultaneously performed with the SUMER spectrometer and EIT.

The SUMER (Wilhelm et al. 1995, 1997; Lemaire et al. 1997) observations consist of temporal series in N IV 765 Å and Ne VIII 770 Å obtained using a $1'' \times 300''$ slit and 60 s exposure time on the KBr-coated part of detector B during ~10 hr. The instrument was pointed at an EECH at coordinates Solar_X = $0''$ and Solar_Y = $-140''$. The observations started on October 19 at 20:22 UT and finished on October 21 at 06:50 UT. No compensation for the solar rotation was applied, and therefore, with the solar rotation rate at these coordinates of ~$9.''5$, the $1''$ slit covered an area of ~$95''$ on the Sun. The rest wavelength was derived from a profile averaged over a quiet Sun area.

The reduction of the SUMER raw data involves local gain

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CORONAL OSCILLATIONS ABOVE SUNSPOTS?

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(Received 7 July 2003; accepted 22 September 2003)

Abstract. Observational data clearly indicate the presence of 3-min oscillations in sunspots in spectral lines covering a vast temperature range from the low chromosphere to those lines normally associated with coronal temperatures. We show that after folding in the sunspot plume emission measure distribution, the contribution functions for lines normally formed just below 1×10^6 K are shifted to lower temperatures. For example, the Fe IX 171 Å line is shifted to 6×10^5 K for a Maxwellian distribution and to less than 5×10^5 K with a non-Maxwellian distribution. Other lines such as Mg IX 368 Å will also be affected. This then questions some previous work regarding the suggested detection of 3-min oscillations in the corona above sunspots.

1. Introduction

Using ultraviolet data from the Solar Maximum Mission for emission lines formed at temperatures of 7×10^4 K to 1.3×10^5 K, Gurman *et al.* (1982) observed transition region oscillations in sunspots with frequencies in the range of 5.8–7.8 mHz. Their in-phase intensity and velocity oscillations lead them to interpret the oscillations in terms of upward propagating acoustic waves. Thomas *et al.* (1987) detected simultaneously umbral oscillation at different heights, starting from the chromosphere through to the transition region.

With the launch of SOHO there has been renewed interest in the study of umbral oscillations. Fludra (1999, 2001) investigated 3-min intensity oscillations with the Coronal Diagnostic Spectrometer (CDS) by observing the chromospheric line He I and several transition region lines. He concluded that the 3-min umbral oscillations can occur both in sunspot plumes and in the lower intensity plasma closely adjacent to the plumes. He found the spectral power to be contained in the 5.55–6.25 mHz range.

SUMER observations (in both intensity and velocity) have confirmed that the sunspot oscillations are prominent in transition region lines above the umbra (Maltby *et al.*, 2001). Support for the acoustic wave hypothesis was presented by Brynildsen *et al.* (1999a, b). They observed oscillations in intensity and velocity to test the

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A&A 407, L29–L32 (2003)
DOI: 10.1051/0004-6361:20031057

Astronomy & Astrophysics

Sunspot plume observations in the EUV

The gas pressure differential between the umbra and surrounding region

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Received 30 April 2003 / Accepted 3 July 2003

Abstract. The electron density over a bright sunspot plume region was evaluated using lines within the O v 760 Å multiplet. The plume showed an intensity enhancement factor of ≈9 in the O v lines compared to regions outside the sunspot umbra. Internal agreement between the various ratios is excellent which would suggest that the O v lines do not suffer from blending problems. The derived mean electron densities for the sunspot plume is $\log N_e/\mathrm{cm}^{-3} \approx 9.9$ compared to $\log N_e/\mathrm{cm}^{-3} \approx 10.20{-}10.45$ in the surrounding area. The derived gas pressure in the plume compared to that outside leads weight to the suggestion that it is plasma flowing from outside the spot into the umbra at transition region temperatures that is the main cause of the down-flows. The plume non-thermal velocities are 5 to 10 km s^{-1} smaller than those measured in regions external to the spot, suggesting significantly less turbulence within the umbra.

Key words. Sun: SoHO–SUMER: transition region: sunspot plumes: electron density

1. Introduction

Sunspots, the cool dark features visible on the Sun's surface are complex magnetic structures, perhaps even more so than previously considered as shown by recent high spatial resolution data (Scharmer et al. 2002). Based on SKYLAB data obtained in the mid-seventies, Foukal et al. (1974) and Noyes et al. (1985) showed the existence of plume features when viewed in lines formed around $1{-}2.5 \times 10^5$ K. These authors showed that lines formed around these temperatures were enhanced in radiance by factors up to 15–25 over the normal quiet Sun values. More recent work by Brynildsen et al. (2001) confirm these earlier studies and often show that these plume structures are largely dominated by down-flows of 20–30 km s^{-1}, similar to the earlier data reported by Dere (1982). From the dynamical viewpoint, this would suggest a pressure imbalance between the sunspot and the surrounding region. Although electron density estimates exist for sunspot plumes formed around 1×10^5 to 2.5×10^5 K (e.g. Doyle et al. 1985), none of these provide a comparison with data taken simultaneously in nearby structures outside of spots.

For a determination of the electron density, two such methods exist; line ratios and emission measure. Because structures in the transition region of the solar atmosphere are much less than the resolving power of any imaging experiment, estimates based on the emission measure are only lower limits to the true density. Thus the only accurate technique is the first, assuming that the lines are from the same ion and that accurate atomic data exist for that particular ion. In this work we use data acquired with the SUMER instrument on-board SoHO taken around 760 Å.

This wavelength region includes the O v 760 Å multiplet. In ionization equilibrium, O v is formed at an approximate temperature of 2.5×10^5 K. Within this multiplet there are four line ratios, each using the 761.13 Å line. Here we use only three of these ratios due to blending in the fourth. All these lines are separated by less than 3 Å, thus this eliminates possible calibration uncertainties which can arise if the two lines have a large wavelength separation. In Sect. 2 we discuss the observational data, while Sect. 3 contains the results, including line width measurements.

2. Observational material

The *Solar Ultraviolet Measurements of the Emitted Radiation* (SUMER) instrument aboard the *Solar and Heliospheric Observatory* (SoHO) is a high resolution, stigmatic, normal incidence spectrometer covering the wavelength range from 660–1610 Å and 465–805 Å in first and second order, respectively (Wilhelm et al. 1995, 1997; Lemaire et al. 1997), with an angular pixel size in the direction along the slit of ≈1″ and a spectral pixel size between 0.042–0.045 Å in first order. The dataset analysed in this paper was obtained on 18 March 1999, exposing a band of 120 spatial × 1024 spectral pixels from detector B

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A&A 403, 731–741 (2003)
DOI: 10.1051/0004-6361:20030397

Astronomy & Astrophysics

Simultaneous observations of solar transition region blinkers and explosive events by SUMER, CDS and BBSO

Are blinkers, explosive events and spicules the same phenomenon?

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Received 16 September 2002 / Accepted 11 March 2003

Abstract. The SoHO discovery of the new "blinker" phenomena focused our study on the search of its relation to already known phenomena such as explosive events and spicules. The study was performed using a specially planned joint observing program involving the Coronal Diagnostic Spectrometer (CDS), Solar Ultraviolet Measurements of Emitted Radiation spectrograph (SUMER) and Big Bear Solar Observatory (BBSO) magnetograph. Within each blinker, the SUMER data reveal the presence of small-scale (3″–5″), short-lived (2–3 min) bright features not seen in the CDS data which has sometimes being interpreted as oscillations in SUMER data. With this data we have clearly identified UV explosive events in CDS data. The explosive events show a size close to the small-scale brightenings forming the blinker core. However, they appear in the SUMER data with their typical strong blue and red wings while the blinker shows at best only a small increase in the emission of the blue and red wings and in most instances the typical transition region red-shift in the center of the line. In all cases the explosive events cover one pixel in CDS corresponding to a size of $4'' \times 4''-6''$. All identified explosive events were located at the border of the bright network i.e. the blinker, in the network or even in the internetwork. From this data, we believe that blinkers and explosive events are two separate phenomena not directly related or triggering each other. In this study, the Doppler shift was derived in a blinker phenomenon for the first time. It ranges from –5 to 25 km s^{-1} and is predominantly red-shifted. The observed magnetic flux increase during the blinker phenomena seems to play a crucial role in the development of this event. We suggest that "blinkers" maybe the on-disk signature of spicules.

Key words. Sun: corona – Sun: transition region – Sun: activity: Sun: UV radiation

1. Introduction

A new transient phenomenon named as "blinker" was first introduced and analysed by Harrison (1997) and Harrison et al. (1999) using data obtained with the Coronal Diagnostic Spectrometer (CDS) on-board SoHO. Blinkers represent an enhancement in the flux of transition region lines such as O III 599 Å, O IV 554 Å and O V 629 Å with formation temperatures 1×10^5, 1.6×10^5 and 2.5×10^5 K, respectively. The above authors found no significant presence in lines such as Mg IX 368 Å (1×10^6 K) and Mg X 624 Å (1×10^6 K) formed at coronal temperatures. Furthermore, they found only a modest increase in the chromospheric/low transition region He I 584 Å line. However, as was already pointed out by Harrison et al. (1999), the blinker presence at 'cool' temperatures is still not clear, because of the optical thickness of the He I line (Brooks et al. 1999).

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It was found that blinkers have a typical size of ∼8″ × 8″ and an average lifetime of ∼16 min. The large number of longer-duration blinkers put the average blinker duration at almost 40 min (Harrison et al. 1999). Brković et al. (2001), however, using observations which permitted a better detection of shorter and longer lived brightenings, determined a lifetime in the range of 3–110 min, with an average duration of 23 min in He I, 16 min in O V and 12 min in Mg IX. The average intensity enhancement found by Harrison et al. (1999) in O V and O IV was 1.48 and 1.43, respectively. The intensity increase was 1.04 for Mg IX and 1.08 for He I, while Brković et al. (2001) found higher values of 1.09 and 1.22, respectively, which could be due to the different method of threshold determination.

Blinkers are preferentially located in the network lanes (Harrison et al. 1999; Bewsher et al. 2002). Brković et al. (2001), however, reported an appearance of brightenings also in the internetwork. Blinkers were also studied in detail both in the quiet Sun and active regions by Bewsher et al. (2002) and Parnell et al. (2002). Their analysis of the magnetic fragments in the "quiet" Sun using Michelson Doppler Imager (MDI)

A&A 398, 775–784 (2003)
DOI: 10.1051/0004-6361:20021732

Astronomy & Astrophysics

An EUV Bright Point as seen by SUMER, CDS, MDI and EIT on-board SoHO

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Received 29 October 2002 / Accepted 21 November 2002

Abstract. This paper presents the formation, evolution and decay of a coronal bright point via a spectroscopic analysis of its transition region counterpart and the evolution of the underlying magnetic bipole during 3 days of almost continuous observations. The data were obtained with various instruments on-board SoHO, including the SUMER spectrograph in the transition region line S vi 933.40 Å, CDS in the He i 584.33, O v 629.73 and Mg ix 368.06 Å lines, plus MDI and EIT. The existence of the coronal feature is strongly correlated with the evolution of the underlying bipolar region. The lifetime of the bright point from the moment when it was first visible in the EIT images until its complete disappearance was ~18 hrs. Furthermore, the bright point only became visible at coronal temperatures when the two converging opposite magnetic polarities were ~7000 km apart. As far as the temporal coverage of the data permits, we found that the bright point disappeared at coronal temperatures after a full cancellation of one of the magnetic polarities. The spectroscopic analysis reveals the presence of small-scale (~6″) transient brightenings within the bright point with a periodicity of ~6 min. The Doppler shift in the bright point was found to be in the range of −10 to 10 km s^{-1} although it is dominated by a red-shifted emission which is associated with regions characterized by stronger "quiet" Sun photospheric magnetic flux. Small-scale brightenings within the bright point show velocity variations in the range 3–6 km s^{-1}. In general the bright point has a radiance ~4 times higher than that of the network. No relation was found between the bright point and the UV explosive event phenomena.

Key words. Sun: corona – Sun: transition region – Sun: activity – Sun: UV radiation

1. Introduction

Coronal X-ray/EUV bright points (hereafter BPs) are among the coronal phenomena claimed to play an important role in the coronal heating problem. They were first identified in the X-rays in 1969 by Vaiana et al. (1970) and later analysed and described in detail during the Skylab mission (for reviews see Golub 1980; Webb 1986; Habbal 1992). BPs are small (30″–40″ size) coronal features of enhanced emission with a 5″–10″ bright core. They were associated with small bipolar magnetic features, except for newly emerging or old and decaying BPs where only one of the polarities is visible (Golub et al. 1977). They were found in the "quiet" Sun regions and coronal holes, at the network boundaries where the "quiet" Sun magnetic field is mainly concentrated (Habbal et al. 1990). Sheeley & Golub (1979) obtained a unique sequence of high resolution Naval Research Laboratory (NRL) *Skylab* spectroheliograms with a spatial resolution of ~2″. They showed that the coronal BPs pattern consists of 2 or 3 miniature loops (2 500 km in diameter and ~12 000 km long) evolving on a time scale of ~6 min. Observations by Habbal et al. (1990) confirmed this result showing that simultaneously measured peaks of emission in six different lines (emitted from the chromosphere to the corona) were not always co-spatial, implying that the BPs consist of a complex of small-scale loops at different temperatures. The average lifetime of a BP is ~20 hrs (Zhang et al. 2001) as observed in EUV lines and 8 hrs as determined by *Skylab* X-ray observations (Golub et al. 1974). Zhang et al. (2001) suggested that the temperature of BPs is generally below 2×10^6 K, which explains their smaller size and shorter lifetime in X-rays.

BPs were also observed in the transition region and chromosphere, where some of them appeared at a low contrast with a brightness similar to the brightness of the network elements (Habbal & Withbroe 1981; Habbal et al. 1990; Habbal 1992). Using the High Resolution Telescope and Spectrograph (HRTS), Moses et al. (1994) performed a spectroscopic study aimed at investigating the correspondence of small-scale structures from different temperature regimes in the solar atmosphere and in particular the relationship between X-ray BPs (XBPs) and UV transition region explosive events. They found that the features in C iv 1548 Å corresponding to XBPs were in general bright, larger scale (~10″) regions of complex velocity fields of the order of 40 km s^{-1} which, according to the authors, is typical for the brighter C iv network elements.

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Mon. Not. R. Astron. Soc. **337,** 901–909 (2002)

The O IV and S IV intercombination lines in the ultraviolet spectra of astrophysical sources

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Accepted 2002 August 9. Received 2002 July 29; in original form 2002 April 23

ABSTRACT

New electron density diagnostic line ratios are presented for the O IV $2s^22p\ ^2P–2s2p^2\ ^4P$ and S IV $3s^23p\ ^2P–3s3p^2\ ^4P$ intercombination lines around 1400 Å. A comparison of these with observational data for the symbiotic star RR Telescopii (RR Tel), obtained with the Space Telescope Imaging Spectrograph (STIS), reveals generally very good agreement between theory and observation. However the S IV $^2P_{3/2}–^4P_{1/2}$ transition at 1423.824 Å is found to be blended with an unknown feature at 1423.774 Å. The linewidth for the latter indicates that the feature arises from a species with a large ionization potential. In addition, the S IV $^2P_{1/2}–^4P_{3/2}$ transition at 1398.044 Å is identified for the first time (to our knowledge) in an astrophysical source other than the Sun, and an improved wavelength of 1397.166 Å is measured for the O IV $^2P_{1/2}–^4P_{3/2}$ line. The O IV and S IV line ratios in a sunspot plume spectrum, obtained with the Solar Ultraviolet Measurements of the Emitted Radiation (SUMER) instrument on the *Solar and Heliospheric Observatory*, are found to be consistent, and remove discrepancies noted in previous comparisons of these two ions.

Key words: atomic data – Sun: UV radiation – binaries: symbiotic.

1 INTRODUCTION

The O IV $2s^22p\ ^2P–2s2p^2\ ^4P$ and S IV $3s^23p\ ^2P–3s3p^2\ ^4P$ intercombination multiplets around 1400 Å show prominent emission lines in the spectra of the Sun and other astrophysical sources (see, for example, Feldman et al. 1997; Keenan et al. 1993). It has long been known that intensity ratios involving these transitions provide very useful electron density (N_e) diagnostics for the emitting plasma (Flower & Nussbaumer 1975; Bhatia, Doschek & Feldman 1980). However, more recently several authors have noted discrepancies between theoretical line ratios and observational data. For example, Cook et al. (1995) found that the O IV ratios imply densities which differ by up to an order of magnitude, while some observed S IV line ratios lay outside the range of values allowed by theory. Although some of these discrepancies were subsequently resolved by improved atomic data for O IV (Brage, Judge & Brekke 1996), several still remain, such as a disagreement between theory and observation for the $I(1397.2\ \text{Å})/I(1404.7\ \text{Å})$ intensity ratio in O IV (Harper et al. 1999).

In this paper we use the most up-to-date atomic physics calculations for O IV and S IV to derive intercombination line ratios applicable to a wide range of astrophysical phenomena. These calculations are subsequently compared with high spectral resolution and signal-to-noise ratio observational data, in particular a spectrum of the symbiotic star RR Telescopii (RR Tel) recently obtained with the *Hubble Space Telescope* (*HST*). The aim of this work is to investigate the accuracy of the O IV and S IV diagnostics, and to assess the importance of possible blending in the observations.

2 ADOPTED ATOMIC DATA AND THEORETICAL LINE RATIOS

The model ion for O IV consisted of the 15 energetically lowest fine-structure levels ($2s^22p\ ^2P_{1/2,3/2}$; $2s2p^2\ ^4P_{1/2,3/2,5/2}, ^2D_{3/2,5/2}, ^2S, ^2P_{1/2,3/2}$; $2p^3\ ^4S, ^2D_{3/2,5/2}, ^2P_{1/2,3/2}$), while that for S IV comprised the

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A&A 396, 255–267 (2002)
DOI: 10.1051/0004-6361:20021361

Astronomy & Astrophysics

Temporal variability in the Doppler-shift of solar transition region lines

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Received 19 December 2001 / Accepted 19 September 2002

Abstract. High cadence datasets taken in C III 977 Å, O VI 1032 Å and Ne VIII 720 Å were analysed in an effort to establish the extent of the variability in the Doppler-shift of typical mid-transition region lines. The shortest time-scale variability seems to occur in the network boundary regions where the line-shift can vary by 7–8 km s^{-1} in less than 1 min. The internetwork region also shows variability although this tends to be longer lived, ~2–3 min. The average line-shift in C III is a red-shift which ranges from ~2 km s^{-1} to ~20 km s^{-1} with an average value for all regions selected being around 10 km s^{-1} in very good agreement with that derived by others. The red-shift values indicate a clear difference between network and internetwork regions, with the largest red-shift being present at the network boundary. For O VI, this gives an average red-shift ranging from 5 to 10 km s^{-1}. For Ne VIII, there is a 13 km s^{-1} difference between internetwork and bright network plasma with the bright network being more red-shifted. This could imply that the bright network regions are dominated by spicule down-flow.
In the second part we present results from 2-dimensional (2D) dissipative magnetohydrodynamic (MHD) simulations of the response of the solar transition region to micro-scale energy depositions. A variety of temperatures at which the energy deposition takes place as well as the amount of energy deposited are examined. This work is a continuation of previous related simulations where small-scale energy depositions were modelled in 1D hydrodynamics. The observable consequences of such transient events are then computed for three transition region lines, namely C IV 1548 Å, O VI 1032 Å, and Ne VIII 770 Å, under the consideration of non-equilibrium ionization.

Key words. Sun: atmosphere – Sun: transition region – Sun: activity

1. Introduction

It is now well established that spectral lines formed at around 100 000 K in the solar transition region exhibit a net red-shift. If this observed red-shift can be attributed to plasma down-flow, it should be very important from the point of the transition region dynamics and may have implications for the energy balance in the outer solar atmosphere. Models attempting to explain the net mass flows in magnetic loops include those where the flows are driven by asymmetries (such as heating or pressure imbalances) between the two legs of the loop (Mariska & Boris 1983; Mariska 1988; Spadaro et al. 1991) or by radiatively-cooling condensations (Reale et al. 1997). Another model suggests that the observed red-shift could be due to the return of spicular material (Pneuman & Kopp 1978). This model has recently been re-evaluated by Wilhelm (2000).

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Hansteen (1993) showed that red-shifted transition region lines are predicted for downward propagating acoustic waves, and blue-shifted lines are predicted when the perturbations propagate towards the corona (Hansteen & Wikstøl 1994). A followup study by Hansteen et al. (1977) give additional simulation results using nonlinear Alfven waves which give larger line-shifts. In general, impulsive energy release (*nano/micro-flaring*), at the top of magnetic loops can generate downward traveling MHD waves, perhaps steepening into shocks and leading to both red- and blue-shifts, depending on the line formation temperature. Recently, Chae et al. (1997) showed that the enthalpy flux due to down-flow determines the overall energy balance in the transition region at temperatures below 10^5 K.

In a recent observational paper, we looked at the behaviour of spectral lines from the chromosphere to the corona (Teriaca et al. 1999a). It was found that the Doppler velocities ranged from ~0 km s^{-1} at ~20 000 K to a red-shift of

A&A 392, 309–317 (2002)
DOI: 10.1051/0004-6361:20020795

Astronomy & Astrophysics

Transition region explosive events: Do they have a coronal counterpart?

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Received 22 February 2002 / Accepted 27 May 2002

Abstract. EUV explosive events are a prominent class of phenomena characterizing the solar transition region. Their correct location in the wider frame-work of the outer solar atmosphere can provide important insight on the nature of the transition region itself and its relationship with the hotter corona and the cooler chromosphere. In this paper we present new high-cadence SUMER observations of the "quiet" Sun obtained simultaneously in the mid-transition region N v 1238.8 Å line (1.8×10^5 K) and in the coronal Mg x 625 Å line (1.1×10^6 K). These observations are aimed at providing information on the behaviour of the coronal plasma during EUV transition region explosive events detected in N v 1238.8 Å. None of the events observed in N v shows any detectable signature in the Mg x line profile or in its integrated intensity. The analysis of 1996 observations obtained simultaneously in N v 1238.8 Å and S ii 1253.8 Å (3.5×10^4 K) shows, instead, a weak but clear presence of enhanced wings in the S ii line profile during a series of events observed in N v. These results suggest that EUV explosive events are not directly relevant in heating the corona and are characteristic of structures not obviously connected with the upper corona. The evidence of a chromospheric response suggests that, contrary to some previous suggestions, explosive events have a chromospheric origin.

Key words. Sun: transition region, explosive events, corona – UV radiation

1. Introduction

When observed with high spatial (∼1 arcsec) and temporal (∼10–100 s) resolution the "quiet" Sun transition region is anything but "quiet" showing, together with quasi-periodic fluctuations of the intensity and shift of ultraviolet emission lines (O'Shea et al. 2001; Banerjee et al. 2001) also transient events such as brightening (Doyle et al. 1998; Gallagher et al. 1999; Brković et al. 2000 and references therein), blinkers (strong transient brightenings on time-scales of tens of minutes; Harrison 1997; Harrison et al. 1999) and UV explosive events and jets (Brueckner & Bartoe 1983). In particular, UV explosive events are a class of dynamic events quite common in "quiet" Sun areas, with a birthrate over the whole Sun of between 600 s^{-1} (Dere et al. 1989) and 3300 s^{-1} (Ryutova & Tarbell 2000). A similar birthrate is observed also on disk areas within coronal holes (Dere 1992). Explosive events are characterized by spatial scales of ∼2000 km, average lifetime of about 60 s and highly non-Gaussian line profiles showing Doppler shifts up to 250 km s^{-1} (Dere et al. 1989) and often appear in bursts lasting up to 30 min (Innes et al. 1997a; Chae et al. 1998a; Pérez et al. 1999). They are generally observed at the boundaries of the super-granulation cells (Porter & Dere 1991) in regions with weak and mixed polarity fluxes away from the brightest network regions (Chae et al. 1998a). Some of them have also been observed in dark cell-center areas (Wilhelm et al. 1998). The often observed association with episodes of photospheric magnetic flux cancellation (Dere et al. 1991; Chae et al. 1998a; Ryutova & Tarbell 2000) indicates magnetic reconnection to be their likely energy source.

Despite the fact that UV explosive events have been observed for almost 20 years (Brueckner & Bartoe 1983; Dere et al. 1989; Dere et al. 1991; Porter & Dere 1991; Dere 1994; Innes 1997a, 1997b; Wilhelm et al. 1998; Chae et al. 1998a, 1998b; Pérez et al. 1999; Landi et al. 2000; Ryutova & Tarbell 2000; Teriaca et al. 2001) their location in the wider framework of the outer solar atmosphere is still uncertain since the large majority of the observational work was restricted to lines formed below 10^6 K. Dere (1992), from the analysis of HRTS spectra, reports that less than 1% of the explosive events observed in transition region lines are also seen in chromospheric lines such as C i 1561 Å, while they are weakly seen in C ii 1335 Å. However, taking advantage of the higher sensitivity of the SUMER spectrograph, Madjarska & Doyle (2002) offered further evidence that transition region explosive events appear in chromospheric lines such as O i and the optically

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A&A 382, 319–327 (2002)
DOI: 10.1051/0004-6361:20011610

Astronomy & Astrophysics

Temporal evolution of different temperature plasma during explosive events

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Received 18 July 2001 / Accepted 9 November 2001

Abstract. High cadence observations (10 s exposure time) obtained with the SUMER spectrometer on-board SoHO in the Ly 6 (20 000 K) and S VI (200 000 K) lines reveal new insight on the nature of explosive events. A time delay in the response of the S VI line with respect to the Ly 6 line has been observed, with the Ly 6 line responding with about 20–40 s earlier. A temporal series obtained with 30 s exposure time and covering the entire Lyman series plus O I, C II and S VI (temperature range from 15 000 to 200 000 K) has also been explored showing the response of all these lines during transient phenomena. New common features linking explosive events and blinkers were found. During explosive events, the central intensity increases between 1.6 and 2.0 times the pre-event value while the same range of intensity increase was already reported during blinker phenomena. On the other hand the maximum intensity increase in Ly 6 was only 13%.

Key words. Sun: activity – Sun: atmosphere – Sun: magnetic field – Sun: UV radiation

1. Introduction

Observations made with the Naval Research Laboratory's high resolution telescope and spectrograph (HRTS) revealed the existence of high velocity small-scale events seen in lines from ions formed at temperatures from 2×10^4 K (C II) to 2×10^5 K (N V) with no signature in chromospheric lines such as Si II (1.3×10^4 K), C I ($6–10 \times 10^3$ K) and O I (1.5×10^4 K), formed below 2×10^4 K (Brueckner & Bartoe 1983). Discovered and classified by Brueckner & Bartoe (1983) as turbulent events and jets, they are characterized by non-Gaussian profiles due to an enhancement in the blue and red wings, often observed with an offset along the slit (Dere et al. 1989; Innes et al. 1997a). Most of the events are predominantly blueshifted, showing velocities up to 250 km s^{-1}. Their first identification was followed by several studies based on observations obtained with HRTS and the spectrometer Solar Ultraviolet Measurements of Emitted Radiation (SUMER) on-board SoHO performed by Dere et al. (1989), Porter & Dere (1991), Innes et al. (1997a), Chae et al. (1998a), Pérez et al. (1999), Landi et al. (2000) and Teriaca et al. (2001). The authors extended the description of their general characteristics naming them by the term "explosive events".

The explosive events are located in the network lanes at the boundaries of the super-granulation cells where the neutral line separates regions of opposite magnetic polarity (Dere et al. 1991; Porter & Dere 1991). They appear preferably in regions with weak fluxes of mixed polarity or on the border of regions with large concentration of magnetic flux (Chae et al. 1998a). The average lifetime of the explosive events ranges from ∼60 to 350 s (Dere 1994) with spatial dimensions of ∼2500 km. They are often observed in bursts (Innes et al. 1997a) lasting up to 30 min in regions undergoing magnetic cancellation (Chae et al. 1998a). Using the density sensitive line intensity ratio O IV 1401.16/1404.81, Teriaca et al. (2001) found an electron density increase by a factor ∼3 during explosive events. They also showed an increase of the line intensity ratio O IV 1401/O III 703 during an explosive event which suggests a temperature increase during the phenomena.

Explosive events seem to be a product of magnetic reconnection (Parker 1988; Porter & Dere 1991; Dere 1994; Innes et al. 1997b; Wilhelm et al. 1998; Roussev et al. 2001) because they tend to occur on the neutral line separating regions of opposite magnetic polarity, appear as bi-directional jets (Innes et al. 1997b) with velocities comparable to the local Alfvén velocity (Dere 1994), and they are often associated with a cancellation of photospheric magnetic flux (Dere et al. 1991; Dere 1994; Chae et al. 1998a).

After the launch of the SoHO satellite it became possible to observe Lyman lines with high spectral, spatial and temporal resolution. Using these lines as a plasma diagnostic tool has several advantages. They cover heights

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