On the solar origin of in situ observed energetic protons

Rositsa Miteva[1]

Space Research and Technology Institute - Bulgarian Academy of Sciences, acad. Georgy Bonchev st., bl. 1, 1113 Sofia, Bulgaria

Abstract

The aim of this study is to evaluate the differences in the reported solar origin identifications to the same in situ observed energetic proton event and to estimate the possible consequences. In order to assess such issue in a a quantitative manner, the level of certainty on the procedure for solar origin estimation (selection of the solar flare and coronal mass ejection) is utilized. Pearson correlation coefficients are calculated between the parameters of the protons and their solar origin. For the purpose of this study, the 20 MeV SOHO-ERNE proton catalog is finalized and used as a reference proton event list.

Keywords: solar energetic protons, solar flares, coronal mass ejections

1. Introduction

The dilemma in the solar energetic particle (SEP) research gravitates around the still unresolved issue on their solar origin: are the solar flares (SFs) or coronal mass ejections (CMEs) the sole/primary driver [1]. From one side, whether or not SFs and CMEs are able to accelerate particles is not scrutinized: both solar eruptive phenomena are known (directly, by their ability to generate electric fields or indirectly, through the generation of shock waves) to produce non-thermal particle distributions from the background thermal particle ensemble in the solar corona [2, 3, 4]. Electromagnetic (EM) signatures, from gamma to radio emissions, support both the flare-driven magnetic reconnection and the CME-driven shock scenarios [5, 6]. Nevertheless, when the escaping protons and electrons are considered (or at least the portions that could be observed with satellites near Earth, at 1 AU, or, occasionally, out of the ecliptic place), the debate of the SFs vs. CMEs as the SEP-solar origin is far from being resolved.

There are several main reasons. The proton, electron or heavy ions intensities (termed SEP events) measured in situ, at energies ranging from keV to MeV, are modulated due to the following factors: variable efficiency and duration of the particle acceleration process; possibility for trapping and delayed injection of particles in the solar corona due to the event-specific magnetic field topology;

[1]e-mail: rmiteva@space.bas.bg

Solar Physics
DOI: 10.1007/•••••-•••-•••-••••-•

Characteristics of SEP events and their solar origin during active region evolution

L.K. Kashapova[1] · R. Miteva[2] ·
I.N. Myagkova[3] · A.V. Bogomolov[3,4]

Abstract We present the results of a comparative analysis between solar energetic particle (SEP) characteristics, such as the total flux, maximum energy and spectral index of the particles and the parameters of their solar source, namely flare X-ray and radio emission and coronal mass ejection (CME) projected speed. The studied SEP events followed successive flares which occurred in the active region 0069 in August 2002. The SEP acceleration and propagation is discussed based on the analysis of delays between radio and HXR emission and peculiarities of the measured soft and HXR emission spectra.

1. Introduction

The transient enhancements of electron, proton and ion flux we call solar energetic particles (SEPs), also termed solar cosmic rays, together with their solar sources are a topic of an ongoing research (e.g. Reames, 1999; Gopalswamy *et al.*, 2008; Reames, 2015; Desai and Giacalone, 2016). Two particle accelerators of solar origin are usually considered, namely reconnection processes during flares (see, for example, Cane, Erickson, and Prestage, 2002) and shock acceleration driven by coronal mass ejections (CMEs), Reames (1999, 2015). Apart from

✉ L.K. Kashapova
lkk@iszf.irk.ru

R. Miteva
rmiteva@space.bas.bg

[1] Institute of Solar-Terrestrial Physics, SB Russian Academy of Sciences, 664033 Irkutsk, Russia

[2] Space Research and Technology Institute, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria

[3] Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia

[4] Physics Department, Lomonosov Moscow State University, 119991 Moscow, Russia

Solar radio bursts: Implications to the origin of in situ particles

Rositsa Miteva
Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria.
E-mail (rmiteva@space.bas.bg)

Abstract The significance of the solar radio burst signatures for the solar energetic particle (SEP) classification is investigated in the current report. The solar radio bursts associated with the proton-producing solar flares and coronal mass ejections are usually of types II, III and IV. Based on the solar radio burst occurrences in different wavelength ranges, several categories for the SEP origin are adopted. This study evaluates the statistical differences in the flare and CME event samples related to each of these proton categories: flare-driven, CME-driven and mixed-contribution.

Keywords: solar energetic particles; solar flares; coronal mass ejections; solar radio bursts

1. Introduction

The use of remotely observed radio emission (produced by electrons) in the identification of the origin of solar energetic particles (SEPs: electrons, protons and heavy ions with keV-MeV energies) is known for long time (e.g., Lin 1970). However, the same radio signatures (so-called solar radio type II bursts) were used in the SEP classification proposed by Reames (1999). In the subsequent revisions, e.g., by Cliver (2009) and the references therein, it was attempted to repair the initial inconsistency.

Observations in radio wavelengths (from decimetric, dm, to kilometric, km, range) provide independent diagnostic tool for testing electron acceleration mechanisms and following in time the electron propagation, from the low corona to the Earth’s orbit. Although comparing any electron signatures with in situ observed protons is an approximation, this indirect method is frequently used in the literature. Under the assumption that electrons and protons are accelerated by the same mechanism and in the same place, the radio emission will be used in the present study to relate to the origin of the in situ protons.

The radio emission is organized historically into several burst types (see reviews by Nindos et al. 2008, Pick and Vilmer 2008), depending on their appearance in the radio burst spectra, their time and frequency coverage, drift, etc., namely: type II (widely adopted as the signature of shock wave in the corona and/or interplanetary space), type III (emission by electron beams) and type IV (trapped electrons) being the relevant ones for SEP events.

Numerous catalogs of proton (and electron) events also identified the radio signatures provided as complementary information to the particle event lists, e.g., Cane et al. (2010), Vainio et al. (2013), Papaionnou et al. (2016), or radio bursts are used in timing studies between the extrapolated particle injection at the Sun and the release of the radio burst (e.g., Koloumvakos et al. (2015) and the referenced therein). Listing all works using radio bursts in the studies of SEP events is, however, beyond the scope of this paper.

Solar Phys _####################_
https://doi.org/10.1007/s11207-018-1241-5

RADIO AND SPACE-BASED OBSERVATIONS

The Wind/EPACT Proton Event Catalog (1996 – 2016)

Rositsa Miteva[1] · Susan W. Samwel[2] · Marcus V. Costa-Duarte[3]

Received: 13 April 2017 / Accepted: 4 January 2018

Abstract We present the finalized catalog of solar energetic proton events detected by the Wind/EPACT instrument over the period 1996 – 2016. Onset times, peak times, peak proton intensity and onset-to-peak proton fluence are evaluated for the two available energy channels, at about 25 and 50 MeV. We describe the procedure utilized to identify the proton events and to relate them to their solar origin (in terms of flares and coronal mass ejections). The statistical relationships between the energetic protons and their origin (linear and partial correlation analysis) are reported and discussed in view of earlier findings. Finally, the different trends found in the first 8 years of solar cycles 23 and 24 are discussed.

Keywords Energetic particles, protons · Flares · Coronal mass ejections · Solar cycle

Combined Radio and Space-based Solar Observations: From Techniques to New Results
Guest Editors: Eduard Kontar and Alexander Nindos

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11207-018-1241-5) contains supplementary material, which is available to authorized users.

✉ R. Miteva
rmiteva@space.bas.bg

S.W. Samwel
samwelsw@nriag.sci.eg

M.V. Costa-Duarte
mvcduarte@iag.usp.br

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences (SRTI-BAS), 1113 Sofia, Bulgaria

[2] National Research Institute of Astronomy and Geophysics (NRIAG), 11421 Helwan, Cairo, Egypt

[3] Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo (IAG-USP), 05508-090 São Paulo, Brazil

J. Space Weather Space Clim. 2017, 7, A37
© R. Miteva *et al.*, Published by EDP Sciences 2017
https://doi.org/10.1051/swsc/2017035

Available online at:
www.swsc-journal.org

Flares, coronal mass ejections and solar energetic particles and their space weather impacts

Research Article

Open Access

Solar energetic particles and radio burst emission

Rositsa Miteva[1,*], Susan W. Samwel[2] and Vratislav Krupar[3,4,5]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences (SRTI-BAS), 1113 Sofia, Bulgaria
[2] National Research Institute of Astronomy and Geophysics (NRIAG), 11421 Helwan, Cairo, Egypt
[3] Universities Space Research Association, 21046 Columbia, Maryland, USA
[4] NASA Goddard Space Flight Center, 20771 Greenbelt, Maryland, USA
[5] Institute of Atmospheric Physics CAS, 14131 Prague, Czech Republic

Received 31 May 2017 / Accepted 19 November 2017

Abstract – We present a statistical study on the observed solar radio burst emission associated with the origin of in situ detected solar energetic particles. Several proton event catalogs in the period 1996–2016 are used. At the time of appearance of the particle origin (flare and coronal mass ejection) we identified radio burst signatures of types II, III and IV by inspecting dynamic radio spectral plots. The information from observatory reports is also accounted for during the analysis. The occurrence of solar radio burst signatures is evaluated within selected wavelength ranges during the solar cycle 23 and the ongoing 24. Finally, we present the burst occurrence trends with respect to the intensity of the proton events and the location of their solar origin.

Keywords: solar energetic particles / solar radio burst emission / solar cycle

1 Introduction

Solar energetic particles (SEPs) are protons, electrons and heavy ions energized during eruptive event at the Sun to keV–GeV energy (Schwenn, 2006; Desai & Giacalone, 2016). If there is a possibility to escape, the particles propagate into the heliosphere along the interplanetary (IP) magnetic field lines. When these magnetic field lines pass over a particle detector aboard a satellite, it records the increasing particle intensity with time. The observed profile, however, depends on the driver productivity, the connectivity to the acceleration site, the amount of seed particles from previous events, as well as eventual re-acceleration processes or particle loss in the IP medium. The most energetic SEPs (500 MeV) can enter the terrestrial magnetosphere and the secondary products after interaction with atmospheric atoms can be detected by ground-based neutron monitors as ground level enhancements. In general, the SEP phenomena follow the overall solar cycle trend of eruptive phenomena (Miteva et al., 2017b). From terrestrial point of view, however, the energetic particles carry some amount of latent risk. They are a source of the space radiation, which is dangerous to humans, and a reason for various spacecraft malfunction as well as accelerated material aging (Pulkkinen, 2007). Special efforts are carried out to improve the current capabilities to forecast/nowcast SEP events using different approaches and schemes.

The forecasting models are in general a multi-parameter solver based on various numerical techniques. The aim is to provide accurate particle arrival (and/or maximum intensity) prognosis with long warning time, few missed cases and low false alarm rate. The methods feed a mixture of input parameters into their models (Laurenza et al., 2009) or use: electrons as proton precursors (Posner, 2007); location, intensity and steepness of the solar flare emission (Núñez, 2011; Núñez, 2015); radio emission precursors (Winter & Ledbetter, 2015); statistical probabilities (Trottet et al., 2015), and evaluate a set of standard outputs. Validation procedures are imposed to cross-check the performance of each method.

Solar radio bursts were connected in past studies to in situ energetic particles, in terms of appearance of radio signatures (Kahler, 1982a), their duration (Cane et al., 2002) and spectral properties (Chertok, 1990), with ongoing follow-up discussion in the literature. In the present analysis, we focus mainly on the presence or not of radio bursts in relationship to SEP events, their solar origin and strength.

The solar radio domain possesses unique (remote-sensing) diagnostic potential on drivers, environments, processes, particle distributions. The radio emission originates from different physical processes acting on populations of energetic electrons (Melrose, 1985). Decimetric emission (dm, in radio wavelength notation) originates in the low corona and is due to gyrosynchrotron, gyroresonance, and/or bremsstrahlung,

*Corresponding author: rmiteva@space.bas.bg

Observational methods for solar origin diagnostics of energetic protons

Rositsa Miteva
Space Research and Technology Institute – Bulgarian Academy of Sciences
rmiteva@space.bas.bg

Abstract
The aim of the present report is to outline the observational methods used to determine the solar origin – in terms of flares and coronal mass ejections (CMEs) – of the in situ observed solar energetic protons. Several widely used guidelines are given and different sources of uncertainties are summarized and discussed. In the present study, a new quality factor is proposed as a certainty check on the so-identified flare–CME pairs. In addition, the correlations between the proton peak intensity and the properties of their solar origin are evaluated as a function of the quality factor.

Keywords: solar energetic protons, solar flares, coronal mass ejections, space weather

Introduction

The Sun is a constant source of electromagnetic radiation covering almost the entire spectrum. The highest energy wavelengths observed (hard X-rays and gamma-rays) are produced during a specific type of eruptive events named solar flares (Fletcher et al. 2011). Although the flares are equated with the 'flash of light' observed in a specific wavelength range by the observing instrument, they are also a process that involves mass motion (jets), magnetic field restructuring and acceleration of particles. The underlying physical mechanism that drives the solar flare is called magnetic reconnection. Despite that the details of the process need to be better understood, the term is well adopted to qualitatively explain the various eruptive phenomena in the solar corona. A different manifestation of solar activity is the coronal mass ejection (CME). This is an enormous bubble of plasma and embedded magnetic field (Chen, 2011) that escapes the solar pull and continues to expand during their propagation into the interplanetary (IP) space. Ahead of the CME, the plasma and magnetic field are compressed and a turbulent region is formed with suitable conditions for local acceleration of particles (both in terms of reconnection with coronal/IP field lines or due to shock acceleration). Thus both flares and CMEs are regarded as the probable drivers (the solar origin) of energetic particles.

Solar energetic particles (SEPs) is the term used nowadays to describe the population of protons, ions and electrons with energies from keV to MeV that is observed in situ (Schwenn, 2006, Desai and Giacalone, 2016). Presently, the majority of the satellites equipped with particle detectors are situated at L1 (since 1996) together the twin-STEREO mission (since late 2006) orbiting the Sun from opposite directions at a distance of 1AU and in the ecliptic plane.

The interest to study the SEP events is justified due to the risk they pose to technological devices and satellites as a whole. Energetic protons, in particular, can give rise to dangerously elevated radiation doses of astronauts during their time in space. Together with solar flares and CMEs, the SEP events constitute the important components of space weather and are subject to active research (Pulkkinen, 2007).

Great efforts are directed towards the successful forecasting of energetic particles (mostly protons). Numerous schemes are proposed to forecast the proton event on first place, and then their arrival time and the maximum proton intensity (e.g, Nunez 2011). Irrelevant on the methodology used, the forecasts need to be validated against real observations, thus comprehensive lists of observed particle events are needed. Since the observing instruments are subject to data gaps, several independent satellites are needed to compile a consistent particle list. A number of them are already

THE ORIGIN OF SEP EVENTS: NEW RESEARCH COLLABORATION AND NETWORK ON SPACE WEATHER

Rositsa Miteva[1], Larisa Kashapova[2], Irina Myagkova[3], Nataliia Meshalkina[2], Nikola Petrov[4], Andrey Bogomolov[3], Ivan Myshyakov[2], Tsvetan Tsvetkov[4], Dimitar Danov[1], Dmitriy Zhdanov[2]

[1]Space Research and Technology Institute, Bulgarian Academy of Sciences
[2]Institute of Solar Terrestrial Physics SB, Russian Academy of Science
[3]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University
[4]Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences
e-mail: rmiteva@space.bas.bg

Keywords: *Solar energetic particles, Space weather*

Abstract: *A new project on the solar energetic particles (SEPs) and their solar origins (flares and coronal mass ejections) is described here. The main aim of this project is to answer the question – whether the SEPs observed in situ are driven by flares, by CMEs or both accelerators contribute to an extent which varies from event to event – by deducing a quantitative measure of the flare vs. CME contribution, duration and efficiency. New observations (SONG/Koronas-F, Relec/Vernov) and new approaches of analysis will be utilized (e.g., magnetic topology of active regions using 3D extrapolation techniques of detailed case studies together with statistical analysis of the phenomena). In addition, the identification of the uncertainty limits of SEP injection, onset time and testing the validity of assumptions often taken for granted (association procedures, solar activity longitudinal effects, correlation analysis, etc.) are planned. The project outcomes have the capacity to contribute to other research fields for improvement of modeling schemes and forecasting methods of space weather events.*

ПРОИЗХОД НА СЛЪНЧЕВИ ЕНЕРГЕТИЧНИ ЧАСТИЦИ: НОВО НАУЧНО СЪТРУДНИЧЕСТВО И МРЕЖА НА ТЕМА КОСМИЧЕСКО ВРЕМЕ

Росица Митева[1], Лариса Кашапова[2], Ирина Мягкова[3], Наталия Мешалкина[2], Никола Петров[4], Андрей Богомолов[3], Иван Мишяков[2], Цветан Цветков[4], Димитър Данов[1], Дмитрий Жданов[2]

[1]Институт за космически изследвания и технолигии, Българска академия на науките
[2]Институт по слънчево-земна физика СБ, Руска академия на науките
[3]Скобелцин Институт по ядрена физика, Ломоносовски Московски Държавен Университет
[4]Иститут по астрономия и Национална астрономическа обсерватория, Българска академия на науките
e-mail: rmiteva@space.bas.bg

Ключови думи: *слънчеви енергетични частици, космическо време*

Резюме: *Тук е представен новият проект по слънчеви енергетични частици и техния слънчев произход (избухвания и коронално изнасяне на маса). Целта на проекта е да се отговори на въпроса – дали наблюдаваните in situ частици са породени от избухвания, от коронална маса, или и двата източника влияят в степен, която варира между отделните събития – като се изведат количествени характеристики за приноса от всеки източник, тяхната продължителност и ефективност. Нови наблюдения (SONG/Koronas-F, Relec/Vernov) и нови методики за анализ на данни ще бъдат използвани (напр. магнитна топология на активни области чрез триизмерни екстраполации на избрани случаи, заедно със статистическите изследвания на всички събития). В допълнение се планува да се определят неточностите при инжекцията на частици в междупланетното пространство, тяхното начало във времето, както и приложимостта на широко приетите приближения (като процедури за асоциация, ефекти на местоположението на слънчевите събития, корелационен анализ и др.). Резултатите от проекта имат потенциал да допринесат и в други гранични научни сфери с цел подобряване моделите и схемите за прогнозиране на явленията на космическо време.*

SOHO/ERNE PROTON EVENT CATALOG: DESCRIPTION AND FIRST RESULTS

Rositsa Miteva

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: rmiteva@space.bas.bg

Keywords: *Solar energetic particles, Space weather.*

Abstract: *The procedure for compilation of a new proton catalog is presented here. The focus is on the SOHO/ERNE instrument for the period 1996 to 2016 (entire solar cycle 23 and the ongoing solar cycle 24). The main steps of the data analysis are outlined. Namely, as a first approach it is selected that 5-min averaged data will be used to identify the peak proton intensity. Contributions due to local shock acceleration close to Earth are not taken into account. In this report, the main properties of the proton sample in the energy channel 17–22 MeV are presented and discussed.*

КАТАЛОГ НА ПРОТОННИ СЪБИТИЯ НАБЛЮДАВАНИ ОТ SOHO/ERNE: ОПИСАНИЕ И ПЪРВОНАЧАЛНИ РЕЗУЛТАТИ

Росица Митева

Институт за космически изследвания и технологии – Булгаска академия на науките
e-mail: rmiteva@space.bas.bg

Ключови думи: *Слънчеви енергетични частици, космическо време.*

Резюме: *Представени са процедурата за съставянето на нов каталог от протонни събития. Фокусът е върху инструмента SOHO/ERNE за периода от 1996 до 2016 (целия 23-ти слънчев цикъл и настоящия 24-ти). Основните стъпки на анализа на данните са представени. А именно, като първоначален подход е избрано да се работи с осреднени данни (5-минути) за определяне на максимума на протонния поток. Приноси в протонния поток поради ударни вълни близко до Земята не се взимат предвид. Тук се докладват и дискутират основните характеристики на протонните събития в енергийния диапазон 17–22 MeV.*

Introduction

Non-thermal particles – electrons, protons and heavy ions – are a well-known space weather agent [1]. These keV-to-MeV particles follow in time the eruptive phenomena observed at the Sun (flares and coronal mass ejections, CMEs), considered as the solar origin of the particles, with the more energetic population arriving ahead of the slow particles. Nowadays the term solar energetic particles (SEPs) is more frequently used compared to 'solar cosmic rays'. SEP events still await quantitative description on the chain of processes of acceleration, escape and propagation through the interplanetary (IP) space. Moreover, the likelihood for a flare and CME to occur and the early assessment of their properties is a subject of ongoing work. These factors are essential for the improved SEP-forecasting since energetic particles can endanger the performance of terrestrial and satellite technological devices [2] and the health of crew members during polar flights on Earth or in space.

Numerous particle detectors record continuously the SEP intensity (flux) – both in flight (e.g., by the sequence of IMP and GOES spacecraft) and on ground (e.g., by the network of neutron monitors: http://www.nmdb.eu/). Since 1990s, numerous new satellites were launched to observe the Sun – in remote and/or in situ mode, among them, Ulysses (ended in 2009), SOHO, ACE, Wind,

PRESENTATION OF THE PROJECT "AN INVESTIGATION OF THE EARLY STAGES OF SOLAR ERUPTIONS – FROM REMOTE OBSERVATIONS TO ENERGETIC PARTICLES"

Kamen Kozarev[1], Astrid Veronig[2], Peter Duchlev[1], Kostadinka Koleva[1], Momchil Dechev[1], Rositsa Miteva[3], Manuela Temmer[2], Karin Dissauer[2]

[1]Institute of Astronomy and National Astronomical Observatory – Bulgarian Academy of Sciences
[2]IGAM of the University of Graz, Austria
[3]Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: kkozarev@astro.bas.bg

Keywords: *Coronal mass ejections, solar energetic particles, coronal shocks, eruptive filaments*

Abstract: *Coronal mass ejections (CMEs), one of the most energetic manifestations of solar activity, are complex events, which combine multiple related phenomena occurring on the solar surface, in the extended solar atmosphere (corona), as well as in interplanetary space. We present here an outline of a new collaborative project between scientists from the Bulgarian Academy of Sciences (BAS), Bulgaria and the University of Graz, Austria. The goal of the this research project is to answer the following questions: 1) What are the properties of erupting filaments, CMEs, and CME-driven shock waves near the Sun, and of associated solar energetic particle (SEP) fluxes in interplanetary space? 2) How are these properties related to the coronal acceleration of SEPs? To achieve the scientific goals of this project, we will use remote solar observations with high spatial and temporal resolution to characterize the early stages of coronal eruption events in a systematic way – studying the pre-eruptive behavior of filaments and flares during energy build-up, the kinematics and morphology of CMEs and compressive shock waves, and the signatures of high energy non-thermal particles in both remote and in situ observations.*

ПРЕДСТАВЯНЕ НА ПРОЕКТ "ИЗСЛЕДВАНЕ НА РАННИТЕ СТАДИИ НА СЛЪНЧЕВИТЕ ИЗРИГВАНИЯ – ОТ ДИСТАНЦИОННИ НАБЛЮДЕНИЯ КЪМ ВИСОКОЕНЕРГЕТИЧНИ ЧАСТИЦИ"

Камен Козарев[1], Астрид Веронspecific[2], Петър Духлев[1], Костадинка Колева[1], Момчил Дечев[1], Росица Митева[3], Мануела Темер[2], Карин Дисауер[2]

[1]Институт по Астрономия с НАО – Българска академия на науките
[2]Институт по физика, Университет „Карл-Франц", Грац, Австрия
[3]Институт за космически изследвания и технологии – Българска академия на науките
e-mail: kkozarev@astro.bas.bg

Ключови думи: *Коронални изхвърляния на маса, слънчеви високоенергетични частици, коронални ударни вълни, еруптивни влакна*

Резюме: *Короналните изхвърляния на маса (Coronal Mass Ejections – CME), едно от най-енергетичните проявления на слънчевата активност, са комплексни събития, съпътствани от множество свързани феномени върху слънчевата повърхност, в слънчевата атмосфера (короната), както и в междупланетното пространство. Тук представяме нов съвместен проект между учени от Българската академия на науките (БАН), България, и Университет "Карл-Франц", Грац, Австрия. Целта на представения проект е да отговори на следните въпроси: 1) Какви са свойствата на еруптивните протуберанси, короналните изхвърляния на маса и ударните вълни предизвикани от тях в близост до слънцето (в слънчевата корона), както и на произтичащите от тях потоци високоенергетични частици в междупланетното пространство? 2) Как са свързани тези свойства с ускорението на слънчеви високоенергетични частици в короната? За да изпълним научните цели на този проект, ще използваме дистанционни слънчеви наблюдения с висока времева и пространствена разделителна способност, за да изследваме най-ранните етапи на слънчевите изригвания по систематичен начин – като проучим пред-еруптивното поведение на протуберанси и избухвания в*

Proceedings of
Ninth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"
Sunny Beach, Bulgaria, May 30 - June 3, 2017

Solar radio burst emission from proton-producing flares and coronal mass ejections

R. Miteva [1], *S.W. Samwel* [2], *V. Krupar* [3,4,5]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences, Bulgaria
[2] National Research Institute of Astronomy and Geophysics (NRIAG), Egypt
[3] Universities Space Research Association, USA
[4] NASA Goddard Space Flight Center (NASA/GSFC), USA
[5] Institute of Atmospheric Physics (CAS), Czech Republic
E-mail: rmiteva@space.bas.bg

Abstract.

We present the occurrence trends of radio burst types in relations to the origin of solar energetic proton events – flares and coronal mass ejections (CMEs) – during the ongoing solar cycle 24 (2009÷2016). Namely, we analyze the occurrence of type II, type III and type IV radio bursts in specific frequency ranges, either as a support for the flare-origin when the emission originates from the low corona or for the CME-origin, when the radio bursts originate in the high corona.

Introduction

Electrons, protons and heavy ions are energized during acceleration processes in the solar corona and interplanetary (IP) space as evidenced by their remotely observed electromagnetic (EM) emission and in situ detection [*Desai and Giacalone*, 2016]. The radiation due to magnetic reconnection process at solar flares can covers virtually the entire EM range, from gamma to radio wavelengths and is used to deduce the energy range of the accelerated particles as well as the physical mechanisms that take place in the solar atmosphere. In addition, shock acceleration process is expected to take place ahead of coronal mass ejections (CMEs) and is widely used as evidence for particle acceleration in the corona and IP space. [*Klein and Dalla*, 2017] recently reviewed the different acceleration mechanisms of SEP events.

The keV to MeV solar energetic particles (SEPs) cannot enter the terrestrial magnetosphere and are detected only in situ by satellites. Only particles at GeV energies can be detected by ground-based (neutron and muon) detectors via their secondary particles produced during interactions with terrestrial atmosphere. The solar origin is evidenced by the fact that these particles follow in time the eruptions observed at the Sun and the particle profiles show velocity dispersion characteristics.

Radio emission provides a straightforward diagnostic tool to detect and interpret the various radio signatures observed from the low solar atmosphere to Earth see reviews by [*Nindos et al.* 2008 and *Pick and Vilmer*, 2008]. Emission tracks in dynamic radio spectral plots are used as evidence for particle escape from the solar corona, their travel through the IP space, and arrival at Earth.

Historically, the different radio emission signatures were organized into five distinct burst types according to a scheme proposed by [*Wild et al.* 1963]. However types II, III and IV are expected to be the relevant ones for space weather [*Warmuth and Mann* 2005]. Nowadays, it is accepted that type II radio bursts are the signatures of MHD shock wave traveling at speeds of the order of 1000 km/s in the corona and faster than the ambient solar wind in the IP space. Type III bursts are generated by electron beams with typical speed around 0.3 of the speed of light, more often observed to propagate outwards to lower frequencies than inwards, towards the surface [*Aschwanden* 2004, *Pick and Vilmer*, 2008]. Type IV bursts show much more complexity in appearance (as moving/stationary emission patches) and cover much larger frequency and time ranges compared to the other two types. They are regarded as the

Proceedings of
Ninth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"
Sunny Beach, Bulgaria, May 30 - June 3, 2016

On-line catalogs of solar energetic protons at SRTI-BAS

R. Miteva and D. Danov

Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria
E-mail: rmiteva@space.bas.bg

Abstract.

We outline the status of the on-line catalogs of solar energetic particles supported by the Space Climate group at the Space Research and Technology, Bulgarian Academy of Sciences (SRTI-BAS). In addition to the already compiled proton catalog from Wind/EPACT instrument, in the current report we present preliminary results on the high energy SOHO/ERNE proton enhancement identifications as well as comparative analysis with two other proton lists. The future plans for the on-line catalogs are briefly summarized.

Introduction

The importance of solar energetic particles (SEPs: electrons, protons and heavy ions from keV up to GeV energies) in space weather research, in addition to flares and coronal mass ejections (CMEs), has already been recognized [*Schwenn* 2006; *Pulkkinen* 2007]. The risk for SEP produced radiation doses outside the terrestrial magnetosphere is regarded as a severe problem to be solved in order to secure the safety of humans during future space travel flights (https://oig.nasa.gov/audits/reports/FY16/IG-16-003.pdf).

Mitigating the negative effects of space weather drivers is the reason for the observational and theoretical efforts spent in understanding them. The forecasting SEP and flare events is the subject of numerous recently completed and ongoing EU-projects. Many of the forecasting schemes rely on long series of events in order to test and train the forecasting methods (e.g. by machine-learning techniques). This is one of the possible applications for the comprehensive SEP event lists prepared from data provided by different space-borne instruments, in addition to academic-oriented research.

Due to various reasons (e.g., service interruption, event detection threshold, magnetic field line connection, etc.) a single spacecraft is unable to provide a complete list of all SEP events observable at Earth. In a recent study, *Miteva et al.* [2017b] summarized a number of probable instrumental, positional and selection effects that may influence the completeness of a SEP catalog. The different instruments provide observations in several energy channels, particle species, and locations (geostationary orbit, around L1, along the Earth orbit).

In the present report we summarize the current status of the SEP cataloguing performed at the Space Climate group in the Space Research and Technology, Bulgarian Academy of Sciences (SRTI-BAS). The preparation of several catalogs is in progress and using proton data from Wind/EPACT [*von Rosenvinge et al.* 1995] and SOHO/ERNE [*Torsti et al.* 1995] instruments is now confirmed. The first version of the proton catalog based on Wind/EPACT data was announced by [*Miteva et al.* 2016], where the main guidelines for the proton identification were presented, as well as the on-line platform of the catalog. This preliminary version of the Wind/EPACT proton event catalog was used in a study by [*Miteva et al.* 2017a] to explore the solar cycle trends. The finalized version of the proton catalog is now completed and used for comparative and statistical studies [*Miteva et al.* 2017b,c]. At present, we continue with the analysis of proton enhancements above ~20 MeV from the SOHO/ERNE instrument. All particle catalogs (with information on their proton event characteristics – time and peak intensity, overview plots and solar origin – flares and CMEs) will be stored at the dedicated web-site: http://newserver.stil.bas.bg/SEPcatalog.

ARTICLE IN PRESS

Journal of Atmospheric and Solar-Terrestrial Physics xxx (2017) 1–9

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Solar energetic particle catalogs: Assumptions, uncertainties and validity of reports

R. Miteva [a,*], S.W. Samwel [b], M.V. Costa-Duarte [c]

[a] Space Research and Technology Institute, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria
[b] National Research Institute of Astronomy and Geophysics, 11421 Helwan, Cairo, Egypt
[c] Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, 05508-090 São Paulo, Brazil

ARTICLE INFO

Keywords:
Solar energetic particles
Solar flares
Coronal mass ejections

ABSTRACT

The aim of this work is to summarize the main underlying assumptions, simplifications and uncertainties while studying solar energetic particles (SEPs). In general, numerous definitions are used for the evaluation of a given SEP parameter and these different methods lead to different outcomes for a given particle event. Several catalogs of SEP events from various instruments are currently available; however, each catalog is specific to the adopted data and analysis. We investigate the differences while comparing several SEP catalogs and outline probable reasons. We focus on SEP statistical studies and quantify the influences of the particle intensity, solar origin location and projection effects. We found that different definitions and criteria used for these parameters change the values of the correlation coefficients between the SEPs and their solar origin.

1. Introduction

Energetic electrons, protons and heavy ions of solar origin are routinely being detected by in situ measurements as particle intensity enhancements. This phenomenon is known as solar energetic particles (SEPs) or solar cosmic rays, see a recent review by Desai and Giacalone (2016). Energetic particles originate at some solar activity phenomena (e.g., by acceleration processes during solar flares, SFs, and coronal mass ejections, CMEs) because SEPs follow in time these solar eruptions and the SEP time profiles show velocity dispersion characteristics. The energized particles need to escape the acceleration cite (situated in the lower or higher solar corona) and continue to propagate along the heliospheric magnetic field lines. When these field lines sweep over some space-based detector, a particle enhancement is recorded. SEP events are observed by a satellite situated at an isolated point in the heliosphere, either at fixed orbit close to L1 or around the Sun, as the twin STEREO mission (Kaiser et al., 2008), with rare observations done outside the ecliptic plane (by Ulysses (Simpson et al., 1992) during the period 1990–2009). In this work, we will consider particle data from measurements done close to Earth on a routine basis.

Since 1990s several solar dedicated missions were successfully launched. Among them, SOHO (Solar and Heliospheric Observatory, Domingo et al., 1995), ACE and Wind spacecraft continue to provide particle data from their respective instruments. Among these, Energetic and Relativistic Nuclei and Electron (ERNE) instrument (Torsti et al., 1995) on SOHO and Energetic Particle Acceleration, Composition and Transport (EPACT) instrument (von Rosenvinge et al., 1995) on Wind are considered in the present work. Another prominent example is the series of nearly identical spacecraft located on geostationary orbit, Geostationary Operational Environmental Satellite (GOES), that provide, among others, particle data since late 1970s (Rodriguez et al., 2014).

SEP events (usually protons) based on data from the above instruments, are routinely being identified either by observers or via automatic routines. In this work, we consider the following catalogs of proton events: SEPEM (Crosby et al., 2015), GOES-NOAA,[1] IMP-8 (Cane et al., 2010), GOES-SSE (Dierckxsens et al., 2015), GOES-SEP (Papaioannou et al., 2016), Wind/EPACT (Miteva et al., 2016) and SEPServer (Vainio et al., 2013). For the purpose of this study we aim to select several well-known in the SEP community and/or recently compiled proton catalogs. In addition to these, other proton lists also exist.[2]

Each of the catalogs reports 100s of individual proton events. Such large amount of data allows for preparing different statistical studies on SEP events and their parent phenomena as well as the quantitative

* Corresponding author.
E-mail address: rmiteva@space.bas.bg (R. Miteva).

[1] http://umbra.nascom.nasa.gov/SEP/.

[2] http://www.wdcb.ru/stp/index.en.html, see (Posner, 2007; Laurenza et al., 2009) and a summary by Papaioannou et al. (2016).

http://dx.doi.org/10.1016/j.jastp.2017.05.003
Received 30 November 2016; Received in revised form 1 May 2017; Accepted 4 May 2017
Available online xxxx

Please cite this article in press as: Miteva, R., et al., Solar energetic particle catalogs: Assumptions, uncertainties and validity of reports, Journal of Atmospheric and Solar-Terrestrial Physics (2017), http://dx.doi.org/10.1016/j.jastp.2017.05.003

Solar cycle dependence of Wind/EPACT protons, solar flares and coronal mass ejections

Miteva, R. [1], Samwel, S. W. [2], Costa-Duarte, M. V. [3], Malandraki, O. E. [4]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences, Bulgaria.
[2] National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt.
[3] Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, São Paulo, Brazil.
[4] Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, Penteli, Greece.

E-mail (rmiteva@space.bas.bg)

Accepted: 8 September 2016

Abstract The aim of this work is to compare the occurrence and overall properties of solar energetic particles (SEPs), solar flares and coronal mass ejections (CMEs) over the first seven years in solar cycles (SCs) 23 and 24. For the case of SEP events, we compiled a new proton event catalog using data from the Wind/EPACT instrument. We confirm the previously known reduction of high energy proton events in SC24 compared to the same period in SC23; our analysis shows a decrease of 25–50 MeV protons by about 30%. The similar trend is found for X to C-class solar flares which are less by about 40% and also for faster than 1000 km/s CMEs, which are reduced by about 45%. In contrast, slow CMEs are more numerous in the present solar cycle. We discuss the implications of these results for the population of SEP-productive flares and CMEs.

Keywords: solar energetic particles; solar flares; CMEs; solar cycle

1. Introduction

The historical parameter used to describe solar activity and its temporal behavior is the sunspot number. The duration of a given solar cycle (SC), however, varies slightly around the well-known 11-year period (Hathaway, 2010). With the new and improved space-borne observations in various wavelength regimes (mostly since 1996), a number of other solar phenomena could be monitored in great detail for nearly two SCs, among them are the solar flares, coronal mass ejections (CMEs) and solar energetic particles (SEPs). These constitute the main drivers of space weather (Schwenn, 2003) following the overall trend outlined by the sunspot count variation throughout the years.

SEPs (electrons, protons and heavy ions) are the enhancements of the particle intensity observed in situ that follow in time the solar eruptions, flares and CMEs. Usually, SEP events are observed at a single point in space, routinely at L1 and occasionally outside the ecliptic plane. Recent multi-spacecraft observations using the twin STEREO spacecraft (Kaiser et al. 2008) showed simultaneous SEP onsets at large longitudinal extents in the heliosphere (Gomez-Herrero et al. 2015).

Two main physical processes, namely, magnetic reconnection during solar flares and shocks driven by CMEs, can accelerate particles in the solar atmosphere and interplanetary (IP) space, respectively (Cane, Richardson, and von Rosenvinge (2010), Reames (2013) and references therein). Thus, the SEP productivity depends on the overall trend of flare and CME occurrence. The SEP-productive eruptive events, however, are small subsets of the overall flare/CME distributions. Following the acceleration, the energetic particles escape from the corona (Klein et al. 2008, Agueda et al. 2014), sustain various transport effects in the IP space before being finally detected, provided the magnetic field lines sweep over the satellite.

The quantitative comparisons of the occurrence and properties of the SEPs and their solar origin over the SC is a subject of several recent studies. Since SC24 is still ongoing, all reports are based on comparison of partial data samples. The analysis in Gopalswamy (2012) and Chandra et al. (2013) cover about 3.5 and 3 years from SC24, respectively, with about 20 events in each rise phase. Gopalswamy et al. (2014) report about 30 major SEP events in the first 5 years of SC24, whereas Mewaldt et al. (2015) extend their sample to about 5.8 years in each SC. Despite the samples limitation, several trends in SC24 could be identified: a decrease in the number of high energy particles and larger fraction of halo-CMEs resulting into SEPs (Gopalswamy 2012); poor magnetic connectivity, in longitude and latitude, and unfavorable ambient conditions (Gopalswamy et al. 2014); reduced magnetic field strength (McComas et al. 2013; Mewaldt et al. 2015), north-south asymmetry (Gopalswamy 2012; Chandra et al. 2013); reduced number of seed particles (Mewaldt et al. 2015).

The focus of this work is the solar cycle dependence of the observed near Earth proton events and the entire population of solar eruptive phenomena, flares and CMEs, irrespective of their SEP production. The 20-year behavior (1996–2015) of proton events in two energy channels is investigated here using a newly compiled Wind/EPACT proton

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **465,** 68–75 (2017) doi:10.1093/mnras/stw2742
Advance Access publication 2016 October 26

Flare-production potential associated with different sunspot groups

S. Eren,[1★] A. Kilcik,[1★] T. Atay,[1] R. Miteva,[2] V. Yurchyshyn,[3,4★] J. P. Rozelot[5] and A. Ozguc[6]

[1]*Faculty of Science, Department of Space Science and Technologies, Akdeniz University, 07058 Antalya, Turkey*
[2]*Space Research and Technology Institute, Bulgarian Academy of Sciences, Acad. Georgy Bonchev, 1113 Sofia, Bulgaria*
[3]*Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City, CA 92314, USA*
[4]*Korea Astronomy and Space Science Institute, 776 Daedeok-daero, Yuseong-gu, Daejeon 305-348, South Korea*
[5]*Observatoire de la Cote d'Azur , Nice University, Bvd de l'Observatoire, CS 34229, F-06304 Nice Cedex 4, France*
[6]*Kandilli Observatory and Earthquake Research Institute, Bogazici University, 34684 Istanbul, Turkey*

Accepted 2016 October 21. Received 2016 October 21; in original form 2016 March 7

ABSTRACT

In this study, we analysed different types (C, M, and X classes) of X-ray solar flares occurring in sunspot groups. The data cover 1996–2014 time interval, and a total of 4262 active regions (ARs) were included in the data set. We defined the solar-flare-production potential as the ratio of the total number of flares observed in a sunspot group to the total number of the same-class sunspot groups. Our main findings are as follows: (1) large and complex sunspot groups (D+E+F) have the flare-production potential about eight times higher than the small and simple (A+B+C+H) ARs; (2) 79 per cent of all flares were produced by the large and complex sunspot groups, while only 21 per cent of flares were produced by the small groups; (3) the largest and the most complex F-class (very large and very complex) sunspot groups exhibit the highest flare-production potential (2.16 flare per sunspot group), while the smallest and the least complex A class sunspot groups show the lowest (0.05 flare per group) flare-production potential; (4) temporal variation of sunspot counts, sunspot group areas, and the total number of flares (including C flares) showed similar time profiles during both cycles with multiple peaks; (5) the mean area of ARs very well describes the flare-production potential of each group with the regression coefficient of $R^2 = 0.99$. Most of these sunspot groups (>70 per cent) are, according to the Zurich Classification, complex ARs.

Key words: Sun: activity – Sun: atmosphere – Sun: flares – sunspots.

1 INTRODUCTION

Sunspots are strong magnetic-field concentrations in the solar atmosphere. They appear dark in white-light images because of their low temperature, which is due to suppressed convection in the magnetized plasma regions that leads to lower energy flux into a sunspot as compared to their surroundings. Sunspots are transient phenomenon with a lifetime that can vary from a few days to a few weeks or even months. Sunspot data, due to the very long temporal coverage (about 400 years), are valuable for understanding the past variations of solar activity as well the development of modern prediction schemes. They have been systematically observed since the invention of the telescope in 1610 (e.g. Vaquero, Gallego & Trigo 2007) and their counts can also be retrieved from old books extending back in time. Sunspot groups are generally classified according to their morphology and longitudinal extent (LE). They were first separated in five main classes by Cortie (1901), based on their shape and evolution. Later, Waldmeier (1938) introduced the Zurich classification by dividing the sunspot groups in nine classes, which were called A, B, C, D, E, F, G, H, and J. Finally, McIntosh (1990) modified the Zurich classification to better describe the relationship between sunspots and solar flares and to better account for the sunspot main characteristics such as class, size, complexity, etc. The modified Zurich (also called McIntosh) classification now includes seven classes (A, B, C, D, E, F, and H). Note that the G class in Zurich classification was merged into E and F classes, and the J class was merged into the H group. This new classification is based on three main parameters. The first one is the modified Zurich class and it describes the sunspot group morphology and evolution. The second parameter describes the main sunspot in the group according to its penumbral characteristics. The last parameter shows the complexity of the sunspot distribution inside a group.

Complexity of the magnetic fields and the degree of their non-potentiality are responsible for occurrence of solar flares, which are

★E-mail: salihaeren@akdeniz.edu.tr (SE); alikilcik@akdeniz.edu.tr (AK); vayur@bbso.njit.edu (VY)

Proceedings of
Eighth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"
Sunny Beach, Bulgaria, May 30 - June 3, 2016

The online catalog of Wind/EPACT proton events

Miteva R.[1], Samwel S. W.[2], Costa-Duarte M. V. [3], Danov D.[1]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria
[2] National Research Institute of Astronomy and Geophysics, Cairo, Egypt
[3] Institute of Astronomy, Geophysics and Atmospheric Sciences, U. of São Paulo, Brazil
E-mail: rmiteva@space.bas.bg

Abstract

We present the newly compiled solar energetic particle catalog based on data from the Wind/EPACT instrument. The focus of this report is the online contents of the catalog's first version. We summarize the procedure employed to identify and analyze the proton events and their solar origin, which constitute the main ingredients of the online catalog. Planned future updates and improvements are also discussed.

Introduction

A solar energetic particle (SEP) is a generic term used to describe an elevated flux of non-thermal electrons, protons and ions observed in situ [1]. The particle profiles show velocity dispersion and follow in time eruptive phenomena that occurred on the Sun thus supporting the solar origin of the phenomena. Compared to all species, the solar protons are more frequently discussed and finally considered as the SEP events. Occasionally, an additional component in the particle profile can be identified, which is the contribution of accelerated articles in the interplanetary (IP) space due to shocks, co-rotating or/and streaming interaction regions, and not due to the primary acceleration process close to the Sun.

Irrelevant on their exact acceleration driver (flares and coronal mass ejections, CMEs) and mechanism, high energy protons and electrons can be harmful for satellite equipment and can expose humans to radiation, more severely during space travel and less during aircraft flights on polar orbits. Nowadays, SEPs are recognized as one of the major space weather agents [2].

The SEP data is eventually stored in databases and occasionally organized in catalogs. One such proton catalog is based on GOES data (http://umbra.nascom.nasa.gov/SEP/) and reports only events with proton intensity above a constant threshold level. Due to the long time coverage of this catalog (since 1976 to present) it is often used for academic research.

Recently, other proton catalogs based on IMP-8, SOHO and GOES proton data were released, namely Cane et al. proton list [3], SEPServer event list (http://server.sepserver.eu/index.php) [4] and the SEPEM reference proton list (http://dev.sepem.oma.be/help/event_ref.html). In contrast to the proton lists, a comprehensive electron event catalog is still lacking, since the only available electron list [5] is compiled for events with specific intensity profiles.

A comprehensive SEP catalog should provide information for the particle event (onset time, peak time, peak particle intensity, fluence, energy range, etc.), as well as the SEP solar origin (flare and CME characteristics). Usually, SEP catalogs are compiled manually after the actual observations were made. However, automatically produced flare and CME lists are already available.

In order to complement the GOES and SOHO proton catalogs and extend the event statistics, we compiled a comprehensive proton event list based on data from the Wind satellite [6]. This proton database is explored for the first time using visual and numerical methods. All proton events above the pre-event background level (i.e., no threshold applied) were identified and organized in a list. The aim of the present report is to describe the online version of this new proton catalog.

A&A 586, A91 (2016)
DOI: 10.1051/0004-6361/201425520

Astronomy & Astrophysics

Comparison of 30 THz impulsive burst time development to microwaves, Hα, EUV, and GOES soft X-rays (*Research Note*)

R. Miteva[1,2], P. Kaufmann[1,3], D. P. Cabezas[1], M. M. Cassiano[1], L. O. T. Fernandes[1], S. L. Freeland[4], M. Karlický[5], A. Kerdraon[6], A. S. Kudaka[1], M. L. Luoni[7], R. Marcon[8,9], J.-P. Raulin[1], G. Trottet[6], and S. M. White[10]

[1] Center of Radio Astronomy and Astrophysics, Engineering School, Mackenzie Presbyterian University, São Paulo, SP, Brazil
[2] Space Research and Technology Institute, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria
e-mail: rmiteva@space.bas.bg
[3] Center of Semiconductor Components, State University of Campinas, Campinas, SP, Brazil
[4] Lockheed Martin Solar and Astrophysics Laboratory, Palo Alto, CA 94304, USA
[5] Astronomical Institute of the Academy of Sciences of the Czech Republic, 251 65 Ondřejov, Czech Republic
[6] LESIA-Observatoire de Paris, 92190 Meudon, France
[7] Instituto de Astronomía y Física del Espacio (IAFE), CONICET-UBA, Buenos Aires, Argentina
[8] "Gleb Wataghin" Physics Institute, State University of Campinas, Campinas, SP, Brazil
[9] "Bernard Lyot" Solar Observatory, Campinas, SP, Brazil
[10] Air Force Research Laboratories, Space Vehicles Directorate, Albuquerque, NM 87117, USA

Received 15 December 2014 / Accepted 20 November 2015

ABSTRACT

The recent discovery of impulsive solar burst emission in the 30 THz band is raising new interpretation challenges. One event associated with a GOES M2 class flare has been observed simultaneously in microwaves, Hα, EUV, and soft X-ray bands. Although these new observations confirm some features found in the two prior known events, they exhibit time profile structure discrepancies between 30 THz, microwaves, and hard X-rays (as inferred from the Neupert effect). These results suggest a more complex relationship between 30 THz emission and radiation produced at other wavelength ranges. The multiple frequency emissions in the impulsive phase are likely to be produced at a common flaring site lower in the chromosphere. The 30 THz burst emission may be either part of a nonthermal radiation mechanism or due to the rapid thermal response to a beam of high-energy particles bombarding the dense solar atmosphere.

Key words. Sun: flares – Sun: chromosphere – Sun: radio radiation – Sun: UV radiation

1. Introduction

The terahertz (THz) band is the last unexplored part of the electromagnetic spectrum in solar flare observations. Earlier observations addressed emission from the quiet Sun and quiescent active regions (Turon & Léna 1970; Lindsey & Heasley 1981; Gezari et al. 1999; Marcon et al. 2008; Cassiano et al. 2010). Weak and rapid mid-infrared (mid-IR) pulsations, associated with GOES B and C-class flares (Melo et al. 2006, 2009; Cassiano et al. 2010), were detected.

The first intense impulsive 30 THz bursts were recently reported. One burst reported on 13 March 2012 was associated with a GOES class M8 soft X-ray event. This burst exhibited a time profile that was well correlated with microwaves, El Leoncito 45, 90, and 212 GHz observations, Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) and *Fermi* (Atwood et al. 2009) high-energy X-rays, and white-light data (Kaufmann et al. 2013). The 30 THz emission was spatially consistent with the white-light source, RHESSI hard X-rays (HXRs), extreme ultra-violet (EUV), and Hα sources, exhibiting a peak flux of 12000 sfu (1 solar flux unit (sfu) = 10^{-22} W m^{-2} Hz^{-1}).

The largest 30 THz impulsive burst so far was observed from a GOES class X2 flare on 27 October 2014, exhibiting 35 000 sfu (Kaufmann et al. 2015). The 30 THz peak was co-aligned in space with a pair of brightenings that were visible in both Hα and white-light data, and well correlated in time to sub-THz peaks at 0.2 and 0.4 THz, RHESSI HXRs, and white light.

These first discoveries suggest that 30 THz impulsive emission may arise lower in the denser chromosphere, and at the same site produce the other observed radiations. The 30 THz emission might be an extension of the synchrotron spectrum that produces the sub-THz emissions. However, the good correlation with HXRs and white-light emission may also favor thermal heating of the dense lower solar atmosphere by high-energy particle beams as a thermal back-warming process; see Najita & Orrall (1970), Machado et al. (1989), Xu et al. (2006), Martínez Oliveros et al. (2012).

We report here the first 30 THz impulsive flare observed by the new São Paulo telescope (Kudaka et al. 2015). This event exhibits more complex spatial and temporal relationships between the 30 THz time profile and the microwave, Hα, EUV, soft X-ray (SXR), and metric−decimetric (m−dm) emissions than was seen in the two earlier events.

Solar Phys (2015) 290:819–839
DOI 10.1007/s11207-014-0628-1

Statistical Evidence for Contributions of Flares and Coronal Mass Ejections to Major Solar Energetic Particle Events

G. Trottet · S. Samwel · K.-L. Klein · T. Dudok de Wit · R. Miteva

Received: 14 June 2014 / Accepted: 10 November 2014 / Published online: 19 December 2014

Abstract Solar energetic particle (SEP) events are related to flares and coronal mass ejections (CMEs). This work is a new investigation of statistical relationships between SEP peak intensities – deka-MeV protons and near-relativistic electrons – and characteristic quantities of the associated solar activity. We consider the speed of the CME and quantities describing the flare-related energy release: peak flux and fluence of soft X-ray (SXR) emission and the fluence of microwave emission. The sample comprises 38 SEP events associated with strong SXR bursts (classes M and X) in the western solar hemisphere between 1997 and 2006, in which the flare-related particle acceleration was accompanied by radio bursts indicating electron escape into the interplanetary space. The main distinction of the present statistical analysis from earlier work is that in addition to the classical Pearson correlation coefficient, the partial correlation coefficients are calculated to remove the correlation effects between the solar parameters themselves. The classical correlation analysis shows the

G. Trottet · K.-L. Klein (✉) · R. Miteva
Observatoire de Paris, LESIA-CNRS UMR 8109, Univ. P & M Curie and Paris-Diderot, Observatoire de Meudon, 92195 Meudon, France
e-mail: ludwig.klein@obspm.fr

G. Trottet
e-mail: gerard.trottet@obspm.fr

R. Miteva
e-mail: rositsa.miteva@obspm.fr

S. Samwel
National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt
e-mail: samwelsw@nriag.sci.eg

T. Dudok de Wit
Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, 3A, Avenue de la Recherche Scientifique, 45071 Orléans cedex 2, France
e-mail: ddwit@cnrs-orleans.fr

Present address:
R. Miteva
Space Research and Technology Institute, Bulgarian Academy of Sciences, Acad. Georgy Bonchev st, 1113 Sofia, Bulgaria

Solar Phys (2014) 289:2601–2631
DOI 10.1007/s11207-014-0499-5

Solar Energetic Particles and Associated EIT Disturbances in Solar Cycle 23

R. Miteva · K.-L. Klein · I. Kienreich · M. Temmer · A. Veronig · O.E. Malandraki

Received: 10 October 2013 / Accepted: 10 February 2014 / Published online: 28 February 2014

Abstract We explore the link between solar energetic particles (SEPs) observed at 1 AU and large-scale disturbances propagating in the solar corona, named after the *Extreme ultraviolet Imaging Telescope* (EIT) as EIT waves, which trace the lateral expansion of a coronal mass ejection (CME). A comprehensive search for SOHO/EIT waves was carried out for 179 SEP events during Solar Cycle 23 (1997 – 2006). 87 % of the SEP events were found to be accompanied by EIT waves. In order to test if the EIT waves play a role in the SEP acceleration, we compared their extrapolated arrival time at the footpoint of the Parker spiral with the particle onset in the 26 eastern SEP events that had no direct magnetic connection to the Earth. We find that the onset of proton events was generally consistent with this scenario. However, in a number of cases the first near-relativistic electrons were detected too early. Furthermore, the electrons had in general only weakly anisotropic pitch-angle distributions. This poses a problem for the idea that the SEPs were accelerated by the EIT wave or in any

R. Miteva (✉) · K.-L. Klein
LESIA – Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot,
5 place Jules Janssen, 92195 Meudon, France
e-mail: rositsa.miteva@obspm.fr

K.-L. Klein
e-mail: ludwig.klein@obspm.fr

I. Kienreich · M. Temmer · A. Veronig
Kanzelhöhe Observatory – IGAM, Institute of Physics, University of Graz, Universitätsplatz 5,
8010 Graz, Austria

I. Kienreich
e-mail: ines.kienreich@uni-graz.at

M. Temmer
e-mail: manuela.temmer@uni-graz.at

A. Veronig
e-mail: astrid.veronig@uni-graz.at

O.E. Malandraki
IAASARS, National Observatory of Athens, 15236 Panteli, Greece
e-mail: omaland@astro.noa.gr

J. Space Weather Space Clim. **3** (2013) A12
DOI: 10.1051/swsc/2013030

RESEARCH ARTICLE — OPEN ACCESS

The first *SEPServer* event catalogue ~68-MeV solar proton events observed at 1 AU in 1996–2010

Rami Vainio[1,*], Eino Valtonen[2], Bernd Heber[3], Olga E. Malandraki[4], Athanasios Papaioannou[4], Karl-Ludwig Klein[5], Alexander Afanasiev[1], Neus Agueda[6], Henry Aurass[7], Markus Battarbee[2], Stephan Braune[7], Wolfgang Dröge[8], Urs Ganse[8], Clarisse Hamadache[9], Daniel Heynderickx[10], Kalle Huttunen-Heikinmaa[2], Jürgen Kiener[9], Patrick Kilian[8], Andreas Kopp[3], Athanasios Kouloumvakos[11], Sami Maisala[1], Alexander Mishev[12], Rositsa Miteva[5], Alexander Nindos[11], Tero Oittinen[1], Osku Raukunen[2], Esa Riihonen[2], Rosa Rodríguez-Gasén[5,9], Oskari Saloniemi[2], Blai Sanahuja[6], Renate Scherer[3], Felix Spanier[8], Vincent Tatischeff[9], Kostas Tziotziou[4], Ilya G. Usoskin[12], and Nicole Vilmer[5]

1 Department of Physics, University of Helsinki, 00014 Helsinki, Finland
*Corresponding author: e-mail: rami.vainio@helsinki.fi
2 Department of Physics and Astronomy, University of Turku, 20014 Finland
3 Institut für Experimentelle und Angewandte Physik, Christian-Albrechts-Universität zu Kiel, 24118 Kiel, Germany
4 Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, 11810 Athens, Greece
5 CNRS-LESIA, Observatoire de Paris, Meudon, France
6 Dept. d'Astronomia i Meteorologia & Institut de Ciències del Cosmos, Universitat de Barcelona, Spain
7 Solar Physics Group, Leibniz Institut für Astrophysik Potsdam, Germany
8 Lehrstuhl für Astronomie, Julius-Maximilians Universität, Würzburg, Germany
9 CSNSM Orsay, CNRS-IN2P3 et Université Paris-Sud, 91400 Orsay, France
10 DH Consultancy BVBA, Leuven, Belgium
11 Department of Physics, Section of Astrogeophysics, University of Ioannina, Greece
12 Sodankylä Geophysical Observatory, Oulu Unit, University of Oulu, Finland

Received 20 June 2012 / Accepted 13 February 2013

ABSTRACT

SEPServer is a three-year collaborative project funded by the seventh framework programme (FP7-SPACE) of the European Union. The objective of the project is to provide access to state-of-the-art observations and analysis tools for the scientific community on solar energetic particle (SEP) events and related electromagnetic (EM) emissions. The project will eventually lead to better understanding of the particle acceleration and transport processes at the Sun and in the inner heliosphere. These processes lead to SEP events that form one of the key elements of space weather. In this paper we present the first results from the systematic analysis work performed on the following datasets: *SOHO*/ERNE, *SOHO*/EPHIN, *ACE*/EPAM, *Wind*/WAVES and *GOES* X-rays. A catalogue of SEP events at 1 AU, with complete coverage over solar cycle 23, based on high-energy (~68-MeV) protons from *SOHO*/ERNE and electron recordings of the events by *SOHO*/EPHIN and *ACE*/EPAM are presented. A total of 115 energetic particle events have been identified and analysed using velocity dispersion analysis (VDA) for protons and time-shifting analysis (TSA) for electrons and protons in order to infer the SEP release times at the Sun. EM observations during the times of the SEP event onset have been gathered and compared to the release time estimates of particles. Data from those events that occurred during the European day-time, i.e., those that also have observations from ground-based observatories included in *SEPServer*, are listed and a preliminary analysis of their associations is presented. We find that VDA results for protons can be a useful tool for the analysis of proton release times, but if the derived proton path length is out of a range of 1 AU $< s \lesssim 3$ AU, the result of the analysis may be compromised, as indicated by the anti-correlation of the derived path length and release time delay from the associated X-ray flare. The average path length derived from VDA is about 1.9 times the nominal length of the spiral magnetic field line. This implies that the path length of first-arriving MeV to deka-MeV protons is affected by interplanetary scattering. TSA of near-relativistic electrons results in a release time that shows significant scatter with respect to the EM emissions but with a trend of being delayed more with increasing distance between the flare and the nominal footpoint of the Earth-connected field line.

Key words. SEP – radiation – flares – radio emissions (dynamic) – projects

ISSN 1845–8319

RADIO SIGNATURES OF SOLAR ENERGETIC PARTICLES DURING THE 23rd SOLAR CYCLE

R. MITEVA[1], K.-L. KLEIN[1], S. W. SAMWEL[2], A. NINDOS[3], A. KOULOUMVAKOS[3,4] and H. REID[1,5]

[1] *LESIA-Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon, CNRS, UPMC, Univ. Paris-Diderot, France*
[2] *National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt*
[3] *Section of Astrogeophysics, Physics Department, University of Ioannina, Ioannina GR-45110, Greece*
[4] *Department of Astrophysics, Astronomy and Mechanics, Faculty of Physics, University of Athens, Athens, Greece*
[5] *SUPA School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK*

Abstract. We present the association rates between solar energetic particles (SEPs) and the radio emission signatures in the corona and IP space during the entire solar cycle 23. We selected SEPs associated with X and M-class flares from the visible solar hemisphere. All SEP events are also accompanied by coronal mass ejections. Here, we focus on the correlation between the SEP events and the appearance of radio type II, III and IV bursts on dynamic spectra. For this we used the available radio data from ground-based stations and the Wind/WAVES spacecraft. The associations are presented separately for SEP events accompanying activity in the eastern and western solar hemisphere. We find the highest association rate of SEP events to be with type III bursts, followed by types II and IV. Whereas for types III and IV no longitudinal dependence is noticed, these is a tendency for a higher SEP-association rate with type II bursts in the eastern hemisphere. A comparison with reports from previous studies is briefly discussed.

Key words: solar energetic particles - radio bursts - solar cycle 23

1. Introduction

Solar energetic particle (SEP) events are transient flux enhancements of electrons, protons and ions due to acceleration processes in the solar corona and interplanetary (IP) space. The high energy particles can pose a serious risk for the near Earth and ground-based technological devices, may dis-

Solar Phys (2013) 282:579–613
DOI 10.1007/s11207-012-0195-2

Solar Energetic Particle Events in the 23rd Solar Cycle: Interplanetary Magnetic Field Configuration and Statistical Relationship with Flares and CMEs

R. Miteva · K.-L. Klein · O. Malandraki · G. Dorrian

Received: 28 February 2012 / Accepted: 6 November 2012 / Published online: 28 November 2012

Abstract We study the influence of the large-scale interplanetary magnetic field configuration on the solar energetic particles (SEPs) as detected at different satellites near Earth and on the correlation of their peak intensities with the parent solar activity. We selected SEP events associated with X- and M-class flares at western longitudes, in order to ensure good magnetic connection to Earth. These events were classified into two categories according to the global interplanetary magnetic field (IMF) configuration present during the SEP propagation to 1 AU: standard solar wind or interplanetary coronal mass ejections (ICMEs). Our analysis shows that around 20 % of all particle events are detected when the spacecraft is immersed in an ICME. The correlation of the peak particle intensity with the projected speed of the SEP-associated coronal mass ejection is similar in the two IMF categories of proton and electron events, $\approx$0.6. The SEP events within ICMEs show stronger correlation between the peak proton intensity and the soft X-ray flux of the associated solar flare, with correlation coefficient $r = 0.67 \pm 0.13$, compared to the SEP events propagating in the standard solar wind, $r = 0.36 \pm 0.13$. The difference is more pronounced for near-relativistic electrons. The main reason for the different correlation behavior seems to be the larger spread of the flare longitude in the SEP sample detected in the solar wind as compared to SEP events within ICMEs. We discuss to what

R. Miteva (✉) · K.-L. Klein
LESIA-Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, 5 place Jules Janssen, 92195 Meudon, France
e-mail: rositsa.miteva@obspm.fr

K.-L. Klein
e-mail: ludwig.klein@obspm.fr

O. Malandraki · G. Dorrian
Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, Athens, Greece

O. Malandraki
e-mail: omaland@astro.noa.gr

G. Dorrian
e-mail: gdorrian@astro.noa.gr

Understanding Solar Activity: Advances and Challenges
M. Faurobert, C. Fang and T. Corbard (eds)
EAS Publications Series, **55** *(2012) 321–326*
www.eas.org

THE SUN-EARTH CONNECTION OF ENERGETIC PARTICLES

K.-L. Klein[1], S. Masson[2], R. Miteva[1], S. Samwel[3], O. Malandraki[4] and G. Trottet[1]

Abstract. The origin of solar energetic particle (SEP) events is an issue for the understanding of particle acceleration and transport in astrophysics, as well as for space weather. We outline some recent studies addressing from the observational viewpoint the relationship between interacting and escaping particles, conditions for particle escape from the Sun, and the interplanetary magnetic field configurations where the particles propagate.

1 Introduction

Solar energetic particles (SEPs) are charged particles of solar origin that escape to interplanetary space and can be detected with space borne instrumentation or, for the protons and ions of relativistic energies, by neutron monitors, neutron telescopes or muon telescopes on the Earth. In this contribution we give an overview of our recent work on observational evidence for the acceleration, coronal and interplanetary propagation of SEPs using comparative analyses of particle measurements and detection o electromagnetic emissions.

2 Flares, CMEs, and solar energetic particles

Large SEP events are statistically associated with both fast and broad CMEs and flares. This was recently again confirmed by a systematic study of the 23rd

[1] LESIA, Observatoire de Paris, CNRS, Universités Paris 6 et 7, 5 place Jules Janssen, 92195 Meudon, France
[2] Space Weather Laboratory, NASA - Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[3] National Research Institute for Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt
[4] Institute of Astronomy and Astrophysics, National Observatory of Athens, Lofos Nymfon, Thiseio, PO Box 20048, 11810 Athens, Greece

DOI: 10.1051/eas/1255044

ISSN 1845–8319

PROTON ACCELERATION AT CORONAL SHOCK WAVES

R. MITEVA and G. MANN

Astrophysikalishes Institut Potsdam,
An der Sternwarte 16, D-14482 Potsdam, Germany

Abstract. In the solar corona, shock waves appear as a result of flares and eruptive phenomena as well as bow shocks driven by coronal mass ejections. The possibility that such shocks are able to accelerate electrons via the shock-drift acceleration mechanism (SDA) was already studied. In the present paper, the same theoretical model (SDA), is applied for protons. The analysis performed here confirms that the SDA mechanism is able to accelerate protons up to few tens of MeV under coronal conditions.

Key words: proton acceleration - shock waves - solar corona

1. Introduction

Shock waves can be formed due to different physical processes in the solar corona. A flare event may cause a blast wave to be excited that can further develop into a shock wave (Uchida *et al.*, 1973; Vrsnak *et al.*, 1995). Coronal mass ejections on the other hand can also drive shock waves while propagating outwards through the solar corona due to the piston mechanism (Gopalswamy and Kundu, 1992; Claßen and Aurass, 2002; Lara *et al.*, 2003). Regardless on the generation mechanism, shock waves can be the source of energetic electrons (Holman and Pesses, 1983; Mann and Klassen, 2005), that can be observed by their radio radiation in terms of solar type II radio bursts (Nelson and Melrose, 1985; Mann, 1995). Shock waves are also able to accelerate protons, that are thought to be the source of solar energetic particle events, see e.g., Kahler (1994); Cliver and Ling (2007).

Here, we present a study of proton acceleration by *shock drift acceleration* (SDA) at the so-called termination shock (TS) in the solar corona. This is a standing shock wave, formed when the reconnection jet gets decelerated at the post-flare loops. The radio signatures of such a shock wave were reported by Aurass *et al.* (2002) and it was confirmed by Aurass and

J. Plasma Physics (2008), *vol.* 74, *part* 5, *pp.* 607–628. © 2008 Cambridge University Press
doi:10.1017/S0022377808007058 Printed in the United Kingdom

On nonlinear waves in Hall–MHD plasma

R. MITEVA and G. MANN

Astrophysikalisches Institut Potsdam, An der Sternwarte 16,
Potsdam, D-14482, Germany
(rmiteva@aip.de, gmann@aip.de)

(Received 26 July 2007 and accepted in revised form 27 November 2007, first published online 13 February 2008)

Abstract. Low-frequency magnetic field fluctuations are observed in space plasmas, e.g. as upstream waves at the Earth's bow shock. Such upstream waves can steepen into very large amplitude wave phenomena, e.g. short large-amplitude magnetic structures (or SLAMS for short), shocklets or discrete wave packets. Such observations motivated us to study the nonlinear behavior of low-frequency and large-amplitude plasma waves in terms of the full nonlinear Hall–MHD framework. In the case of stationary (nonlinear) waves, the Hall–MHD equations can be rewritten in the so-called Sakai–Sonnerup system of equations that describe this plasma state and provide oscillatory and solitary types of solutions. An overall parameter study on the polarization characteristics, together with the magnetic field components and density variations of the different ranges of solutions, is presented here. These results can be further on applied to the theoretical treatment of particle interaction with such waves, e.g. at shocks in space plasmas, possibly leading to particle acceleration.

1. Introduction

Nonlinear waves are already observed in different space plasma environments and also in terms of different wave-like structures. For example, large-amplitude magnetic field fluctuations are often observed by *in situ* measurements in space, e.g. at the Earth's bow shock (see Paschmann et al. 1979; Hoppe et al. 1981; Mann and Lühr 1991; Mann et al. 1994), at other planetary bow shocks (e.g. Fairfield and Behannon 1976; Hoppe and Russell 1981; Goldstein et al. 1983), in the vicinity of comets (e.g. Riedler et al. 1986; Tsurutani et al. 1987a,b), and at co-rotating interaction regions (CIRs) (e.g. Tsurutani et al. 1995). In general, all of these wave phenomena are thought to be generated by energetic particles produced at the related shocks (Paschmann et al. 1979). That is also confirmed by numerical simulations, as has been done in Akimoto et al. (1991) and Scholer et al. (1992).

An example of such magnetic field fluctuations are the so-called low-frequency upstream waves that appear, for instance, in the upstream region of the Earth's bow shock. Dual spacecraft measurements (e.g. Hoppe and Russell 1983) reveal that they have typical frequencies of 0.1 of the proton cyclotron frequency and amplitudes in the magnetic field fluctuations of 0.3 of the undisturbed magnetic field (e.g. Mann and Lühr 1991). They are correlated with density fluctuations (see Paschmann et al. 1979), i.e. they have been classified as fast magnetosonic waves.

Since the above-mentioned waves are compressive ones, they steepen into so-called shocklets, which are attached by magnetic field fluctuations with a higher

A&A 461, 1127–1132 (2007)
DOI: 10.1051/0004-6361:20053736

Astronomy & Astrophysics

Excitation of electrostatic fluctuations by jets in a flaring plasma

R. Miteva, G. Mann, C. Vocks, and H. Aurass

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: rmiteva@aip.de

Received 30 June 2005 / Accepted 6 September 2006

ABSTRACT

Context. During magnetic reconnection as the proposed basic process of solar flares, hot high speed plasma streams (jets) are ejected from the reconnection site. Jets are sometimes associated with type III radio bursts as signatures of electron beams in the solar corona.
Aims. The interaction of such a jet with the surrounding coronal plasma is investigated concerning the generation of electrostatic fluctuations.
Methods. The conditions of excitations of such waves are studied in detail under coronal conditions by solving the linearized Vlasov-Maxwell equations.
Results. The interaction of a jet with the background plasma leads to an instability for a small range of jet speeds exciting electrostatic waves in the sense of the ion-acoustic mode. Electrons can be energized by their interaction with these electrostatic fluctuations. Such energetic electrons can be the source of type III radio bursts and/or non-thermal X-ray radiation as observed during solar flares.

Key words. waves – instabilities – acceleration of particles – Sun: flares – Sun: radio radiation

1. Introduction

During solar flares stored magnetic field energy is suddenly released and transferred into plasma heating, mass motions (e.g., jets and/or coronal mass ejections), energetic particles (e.g., electrons, protons, and heavy ions), and radiation across the whole electromagnetic spectrum, i.e., from radio waves up to γ-rays (Heyvaerts 1981). It is commonly accepted that the process of magnetic reconnection is responsible for this happening. If two magnetic field lines with opposite directions approach each other due to their photospheric footpoint motion, a current sheet is established between them (see Fig. 1). If the electric current exceeds a certain critical value, the anomalous resistivity is suddenly increased by exciting plasma waves owing to various plasma instabilities (see, e.g., Treumann & Baumjohann 1997). That leads to the onset of magnetic reconnection. Due to the strong curvature of the magnetic field lines after their reconnection, the plasma is shooting away from the reconnection site leading to the establishment of (sometimes oppositely directed) jets of hot plasma (see Fig. 1). As already discussed by Yokoyama & Shibata (1994, 1995), magnetic reconnection is the most probable mechanism leading to the generation of the solar jets. For instance, such jets are really seen in soft X-ray images from *Yohkoh* (Shibata et al. 1992, 1994; Strong et al. 1992).

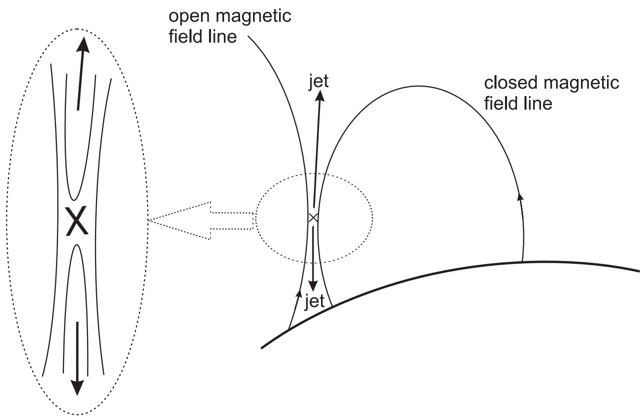

Fig. 1. Sketch of the magnetic field configuration possibly leading to reconnection and, subsequently, to the establishment of jets in the solar corona. The insert on the left-hand side shows an enlargement of the magnetic field lines at the reconnection site.

Aurass et al. (1994) reported on the first detection of correlated type III radio bursts and plasma jets in the corona by a comprehensive analysis of radio and soft X-ray data. Solar type III radio bursts are usually regarded as the signature of beams of supra-thermal electrons (Nelson & Melrose 1985). These electron beams excite high frequency plasma (e.g., Langmuir) waves, which convert into escaping radio waves by scattering at ion density fluctuations and/or by coalescence with other plasma waves. Thus, the radio emission takes place near the local electron plasma frequency $f_{pe} = (e^2 N_e/(\pi m_e))^{1/2}$ (e, elementary charge; N_e, electron number density; m_e, electron mass) and/or its harmonics (Melrose 1985). Since the electron plasma frequency depends on the electron number density, the higher/lower frequencies are emitted in the lower/higher corona, respectively, due to the gravitational stratification of the solar atmosphere. An example of a solar type III radio burst is presented in Fig. 2. It shows a dynamic radio spectrum in the range 110–400 MHz. At first, a stripe of enhanced radio emission starts near 350 MHz at 08:18:51 UT and rapidly drifts towards lower frequencies down to 110 MHz. That is a typical type III radio burst, which is considered to be an electron beam traveling along open magnetic field lines outwards in the corona. Another feature started near 300 MHz at 08:18:53 UT reached 230 MHz at 08:18:57 UT and turned back towards higher frequencies. It reached 400 MHz at 08:19:00 UT. Such a feature is called a type U radio burst.

A&A 474, 617–625 (2007)
DOI: 10.1051/0004-6361:20066856

Astronomy & Astrophysics

The electron acceleration at shock waves in the solar corona

R. Miteva and G. Mann

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
e-mail: rmiteva@aip.de

Received 1 December 2006 / Accepted 26 July 2007

ABSTRACT

Context. In the solar corona, shock waves are generated by flares and/or coronal mass ejections. They are able to accelerate electrons up to high energies and can thus be observed as type II bursts in the nonthermal solar radio radiation. In-situ measurements of shock waves in interplanetary space have shown that shock waves attached by whistler waves are preferably accompanied by the production of energetic electrons.
Aims. Motivated by these observations, we study the interaction of electrons with such whistlers, which are excited by the protons accelerated by the shock.
Methods. We start with a resonant whistler wave-proton interaction that accounts for the initial whistler wave generation. Then, we consider resonant whistler wave-electron interaction, treated with a relativistic approach that is responsible for the electron energization in the whistler wave field.
Results. As a result, we show that electrons can be accelerated by a resonant wave particle (i.e., whistler-electron) interaction. This mechanism acts in the case of quasi-perpendicular shock waves. After acceleration, the energetic electrons are reflected by the associated shock wave back into the upstream region. The theoretical results are compared with observations, e.g., solar type II radio bursts.

Key words. shock waves – acceleration of particles – Sun: flares – Sun: radio radiation

1. Introduction

Shock waves play an important role in astrophysics, since they are responsible for particle acceleration in space plasmas (Fermi 1949; Axford et al. 1978; Schlickeiser 1984; Kirk 1994). The production of energetic electrons at shocks is of special interest, since these electrons can be the source of nonthermal radio and X-ray radiation, which can be observed by remote sensing techniques.

In the solar corona, shock waves can be generated either by blast waves due to the flare process (Uchida et al. 1973; Vrsnak et al. 1995) and/or by coronal mass ejections (CMEs) (Stewart et al. 1974a,b; Gopalswamy & Kundu 1992; Classen & Aurass 2002; Lara et al. 2003). It is still an ongoing debate whether the shock waves are generated by a flare-associated blast wave (Vrsnak et al. 1995) or if they are CME-driven (Gopalswamy & Kundu 1992; Gopalswamy 2006). But it should be emphasized that a shock wave is a discontinuity accompanied by an increase in the entropy. The jump in the density, temperature, and magnetic field across the shock is governed by the Rankine-Hugoniot relationships (Priest 1982); i.e., the shock itself and the processes immediately associated with it should be considered as independent of its exciter.

In the corona, shock waves can be observed as type II bursts in the solar radio radiation (Wild & McCready 1950; Uchida et al. 1973). A type II radio burst can morphologically be divided into two types of emission in its dynamic radio spectrum (see Fig. 1, for instance), the "backbone" and the "herringbone" emission. The so-called backbone emission (see Fig. 1), is slowly drifting from high to low frequencies with a typical drift rate of about −0.1375 MHz s^{-1} at 55 MHz (whereas Mann & Klassen (2005) reported mean value on the order of −0.133 MHz s^{-1}), and shows often a fundamental-harmonic structure. It is widely accepted to be the radio signature of a shock wave traveling through the corona (Nelson & Melrose 1985; Mann 1995; Aurass 1997; Mann 2006). Sometimes, very fast, drifting patches of emission (see Fig. 1) can be seen to emanate from the backbone, toward both lower or higher

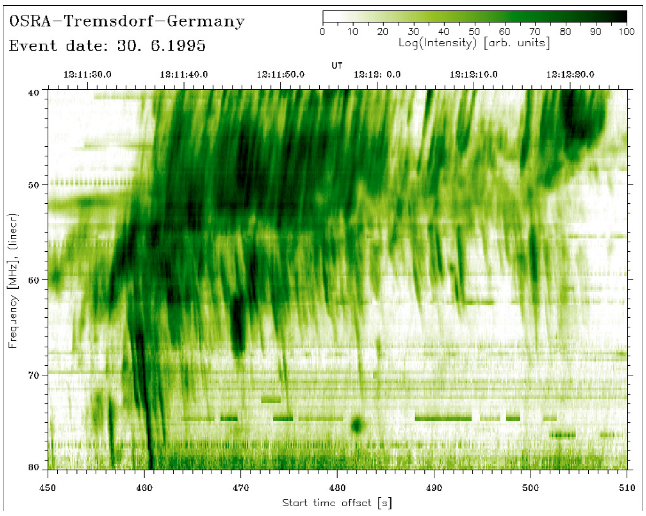

Fig. 1. Dynamic radio spectrum recorded by the radio spectralpolarimeter (Mann et al. 1992) of the Astrophysical Institute Potsdam. It shows an example of a solar type II radio burst. Further explanations are given in Sect. 1.

ISSN 1845–8319

ELECTRON ACCELERATION AT WHISTLER WAVE PACKETS ATTACHED TO CORONAL SHOCK WAVES

R. MITEVA and G. MANN

Astrophysikalishes Institut Potsdam,
An der Sternwarte 16, D-14482 Potsdam, Germany

Abstract. A new mechanism for electron acceleration in the solar corona at quasi-perpendicular shocks is presented, where the crucial role is played by whistler packets in the upstream region of the shock front. The model accounts for the whistler wave generation via resonant interaction with shock-accelerated protons co-moving with the shock. The so excited whistlers interact resonantly with the in-flowing electrons, that gain energy in the whistler wave field. Finally, the accelerated electrons reach the shock front where they are mirror-reflected. After the reflection the electrons are co-moving with the whistlers and because they are not in resonance, they can reach the far upstream region and be detected as herringbone emission in the solar radio radiation.

Key words: Electron acceleration - shock waves - solar corona

1. Introduction

In the solar corona, shock waves can be generated either by flare associated blast waves, (Vrsnak *et al.*, 1995), and/or by coronal mass ejections (CMEs), (Gopalswamy and Kundu, 1992). Coronal shock waves can be observed as type II bursts (Uchida *et al.*, 1973) in dynamic radio spectra (see Figure 1), where two types of emission can be present: a so-called 'backbone' and/or 'herringbone' emission. The backbone emission is slowly drifting from high to low frequencies with a typical drift rate of about $-0.0025\,\mathrm{MHz}^{-1}$ at 55 MHz (Mann and Klassen, 2002) and shows often a fundamental–harmonic structure. It is widely accepted to be the radio signature of a propagating shock wave travelling through the corona (Nelson and Melrose, 1985; Mann, 2006). The so-called herringbone emission, is regarded as the radio signature of shock-accelerated electrons (Cairns and Robinson, 1987; Mann and Klassen, 2005), and can be seen as very fast drifting patches of emission (see Figure 1) emanating from the backbone, toward both lower or higher

EXCITATION OF ELECTROSTATIC WAVES IN A FLARING PLASMA

R. Miteva* and G. Mann*

Abstract

Solar flare events release in explosive manner the stored magnetic field energy in the corona. An enormous amount of energy (typically 10^{27} ergs) is then transferred into mass motions, plasma heating, electromagnetic radiation, and energetic particles. The process of magnetic reconnection is presently believed to be responsible for this to happen. Soft X-ray images show hot high speed plasma streams that are ejected from the reconnection site. During their propagation through the surrounding coronal plasma, electrostatic fluctuations may arise. Here, we study the conditions for excitation of such electrostatic waves which may later on interact with the electrons and lead to their energization and acceleration.

1 Introduction

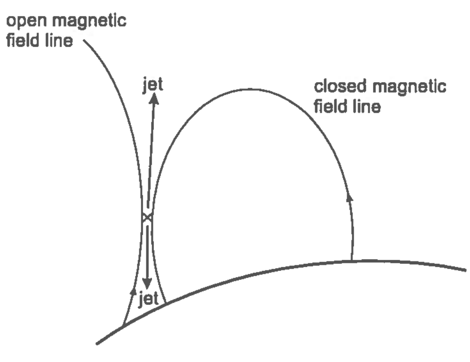

Figure 1: Sketch of the magnetic field configuration possibly leading to formation of jets in the solar corona.

During solar flares the stored energy in the magnetic field is suddenly released and transfered into plasma heating, mass motions (e.g. jets and/or coronal mass ejections), energetic particles (electrons, protons, and heavy ions), and electromagnetic radiation (from radio up to γ-rays), see e.g. in Heyvaerts (1981). If two magnetic field lines with opposite directions come close to each other in the corona, because of their photospheric footpoint motion, a process known as magnetic reconnection takes place. The tension due to the strong curvature of the reconnected magnetic field lines is shooting the plasma away from the reconnection site. This leads to the establishment of (sometimes oppositely directed) jets of hot plasma (see Figure 1).

*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D–14482 Potsdam, Germany

Solar Activity and its Magnetic Origin
Proceedings IAU Symposium No. 233, 2006
V. Bothmer & A. A. Hady, eds.

doi:10.1017/S1743921306002080

Parameter study on Kelvin–Helmholtz instability in solar wind type flowing structures

R. Miteva[1,2], S. Ivanovski[1] and I. Zhelyazkov[2]

[1]Astrophysikalisches Institut Potsdam, an der Sternwarte 16, 14482 Potsdam, Germany
email:rmiteva@aip.de

[2]Department of Physics, Sofia University, 5 J. Bourchier blvd., 1164 Sofia, Bulgaria

Abstract. The stability behaviour of the wave modes that propagate in the solar wind plasma is considered in the framework of the Hall-magnetohydrodynamics. The Hall-MHD theory extends the wave frequency limit up to or higher than the ion cyclotron frequency. Due to the different flow velocities of the adjacent media in the solar wind, a Kelvin–Helmholtz instability is naturally expected to arise. The behaviour of the wave modes due to this particular kind of instability is studied under solar wind conditions typical for 1 AU. This is a preliminary study on the stability problem in the solar wind flowing structures and it could be relevant for the interplanetary and space weather research.

Keywords. solar wind, MHD, instabilities

1. Introduction

Stability analysis is performed on the problem of surface waves propagating on solar wind type flowing structures. We follow the procedure discussed in Miteva *et al.* (2004) but for much simpler magnetic structure configuration. Two media (denoted with indexes 1 and 2, correspondingly) are considered in the present study, with parameters of the plasma at 1AU (and given here with standard notation, namely, v_{A}, Alfvén velocity, v_{s}, sound velocity, V initial flow velocity of the plasma medium, M, Mach number, ρ, plasma density, n_{e}. electron number density and B, magnetic field): $v_{\mathrm{A}_1} = 65\,\mathrm{km\,s^{-1}}$, $v_{\mathrm{A}_2} = 100\,\mathrm{km\,s^{-1}}$, $v_{\mathrm{s}_1} = 65\,\mathrm{km\,s^{-1}}$, $v_{\mathrm{s}_2} = 70\,\mathrm{km\,s^{-1}}$, $V_1 = 500\,\mathrm{km\,s^{-1}}$, $M_1 = V_1/v_{\mathrm{A}_1} = 7.7$, $V_2 = 480\,\mathrm{km\,s^{-1}}$, $M_2 = V_2/v_{\mathrm{A}_2} = 4.8$, $\rho_1/\rho_2 = 1.708$, $n_{\mathrm{e}} = 3 \times 10^6\,\mathrm{m^{-3}}$, $B_1/B_2 = 1.177$, $B_1 = 5 \times 10^{-9}\,\mathrm{T}$.

2. Hall-MHD theory

The Hall-magnetohydrodynamic approach accounts for the ion-cyclotron/Hall term in the generalized Ohm's law (reflecting some aspects on kinetic theory) on the dispersion characteristics and the damping of hydromagnetic waves. The Hall-magnetohydrodynamics (Hall-MHD) is defined to be the conventional magnetohydrodynamics together with the Hall term in Faraday's law (i.e. $\nabla \times (\mathbf{j} \times \mathbf{B})/n_{\mathrm{e}}e$, Huba (1995), where $\mathbf{j}$ is the current and e is the elementary charge). In this way it is possible to describe waves with frequencies up to the ion-cyclotron frequency ($\omega \approx \omega_{\mathrm{ci}}$). Since the model still neglects the electron mass, it is limited to frequencies below the lower hybrid frequency. Generally speaking, the theory of Hall MHD is relevant to plasma dynamics occurring on length scales shorter than an ion inertial length ($L < L_{\mathrm{Hall}} = c/\omega_{\mathrm{pi}} = v_{\mathrm{A}}/\omega_{\mathrm{ci}}$), and time scales shorter than an ion cyclotron period ($t < \omega_{\mathrm{ci}}^{-1}$). With the so-chosen plasma parameters the Hall length here is $l_{\mathrm{Hall}} \approx 140\,\mathrm{km}$ and the ion cyclotron frequency is $\omega/2\pi = 76\,\mathrm{mHz}$.

Solar Activity and its Magnetic Origin
Proceedings IAU Symposium No. 233, 2006
V. Bothmer & A. A. Hady, eds.

doi:10.1017/S1743921306001761

Mechanism for electron acceleration due to propagation of jets in the solar corona

R. Miteva, C. Vocks, G. Mann, and H. Aurass

Astrophysicalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
email: rmiteva@aip.de

Abstract. A kinetic analysis is performed here considering close relationship between plasma jets in the solar corona and a consequent acceleration of electrons. Solar jets are formed when a plasma stream is shooted out from a reconnection site. In some cases these jets are temporally and spatially associated with type III radio bursts, the latter being the radio signatures of non-thermal electron beam propagation through the corona. This theoretical work on jet associated type III burst argue the possibility of regarding the plasma jet as a trigger mechanism for electron energization (heating or/and acceleration). While the jet propagates in the solar corona, it creates wave-like disturbances in the background plasma, that are in general unstable. Further on we are interested in how a test electron will behave in such (electrostatic) wave field. The settings for the jet and the test electron are done under typical coronal conditions.

Keywords. Sun: corona, acceleration of particles, X-rays: solar jets

1. Introduction

In the solar corona, jets are streams of hot plasma expelled from a reconnection site. The reconnection model is one of the possible explanation for the generation of the jets, Yokoyama & Shibata (1995). When magnetic field lines with opposite direction approach each other and reconnect, the re-arrangement of the new magnetic configuration shoot plasma away in the corona, forming the observed with *Yohkoh*/SXT solar jets, Shibata *et al.* (1994).

Additionally number of authors performed data analysis on whether solar jet can be closely associated with propagation of non-thermal electron beams in the solar corona (so-called type III/U burst in the radio spectrum), see Aurass *et al.* 1994, Pick *et al.* 1994, Kundu *et al.* 1995, Raulin *et al.* 1996.

In the present paper, we argue whether electron acceleration is possible due to the propagation of plasma jets in the solar corona. Our aim is to look for the possibility and the favourable conditions for a solar jet to be regarded as a trigger of electron heating or/and acceleration. We apply the kinetic approach to one special configuration of jet aligned to the magnetic field lines and additionally the excited wave-like disturbance propagates in the same direction. Thus we restrict the general problem up to an electrostatic and collisionless case.

2. Kinetic approach

2.1. *Dispersion relation for electrostatic ion-acoustic waves*

We start the present study from the linearized Vlasov-Maxwell equations for describing the evolution of the electric field vector **E**. We assume that the jet is aligned to the magnetic field lines and so we approximate the general problem considering only a 1D

Advances in Physics and Astrophysics of the 21st Century
ed. I. Zhelyazkov, Heron Press, Sofia, 2005

Solar jets as a trigger mechanism for the generation of electrostatic instability in the solar corona

R. Miteva[1,2] and **G. Mann**[2]

[1]Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria

[2]Astrophysikalisches Institut Potsdam, G-14482 Potsdam, Germany

Abstract.

When a process of magnetic reconnection takes place in the solar corona, the magnetic field lines are rearranged and the relaxation of the new configuration can shoot plasma away from this site. While propagating further in the corona, the newly formed plasma jets create disturbances in the background medium. Such configuration can lead to the excitation of electrostatic waves that are expected to be highly instable in general sense. Here, the conditions for generation of such electrostatic instability is studied using a multifliud approach. The propagation of plasma jets through the solar corona could be one of the possible trigger mechanisms for the generation of electrostatic instability that later on could lead to energization (heating and/or acceleration) of electrons in the solar corona.

1 Introduction

As already discussed by [1] magnetic reconnection is the most probable mechanism leading to the generation of the solar X-ray jets. If two magnetic field lines with opposite directions come close to each other in the corona, because of their photospheric footpoint motion, a process known as magnetic reconnection takes place. The tension due to the strong curvature of the reconnected magnetic field lines is shooting the plasma away from the reconnection site. This leads to the establishment of (sometimes oppositely directed) jets of hot plasma. Such jets are impressively seen in soft X-ray images from *Yohkoh*, as presented in [2].

These soft X-ray observation correlate with the metric radio signatures of electron beams propagating in the corona [3–6]. The so-called type III and U radio bursts are recorded in the radio spectrum when electron beams travel along

ELECTRON ACCELERATION DUE TO JETS IN THE SOLAR CORONA

Rossitsa Miteva and Gottfried Mann

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
E-mail: rmiteva@aip.de, gmann@aip.de

ABSTRACT

During solar flare events via the process of magnetic reconnection the stored magnetic field energy is released and transferred into mass motions, plasma heating, electromagnetic radiation, and energetic particles. Out of the reconnection cite jets of plasma are formed and during their propagation through the corona they also create disturbances in the plasma. Such configuration leads to excitation of electrostatic waves that are subject to instability. Here, we study the conditions for excitation of such electrostatic waves that later on may interact in terms of electrostatic fluctuations with the electrons and lead to their collisionless energization and acceleration. Beams of accelerated electrons (being the exciting agent of type III/U radio bursts) are already temporally and spatially associated with (soft X-ray) plasma jets.

Key words: Sun: soft X-ray jet; Instability; Acceleration of particles.

1. INTRODUCTION

During solar flares the stored energy in the magnetic field is suddenly released and transfered into plasma heating, mass motions (e.g. jets and/or coronal mass ejections), energetic particles (electrons, protons, and heavy ions), and electromagnetic radiation (from radio up to γ-rays), see e.g. in Heyvaerts (1981). If two magnetic field lines with opposite directions come close to each other in the corona, because of their photospheric footpoint motion, a process known as magnetic reconnection takes place. The tension due to the strong curvature of the reconnected magnetic field lines is shooting the plasma away from the reconnection site. This leads to the establishment of (sometimes oppositely directed) jets of hot plasma (see Fig. 1). Such jets are detected with *Yohkoh*/SXT (soft X-ray telescope), as presented in Shibata et al. (1994). The most probable mechanism leading to the generation of the solar X-ray jets is the magnetic reconnection, as already discussed by Yokoyama and Shibata (1995).

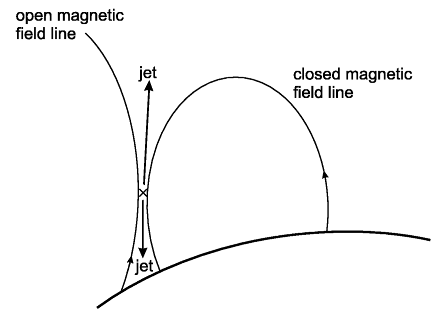

Figure 1. Sketch of the magnetic field configuration possibly leading to formation of jets in the solar corona.

Shortly after the discovery of the solar soft X-ray jets, Aurass et al. (1994) reported on correlated type III and U radio bursts with plasma jets by a common analysis of radio and soft X-ray data. Type III and U radio bursts are considered to be the radio signatures of electron beams traveling along open and closed magnetic field lines, respectively (see e.g. Suzuki and Dulk (1985) for a review). Thus, it was noticed for the first time that accelerated electrons, being the exciting agent for fast drift bursts, originate above a site where a soft X-ray jet was present. A further evidence for the production of nonthermal electrons associated with soft X-ray jets was given by Pick et al. (1994), Kundu et al. (1995) and Raulin et al. (1996). In general a good association (temporal and spatial) was found between metric type III bursts and soft X-ray jets.

The interaction of a hot neutral plasma stream (jet) with the surrounding background plasma is studied here in terms of the multi-fluid approach. This interaction gives rise to the excitation of electrostatic fluctuations. These wave-like disturbances are unstable in nature and consequently the electrons can be trapped in these wave packages and become energized up to relativistic velocities. If the energized electrons leave the wave they can propagate along the magnetic field lines and lead to the establishment of metric type III and U radio bursts.

Proceedings of the 11th European Solar Physics Meeting - The Dynamic Sun: Challenges for Theory and Observations, 11-16 September 2005 (ESA SP-596, December 2005)

New Journal of Physics
An Institute of Physics and Deutsche Physikalische Gesellschaft Journal

Hall-magnetohydrodynamic surface waves in solar wind flow-structures

Rossitsa Miteva[1], **Ivan Zhelyazkov**[1] **and Robert Erdélyi**[2]
[1] Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria
[2] Department of Applied Mathematics, Space and Atmosphere Research Center, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK
E-mail: izh@phys.uni-sofia.bg and robertus@shef.ac.uk

New Journal of Physics **6** (2004) 14
Received 15 September 2003
Published 3 February 2004
Online at http://www.njp.org/ (DOI: 10.1088/1367-2630/6/1/014)

Abstract. This paper investigates the parallel propagation of magnetohydrodynamic (MHD) surface waves travelling along an ideal steady plasma slab surrounded by a steady plasma environment in the framework of Hall magnetohydrodynamics. The magnitudes of the ambient magnetic field, plasma density and flow velocity inside and outside the slab are different. Two possible directions of the relative flow velocity (in a frame of reference co-moving with the ambient flow) have been studied. In contrast to the conventional MHD surface waves which are usually assumed to be pure surface or pseudo-surface waves, the Hall-MHD approach makes it necessary to treat the normal MHD slab's modes as *generalized* surface waves. The latter have to be considered as a superposition of two partial waves, one of which is a pure/pseudo-surface-wave whereas the other constitutive wave is a leaky one. From the two kinds of surface-wave modes that can propagate, notably *sausage* and *kink* ones, the dispersion behaviour of the kink mode turns out to be more complicated than that of the sausage mode. In general, the flow increases the waves' phase velocities comparing with their magnitudes in a static Hall-MHD plasma slab. The applicability of the results to real solar wind flow-structures is briefly discussed.

Surface wave propagation in steady ideal Hall-magnetohydrodynamic magnetic slabs

Rossitsa Miteva and Ivan Zhelyazkov[a)]
Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria

Robert Erdélyi
Space and Atmosphere Research Center, Department of Applied Mathematics, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, United Kingdom

(Received 10 April 2003; accepted 4 August 2003)

This paper studies the dispersion characteristics of sausage and kink surface waves traveling along a plasma layer within the framework of Hall magnetohydrodynamics in steady state. While in a static plasma slab these waves are Alfvén ones (their phase velocities are close to the Alfvén speed in the layer); in a slab with steady flows they may become super Alfvénic waves. Moreover, there exist two types of waves: forward and backward ones bearing in mind that the flow velocity defines the positive (forward) direction. As a typical representative of a magnetic slab in steady state here is considered a solar wind flux rope with a finite β plasma flow (typically $\beta \sim 1$). The forward sausage surface mode exhibits an increased dispersion at small wave numbers while the forward kink waves become practically non-dispersive. Both backward propagating sausage and kink surface modes show an increased dispersion for large wave numbers. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1615769]

I. MOTIVATION AND INTRODUCTION

The solar atmosphere, from the photosphere to the corona and the solar wind is a highly structured medium. Satellite observations have confirmed the existence of photospheric flux tubes, coronal holes, coronal loops, and magnetic arcades. Another key observation of the solar atmosphere is the presence of steady flows. Bulk motions are registered along or nearly along the magnetic field lines which outline the magnetic structures.[1] Recent observations made by two HELIOS spacecrafts have revealed fine structures in high-speed solar-wind flows. These structures are in the form of thin flow layers (or tubes) that are adjacent to each other with differences in their plasma parameters (density, magnetic field, steady flow-speed).[2] The structures can be separated by tangential discontinuities in the magnetic field, across which the total (gas+magnetic) pressure is continuous. Parker[3] predicted first the existence of such long and thin spaghetti-like stream structures as the constituent units of solar-wind high-speed streams. These structures originate in the Sun, from where they spread out in the heliosphere, thus maintaining their identity even at a distance of 1 AU from the Sun.

Satellite measurements of plasma characteristics, such as the magnetic field, the thermal and flow velocity, and density of the plasma or plasma compositions are important to understand the various plasma wave modes which may occur. However, wave analysis requires further information and special tools in order to identify which set of modes is contributing to observed wave features. In practice, one may use filters to perform *pattern recognition* to detect the various kinds of modes that may propagate in the plasma and to determine their contributions to the wave energy.[4]

The magnetohydrodynamic (MHD) formalism widely used in studying wave phenomena in the solar atmosphere is a plasma model which neglects the ion inertia. Therefore it is only applicable to frequencies well below the ion cyclotron frequency ω_{ci}.[5] Multi-fluid models are plasma theories whose validity does not exhibit any frequency limit, however their applicability to the mode filter concept seems to be practically very tough.[4] An important step in expanding the frequency range is the change from conventional MHD to the Hall-MHD. The Hall-MHD formalism treats the plasma as a single fluid like MHD does, though it also takes into account the finite ion inertia. In this way it is possible to describe waves with frequencies up to $\omega \approx \omega_{ci}$. Because the model still neglects the electron mass, it is limited to frequencies well below the lower hybrid frequency: $\omega \ll \omega_{\mathrm{LH}}$. Generally speaking, Hall-MHD theory is relevant to plasma dynamics occurring on length scales shorter than an ion inertial length ($L < l_{\mathrm{Hall}} = c/\omega_{pi}$), and time scales shorter than an ion cyclotron period ($t < \omega_{ci}^{-1}$).[6]

Hydromagnetic surface waves in the solar atmosphere in the framework of conventional MHD have been discussed over the last two decades by several authors (e.g., Wentzel,[7] Roberts and Webb,[8] Roberts,[9] Uberoi and Somasundaram,[10,11] Edwin and Roberts[12]). Surface waves differ distinctly from the bulk waves in amplitude of vibrations. At a plane interface, the amplitude of a surface wave decreases exponentially, in the direction normal to the interface, while the amplitude remains constant along the interface. Inside a slab the amplitude of a surface wave decreases as cosh(x) or sinh(x) while decreasing exponentially outside the slab. The inclusion of the Hall term in the generalized

[a)]Electronic mail: izh@phys.uni-sofia.bg

Propagation of surface waves in flowing solar wind structures in the framework of Hall magnetohydrodynamics

Rossitsa Miteva and Ivan Zhelyazkov
Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria
Robert Erdélyi
Space and Atmosphere Research Center,
Department of Applied Mathematics, University of Sheffield,
Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK
E-mail: izh@phys.uni-sofia.bg and robertus@shef.ac.uk

1 Introduction

Now it is well established that the solar atmosphere, from the photosphere to the corona and the solar wind is a highly structured medium. Satellite observations have confirmed the existence of photospheric flux tubes, coronal holes, coronal loops and magnetic arcades. Another key observation of the solar atmosphere is the presence of steady flows. Bulk motions are registered along or nearly along the magnetic field lines which outline the magnetic structures. Recent observations made by two *HELIOS* spacecrafts have revealed fine structures in high-speed solar wind flows. These structures are in the form of thin flow layers (or tubes) that are adjacent to each other with differences in their plasma parameters (density, magnetic field, steady flow-speed) [1]. The structures can be separated by tangential discontinuities in the magnetic field, across which the total (kinetic plus magnetic) pressure is continuous. Parker [2] was the first to predict the existence of such long and thin spaghetti-like stream structures as constituent units of the solar wind high-speed streams. These structures originate in the Sun, from where they spread out in the heliosphere, thus maintaining their identity even at a distance of 1 AU from the Sun.

Satellite measurements of plasma characteristics, such as the magnetic field, the thermal and flow velocity and density of the plasma or plasma compositions are important to understand the various plasma wave modes which may occur. However, wave analysis requires further information and special tools in order to identify which set of modes is contributing to observed wave features. In practice, one may use filters' *pattern recognition* to detect the various kind of modes that may propagate in the plasma and to determine their contributions to the wave energy [3].

The magnetohydrodynamic formalism widely used in studying wave phenomena in the solar atmosphere is a plasma model which neglects the ion inertia. Therefore it is only applicable to frequencies well below the ion cyclotron frequency ω_{ci}. Multi-fluid models are plasma theories whose validity does not exhibit any frequency limit, however their applicability to the mode filter concept seems to be practically very tough [3]. An important step in expanding the frequency range is the change from conventional magnetohydrodynamics to the Hall magnetohydrodynamics. The Hall-MHD approach in studying wave phenomena in astrophysical plasmas is relatively new. It accounts for the ion-cyclotron/Hall term in the generalized Ohm's law on the dispersion characteristics and the damping of hydromagnetic waves. The Hall-MHD formalism treats the plasma as a single fluid like the magnetohydrodynamics does, though it also takes into account the finite ion inertia. In this way it is possible to describe waves with frequencies up to $\omega \approx \omega_{ci}$. Because the model still neglects the electron mass, it is limited to frequencies well below the lower hybrid frequency: $\omega \ll \omega_{LH}$. Generally speaking, the theory of Hall-MHD is relevant to plasma dynamics occurring on length scales shorter than an ion inertial length ($L < l_{Hall} = c/\omega_{pi}$), and time scales shorter than an ion cyclotron period ($t < \omega_{ci}{}^{-1}$) [4].

From a solar wind point of view, sufficiently away from the Sun, a more realistic Hall-MHD plasma is that with a plasma β ($= 2\mu_0 n_e k_B T_e/B_0^2$) of order of unity. Another important consideration for choosing such a value for β is the circumstance that the MHD surface waves whose speeds are closer to the sound speed v_s are less attenuated than those which possess phase speeds equal or higher than the Alfvén speed v_A [1]. In the following sections, we investigate the influence of the flow velocity on the dispersion characteristics of hydromagnetic surface waves (sausage and kink modes)

Meetings in Physics at University of Sofia, vol. 4
ed. A. Proykova, Heron Press, Sofia, 2003

MAGNETOHYGRODYNAMIC SURFACE WAVES IN FLOWING HALL PLASMA LAYER

Rossitsa Miteva and Ivan Zhelyazkov

Department of Radiophysics & Electronics, Faculty of Physics, University of Sofia, 5 James Bourchier Blvd, BG-1164 Sofia

Abstract. We study the dispersion characteristics of sausage and kink surface waves travelling along a flowing plasma layer within the framework of Hall magnetohydrodynamics. While in a unmoving plasma slab these waves are Alfvén ones (their phase velocities are close to the Alfvén speed in the layer), in a slab with a steady flow velocity they become super Alfvénic waves. Moreover, one can exist two type of waves, notably forward and backward ones bearing in mind that the flow velocity defines the positive (forward) direction. It turns out that the dispersion of the backward waves in the short-wavelength limit is stronger influenced by the flow compared with the slight dispersion change of the forward waves in the long-wavelength limit.

1 Introduction

It is now well-established that the solar atmosphere, from the photosphere to the corona and the solar wind is a highly structured medium. Satellite measurements of solar-wind characteristics such as the magnetic field, the velocity and plasma density are important to understand the different plasma wave modes which may occur. However, wave analysis requires further information and special tools in order to be able to identify which set of modes is contributing to observed wave features [1]. In other words, it is necessary to investigate in detail the wave modes supported by a given plasma configuration. Recent observations made by two *HELIOS* spacecrafts have confirmed the existence of fine structures in high-speed wind flows. Thus the study of low-frequency waves in flowing flux tubes is a current problem of the solar astrophysics. The two general type of waves (slow and intermediate/fast (or Alfvén) modes), well-known with parallel wave propagation in infinite magnetohydrodynamic (MHD) plasmas, occur in bounded plasmas, too. However, while the frequencies of ordinary MHD waves are much below the ion cyclotron frequency ω_{ci}, the frequency range of Hall-MHD waves is expanded up to ω_{ci}. Recall that the Hall-MHD theory is relevant to plasma dynamics occurring on length scales shorter than an ion inertial length ($L < l_{\mathrm{Hall}} = c/\omega_{pi}$, where c is the speed of light and ω_{pi} – the ion plasma frequency) and time scales shorter than an ion cyclotron period ($t < {\omega_{ci}}^{-1}$) [2]. Assuming the solar-wind plasma is structured due to different plasma/mass densities inside and outside the slab [3], the Hall length scale for a solar-wind flux tube at 1 AU with ambient magnetic field $B_0 = 3.6 \times 10^{-9}$ T (and accordingly ion cyclotron frequency $\omega_{ci}/2\pi = 0.055$ Hz), electron number density $n_e = 2 \times 10^6$ m^{-3}, and electron temperature $T_e = 2 \times 10^5$ K is $l_{\mathrm{Hall}} = 160$ km. This scale length is smaller than, but not negligible compared to layer's width of a few hundred kilometers. The Alfvén speed is $v_{\mathrm{A}} = 56$ km s^{-1}, sound speed being $v_s = 52$ km s^{-1} and hence the plasma $\beta \approx 1$ that is typical for the solar wind beyond $\sim$0.5 AU. The slab steady flow speed is $v_0 \approx 400$ km s^{-1}.

ICPIG XXVI
International Conference on Phenomena in Ionized Gases
Vol. 4
Greifswald, Germany 2003

Hall-MHD surface waves in flowing solar-wind plasma slab

R. Miteva and I. Zhelyazkov
Faculty of Physics, Sofia University, BG-1164 Sofia, Bulgaria

We study the influence of a steady flow velocity on the dispersion characteristics of Hall-magnetohydrodynamic forward and backward sausage and kink surface waves travelling along a solar-wind plasma slab. Both surface modes, being Alfvén waves in an immovable layer, become super Alfvénic ones in flowing slab with increased dispersion at small wave numbers for forward waves and at large wave numbers for backward waves, respectively.

1. Motivation

Recent observations made by two *HELIOS* spacecrafts have confirmed the existence of fine structures in high-speed solar-wind flows. Satellite measurements of plasma characteristics such as the magnetic field, the velocity and density of the plasma are important to understand the different plasma wave modes which may occur. However, wave analysis requires further information and special tools in order to be able to identify which set of modes is contributing to observed wave features [1]. While the magnetohydrodynamic (MHD) waves (acoustic, Alfvén and magnetosonic modes) possess frequencies much below the ion cyclotron frequency ω_{ci}, the frequency range of Hall-MHD waves is expanded up to ω_{ci}. Recall that Hall-MHD theory is relevant to plasma dynamics occurring on length scales shorter than an ion inertial length ($l_{\rm Hall} < c/\omega_{pi}$, where c is the speed of light and ω_{pi}—the ion plasma frequency) [2]. Assuming the solar-wind plasma is structured due to different plasma/mass densities inside and outside the slab [3], the Hall length scale for a solar-wind flux tube at 1 AU with ambient magnetic field $B_0 = 3.6 \times 10^{-9}$ T (and accordingly ion cyclotron frequency $\omega_{ci}/2\pi = 0.055$ Hz), electron number density $n_e = 2 \times 10^6$ m^{-3}, electron temperature $T_e = 2 \times 10^5$ K is $l_{\rm Hall} = 160$ km. The Alfvén speed is $v_{\rm A} = 56$ km s^{-1}, sound speed being $v_s = 52$ km s^{-1} and hence the plasma β equals approximately unity. The slab steady flow speed is $v_0 \approx 400$ km s^{-1}.

2. Basic equations and relations

Consider a flowing plasma slab of uniform density ρ_0 and thickness $2x_0$, bounded by immovable plasmas of densities ρ_e, the interfaces being the surfaces $x = \pm x_0$. The uniform magnetic field $\mathbf{B}_0$ and the steady flow velocity $\mathbf{v}_0$ point in the z direction. The wave vector $\mathbf{k}$ lies also along the z axis and its direction is the same as that of $\mathbf{B}_0$ and $\mathbf{v}_0$ for forward waves and opposite for backward waves, respectively. The basic equations for Hall-MHD waves are the linearized equations governing the evolution of perturbed plasma density $\delta\rho$, pressure δp, fluid velocity $\delta\mathbf{v}$ and wave magnetic field $\delta\mathbf{B}$ [4],

$$\frac{\partial}{\partial t}\delta\rho + (\mathbf{v}_0\cdot\nabla)\,\delta\rho + \rho_0\nabla\cdot\delta\mathbf{v} = 0,$$

$$\rho_0\frac{\partial}{\partial t}\delta\mathbf{v} + \rho_0\,(\mathbf{v}_0\cdot\nabla)\,\delta\mathbf{v} + \nabla(\delta p + \frac{1}{\mu_0}\mathbf{B}_0\cdot\delta\mathbf{B}) - \frac{1}{\mu_0}\,(\mathbf{B}_0\cdot\nabla)\,\delta\mathbf{B} = 0,$$

$$\nabla\cdot\delta\mathbf{B} = 0,$$

$$\frac{\partial}{\partial t}\delta\mathbf{B} - (\mathbf{B}_0\cdot\nabla)\,\delta\mathbf{v} + \mathbf{B}_0\nabla\cdot\delta\mathbf{v} + (\mathbf{v}_0\cdot\nabla)\,\delta\mathbf{B} + l_{\rm Hall}\frac{v_{\rm A}}{B_0}\mathbf{B}_0\cdot\nabla\nabla\times\delta\mathbf{B} = 0,$$

$$\frac{\partial}{\partial t}\delta p + (\mathbf{v}_0\cdot\nabla)\,\delta p + \gamma p_0\nabla\cdot\delta\mathbf{v} = 0,$$

where $v_{\rm A} = B_0/(\mu_0\rho_0)^{1/2}$ and $\gamma = 5/3$. The pressure perturbation δp is related to the mass density perturbation $\delta\rho$ via $\delta p = c_s^2\delta\rho$, where $v_s = (\gamma p_0/\rho_0)^{1/2}$ is the sound speed. Following the way of solving the above set of equations developed in Ref. [4], after Fourier transforming all perturbed quantities $\propto g(x)\exp(-i\omega t + ikz)$, we derive two coupled second order differential equations for δv_x and δv_y. All other perturbed quantities are expressed in terms of δv_x and δv_y. By applying the boundary conditions for continuity of $\delta v_x/(\omega - \mathbf{k}\cdot\mathbf{v}_0)$, the full perturbed pressure $\delta p_{\rm total}$ (kinetic + magnetic), the y-component of perturbed wave electric field δE_y, and the x-component of perturbed electric displacement $\delta D_x = \varepsilon_0\,(K_{xx}\delta E_x + K_{xy}\delta E_y)$ (where K_{xx} and K_{xy} are the low-frequency components of the plasma dielectric tensor [5]) at the interfaces, we arrive at the dispersion relations of Hall-MHD sausage and kink surface waves presented symbolically in the form

$$\mathcal{D}\,(\omega, k, v_0, B_0, l_{\rm Hall}, x_0, \beta, \rho_o, \rho_e) = 0.$$

Solving numerically the waves' dispersion relations we get the wave phase velocity ω/k (being Doppler-shifted inside the slab), normalized with respect to the Alfvén speed $v_{\rm Ao}$, as a function of the dimensionless wave number kx_0 with four entry parameters, notably the ratio $\rho_o/\rho_e = 4$, the plasma $\beta = 1$, the ratio $l_{\rm Hall}/x_0 = 0.4$, and the Alfvén Mach number $v_0/v_{\rm Ao}$ lying in the range 7–8 (because the steady flow velocity v_0 is not a constant, but swinging around the aforementioned value of 400 km s^{-1}).

Topic 13
Waves and instabilities, including surface waves

Annuaire de l'Université de Sofia "St. Kliment Ohridski", Faculté de Physique, 96, 2003

PARALLEL PROPAGATION OF SURFACE HALL-MHD WAVES ALONG AN IDEAL FLOWING PLASMA SLAB BOUNDED BY FLOWING PLASMA ENVIRONMENT

ROSSITSA MITEVA, IVAN ZHELYAZKOV

Department of Radiophysics and Electronics

Росица Митева, Иван Желязков. ПАРАЛЕЛНО РАЗПРОСТРАНЕНИЕ НА ПОВЪРХНИННИ ХОЛОВИ МХД ВЪЛНИ В ИДЕАЛЕН ТЕЧАЩ ПЛАЗМЕН СЛОЙ В ТЕЧАЩА ПЛАЗМЕНА СРЕДА

Изследва се паралелното разпространение (по направление на външното магнитно поле) на магнитохидродинамични (МХД) повърхнинни вълни по идеален течащ плазмен слой, намиращ се в течаща плазмена среда, в приближение на холовата магнитохидродинамика. Стойностите на плазмените скорост и плътност вътре и вън от слоя са различни. Разглеждат се две възможни посоки на относителната скорост (в координатна система, свързана с външния поток). Включването на постоянен поток вън от слоя променя дисперсионните характеристики на повърхнинните вълни, разпространяващи се по течащия слой, в сравнение със случая, когато външната среда е неподвижна. От двата вида повърхнинни вълни, които могат да се разпространяват в слоя, а именно *sausage* и *kink*, дисперсионното поведение на kink-мода по посока на относителната скорост се оказва много по-сложно, отколкото онова на sausage-мода.

Rossitsa Miteva, Ivan Zhelyazkov. PARALLEL PROPAGATION OF SURFACE HALL-MHD WAVES ALONG AN IDEAL FLOWING PLASMA SLAB BOUNDED BY FLOWING PLASMA ENVIRONMENT

The parallel propagation of magnetohydrodynamic (MHD) surface waves along an ideal flowing plasma slab, bounded by flowing plasma environment in the Hall magnetohydrodynamics approach is investigated. The magnitudes of the plasma velocity and density inside and outside the slab are different. Two possible directions of the relative velocity (in a frame of reference co-moving with the ambient flow) are considered. The inclusion of the steady flow outside the slab changes the dispersion characteristics of the surface waves travelling along the flowing slab in comparison with the case when the external medium is at rest. From the two kind surface wave modes that may occur, notably *sausage* and *kink*, the dispersion behaviour of the kink mode along the relative flow turns out to be much more complex than that of the sausage mode.

Keywords: Hall-MHD waves, solar-wind plasma, flow-tube structures

PACS numbers: 52.35.Bj; 96.50.Ci