

STUDY OF THE GEOEFFECTIVENESS OF CORONAL MASS EJECTIONS

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ABSTRACT

This dissertation is an attempt to investigate geoeffectiveness of CMEs. The study was focused on two important aspects regarding the prediction of space weather. Firstly, it was presented relationship between energetic phenomena on the Sun and CMEs producing solar energetic particles. Scientific considerations demonstrated that very narrow CMEs can generate low energy particles (energies below 1 MeV) in the Earth's vicinity without other activity on the Sun. It was also shown that SEP events associated with active regions from eastern longitudes have to be complex to produce SEP events at Earth. On the other hand, SEP particles originating from mid-longitudes ($30^\circ < \text{latitude} < 70^\circ$) on the west side of solar disk can be also associated with the least complex active regions. Secondly, two phenomena affecting CMEs detection in coronagraphs have been defined. During the study the detection efficiency of LASCO coronagraphs was evaluated. It was shown that the detection efficiency of the LASCO coronagraphs with typical data availability is sufficient to record all potentially geoeffective CMEs. However, coronagraphic observations of CMEs are subject to projection effects. This makes it practically impossible to determine the true properties of CMEs and therefore makes more difficult to forecast their geoeffectiveness. In this study, using quadrature observations with the two STEREO spacecrafts, projection effects affecting velocity of CMEs included in the SOHO/LASCO catalog were estimated. It was demonstrated that this effect depends significantly on width and source location of CMEs. All these results could be very useful for forecasting of space weather.

ABSTRACT IN POLISH (STRESZCZENIE)

Niniejsza rozprawa prezentuje wyniki badań nad geoefektywnością koronalnych wyrzutów masy (KWM). Badania były skoncentrowane na dwóch istotnych aspektach dotyczących prognozowania pogody kosmicznej. Jednym aspektem badań było pokazanie korelacji między zjawiskami na słońcu a KWM produkującymi energetyczne cząstki. Badania pokazały, że bardzo wąskie KWM mogą generować w pobliżu Ziemi nisko-energetyczne cząstki (energii poniżej 1 MeV) bez dodatkowej aktywności na Słońcu. Pokazano także, iż obszary aktywne zlokalizowane na wschodniej części tarczy słonecznej mogą produkować energetyczne cząstki jedynie jeżeli ich struktura magnetyczna jest bardzo złożona. Natomiast obszary aktywne zlokalizowane w środkowej oraz zachodniej części tarczy słonecznej nie muszą mieć złożonej struktury magnetycznej aby produkować energetyczne cząstki.

Drugi aspekt badań dotyczył zdefiniowania zjawisk wpływających na badanie KWM przy wykorzystaniu koronografów. W tych badaniach oceniono efektywność detekcji koronografów LASCO i pokazano, że te koronografy są w stanie wykryć wszystkie potencjalnie geoefektywne KWM. Jednak obserwacje przy użyciu koronografów są obarczone efektem projekcji. Z tego powodu praktycznie niemożliwe jest wyznaczenie rzeczywistych parametrów KWM przez co trudniej jest przewidzieć ich geoefektywność. W tych badaniach, wykorzystując obserwacje z satelit STEREO będących w kwadraturze względem Ziemi, oszacowany został efekt projekcji wpływający na wyznaczanie prędkości KWM. Pokazano, że ten efekt zależy w dużym stopniu od szerokości kątowych oraz lokalizacji KWM na Słońcu. Wszystkie otrzymane wyniki mogą być bardzo przydatne do prognozowania pogody kosmicznej.

LIST OF PUBLICATIONS

This dissertation has been written as a summary of the scientific activities previously reported in the following articles:

1. **Bronarska, K.**, Michalek, G., *Characteristics of active regions associated with large solar energetic proton events*, 2017, *Advances in Space Research*, 59, 384
2. **Bronarska, K.**, Michalek, G., Yashiro, S., Akiyama, S., *Visibility of coronal mass ejections in SOHO/LASCO coronagraphs*, 2017, *Advances in Space Research*, 60, 2108
3. **Bronarska, K.**, Michalek, G., *Determination of projection effects of CMEs using quadrature observations with the two STEREO spacecraft*, 2018, *Advances in Space Research*, 62, 408
4. **Bronarska, K.**, Wheatland, M.S., Gopalswamy, N., Michalek, G., *Very Narrow CMEs Producing Solar Energetic Particles*, 2018, *Astronomy & Astrophysics*, 619, 6

ACRONIMS

ACE	Advanced Composition Explorer
AR	Active Region
CACTus	Computer Aided CME Tracking
CME	Coronal Mass Ejection
EPAM	Electron, Proton, and Alpha Monitor
GLE	Ground Level Enhancement
GOES	Geostationary Operational Environmental Satellites
LASCO	Large Angle and Spectrometric Coronagraphs
LESP	Low Energetic Solar Particle
MSCS	McIntosh Sunspot Classification Scheme
SEP	Solar Energetic Particle
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEM	Synchronous Environmental Satellites
SOHO	Solar and Heliospheric Observatory
STEREO	Solar Terrestrial Relations Observatory

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Part I

CURRENT STATE OF THE KNOWLEDGE

In the first part of this dissertation, a brief introduction to the problem of space weather is presented. The basic properties of coronal mass ejection and their influence on space weather are described. Then, special classes of coronal mass ejection are briefly characterized.

1 INTRODUCTION

1.1 Space Weather

We live in the world of advanced technology that is highly sensitive to the activity of the Sun. Energetic eruptions from the Sun may significantly disrupt our live on the Earth. Predicting geomagnetic storms and forecasting their intensity are very important issues raised before space science. For four decades we have known that space weather is mainly controlled by coronal mass ejections. CMEs are huge expulsions of magnetized plasma that can affect our environment in two ways. They may directly hit Earth's magnetosphere during their propagation in the interplanetary medium or may generate fluxes of very dangerous energetic particles. These two factors play the main part in the formation of space weather and are important issues for researches. Of course, not all CMEs are geoeffective. Their geoeffectiveness mostly depends on magnetic field and speed (e.g., Gosling et al., 1990). Both these parameters are crucial for generating geomagnetic storms due to the process of magnetic reconnection with the Earth's magnetosphere. The most severe geomagnetic storms are generated if ejection includes a strong southward component of the magnetic field (e.g., Akasofu, 1981). There are numerous studies considering relation between in situ properties of CMEs and intensities of geomagnetic storms (e.g., Verbanac et al., 2013, and references therein). Unfortunately, monitoring the near-Earth solar wind parameters can give a prediction of harmful events only a hour before the onset of the geomagnetic disturbance. Therefore, it would be more useful to forecast of space weather conditions using observations near the Sun. Numerous studies have been conducted out to relate intensities of geomagnetic storms with properties of CMEs or flares. These considerations demonstrated that geomagnetic disturbances depend on CME initial speed, apparent angular width, source region location, the intensity of associated flare and occurrence of successive CMEs (Dumbović et al., 2015, and reference there in).

1.2 Coronal Mass Ejections - Overview

CMEs were first observed in the 1970s by the Orbiting Solar Observatory (Tousey, 1973). Since that time, they have been extensively studied (see, e.g., St. Cyr et al., 2000; Yashiro et al., 2004) in particular using the sensitive Large Angle and Spectrometric Coronagraphs (Brueckner et al., 1995) on board the Solar and Heliospheric Observatory mission. The SOHO/LASCO instruments have already recorded more than 30,000 CMEs by December 2017. The basic attributes of CMEs are routinely determined and are stored in the SOHO/LASCO catalog (cdaw.gsfc.nasa.gov/CME_list, Yashiro et al., 2004, Gopalswamy et al., 2009). The initial velocity of CMEs obtained by fitting a straight line to the height-time data points determined manually has been the basic parameter used in prediction intensity of geomagnetic disturbances. Among the thousands of CMEs observed by LASCO coronagraphs only a couple have speeds exceeding 3000 km s^{-1} . An average CME speed is about 450 km s^{-1} (Yashiro et al., 2004, Webb and Howard, 2012) and it changes with the solar cycle (Yashiro et al., 2004) from $\approx 300 \text{ km s}^{-1}$ during the minimum up to $\approx 500 \text{ km s}^{-1}$ during the maximum of solar activity. The rate of expansion of CMEs depends on the Lorentz force that drives them and the conditions prevailing in the interplanetary medium.

CMEs are large expulsions of magnetized plasma from the Sun and, when they are directed towards the Earth, they are potential sources of geomagnetic activity. They are faint and mostly observed by using coronagraphs placed in the space. Figure 1 shows a typical CME having a three-part structure: a bright front, a dark cavity, and a bright core. However, in the vast majority (above 60%) CMEs show more complex morphological structures (Munro and Sime, 1985; Howard et al., 1985). The diverse appearance of CMEs can be caused by the projection effect. In coronagraphic images three dimensional structure of CMEs is projected onto a plane-of-sky hence their appearance depends on its orientation. Only CMEs that erupts on the solar limb and propagates at right angles to the observer are free from projection

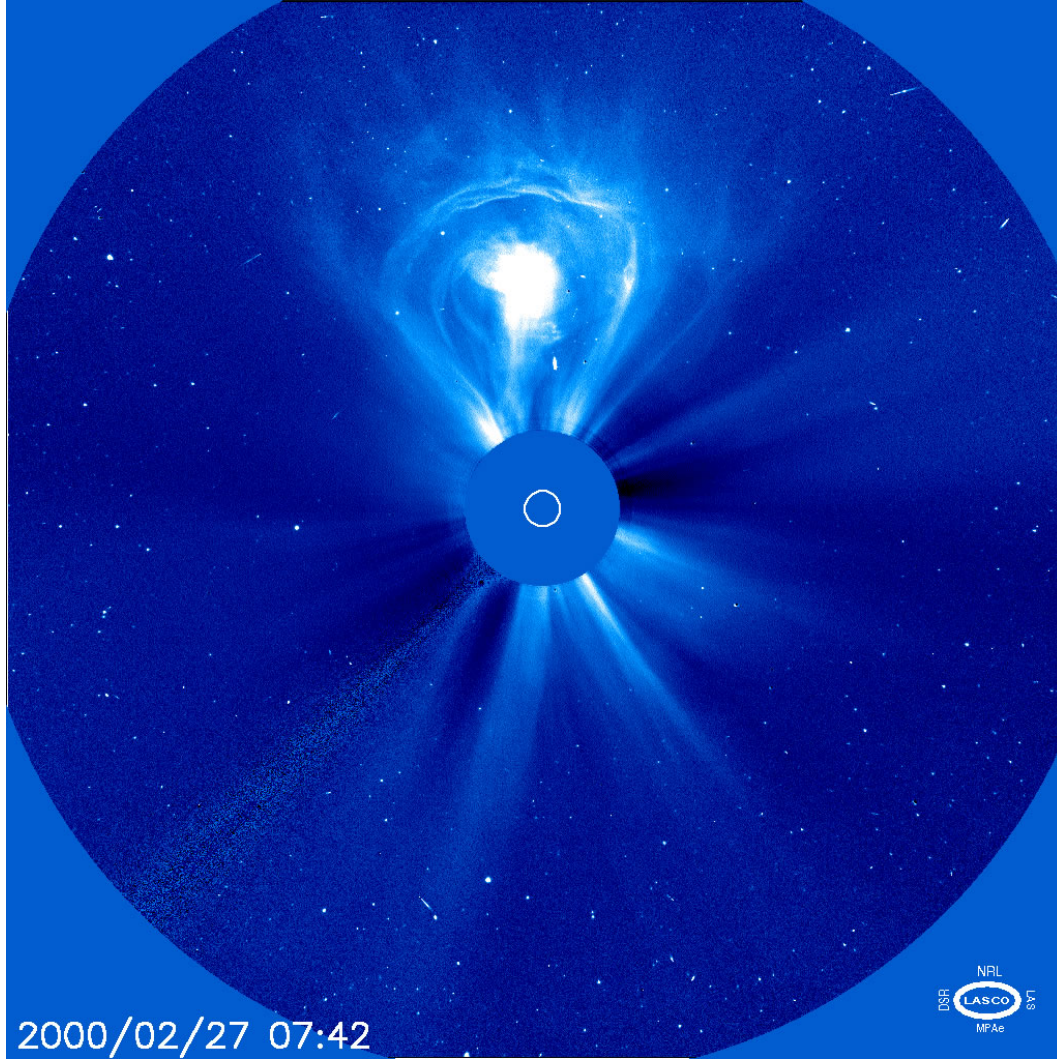


Figure 1: A ‘typical’ CME recorded by LASCO C3 coronagraph. Showing a bright front surrounding a dark cavity, with a bright core at the centre. The central disk is the occulter of the coronagraph, blocking out the bright light of the solar photosphere. The white circle represents the solar disk. Image from <https://eclipse2017.nso.edu/coronal-mass-ejections-cme/>.

effect. Their measured widths and velocities do not suffer from projection effects. The limb CMEs have an average angular width of approximately 50° but the CMEs originating from the center of the Sun can be observed, due to projection effects, as full halos having angular extent 360° (Yashiro, et al., 2004). These events, if are

front-side, are directed to the Earth and are potentially geoeffective. Halo events cause our immediate concern.

2 SPECIAL CLASSES OF CMEs

In the study we considered only two special classes of CMEs. In the next two sections, I present their characteristics.

2.1 Narrow CMEs

Despite the wide diversity of expulsions, at first it seemed that it would be possible to construct a unified model explaining all the different morphological classes of CMEs. However, recent observations have demonstrated that it is necessary to divide CMEs into, at least, two categories: narrow and normal CMEs. It is assumed that the narrow CMEs have mostly an angular width $<20^\circ$. Note, however, that there is no strict limit in the angular width between the two classes of events. The real difference between them is that the narrow CMEs have an elongated jet-like shape, whereas the normal CMEs seem to be closed magnetic loops. This difference in appearance between the two classes of CMEs probably reflects the different mechanism of their initiation.

The normal CMEs mostly originate from closed magnetic structures as erupting flux rope systems, consisting of a typical three-part structure (a leading front, a dark cavity and a bright core). Improved techniques of observations, particularly data from the SOHO satellite, revealed that the narrow events do not form one coherent class of events, but among them we can distinguish a few clear subsets. As a matter of fact, the narrow CMEs have been divided into three categories: structured CMEs, unstructured CMEs, and jets (Gilbert et al., 2001, Dobrzycka et al., 2003). The structured events exhibit a well defined interior feature in the LASCO images while unstructured events are featureless. There is not any obvious difference between these two groups of events and the normal CMEs, but their

appearance. The jets are sometimes not classified as CMEs, because open magnetic structures from coronal holes are involved in their ejection. On the other hand, they fulfill the commonly accepted definition of CMEs, introduced by Munro et al. (1979). In addition, Bemporad et al. (2005) separated a new variety of narrow CMEs called dubbed streamer puffs. These ejections seem to be different from the previously studied narrow CMEs because they are expelled from the flanks of coronal streamers.

These narrow outbursts should raise our greatest interest because they are a potential source of solar energetic particles. Wang and Sheeley (2002) described a population of the jets ejected close to the solar maximum. These jets, which tend to be brighter and wider than the polar jets, could be initiated close to the equatorial coronal holes and could be geoeffective.

The narrow CMEs are a small minority of all coronal ejections and they have not been extensively studied. They have relatively small angular size and origin from simpler magnetic structure (in open magnetic structures so they are sometimes called polar jets, not CMEs) than the normal CMEs. This should be very helpful in understanding the physical process responsible for their formation.

2.2 CMEs producing SEPs

Solar energetic particles are high-energy particles coming from the Sun. They had been first observed in the early 1940s. They consist of protons, electrons and heavy ions with energy ranging from a few tens of keV to GeV (the fastest particles can reach speed up to 80% of the speed of light). Understanding the mechanism by which SEPs are accelerated is a long-standing problem in solar physics (Cliver, 2009a,b). There is evidence for particle acceleration by two different processes: a flare reconnection process (impulsive SEP events not accompanied by a CME) and a CME driven shock (gradual SEP events and energetic storm particles). Large SEP events (particle intensity in the >10 MeV energy channel exceeds 10 particles

$\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-2}$) are always associated with large flares and CME-driven shock. Both the flare and shock processes must be employed to the particle flux however, the relative contribution from them is unknown (Cliver, 2009a,b; Klecker et al., 2007). Type III and II radio burst are signatures of the flare or shock acceleration, respectively (Gopalswamy et al. 2006). These burst are produced by low-energy electrons escaping from the flare site (type III burst) and shock front (type II burst). Cane et al. (2002) and MacDowall et al. (2003) associated MeV SEPs with complex (duration longer than 15 minutes) type III bursts observed at frequencies below 14 MHz. Recently, MacDowall et al. (2009) revisited this problem and found that the type III burst duration and complexity were always greater for SEP events. On the other hand, Cliver and Ling (2009) demonstrated that the type III burst associated with impulsive and gradual SEP events are similar and the type III complexity does not distinguish between the two classes of SEP events, but the presence of a type II burst do. The presence of a type II burst favors the shock acceleration for large SEP events. Recently, Gopalswamy and Makela (2010) analyzed the CMEs, flares and type II radio burst associated with a set of three complex, long-duration type III bursts from active region 10588. One of the three type III burst was not associated with a type II burst and also with a SEP event. This result suggested that the occurrence of a complex type III bursts are not good indicator of large SEP events. It is evident that our knowledge about generation of SEP events is still puzzled and need additional studies.

The past decade was successful in our understanding of particle acceleration at the Sun and in the heliosphere. However, much remains to be learned about the spatial and temporal evolution of the SEP sources and about the role of both flares and CME-driven shocks in the acceleration of SEPs. Prediction of occurrence of SEP events is the most important from the point of view of space weather forecasting. They travel from the Sun with velocities close to the speed of light ($0.8c$) and since the moment of ejection into interplanetary medium they need only 20 minutes to

hit satellites and astronauts in outer space. Many SEP events are produced by halo CMEs. They originate from the center of solar disk and are observed around the entire occulting disk. The STEREO mission has opened new possibilities in the study of CMEs. Using data from STEREO/SECCHI and SOHO/LASCO coronagraphs allow us to observe the SEP events from different points of view. It is worth adding here that two important aspects related to the observations carried out with the use of coronagraphs constitute an important part of the presented doctoral dissertation.

Part II

RESULTS OF THE PUBLISHED ARTICLES

Second part of this thesis is a summary of my scientific effort undertaken to expand our knowledge of CMEs generating geomagnetic disturbances. Relevant publications were discussed and final conclusions were drawn. Publication are presented in chronological order.

3 Aims and objectives of the thesis

Coronal mass ejections, which are expulsions of magnetized plasma from the Sun, are potentially harmful to advanced technology, including communications and power systems. They generate the largest geomagnetic storms and cause our immediate concern. Consideration of any aspect of the CME phenomenon is very important for space weather predictions. Since more than two decades, using observations from SOHO satellite, they have been intensively studied however they still need further considerations.

All four papers that constitute the doctoral dissertation, are concentrated on the important issues concerning CMEs and space weather. The study was focused on two important aspects regarding the prediction of space weather. Firstly, it was presented relationship between energetic phenomena on the Sun and CMEs producing solar energetic particles. Secondly, two phenomena (projection effects and the visibility function) that may affect the detection of CMEs using coronagraphs have been described. The data from STEREO and SOHO satellites have been mostly employed in this study. The obtained results could be very useful for forecasting of space weather.

4 Characteristics of active regions associated with large solar energetic proton events

4.1 Purpose of research

In my first study, I decided to search for the relationship between properties of ARs and CMEs generating SEPs (protons with energy 10 MeV). For this purpose I studied 84 SEP events recorded during the SOHO era (1996–2014). Then I compared properties of these SEP events with associated ARs, flares and CMEs. This is important from the point of view of prediction of generation of SEPs. The main

purpose of these studies was to develop a simple but effective method to predict the occurrence and intensity of SEPs.

4.2 Methodology

In the study different databases characterising associated CMEs, flares, SEPs and ARs were used. However, for the purpose of the present research, the most important were reports produced by the Space Weather Prediction Center (Solar Region Summary, www.swpc.noaa.gov). These reports provide the following description of ARs: NOAA number, location, area, McIntosh classification, longitudinal extent, total number of visible sunspots in the group and magnetic classification of the group. The reports include also the locations and X-ray fluxes of X-flares. Properties of ARs taken from these reports were compared to intensities of SEP events. During the SOHO era (1996–2014) 116 large SEPs, with intensity ≥ 10 pfu (pfu = $1 \text{ particle cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) in the 10 MeV energy channel, were recorded. Some of these SEPs were generated by CME-driven shock originating behind the west solar limb, in that case the associated ARs could not be determined. However, a coronal shock, strongly deviating interplanetary magnetic field structures or even cross-field diffusion may explain an intensity increase at a far separated observer. For 84 SEPs it was able to determine the MCSC for associated ARs and these events are used for the study. The most energetic solar particles are not only observed by satellites placed in the Earth’s vicinity but they can reach detectors on the Earth’s surface. These events are termed “ground level enhancement”. In the considered period of time 14 GLEs were recorded and they are also included in the study. They are a smaller sub-sample of the all considered CMEs.

4.3 Results

These studies allowed us to obtain a number of interesting results. It has been demonstrated that SEPs are likely to be observed from complex ARs consisting

of large bipolar structures (denoted C, D, E, F in the first code of MSCS) with asymmetric penumbrae around the largest spots (A, K in the second code of MSCS) and many smaller spots in the group (O, I, C in the third code of MSCS). It is also shown that increased flux of SEPs is associated with increasing magnetic complexity of ARs.

It has been demonstrated that ARs associated with eastern SEP events are found to be significantly larger than those associated with western SEP events. This suggests that CMEs producing SEPs from the eastern side of the Sun may be wider than those associated with western SEP events. This is a new and interesting result because coronagraphic observations cannot provide angular widths of halo events associated with larger SEP events. This fact may explain why energetic events with source regions on the east side of the Sun can generate energetic particles in the Earth's vicinity.

It has been also demonstrated that flares associated with SEP events, which are assumed to be the source locations for these events, mostly appear at the eastern sides of ARs (displaced by 6 to 8 degrees from the center of the AR). This result could allow to predict, with higher accuracy, the source location of potentially energetic events on the Sun.

Finally, it has been introduced a new method for predicting fluxes of SEP events, based on the McIntosh codes.

5 Visibility of coronal mass ejections in SOHO/LASCO coronagraphs

5.1 Purpose of research

In the second paper, I evaluated detection efficiency of LASCO coronagraphs. Due to the nature of coronagraphic observations detection of some CMEs is sometimes difficult. For example, potentially geoeffective events originating from the disk center

are the most difficult to observe. So it is interesting to recognize characteristics of "invisible" events. To examine the visibility function we compared CMEs recorded by SOHO/LASCO and STEREO/SECCHI coronagraphs.

5.2 Methodology

Since 2006 we have an additional pair of STEREO twin spacecrafts that allow us to observe the solar corona from two additional directions. These observations provide a unique opportunity to evaluate the visibility functions. This is especially possible when the spacecrafts are separated from the Earth by about 90° . These unprecedented observations enable the direct detection of CMEs that are not visible in LASCO coronagraphs (invisible events). Determination of these events allowed to evaluate the detection efficiency of LASCO coronagraphs.

Presented research considered all CMEs recorded by SOHO/LASCO and STEREO/SECCHI coronagraphs during the period of June – November 2011. A subsample of events detected by SECCHI instruments but not included in the SOHO/LASCO catalog has been selected. These events are called as invisible-to-LASCO observations.

5.3 Results

It was demonstrated that the total visibility function is about 0.80. This function is almost perfectly anti-correlated with longitude of source location. The invisible-to-LASCO events in comparison to visible-to-LASCO events are, on average, slower (about 10%), narrower (about two times) and originate only from the disk center. It has been demonstrated that the invisible events are not energetic. This study clearly revealed that LASCO coronagraphs are not likely to miss events that potentially could be geoeffective.

6 Determination of projection effects of CMEs using quadrature observations with the two STEREO spacecraft

6.1 Purpose of research

In the third study, I considered a projection effect which disturb coronagraphic observations of CMEs. Since 1995 CMEs have been routinely observed thanks to the sensitive LASCO coronagraphs on board SOHO mission. Their observed characteristics are stored, among other, in the SOHO/LASCO catalog. These parameters have been commonly used in scientific studies. Unfortunately, coronagraphic observations of CMEs are subject to projection effects. The three-dimensional structure of the CMEs is projected onto the plane of the sky. This makes it practically impossible to determine the true properties of CMEs and therefore makes it more difficult to forecast their geoeffectiveness. In this study, using quadrature observations with the STEREO spacecrafts, we estimate the projection effect affecting velocity of CMEs included in the SOHO/LASCO catalog.

6.2 Methodology

To evaluate the projection effect we used, just like in the previous publication, observations from the LASCO and STEREO coronagraphs. However, in the present study the basic attributes of CMEs recorded simultaneously by both coronagraphs were compared. We concentrated on the period time when the STEREO spacecrafts were found in quadrature. The configurations of the STEREO spacecrafts enable us to observe, without projection effects, CMEs originating close to the disk center in respect to the point of view of the Earth. This unique configuration of the satellites allows us to study the projection effect for both instruments. Nevertheless, in this work, we considered projection effects affecting SOHO/LASCO observations. For this purpose, we compared basic attributes (e.g. velocity, acceleration and width) of the same CMEs included in the SOHO/LASCO CME (LASCO observations)

and CACTus (STEREO observations) catalogues. In order to obtain reliable results, a thorough analysis of the consistency of the CMEs parameters included in both catalogs was carried out.

6.3 Results

It was demonstrated that observations of CMEs included in the SOHO/LASCO and CACTus catalogs are subject to the projection effect. It is consistent with the previous studies (Gopalswamy et al., 2000; Burkepile et al., 2004; Sheeley et al., 1999; Leblanc et al., 2001).

This effect, on average, is equal about 130 km s^{-1} or 0.3 in absolute or relative values, respectively. It has been also shown that this effect significantly depends on the width and longitude of source location of CMEs. It can be very significant for narrow events ($\text{width} < 30^\circ$) and it can be neglected only for very wide events ($\text{width} > 200^\circ$). Depending on width of CME we provided upper limit for the projection effect.

It has been evaluated dependence of projection effects on longitude of source location. It was demonstrated that projection effects could be very significant for events originating from the disk center. It systematically decreases with increasing longitude of source location. Only halo CMEs origination close to disk center ($|\text{longitude}| < 40^\circ$) are subject to the projection effect.

It has been demonstrated that this method can not be used to determine projection effect for width of CMEs. Unfortunately, both considered catalogs have different method to determine width of CMEs so their comparison is not conclusive.

7 Very Narrow CMEs Producing Solar Energetic Particles

7.1 Purpose of research

In the last paper, I considered narrow CMEs (“jets”) to show that such events (without other activity on the Sun, i.e., without flares) are able to produce low energy solar particles (LESPs). This is an important issue because these types of particles can also be harmful to the technology placed in space.

In comparison to previous investigations, in the first stage I considered a coherent sample of jets (mostly originating from the boundaries of coronal holes) to identify properties of events that produce SEPs (velocities, widths, and PAs). This is a new approach and scientific goal.

7.2 Methodology

For the purpose of our research I considered 125 very narrow CMEs recorded by LASCO coronagraphs during the maximum activity of solar cycle 23. These events were chosen on the basis of their source location. It has been studied only very narrow CMEs at the western limb, which are expected to have good magnetic connectivity with Earth.

We found 24 very narrow CMEs associated with energetic particles such as ions (protons and ^3He), electrons, or both. to make sure that these CMEs are a source of LEPs, a series of analyzes have been carried out. The association between very narrow CMEs and energetic particles was based on the consistency between estimates for particle travel times from the Sun and the appearance times for the SEP events at the Earth. To be sure that these associations are real we considered only isolated narrow CMEs without any additional energetic phenomena on the Sun. To ensure that associations between the narrow CMEs and SEPs are real we conducted an additional test. We chose, at random, thirty narrow and isolated events with position angles excluding their magnetic connection to the Earth. These events were

not likely to produce SEPs near the Earth. If in our study an accidental coincidence between SEPs and the very narrow CME appeared, we should also find energetic particles for these events. But we did not find any SEPs associated with these CME events. This result clearly demonstrates that our considerations are correct.

7.3 Results

Using data from the EPAM instrument on board the ACE satellite, it has been found 24 (19% of all the considered events) low-energy solar particle fluxes that we associated with narrow CME events. This study presents a new approach and set of results, and confirms that very narrow CMEs can generate low-energy particles without other activity on the Sun. Admittedly, low-energy particles are less dangerous for astronauts, but they are harmful for satellites.

Additionally, we performed a statistical analysis of the narrow CMEs. We separately considered the narrow CMEs associated with energetic particles and those without energetic particles. We demonstrated a statistical difference for the angular width of the SEP-related events in comparison to the other narrow events. This suggests that these events constitute a separate group of very narrow CMEs that are sufficiently powerful to produce energetic particles that can be detected at Earth. We demonstrated that the velocity distributions for CMEs without SEPs that are associated with SEPs are very similar. However, the latter are on average about 100 km s^{-1} faster than CMEs without associated SEPs. Additionally, we showed that CMEs producing SEPs show a correlation between their PAs and widths.

8 Final conclusions

The study allowed us to present finale general results:

1. It was shown that the basic observational parameters of ARs on the Sun can be used to predict the geoefficiency of CMEs ejected from them.

2. It was clearly revealed that LASCO coronagraphs are not likely to miss events that potentially could be geoeffective.
3. It was demonstrated that coronagraphic observation are subject to projection effects. It was revealed that this effect depends significantly on width and source location of CMEs. It can be very significant for narrow events originating from the disk center.
4. It was demonstrated that narrow CMEs, without any additional signatures on the Sun, can generate energetic particles (potentially harmful for space technology) in the vicinity of the Earth.

9 References

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Part III

PUBLICATIONS

The last part contains all four journal articles that have been used as a basis of this dissertation. All of them have been included in the default journal format.

Characteristics of active regions associated to large solar energetic proton events[☆]

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Abstract

The relationship between properties of active regions (ARs) and solar energetic particles (SEP events, protons with energy ≥ 10 MeV) is examined. For this purpose we study 84 SEP events recorded during the SOHO era (1996–2014). We compare properties of these SEP events with associated ARs, flares and CMEs. The ARs are characterized by McIntosh classification. Statistical analysis demonstrates that SEP events are more likely to be associated to the ARs having complex magnetic structures and the most energetic SEPs are ejected only from the associated ARs having a large and asymmetric penumbra. This tendency is used to estimate intensities of potential SEP events. For this purpose we express a probability of occurrence of an SEP event from a given AR which is correlated with fluxes of associated SEPs. We find that SEP events associated with ARs from eastern longitudes have to be more complex to produce SEP events at Earth. On the other hand, SEP particles originating from mid-longitudes ($30^\circ < \text{longitude} < 70^\circ$) on the west side of solar disk are associated to the least complex ARs. These results could be useful for forecasting of space weather.

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Keywords: Sun: activity; Sun: coronal mass ejection (CMEs); Sun: particle emission; Sun: flares

1. Introduction

Coronal mass ejections (CMEs) are large expulsions of magnetized plasma from the Sun which are potentially harmful to advanced technology. Energetic CMEs can generate geomagnetic storms and solar energetic particles (SEPs) (e.g. [Gopalswamy et al., 2007](#)). Large SEP events, with intensity ≥ 10 pfu (pfu = 1 particle $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) in the 10 MeV energy channel, cause immediate concern because they can reach Earth's vicinity in about an hour after their acceleration near the Sun. Understanding the mechanism by which SEPs are accelerated is a long-standing problem in solar physics ([Cliver, 2009a,b](#)). There

is evidence for particle acceleration by two different processes (e.g. [Reames, 1999](#)): a flare reconnection process (for impulsive SEP events not accompanied by a CME) and a CME driven shock (for gradual SEP events and energetic storm particles). There were many attempts to identify a basic accelerator. The studies were based on determination of statistical correlation between SEP parameters, especially their peak intensity, and the basic attributes of flares or CMEs ([Kahler, 2001](#); [Gopalswamy et al., 2003](#); [Cane et al., 2010](#); [Cliver et al., 2012](#); [Richardson et al., 2014](#)). Results of these considerations were not conclusive because similar correlations were found for flare X-ray peaks and CME speeds as well. Therefore is widely accepted that large SEP events are usually associated with large flares and CME-driven shocks ([Gopalswamy et al., 2015](#)). Both flare and shock processes may contribute to the particle flux but the relative contribution is unclear ([Cliver, 2009a](#); [Klecker et al., 2007](#)).

[☆] This template can be used for all publications in Advances in Space Research.

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Recently, Trottet et al. (2015) have been used the partial correlation analysis to determine the relation between the properties of CME (speed) and flares (peak flux and fluence of soft X-ray (SXR) emission, fluence of microwave emission) and the large SPE events. This analysis shown that the only parameters that affect significantly the SEP intensity are the CME speed and the SXR fluence.

It is well known that the source of solar eruptions (flares or CMEs) is the free energy stored in nonpotential magnetic field. This energy can be suddenly released through magnetic reconnection when evolution of magnetic field leads to unstable configurations. Frequently photospheric flows, flux emergence or canceling are responsible for building up energy and triggering eruption. These processes produce highly sheared (complex) magnetic field. Therefore there are two factors determining the solar eruptions: magnetic free energy stored in ARs (size) and unstable magnetic field configuration (tension of magnetic field). The tight linkage between shear flows and flare (Meunier and Kosovichev, 2003) and CME (Falconer et al., 2002) productivity was established. A high correlation between complexity of ARs and intensity of flares and velocity of CMEs was found (Guo et al., 2006). Therefore complex active regions, including highly sheared magnetic field, tend to produce large flares and CMEs (e.g. Zirin and Liggett, 1987; Sammis et al., 2000). It is also widely accepted that complex active regions tend to produce large flares and CMEs (e.g. Zirin and Liggett, 1987; Sammis et al., 2000). The most energetic CMEs and flares originate from large active regions (ARs) that have closed magnetic structures and sufficient stored magnetic energy (Liu et al., 2006; Michalek and Yashiro, 2013). If these large eruptive events (flares or CMEs) originate from the western hemisphere they may accelerate SEPs (see e.g. McCracken, 1962). Recently, many statistical studies have investigated the types of solar events which produce solar energetic particles. These studies mostly concentrated on the dependence of SEP events on various parameters of the associated flares or CMEs (e.g. Kahler, 2001; Gopalswamy et al., 2008; Richardson et al., 2014; Dierckx et al., 2015).

The ARs may be classified in terms of the morphology of the sunspot groups. The most common classification of ARs was introduced by McIntosh (1990). The McIntosh Sunspot Classification Scheme (MSCS) assigns three descriptive codes characterizing the size (A, B, C, D, E, F, H), penumbra (X, R, S, A, H, and K) and compactness (X, O, I, and C) of ARs. The paper by Michalek and Yashiro (2013) describes the McIntosh classification in greater detail. To improve the readability of the paper we include Table 1 that shortly explains the MSCS. The MSCS may be used as a proxy for magnetic structures in the ARs and, hence, is expected to correlate with the production of CME-driven shocks generating SEPs. Bornmann et al. (1994) showed that most ARs (35%) have simple magnetic structures classified as AXX or BXX, and they also studied the rates of transition between classes. The relation of flare rate per day with McIntosh class was considered by

Bornmann and Shaw (1994). Recently, Michalek and Yashiro (2013) considered the relationship between the ARs and coronal mass ejections (CMEs). They demonstrated that speeds of CMEs are correlated with McIntosh class and the fastest CMEs can be ejected only from the most complex classes of ARs.

The dynamic pressure of the solar wind dominates over the magnetic pressure in the inner heliosphere, so the solar magnetic field is pulled into an Archimedean spiral pattern due to the combination of the outward motion and the Sun's rotation (Smith, 2001). The motion of charged particles from the Sun is constrained by this magnetic field pattern. Hence the location of the source is very important for characteristics of SEP events. Events from the western hemisphere generally have better magnetic connectivity to the Earth than those from the eastern hemisphere, so western events are more likely to produce large SEP events (Gopalswamy et al., 2014).

Falewicz et al. (2009) found that peak X-ray fluxes of flares are not significantly associated with productivity of energetic particles during the reconnection process. Michalek and Yashiro (2013) found that the velocities of CMEs, especially for halo events which are mostly associated with the large SEP events, include to significant error due to projection effects and may be significantly different from the real velocities of the CMEs.

In the present paper we propose a new approach to investigate the appearance of SEP events. We seek to identify which MSCS classes indicate a tendency to produce SEPs. The MSCS parameters serve as proxies for the magnetic structure of ARs and should be correlated with production of SEPs. We consider a set of 116 SEP events recorded during 1996–2014. We study the magnetic structure of the source ARs to see if this can account for the observed productivity and fluxes of SEPs. We propose a simple but effective method to predict the arrival of energetic particles in the Earth's vicinity. The paper is divided as follows. The data used for this study are described in Section 2. A statistical analysis of properties of ARs producing SEPs is presented in Section 3. In Section 4 we present the results of our analysis and draw conclusions.

2. Data

Our statistical study covers the SOHO era (1996–2014) of CME observations from the Large Angle and Spectrometric Coronagraph (LASCO). In the considerations we use three databases which are described in this section. The basic list of large SEP events is from the NOAA Space Weather Prediction Center (<http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt>). This list has been compiled since 1976 and includes fluxes of protons in the ≥ 10 MeV channel and associated CMEs, flares, and ARs. The Space Environment Monitor (SEM) onboard the Synchronous Meteorological Satellites (SMS-1 and SMS-2) and the Geostationary Operational Environmental Satellites (GOES-1, GOES-2, etc.) have been routinely used for monitoring the

Table 1
The MSCS classification scheme.

The first code-defines the length of sunspot groups	The second code-characterizes the type of largest spot in a group	The third code-specifies spottedness in the interior of a sunspot group
A-unipolar group with no penumbra	X-the main spot without penumbra	X-a unipolar group (no additional spots)
B-bipolar group without penumbra on any spots	R-rudimentary penumbra partially surrounds the largest spot	O-few spots between leader and follower
C-bipolar group with penumbra on one end of the group	S-small, symmetric penumbra ($\leq 2.5^\circ$)	I-numerous spots between leader and follower
D-bipolar group with penumbra on spots at both ends of the group, and with length $< 10^\circ$	A-small, asymmetric penumbra ($\leq 2.5^\circ$)	C-many strong spots between leader and follower
E-bipolar group with penumbra on spots at both ends of the group, and with length defined as: $10^\circ < \text{length} \leq 15^\circ$	H-large, symmetric penumbra ($> 2.5^\circ$)	
F-bipolar group with penumbra on spots at both ends of the group, and length $> 15^\circ$	K-large, asymmetric ($> 2.5^\circ$)	
H-unipolar group with penumbra. The principal spot is usually the leader spot remaining from a pre-existing bipolar group		

Earth’s environment and detection of SEPs. The SEM has provided magnetometer, energetic particle, and soft X-ray data continuously since July 1974. The characteristics of CMEs are obtained from the SOHO/LASCO CME catalog (http://www.cdaw.gsfc.nasa.gov/CME_list). This catalog includes a full description of CMEs within the distance range of 2–30 solar radii (Yashiro et al., 2004).

The characteristics of ARs and flares are taken from reports produced by the Space Weather Prediction Center (Solar Region Summary, <http://www.swpc.noaa.gov>). These reports provide the following description of ARs: NOAA number, location, area, McIntosh classification, longitudinal extent, total number of visible sunspots in the group and magnetic classification of the group. The reports include also the locations and X-ray fluxes of X-flares. During the SOHO era (1996–2014) 116 large SEP events, with intensity ≥ 10 pfu (pfu = 1 particle $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) in the 10 MeV energy channel, were recorded. Some of these SEP events were generated by CME-driven shock originating behind the west solar limb, in that case the associated ARs could not be determined. However, a coronal shock, strongly deviating interplanetary magnetic field structures or even cross-field diffusion may explain an intensity increase at a far separated observer. For 84 SEP events we were able to determine the MCSC for associated ARs and these events are used for our study. The most energetic solar particles are not only observed by satellites placed in the Earth’s vicinity but they can reach detectors on the Earth’s surface. These events produce a ground level enhancement (GLE). In the considered period of time 14 GLEs were recorded and they are also included in our study. They are a smaller sub-sample of all considered CMEs.

3. Results

3.1. Properties of ARs associated with large SEP events

Fig. 1 shows the distributions of the three codes of the MSCS for the ARs associated with SEP events, for the ARs associated with GLE events, and for the general population of ARs considered by Bornmann and Shaw (1994). The SEP events are divided into three sub-samples on the basis of their flux intensity. According to this division we selected 64 SEP events with flux between 10–500 pfu, 15 SEP events with flux between 500–5000 pfu and 5 very energetic SEPs with flux above 5000 pfu. The distribution of MSCS codes for a general population of ARs (all ARs recorded during one solar cycle) is presented for comparative purposes. The distributions in panels (m), (n), (o) demonstrate that in general ARs have predominantly simple magnetic structures (A or B classes for the first code of the MSCS). On the contrary, events on the Sun producing SEPs are associated with ARs with more complicated morphology, shown in panels (a)–(i). Our present studies investigate and explain this relationship. Fig. 1 also shows data for 14 GLEs in panels (j), (k), (l). We consider separately

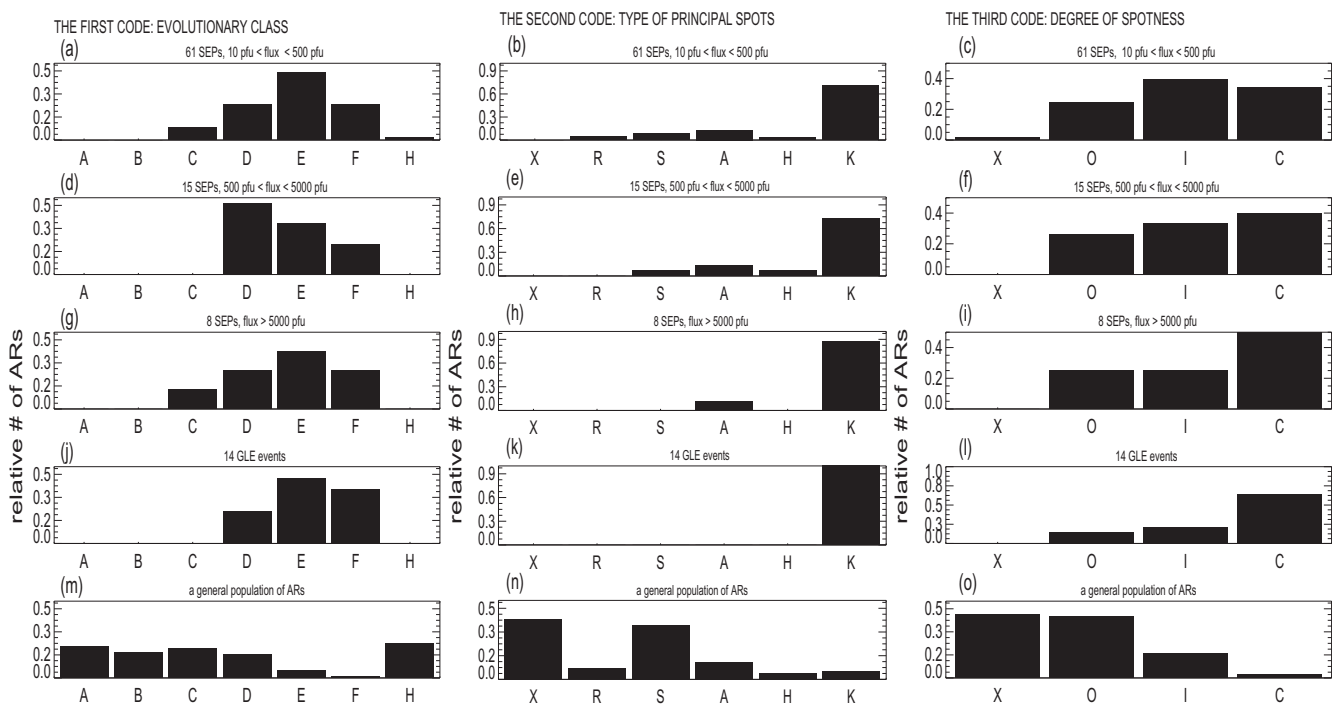


Fig. 1. The distribution of three codes of the MSCS for ARs associated with SEPs (protons) having flux between 10 and 500 pfu (top row; (a), (b), and (c) panels), ARs associated with SEP events having flux between 500 and 5000 pfu ((d), (e) and (f) panels), ARs associated with SEP events having flux above 5000 pfu ((g), (h) and (i) panels), ARs associated with GLEs ((j), (k) and (l) panels) and a general population of ARs considered by [Bornmann and Shaw \(1994\)](#) (bottom row; (m), (n), and (o)).

the GLEs because they are the most energetic events and cause effects on the Earth's surface. Panels (j)–(l) indicate also that GLEs are produced by ARs with more complex magnetic structures, as explained below.

The first column of the panels (Fig. 1(a), (d), (g), (j) and (m)) shows the frequency distributions of the first code of MSCS for the four sub-samples of the ARs and for a general population of ARs. This code is a modified Zurich class indicating the evolutionary stage of the spot group ([McIntosh, 1990](#)). The general distribution of ARs predominantly consists of compact classes (Fig. 1(m)): 93% all of the ARs appear as A (20%), B(18%), C(17%), D (16%) or H(22%) sub-classes of the MSCS which have length $\leq 10^\circ$. Only 7% of all the ARs have more elongated structures (E, F sub-classes). However, the ARs associated with SEP events are generally extended (Fig. 1(a), (d) and (g)), with 67% of SEP events ejected from elongated bipolar ARs classified as E(41%) or F(26%). This tendency is also seen for the ARs associated with the GLEs (Fig. 1(j)), with 75% of the GLEs originating from the most elongated ARs (classes E and F). To check the quantitative difference between the distributions displayed in the panels the Kolmogorov-Smirnov (KS) test is applied. This test is used through this manuscript. We reject the hypothesis that samples are drawn from the same distribution if the p -value from the KS test is less than an assumed significance level (chosen to be 5%). Using the KS test we cannot reject the hypothesis that the distributions presented in the panels (a), (d), (g) and (j) are drawn from

the same distribution. On the other hand, the same test rejects the hypothesis that the general population of ARs (panels (m)–(o)) is the same as the distributions of ARs associated with SEP events (panels (a)–(l)).

The frequency distributions of the second code of MSCS are shown in the second column of Fig. 1 (panels (b), (e), (h), (k) and (n)). This code indicates the characteristics of the largest spot ([McIntosh, 1990](#)). Panel (n) of Fig. 1 demonstrates that the largest spot in each AR in the general population is usually encompassed by a small and symmetric penumbra, with 76% of all the ARs observed as X (39%) and S (37%) sub-classes of the MSCS. Panels (b), (e) and (h) show that the ARs that are related to the SEP events mostly have large and asymmetric penumbras around the main spot, with 80% of these ARs in the K sub-class of the MSCS. The most interesting result is observed for GLEs (panel (k)) and SEP with flux above 5000 pfu (e). These very energetic events originate only from the most complex magnetic structures, represented by the K class for the second code of the MSCS. Panels (b), (e), (h) and (k) indicate that SEP events are produced by ARs with complex main spots. This tendency is statistically significant: using the KS test we can reject the hypothesis that the distributions presented in the panels (b), (e), (h), (k) and (n) are drawn from the same distribution (at the 5% level of significance).

The frequency distributions of the third code of the MSCS are displayed in the third column of Fig. 1 ((c), (f), (i), (l) and (o)). This code indicates the degree of

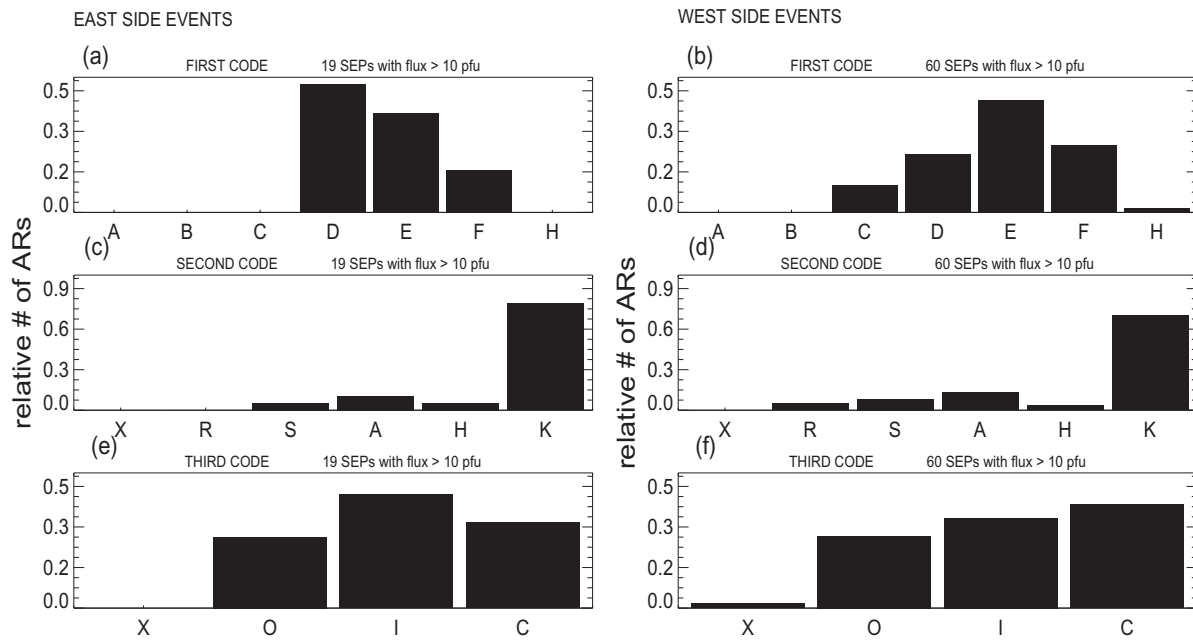


Fig. 2. The distribution of three codes of MSCS for ARs associated with SEP events originating from the eastern (left column: (a), (c), and (e) panels) and the western (right columns: (b), (d) and (f) panels) hemispheres.

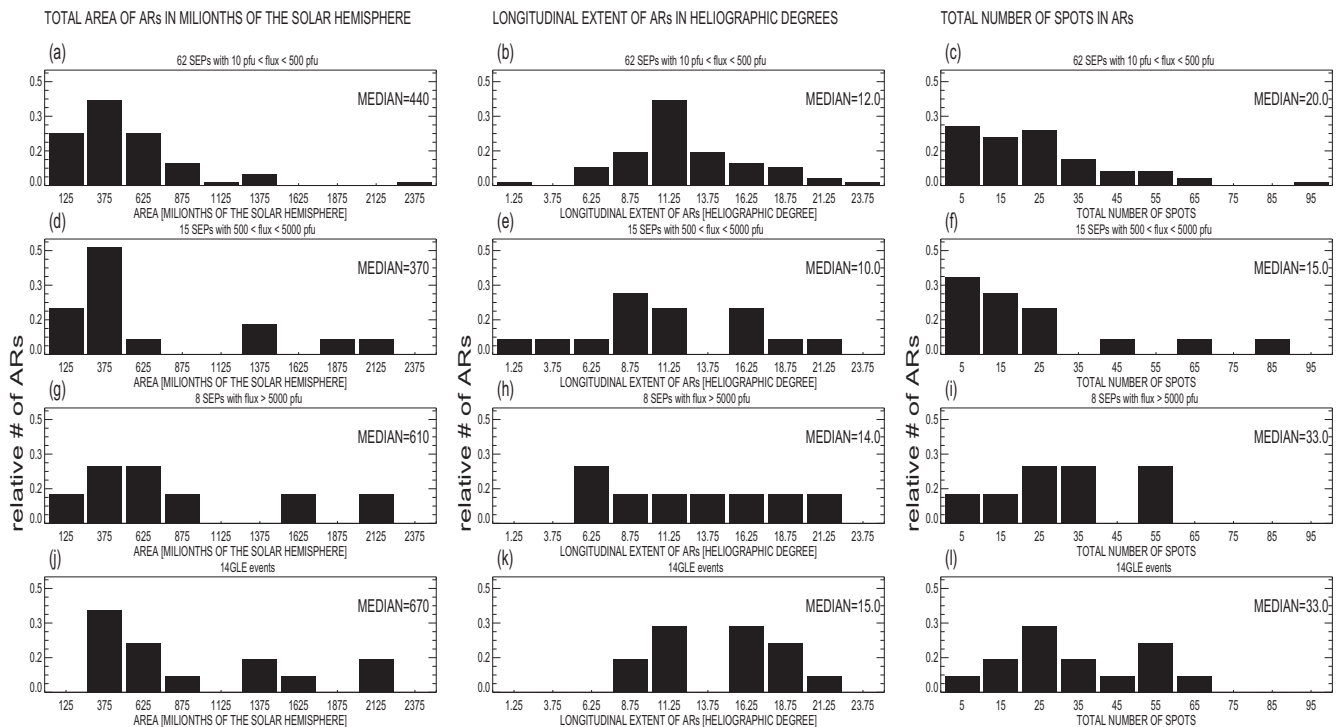


Fig. 3. The distribution of the total area of ARs associated with SEP events (first column; (a), (d), (g) and (j) panels), the distribution of longitudinal extent of ARs associated with SEP events (second column; (b), (e), (h) and (k) panels), and the distribution of the total number of spots in ARs associated with SEP events (third column; (c), (f), (i) and (l)).

spottedness within the sunspot group. The general population of ARs (Fig. 1 panel (o)) is dominated by simple MSCS sub-classes, predominantly X (41%) and O (39%). In contrast, the ARs associated with SEP events are more likely to have multiple small spots and hence belong to

sub-classes I and C indicating that they have complex magnetic structures. For the most energetic SEP events (events with flux > 5000 pfu) 80% of ARs appear as the C subclass of the third code of the MSCS. The similar trend is observed for the GLE events. Using the KS test we cannot

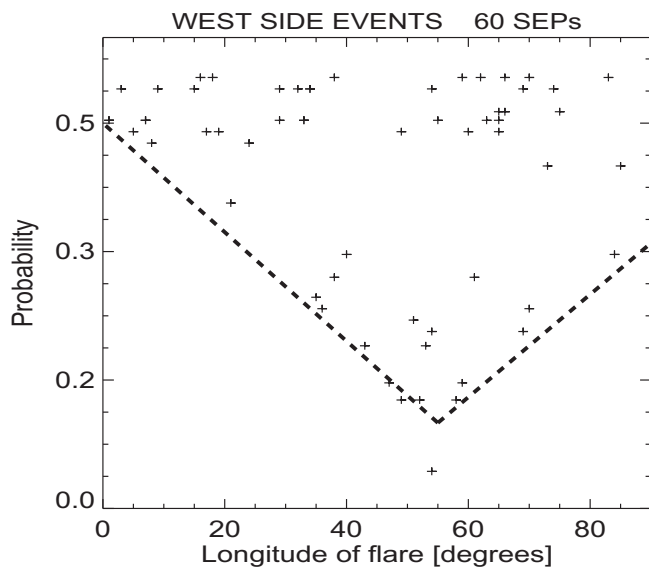


Fig. 4. Scatter plot of the probability of occurrence of SEP events versus longitude of flares associated with SEP events. Dashed lines indicate approximate boundaries of solar longitudes of X-ray flares associated to SEP events.

reject the hypothesis that the distributions presented in the panels (c), (f), (i) and (l) are drawn from the same distribution. On the other hand, the same test rejects the hypothesis that the general population of ARs (panel (o)) is the same as the distributions of ARs associated with SEP events (at the 5% level of significance).

3.2. Properties of ARs associated with large SEP events from the eastern and western solar hemispheres

Based on the location of X-ray flares associated with the SEP events we can divide the SEP events into two sub-samples originated from the western and eastern hemispheres. The hemispheres were divided at the central meridian. In Fig. 2 the distributions of the three codes of MSCS for the ARs associated with the SEP events originating from the eastern (left column) and western (right column) solar hemisphere are presented. 60 SEP events originated from the western hemisphere and 19 large SEP events originated from the eastern hemisphere. In these considerations 5 SEP events, without determined locations of X-ray flare, were omitted. The left hand column shows that the ARs producing SEPs are in the east and large (D, E, F sub-classes for the first code of MSCS); have developed penumbra (S, A, H and K sub-classes for the second code of MSCA); and have many other spots within the group (O, I and C sub-classes for the third code of MSCS). Almost 90% of the ARs associated with the eastern SEP events have the most complex penumbra (K sub-class for the second code of MSCS). On the other hand, the right hand column of Fig. 2 shows that ARs in west which produce SEPs are characterized by C, D, E, F and H sub-classes for the first code of MSCS

corresponding to spot groups with small spatial extent. The distributions of the second and third codes of MSCS for the western and eastern ARs appear similar. The KS test does not reject the hypothesis that the two samples are from the same distribution. However the KS test rejects the hypothesis that the samples of the first code of MSCS presented in the (a) and (b) panels are drawn from the same distribution. This means that SEP events originating from the eastern hemisphere are associated with larger ARs in comparison with these originating from the western hemisphere. The result suggests that to generate SEPs in the Earth's vicinity from the eastern hemisphere, ARs must be sufficiently large. We can only suppose that eastern CMEs producing SEP events are wider in comparison to western CMEs.

3.3. Other characteristics of active regions versus SEP events

The Space Weather Prediction Center Solar Region Summary (SRS) provides also a few additional parameters characterizing ARs, e.g. total area, longitudinal extent, and total number of spots. In Fig. 3, the distributions of these three parameters characterizing ARs associated with SEP events are displayed. The panels (a), (d), (g) and (j) in the first column show the frequency distributions of the total area of ARs associated with SEP events. From the top down, the rows are for events with fluxes in the ranges $10 \text{ pfu} < \text{flux} < 500 \text{ pfu}$, $500 \text{ pfu} < \text{flux} < 5000 \text{ pfu}$, and $\text{flux} > 5000 \text{ pfu}$, and for GLEs. On average the ARs associated with SEP events are large, and overall the area increases with increasing flux of energetic particles. The median value of the total area of ARs increases from $420 \mu\text{-hemispheres}$ for SEP events with fluxes less than 500 pfu up to $790 \mu\text{-hemispheres}$ for GLEs. The distributions of the total area of ARs associated with increasing particle fluxes are not the same (e.g. the KS test indicates that the probability that the distributions presented in the panels (a) and (g) are drawn from the same distribution is 0.006). The figure also indicates that SEPs are only observed for ARs having areas greater than $125 \mu\text{-hemispheres}$.

The second column in Fig. 3 shows the frequency distributions of the longitudinal extent of ARs associated with SEP events with increasing particle flux. Overall the average longitudinal extent of the ARs increases with increasing flux of the energetic particles. The median value of the longitudinal extent of ARs is 11 degrees for SEP events with fluxes less than 500 pfu and is 15 degrees for GLEs. The distributions of the longitudinal extent of ARs for different particles fluxes are significantly different (e.g. the KS test indicates that the probability that the distributions presented in the panels (b) and (h) are drawn from the same distribution is 0.03 at the 5% level of significance).

The third column of Fig. 3 shows the frequency distributions of the total number of sunspots in the ARs associated with SEP events with including particle flux. The median value of the total number of sunspots in ARs is 20 for SEP events with fluxes less than 500 pfu and is 37 for

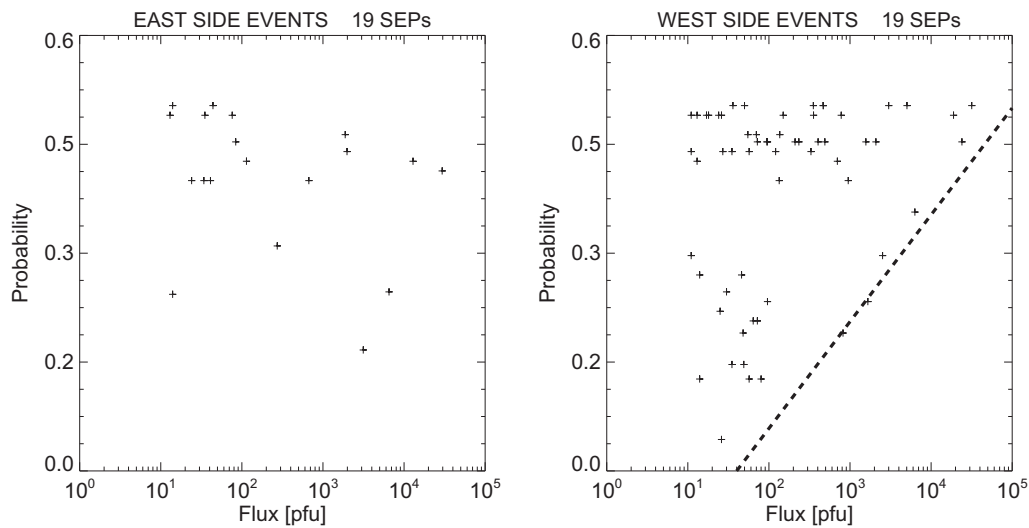


Fig. 5. Scatter plots of particle fluxes versus the probability of occurrence of SEP events for eastern (left panel) and western (right panel) ARs. The dashed line (right panel) indicates the approximate limit for energetic particle fluxes ejected from ARs having a given probability to generate SEPs.

SEP events with fluxes above 5000 pflu. The distributions of the total number of sunspots in the ARs for different particles fluxes are significantly different (e.g. the KS test indicates that the probabilities that the distributions presented in the panels (c) and (i) are drawn from the same distribution is 0.03 at the 5% level of significance). The observed SEP events originate from ARs with at least 5 sunspots.

3.4. Space weather prediction

Previous studies have considered the dependence of SEP events on various parameters characterizing flares and CMEs (e.g. Kahler, 2001; Gopalswamy et al., 2008; Richardson et al., 2014) and have determined associated probabilities for SEP event occurrence (Dierckx et al., 2015). An important issue, from the space weather point of view, is the accurate prediction of fluxes of solar energetic particles at the Earth's vicinity. Utilising characteristics of ARs we propose a new method to predict fluxes of potential SEP events. For this purpose we determine frequencies for association of an SEP event with each value of each MSCS code. The frequencies are obtained from the histograms in panels (b), (d) and (f) of Fig. 2. We used only the western ARs because they are mostly associated to SEP events. The resulting probabilities for SEP association with each MSCS code value are expressed as percentages. This procedure quantifies the observed association of MSCS codes for ARs with SEP event occurrence. If a given code of MSCS appears more frequently overall then it is more important for producing SEPs. Table 2 presents the codes of MSCS together with the assigned frequencies. It shows that for more complex ARs, the probability of generating SEP events is higher. So these probabilities may be used also as proxies of the complexity of magnetic field in ARs. We must note that to get this probability we have not considered all populations of ARs but only the large

SEP events under study. Therefore this parameter express only a probability of the type of AR associated to a large SEP. Using these numerical values we can quantitatively describe the relation between fluxes of SEP events and the magnetic complexity of the associated ARs as measured by the MSCS. For this purpose we can express a probability for occurrence of an SEP event from a given AR as a sum of the three codes of MSCS divided by 300 ($(\text{code1} + \text{code2} + \text{code3})/300$). As the codes of MSCS are expressed as percentages, we divided their sum by 300 to get the probability in the range between 0 and 1. This probability, correlated with complexity of magnetic fields in ARs, can be used to prediction of fluxes of large SEP events originating on the west side hemisphere.

3.4.1. Origin of large SEP events

Fig. 4 shows scatter plots of the longitude of flares versus the probability of occurrence of SEP events. In the figure the longitudes correspond to the locations of flares. Dashed lines indicate approximate boundaries of solar longitudes of X-ray flares associated to SEP events. They were determined by hand. The diagrams demonstrate that ARs, with the probability above the value 0.4 (complex ARs) are observed to produce SEPs from any longitude. ARs with probability below 0.2 produce SEPs only when they appear at mid-longitudes for western events. This is consistent with expectations. The western regions are more likely to be magnetically connected to the Earth. Flare location is obtained from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) the X-ray flare catalog.

3.4.2. Flux prediction

Given our numerical description of the probability of occurrence of SEP events we can predict fluxes of SEP events associated with the ARs. Fig. 5 shows scatter plots of particle flux versus the probability of occurrence of

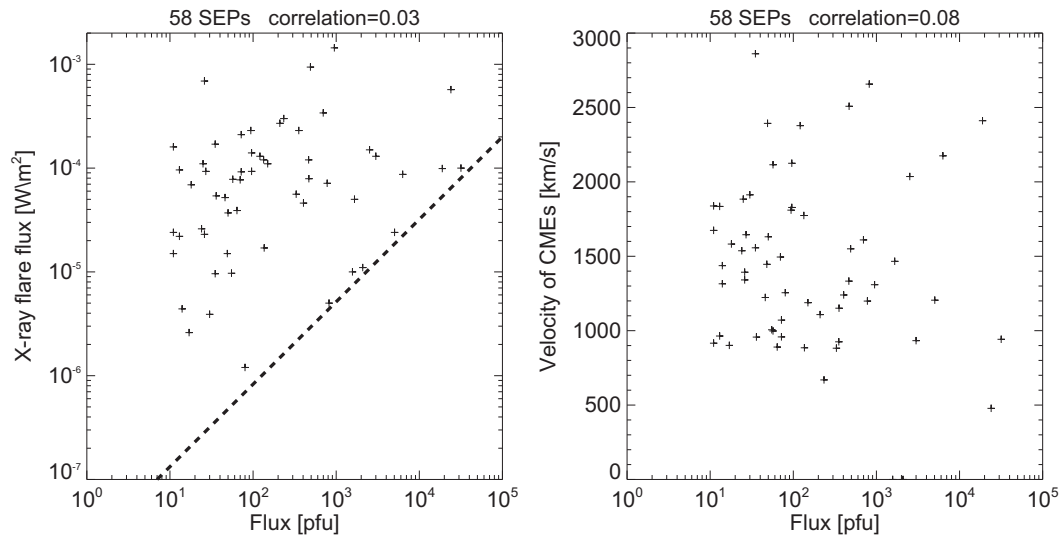


Fig. 6. Scatter plots of fluxes of energetic particles versus X-ray maximal flux of associated flares (left panel) and versus velocity of associated coronal mass ejections (right panel). Only west side events are present.

Table 2
Three codes of MSCS with assigned probability of appearance of an SEP event.

First code		Second code		Third code	
A	0%	X	0%	X	2%
B	0%	R	3%	O	26%
C	9%	S	9%	I	34%
D	22%	A	14%	C	38%
E	41%	H	2%		
F	26%	K	72%		
H	2%				

SEP events for the events from the western (left panel) and eastern (right panel) hemispheres. The dashed line (right panel) indicates the approximate limit for observation of SEP events from ARs having a given probability to generate SEPs. The panels show that ARs with probability above 0.4 produce SEP events with any value of flux. The western events show that less complex magnetic structures (lower probability) produce SEP events with lower fluxes of particles. This trend is indicated by the dashed line. ARs with probability less than 0.3 produce SEP events with flux less than 100 pfu. This diagram may be very useful for space weather forecasting. The eastern events do not show any trend in the association of flux and probability (complexity of ARs).

Fig. 6 shows scatter plots of fluxes of SEP events versus the X-ray peak flux for the associated flares (left panel) and the fluxes of SEP events versus the velocity of the associated coronal mass ejections (right panel). We considered only west side events. These diagrams were produced as a check on whether other parameters could serve as a proxy for prediction of the flux for SEP events. The figure shows no significant evidence for association of the flare with the fluxes of SEP events. For velocities of CMEs we do not recognize a similar trend. Previous considerations

demonstrated some correlations between parameters of flares, CMEs and SEP events (Kahler, 2001; Gopalswamy et al., 2003; Cane et al., 2010; Cliver et al., 2012; Richardson et al., 2014). Nevertheless our results may not be inconsistent with these results. Falewicz et al. (2009), using numerical MHD simulations, found that peak X-ray fluxes of flares are not significantly associated with productivity of energetic particles during the reconnection process. Michalek et al. (2003) found that the velocities of CMEs, especially for halo events which are mostly associated with the large SEP events, include significant error due to projection effects and may be significantly different from the real velocities of the CMEs. Fig. 6 (left panel) suggests there are two populations. This effect can be caused by two reasons: size of the SEP event sample and the second code of MSCS (asymmetry of penumbra) is very important so the H class for the second code may disrupt the smooth distribution of SEP events.

4. Summary and discussion

This paper investigates, for the first time, the properties of the ARs associated with SEP events based on the McIntosh sunspot class scheme (MSCS). We consider a set of 84 large SEP, with intensity ≥ 10 pfu (pfu = 1 particle $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$) in the 10 MeV energy channel, in time period 1996–2014. We demonstrate (Fig. 1) that SEP events are likely to be observed from complex ARs consisting of large bipolar structures (denoted C, D, E, F in the first code of MSCS) with asymmetric penumbrae around the largest spots (A, K in the second code of MSCS) and many smaller spots in the group (O, I, C in the third code of MSCS). It is also shown that increased flux of SEP events is associated with increasing magnetic complexity of ARs. This tendency is the most significant for the second code of MSCS. The most energetic SEPs are only observed from ARs having

very large and complex penumbra (K sub-class for the second code of MSCS).

We consider separately ARs associated with SEP events originating from the western and eastern solar hemispheres (Fig. 2). The ARs associated with eastern SEP events are found to be larger than those associated with western SEP events. This suggests that CMEs producing SEPs from the eastern side of the Sun may be wider than those associated with western SEP events.

Finally, we introduce a new method for predicting fluxes of SEP events, based on the McIntosh codes. We assign a probability of occurrence of SEP from a given AR defined as a sum of the percentages in the Table 2 for the first code, second code, and third code values for the given AR. Given the location and probability, we can then decide whether this particular AR can produce a SEP event, which allows estimation of the flux of the potential SEP event (Figs. 4 and 5). The prediction uses commonly available data and can be made prior to a possible event. This method works well only for ARs appearing on the western hemisphere.

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Visibility of coronal mass ejections in SOHO/LASCO coronagraphs [☆]K. Bronarska ^{a,*}, G. Michalek ^a, S. Yashiro ^b, S. Akiyama ^b^a *Astronomical Observatory of JU, Orla 171, Krakow, Poland*^b *NASA Goddard Space Flight Center, Greenbelt, MD, USA*

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Abstract

We studied the detection efficiency of coronal mass ejections (CMEs) of the Large Angle Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO). For this purpose LASCO/SOHO observations are compared with these obtained by the two Solar Terrestrial Relations Observatory (STEREO) satellites in quadrature in the period of time June–November 2011. These unprecedented observations enable us to the direct detection of CMEs that are not visible in LASCO coronagraphs (invisible events). Determination of these events allowed us to evaluate the detection efficiency of LASCO coronagraphs. We found that the total visibility function is ≈ 0.80 . Having source location, from associated flares or other signatures observed in the corona, longitudinal variation of the visibility function was also found. It was demonstrated that invisible-to-LASCO CMEs are narrow (average width is only 20°), slow (average velocity is 328 km s^{-1}) and originate from the disk center. We have shown that the detection efficiency of the LASCO coronagraphs with typical data availability is sufficient to detect all potentially geoeffective CMEs.

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Keywords: Sun: activity; Sun: Coronal Mass Ejection (CMEs); Sun: particle emission; Sun: flares

1. Introduction

Coronal mass ejections (CMEs) are large expulsions of magnetized plasma from the Sun. They are intensively studied because of their significant effect on the Earth's environment. The first CME was discovered in 1971 using the seventh Orbiting Solar Observatory (OSO-7) coronagraph (Tousey, 1973). Since that time several spaceborne coronagraphs such as the Apollo Telescope Mount (ATM) coronagraph (MacQueen et al., 1974) on board Skylab, the Solwind coronagraph (Michels et al., 1980) on board the P78-1 satellite, the Coronagraph/Polarimeter (MacQueen et al., 1980) on board the Solar Maximum Mission (SMM) recorded ejections from the Sun. Currently the

Large Angle and Spectrometric Coronagraph (LASCO) (Brueckner et al., 1995) on board the Solar and Heliospheric Observatory (SOHO) mission (Domingo et al., 1995) and Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) (Howard et al., 2002). The SOHO/LASCO observations have already recorded about 20000 CMEs by November 2015. A single instrument has never before observed this many CMEs. The basic attributes of these events are included in the SOHO/LASCO catalog (cdaw.gsfc.nasa.gov/CME_list) maintained by coordinated data analysis workshop (CDAW) data center. Some of the properties of the SOHO/LASCO CMEs have been described by Howard and Wang (1997), St. Cyr et al. (2000), Yashiro et al. (2003), and Gopalswamy et al. (2003a,b, 2004). This catalog has been used as a basic tool for a large number of scientific considerations.

However due to the nature of coronagraphic observations detection of some CMEs is sometimes difficult. For

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example, potentially geoeffective events originating from the disk center are the most difficult to observe. The intensity of Thomson-scattered light depends on electron column density, distance from the photosphere, and scattering angle. The two first factors are the most important. Therefore the detection efficiency of halo CMEs is lowest, since they are usually far from the Sun when appear above the coronagraph occulting disk (Vourlidas et al., 2000; Andrews, 2002). However, these events are crucial to observe due to their geoeffective potential. Additionally it is quite clear that also extremely faint CMEs, below the level of sensitivity, can not be recorded. Therefore we can define visibility functions V , (Yashiro et al., 2005) as $V = N_{obs}/N_{total}$, where N_{obs} is the number of observed CMEs and N_{total} is the total number of events. Since the total number of CMEs is unknown special assumptions must be adopted to determine the V . For instance, assuming that all metric II radio bursts are associated with CMEs we can obtain $V = V_{obs}/V_{TypeII}$, where V_{TypeII} is the number of type II bursts. Under this assumption St. Cyr et al. (2000) found that 95% of metric type II burst have association with CMEs. On the other side, Gopalswamy et al. (2001) demonstrated that approximately a third of type II radio burst originating from disk center (longitudes $< 60^\circ$) were not associated with CMEs. A similar result was obtained by Cliver et al. (2005) by using association of CMEs with EIT waves. Frequently an association between X-ray flares and CMEs is considered. Andrews (2003) showed, on the base of large flares (above M-class), that there is no significant longitudinal variation of CME association with energetic X-flares. Yashiro et al. (2005) extended the considerations additionally for average flares (C-class). They considered 1301 X-ray flares (above C3 level) detected by the GOES satellites and examined the longitudinal variation of the CME visibility function. It was demonstrated that the CME association rate increase with X-ray flare size, all X-class flares are associated with CMEs, while half of CMEs associated with C-class flares were invisible. All the analysis to date have been based on assumption on perfect correlation between CMEs and other energetic phenomena on the Sun.

Since 2006 we have an additional pair of STEREO twin spacecrafts that allow us to observe the solar corona from two additional directions. These observations provide a unique opportunity to evaluate the visibility functions. This is especially possible when the spacecrafts are separated from the Earth by about 90° . These unprecedented observations enable the direct detection of CMEs that are not visible in LASCO coronagraphs (invisible events).

To examine the visibility function we compare CMEs recorded by SOHO/LASCO and STEREO/SECCHI coronagraphs. This paper is organized as follows: in Section 2, the method used for the study are described. In Section 3, we present results of our considerations. Finally, conclusions and discussions are presented in Section 4.

2. Method

The aim of the study is to evaluate how accurate the SOHO/LASCO coronagraphs are in term of CME detection. For this purpose we use observations from the two separate STEREO coronagraphs. This method seems to be the best possible however, it is not perfect. The main concern is that we employ different coronagraphs having distinct technical characteristics. Furthermore, we consider two CME catalogues which apply distinct detection and measurement methods. Therefore, it is absolutely crucial to show that the two catalogs nearly perfectly overlap. Yashiro et al. (2008) compared, in solar activity cycle 23, CMEs identified by manual (SOHO/LASCO) and automatic (CACTus) methods. Both catalogs have almost perfect agreement in the case of wide events (width $> 120^\circ$). Unfortunately, there is a significant discrepancy in the properties and detection rate of narrow events (width $< 30^\circ$). Hence the most significant discrepancy between the catalogs was observed during the unusual last minimum of solar activity when the SOHO/LASCO catalog recorded significant number of very narrow events. Fortunately, coherence between the catalogs is very good during the next solar cycle (24), especially during the rising phase of solar activity. A detailed comparison of three databases (CDAW, CACTus, SEEDS (solar eruption event detection system)), including CDAW and CACTus, have been recently performed by Petrie (2015). The study was concentrated on a significant increase in the rate of CMEs detection during solar cycle 24 compared to cycle 23. However, a statistical analysis of detection rate and properties of CMEs for the different databases during the two solar activity cycles was presented as well. The results clearly demonstrated (Fig. 1, 2, 3, 4, 8, 9, 11) that during the rising phase of solar cycle 24 (2010–2012) both databases overlaps nearly perfect. This very important result has been recently indirectly proved by Hess and Colaninno (2017). They compared some automatic CME detection methods used for LASCO and SECCHI observations. That paper was explicitly focused on trends with time between the catalogs, which were shown to be consistent based on correlation coefficient. As was shown, depending on the phase of solar activity cycle, each method provides distinct detection rate and properties of CMEs. Only during the rising phase of solar cycle 24 (2009–2012) all the considered techniques overlap perfectly (Fig. 1, Hess & Colaninno). This is a specific period in the solar activity cycle when all the detection methods are coherent. Petrie (2015) demonstrated that changes in image cadence do not affect detection rate of CMEs. These results are crucial for the present study. Our technique is based on quadrature observations with the two STEREO satellites. The STEREO satellites observe the Sun in quadrature during the rising phase of the last solar cycle. Therefore, we may use CACTus data to determine the visibility function of CMEs in SOHO/LASCO coronagraphs. Furthermore, we do not employ

the databases blindly. During our identification procedure, whenever there were doubts, we inspected movies from the coronagraphs by ourselves.

In the present paragraph, we describe a procedure applied to compile a list of CMEs and their parameters used for the study. To carry out planned investigations, we considered simultaneously images from SOHO/LASCO and STEREO/SECCHI coronagraphs. Observations from both satellites have overlapped since 2006. For the purpose of the present study we employed only observations in the period of June 2011–November 2011. At this time the STEREO spacecrafts were found in quadrature with respect to the Earth. Additionally during this period of time, after the prolonged minimum of solar activity, a major rise in number of events was reported. This can significantly improve our statistical study. The configurations of the STEREO spacecrafts allows to observe easily events originating close to the disk center in respect to the point of view of the Earth. Such observations can reveal earth directed CMEs not recorded by SOHO/LASCO coronagraphs. In the present study we evaluate the detection efficiency of LASCO coronagraphs. Therefore our study was based on the list of CMEs included in the SOHO/LASCO CME catalog (<http://www.cdaw.gsfc.nasa.gov/CME> list). This catalog delivers a full description of CMEs within the distance range of 2–30 solar radii (Yashiro et al., 2004) and has been commonly used for many studies. The basic attributes of CMEs (e.g. velocity, acceleration and width) are determined manually from running difference images. With the large amount of data available from the SOHO and STEREO coronagraphs, automated detection algorithms have been used to construct catalogs, such as CACTus (Robbrecht and Berghmans, 2004). To apply an automatic recognition technique, a clear definition of a CME is necessary. They assumed, identical as in the SOHO/LASCO catalog, “that a CME is a new, discrete, bright, white-light feature in the coronagraph field-of-view with a radially outward velocity” (Robbrecht and Berghmans, 2004). Additionally, to limit the number of false detections, it was assumed that a CME must be recorded at least through 13 and at most through 250 coronagraphic images and have an apparent angular size of at least 7° . These thresholds eliminate very slow and fast, and very narrow CMEs. In the considered period of time, the SOHO/LASCO catalog includes about 20 such events. This represents only 0.2% of all recorded events and is not statistically significant. To find the list of CMEs missed by SOHO/LASCO catalog we utilized data from the STEREO/CACTUS catalog (<http://secchi.nrl.navy.mil/cactus/>). This catalog also includes basic attributes of CMEs but recorded in COR2/STEREO images. In the considered period of time we found 1044 CMEs stored in the SOHO/LASCO catalog. The CACTus list includes slightly fewer events (20% less). To recognise a sub-sample of events not recorded in the LASCO images we applied procedure having two main steps. In the first step we tried to associate a given CACTus CME with an event from the list of events included in the

SOHO/LASCO catalog. During this operation we compared shapes, onset times, and position angles of events from the two databases. In the case of doubtful events we inspected movies from the two instruments. When this verification is complete, we obtained three preliminary lists of events: stored in the both databases or in one of these database. In the second step, having the list of events included only in the CACTus database we verified one more time if any of these events has association to an event from the SOHO/LASCO list. This means that we applied double-checking procedure to associate CMEs from the two databases. This two steps procedure allowed us to get lists of invisible CMEs to each of the coronagraphs. Approximately, 20% of CMEs are not visible to each of the coronagraphs (LASCO, STEREO A, and STEREO B). We may assumed that the visibility function has similar characteristics for each coronagraph.

To study variation of the visibility function with location on the Sun we determined, if it was possible, source locations of CMEs. Source locations were obtained from associated X-ray flares (http://hesperia.gsfc.nasa.gov/hessi-data/dbase/hessi_flare_lofist.txt) or from eruption signatures recognized in EIT/SOHO images.

3. Results

In the considered period of time (June 2011–November 2011) we obtained different sub-samples of CMEs grouped with regard to the instrument which recorded them. We have events observed simultaneously by all three instruments, by two of them, or only by one telescope. These sub-samples of CMEs are characterised in further considerations.

3.1. SOHO/LASCO catalog

Distributions of the most important attributes of CMEs included in the SOHO/LASCO catalog are displayed in Fig. 1. The successive panels show distributions of velocity, width, position angle, longitude and latitude of source location. In the considered period of time the SOHO/LASCO catalog includes 1044 CMEs. The properties of these CMEs run over a wide range of values (e.g. $41\text{--}2425\text{ km s}^{-1}$ for velocity, $4\text{--}311$ degrees for width (excluding halo events)). They mostly appeared close to the solar equator (panel c). The distributions of these parameters are very similar to these obtained for the whole population of CMEs included in the catalog (Yashiro et al., 2004). Longitudes of source location are distributed over all possible values. However, we observe the clear distribution's peak near the west limb of the Sun. This is proved by the average value which is equal 12° which means that visible-to-LASCO events mostly originate from the west side of solar disk. Latitude of source location has a bimodal distribution with the peaks around ± 20 degrees. These narrow belts represent latitudes where active regions appear during this phase of solar activity.

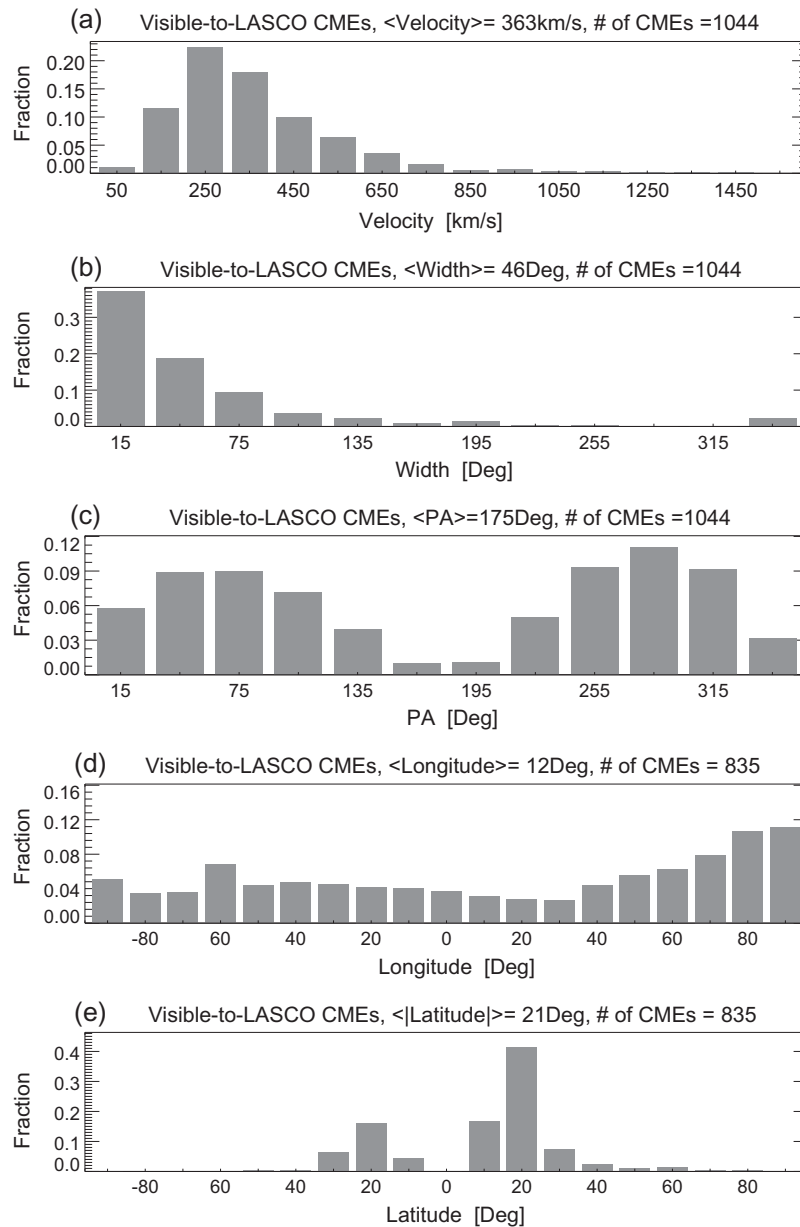


Fig. 1. The distribution of the basic parameters of visible-to-LASCO CMEs (velocity, width, position angle are from the SOHO/LASCO catalog, panels a–c), and longitude and latitude of their source location (panel d and e, June–November 2011).

3.2. Characteristics of CMEs included only in the CACTus catalog

Unfortunately, there are CMEs not observed in the LASCO images. These CMEs can be called as “invisible-to-LASCO CMEs”. Currently we can recognize these CMEs using STEREO coronagraphs. In the considered period of time we found 309 events not included in the SOHO/LASCO catalog. The basic attributes of these CMEs, obtained from the CACTus catalog, are shown in Fig. 2. The successive panels display distributions of velocity, width, position angle, longitude and latitude of source location (the parameters are from the CACTus catalog). If an event was observed by the two spacecrafts then its basic

attributes were calculated as the average value. The properties of invisible-to-LASCO CMEs differ from that recognized by the LASCO coronagraphs. Velocities of invisible-to-LASCO events run over a narrow range of values ($120\text{--}758 \text{ km s}^{-1}$) and their average velocity is about 10% smaller in comparison to SOHO events. The fastest CME was observed by the both coronagraphs (2011/07/27 at 09:24 COR2 A and 09:54 COR2 B). Its velocities were 781 km s^{-1} and 735 km s^{-1} , and widths 26° and 28° in STEREO A and B, respectively. It is very interesting case because this CME is bright and fast but invisible-to-LASCO. The CME was ejected from the back-side of disc center and therefore was invisible-to-LASCO. Widths of invisible-to-LASCO CMEs run over limited

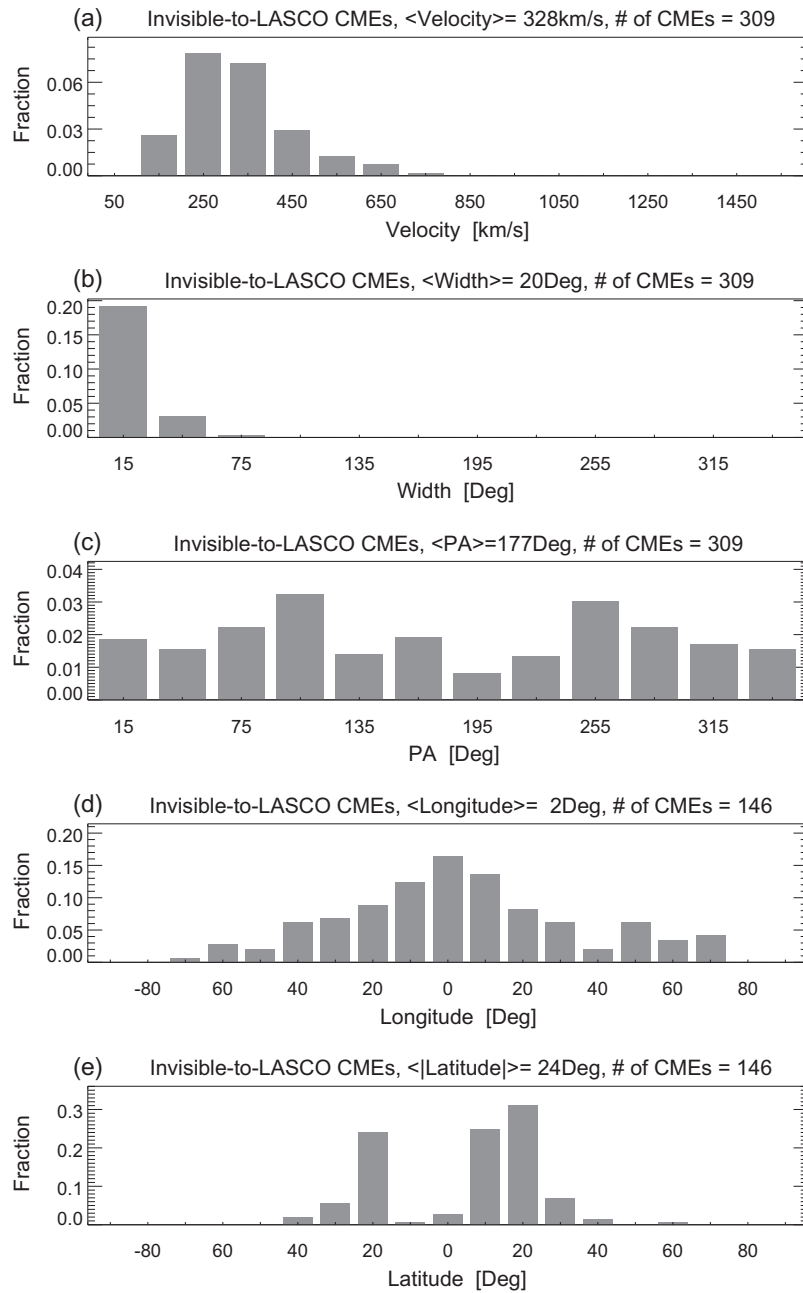


Fig. 2. The distribution of the basic parameters of invisible-to-LASCO CMEs (velocity, width, position angle are from the CATus catalog, panels a–c), and longitude and latitude of their source location (panel d and e, June–November 2011).

range of values (6–72 degrees) and, on average, are two times smaller in comparison to SOHO events. The widest CME was observed on 2011/09/07 at 01:24 by STEREO B coronagraphs. It was backside events blocked out, in the LASCO field of view, by very significant halo CME (on 2011/09/06 at 23:05 in the SOHO/LASCO catalog). The invisible-to-LASCO CMEs, as we could expect, are mostly located in the center of solar disk (panels d and e). The distribution of longitudes has the clear peak near the disk center (the average value of longitude is 2°). If this plot was able to be extended to the longitude of all events, we would expect this plot to be doubly peaked around 0°

and 180° with minimums at $\pm 90^\circ$ as you get away from the occluder and closer to the plane of the sky. We would expect that a roughly equal number of the invisible-to-LASCO CMEs come from both the front and back of the disk. Observational limits will not allow this to be seen.

The results clearly show that the invisible-to-LASCO events have two common attributes. They are not the result of energetic eruptions located near the disk center. The former statement can be also demonstrated by considering X-ray flares associated with CMEs. Histograms showing distributions of classes of X-ray flare associated with the visible-to-LASCO (left panel) and invisible-to-LASCO

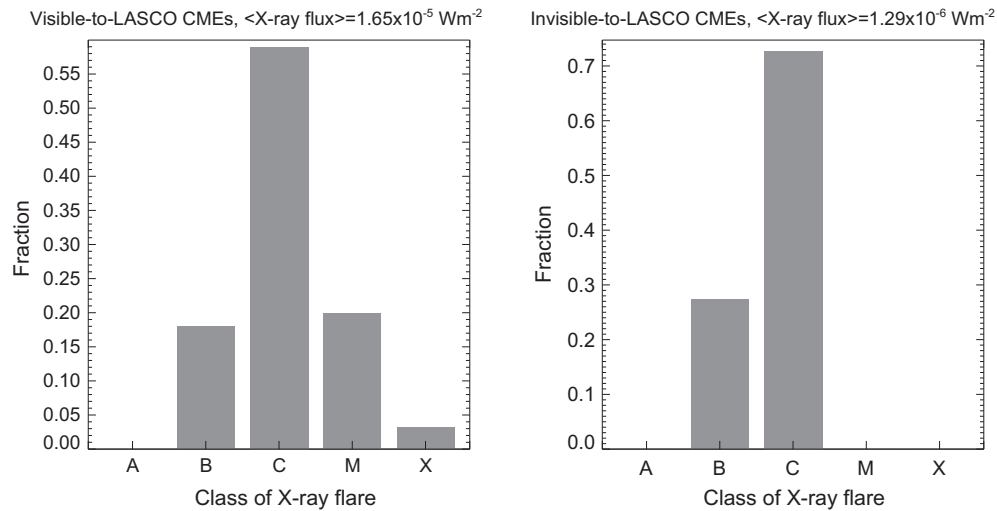


Fig. 3. Histograms showing distributions of classes of X-ray flares associated with visible-to-LASCO (left panel) and invisible-to-LASCO (right panel) CMEs.

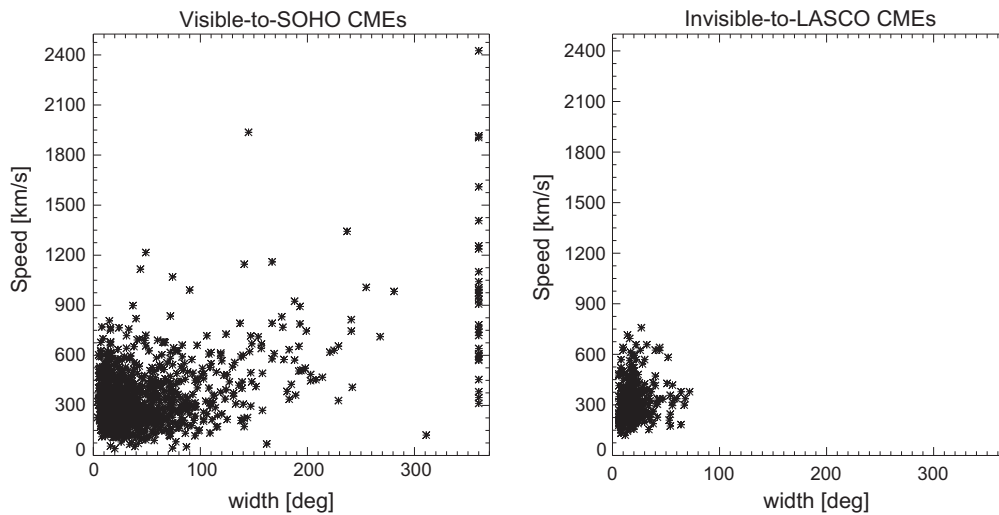


Fig. 4. Scatter plot of velocity versus width for visible-to-LASCO (left panel) and invisible-to-LASCO (right panel) CMEs.

CMEs (right panel) are displayed in Fig. 3. As we expect, the visible-to-LASCO events can be associated with different classes of X-ray flares. On the other side, the invisible-to-LASCO events can be only associated with less energetic flares (classes C and B). The average flux of X-ray flares associated to the invisible-to-LASCO CMEs is about one order of magnitude smaller in comparison to flares associated to the visible-to-LASCO CMEs. Energy of CMEs can be approximately expressed by their velocities and widths. Fig. 4 shows scatter plots of width versus velocity for the visible-to-LASCO (left panel) and invisible-to-LASCO (right panel) events. In the case of the visible-to-LASCO CMEs their velocities are not correlated with widths. Fast, as well as, slow events can have widths from over the whole possible values. The invisible-to-LASCO events have a specific correlation between velocities and widths. Fast events (velocity $>600 \text{ km s}^{-1}$) are narrow (widths $<40^\circ$)

and wide events (width $>40^\circ$) are slow (velocity $<400 \text{ km s}^{-1}$). We must also make it clear that we compared properties of CMEs stored in the two catalogs.

Using our result we can calculate the visibility function. According to the definition we obtained $V = 1044/(1044 + 309) = 0.77$. This means that about 80% of all CMEs can be detected by SOHO/LASCO coronagraphs. This function should depend on source location, velocity and width of the invisible-to-LASCO CMEs. Dependence of the visibility function on these parameters are shown in Fig. 5. In this figure we present fraction of CMEs versus longitude of source location, velocity, and width. We observe almost perfect correlation between the visibility function and longitude of source location (anticorrelation coefficient is equal -0.94). The anticorrelations are also significant in the case of velocity and width, -0.68 and -0.71 respectively. These anticorrelation coefficients

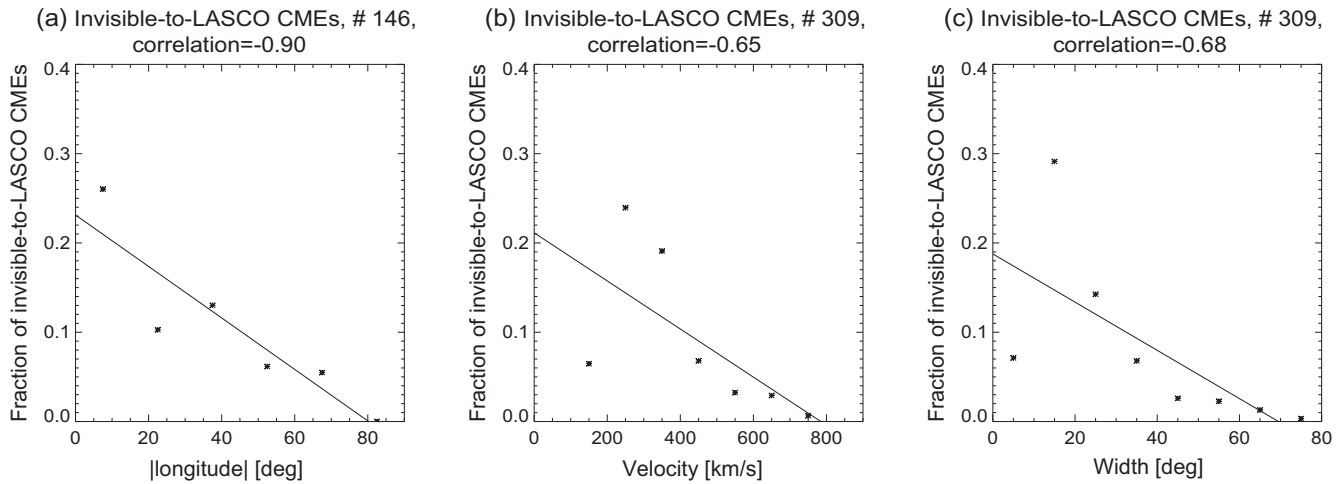


Fig. 5. Scatter plots showing visibility function versus longitude of source location (panel a, fraction of events in 15 degrees bins), velocity (panel b, fraction of events in 100 km/s bins) and width (panel c, fraction of events in 10 degrees bins).

are slightly lower due to deficiency of slow (<50 km/s) and narrow (<5 deg) CMEs.

4. Summary and discussion

We considered all CMEs recorded by SOHO/LASCO and STEREO/SECCHI coronagraphs during the period of June–November 2011. We selected a sub-sample of events detected by SECCHI instruments but not included in the SOHO/LASCO catalog. These events are called as invisible-to-LASCO observations. This study allowed us to evaluate the detection efficiency of LASCO coronagraphs. It was demonstrated that the total visibility function is ≈ 0.80 . This function is almost perfectly anti-correlated with longitude of source location. The invisible-to-LASCO events in comparison to visible-to-LASCO events are, on average, slower (about 10%), narrower (about two times) and originate only from the disk center. We demonstrated that the invisible-to-LASCO events are not energetic. This study clearly revealed that LASCO coronagraphs are not likely to miss events that potentially could be geoeffective. We defined the visibility function based on near quadrature data. This function is likely not static as the separation angle between STEREO and SOHO changes.

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Determination of projection effects of CMEs using quadrature observations with the two STEREO spacecraft

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Abstract

Since 1995 coronal mass ejections (CMEs) have been routinely observed thanks to the sensitive *Large Angle and Spectrometric Coronagraphs* (LASCO) on board the *Solar and Heliospheric Observatory* (SOHO) mission. Their observed characteristics are stored, among other, in the SOHO/LASCO catalog. These parameters are commonly used in scientific studies. Unfortunately, coronagraphic observations of CMEs are subject to projection effects. This makes it practically impossible to determine the true properties of CMEs and therefore makes it more difficult to forecast their geoeffectiveness. In this study, using quadrature observations with the two *Solar Terrestrial Relations Observatory* (STEREO) spacecrafts, we estimate the projection effect affecting velocity of CMEs included in the SOHO/LASCO catalog. It was demonstrated that this effect depends significantly on width and source location of CMEs. It can be very significant for narrow events and originating from the disk center. The effect diminishes with increasing width and absolute longitude of source location of CMEs. For very wide (width $\geq 250^\circ$) or limb events (longitude $\geq 70^\circ$) projection effects completely disappears.

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Keywords: Solar activity; Coronal mass ejection (CMEs); Projection effects of CMEs

1. Introduction

Coronal mass ejections (CMEs) are huge expulsions of magnetized plasma from the Sun. They generate the most severe geomagnetic storms therefore they have been intensively studied. Since 1995 CMEs have been routinely observed thanks to the sensitive *Large Angle and Spectrometric Coronagraphs* (LASCO, Brueckner et al., 1995) on board the *Solar and Heliospheric Observatory* (SOHO) mission. The SOHO/LASCO instruments have already recorded about 30,000 CMEs by December 2016. The basic, observed or derived, attributes of CMEs are stored, among other, in the SOHO/LASCO catalog (cdaw.gsfc.nasa.gov/CME_list, Yashiro et al., 2004; Gopalswamy et al., 2009). This catalog has been widely used for scientific

studies. Unfortunately, coronagraphic observations of CMEs are subject to projection effects. The basic attributes of CMEs (e.g. velocity, acceleration, and width) are obtained from height-time plots. The heights of the leading features of CMEs are determined manually from running difference images. Coronagraphs record 2-dimensional images of the optically-thin CMEs which means that they are observed as projected onto the plane-of-the-sky. This makes it practically impossible to determine the true properties of CMEs and therefore makes it more difficult to forecast their geoeffectiveness. In many scientific studies the impact of projection effect is overlooked. For example, the high accuracy of the CME kinematics are extremely important for considerations of interacting CMEs (e.g., Gopalswamy et al., 2002; Temmer et al., 2012) or their arrival time (e.g., Odstrcil et al., 2005; Vršnak et al., 2013). Some aspects of the projection effect were discussed just before SOHO era by Hundhausen (1993) and

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Hundhausen et al. (1994). Gopalswamy et al. (2000) demonstrated a definite correlation between the longitude of the source location and speed of CMEs confirming the existence of a significant projection effect in the LASCO images. This was also proved by comparison of properties of limb events (having source location at the solar limb) with these obtained from a general population of CMEs (e.g. Burkepile et al., 2004). There were a few attempts to estimate the projection effect based on the width of CMEs (Sheeley et al., 1999; Leblanc and Dulk, 2000) or type III radio bursts associated with CMEs (Michalek et al., 2005). Various cone models (e.g., Zhao et al., 2002; Michalek et al., 2003; Xie et al., 2004; Xue et al., 2005; Michalek, 2006; Zhao, 2008) were developed to estimate the real parameters of halo or partial halo CMEs. It was found that the corrected values of CME parameters can significantly differ from the projected measurements, especially for halo events originating from the disk center. Since the successful launch of the *Solar Terrestrial Relations Observatory* (STEREO, Kaiser et al., 2008) in 2006 we have a unique opportunity to observe the solar corona from two additional directions. Based on multiple-point observations and different assumptions various models to correct the basic attributes of CMEs were developed such as graduated cylindrical shell model (Thernisien et al., 2006, 2009; Thernisien, 2011), triangulation methods (e.g., Temmer et al., 2009; Lugaz et al., 2009, 2010; Liu et al., 2010), mask fitting methods (Feng et al., 2013), geometric localisation (de Koning et al., 2009), and local correlation tracking plus triangulation (Mierla et al., 2010). The accuracy and difference of some models have been compared and discussed by Lugaz et al. (2010) and Feng et al. (2013). These studies mostly have been concentrated only on wide and fast CMEs. However, energetic events represent only few percent of all events included in the SOHO/LASCO catalog. In this paper, we attempt to correct the basic attributes of CMEs, included in the SOHO/LASCO catalog, for the projection effect using quadrature STEREO observations. These observations provide a unique opportunity to evaluate the projection effect for all kinds of CMEs. Without any assumptions or models this approach enables us to the direct determination of the true parameters of CMEs, especially those originating from the disk center.

To evaluate the projection effect we compared the basic attributes of CMEs recorded simultaneously by SOHO/LASCO and STEREO/SECCHI coronagraphs. This paper is organized as follows. The data and method used for the study are described in Section 2. In Section 3, we present results of our study. Finally, conclusions and discussions are presented in Section 4.

2. Method and data

The aim of the study is to evaluate the impact of the projection effect on the basic attributes of CMEs included in the SOHO/LASCO catalog. For this purpose, observations from the two separate STEREO coronagraphs are

employed. This method must be used carefully due to two important concerns. In the study we use data from different coronagraphs having distinct technical properties. Furthermore, we compare data from the two CME catalogues (CMEs identified by manual (SOHO/LASCO) and automatic computer aided CME tracking (CACTus) methods) which use other analytical approaches. To use this technique it is necessary to demonstrate that the two catalogs nearly perfectly overlap. Yashiro et al. (2008) shown that, in Solar Cycle 23, properties of CMEs identified by manual (SOHO/LASCO) and automatic (CACTus) methods are consistent for wide events (width $> 120^\circ$). Unfortunately, for narrow CMEs (width $< 30^\circ$) this coherence disappears. The differences were very significant during the unusual last minimum of solar activity. However, after this period of time, during the rising phase of Solar Cycle 24, this disagreement between the catalogs vanished. Petrie (2015) analyzed three databases (SOHO/LASCO, CACTus, SEED (solar eruption event detection system)). The study shown (Figs. 1, 2, 3, 4, 8, 9, 11) that during the rising phase of Solar Cycle 24 (2010–2012) SOHO/LASCO and CACTus databases almost perfectly overlap. The same result has been recently obtained by Hess and Colaninno (2017). They demonstrated that all considered automatic CME detection techniques, applied for LASCO and SECCHI observations, give the same detection rate and properties of CMEs only during the rising phase of Solar Cycle 24 (2009–2012, Fig. 1, Hess and Colaninno, 2017). This indicates that the rising phase of Solar Cycle 24 is an exceptional period, over the last two solar activity cycles, when all the detection methods are coherent. This coherence resulted due to the specific structure of magnetic field generated on the Sun and condition of the interplanetary medium after the significant last solar minimum (Petrie, 2015; Gopalswamy et al., 2015). Additionally, small differences between catalogs can be neglected since the basic attributes of CMEs included in the SOHO/LASCO catalog are subject to random errors introduced by subjective nature of manual measurements. Our recent study (Michalek et al., 2017) has demonstrated that the mean value of velocity relative errors, due to manual measurements, are about 5% of the velocity itself. All of these argument allow us to employ the different databases to estimate projection effects of CMEs included in the SOHO/LASCO database. It is important to note that this technique has been successfully applied for determination of visibility function of LASCO coronagraphs (Bronarska et al., 2017).

To achieve expected result, we compiled a list of CMEs observed by both satellites. We concentrated on the period of June 2011–October 2011 since at this time the STEREO spacecrafts were found in quadrature with respect to the Earth. Additionally during this period of time, after the unusual minimum of solar activity, a significant rise in the number of events was reported. This is essential for a statistical study. The configurations of the STEREO spacecrafts enable us to observe, without projection effects,

CMEs originating close to the disk center in respect to the point of view of the Earth. These events are potentially geoeffective and cause our immediate concern. In this sense this configurations of spacecrafts is unique. However, this configuration of the satellites allows us to study the projection effect for both instruments. Nevertheless, in this work, we concentrate on projection effects affecting SOHO/LASCO observations. For this purpose, we use the list of CMEs stored in the SOHO/LASCO CME catalog (www.cdaw.gsfc.nasa.gov/CMEList). This catalog include a full description of CMEs within the distance range of 2–30 solar radii (Yashiro et al., 2004). The basic attributes of CMEs (e.g. velocity, acceleration and width) included in the catalog are determined manually. Due to the large amount of data available from the SOHO and STEREO coronagraphs, automated detection algorithms have been also developed (e.g. CACTus; Robbrecht and Berghmans, 2004). This method requires a clear definition of a CME. It was assumed, identical as in the SOHO/LASCO catalog, “that a CME is a new, discrete, bright, white-light feature in the coronagraph field-of-view with a radially outward velocity” (Robbrecht and Berghmans, 2004). Additionally, to limit the number of false detections, it was assumed that a CME must be recorded at least through 13 and at most through 250 coronagraphic images, and have an apparent angular size of at least 7° . These assumptions eliminate very slow, very fast, and very narrow CMEs. Despite these additional requirements, differences between catalogs are neglected. In the considered period of time, only 20 such events are included in the SOHO/LASCO catalog. In the considered period of time we found 1044 CMEs stored in the SOHO/LASCO catalog. The CACTus catalog includes slightly less events ($\approx 20\%$ less). To recognize a sub-sample of events observed by both satellites we used a two-steps procedure. In the first step, having the list of CMEs, from the SOHO/LASCO catalog, we tried to associate them to events included in the CACTus catalog. During this procedure we compared shapes, onset times, and position angles of events from the two databases. For doubtful events we additionally inspected movies from the two instruments. As a result of the procedure we obtained three preliminary lists of events: stored in both databases or in one of these databases. In the next step, having the list of events included only in the CACTus database we verified one more time if any of these events has association to an event from the SOHO/LASCO list. This means that we applied double-checking procedure to associate CMEs from the two databases. This two-steps process allowed us to get the list of CMEs included in both catalogs.

To evaluate variations of projection effects with location of CMEs on the Sun we determined, if it was possible, source locations of CMEs. Source locations of CMEs were obtained from associated X-ray flares (http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_lofist.txt). In our study, from this list, we employed the time of flare onset and the flare location. To associate the flare and CME events, we should defined a time window centered on the

projected onset time of CMEs within which we should look for associated flare activity. Detailed analysis of temporary association between the flares and CMEs were presented by Harrison (1995). It was clearly demonstrated that the 3 h time window (90 min before and 90 min after the onset of the CME) can be taken as reasonable and this time window was applied for our considerations (Harrison, 1995; Yashiro et al., 2004). We are aware that the time window analysis by itself could produce false flare-CME pairs therefore we checked the consistency of these associations by viewing both flare and CME movies in the SOHO/LASCO catalog. We inspected movies obtained by the *Extreme-ultraviolet Imaging Telescope* (EIT) on SOHO and the *Atmospheric Imaging Assembly* (AIA) on *Solar Dynamic Observatory* (SDO) to look for any eruptive surface activities (e.g., filament eruptions, dimmings, and arcade formations) associated with the flares. Such a procedure allowed us to unambiguously associate the flares and CMEs.

3. Results

In the considered period of time (June 2011–October 2011) we obtained the list of events recorded by SOHO/LASCO and at least by one of the STEREO satellites. These events can be statistically analysed to evaluate how projection effects distort derived properties of CMEs.

3.1. Differences between characteristics of CMEs included in both catalogs

Figs. 1 and 2 demonstrate distributions of the differences between the basic attributes of CMEs stored in both databases. Fig. 1 shows results for SOHO/LASCO and STEREO B and Fig. 2 for SOHO/LASCO and STEREO A, respectively. The successive panels (a–d) show distributions of differences between velocities, relative differences between velocities, differences between widths, and relative differences between widths included in both catalogs. In the last panels of Figs. 1 and 2(e) distributions of longitude of source location of CMEs are displayed. In the considered period of time 300 and 222 CMEs were recorded simultaneously by LASCO and STEREO A or B coronagraphs, respectively. The distributions of differences in velocities are almost symmetric and they cover wide range of values ($\pm 500 \text{ km s}^{-1}$). This indicates that velocities determined for both catalogs are consistent and we can assume that the difference between them are mainly due to projection effects. Negative or positive values of these differences mean that the respective CMEs are subject to the projection effect in LASCO and STEREO images, respectively. The mean absolute projection effect is $\approx 130 \text{ km s}^{-1}$. The distributions of relative differences between velocities give more indicative results. They are presented in panels (b). The distributions are almost symmetric and cover wide range of values. The relative differences between velocities can be, in extreme cases, one and a half times larger than

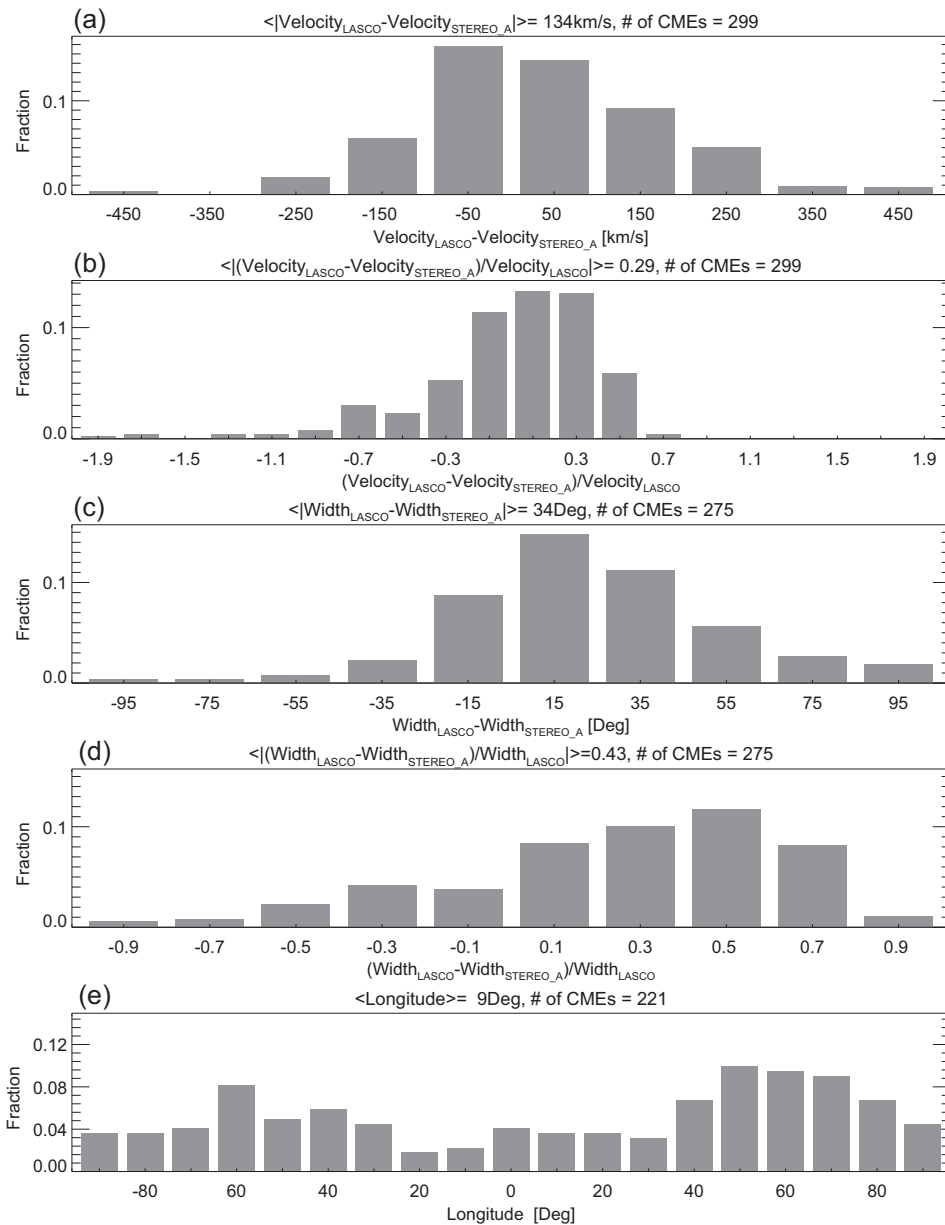


Fig. 1. Distributions of differences between the basic attributes of CMEs (velocity, relative velocity, width, relative width) included in the SOHO/LASCO and CACTus catalogs for STEREO A (panels a–d) and distributions of longitude of their source location (panel e, June–October 2011).

the projected velocity itself. The mean relative projection effect is ≈ 0.30 . In the next two panels (c and d) the absolute and relative differences between width are shown. These distributions are clearly antisymmetric, with SOHO/LASCO events significantly wider in comparison with these from the CACTus catalog. This is due to the different procedures used to estimate this parameter. For the purpose of the SOHO/LASCO catalog the apparent angular width of CMEs is measured from the maximal angular difference between the position angles of the two outer edges of CMEs in the sky plane. In this approach any brightening recorded in the LASCO images are counted as an expulsion of CMEs. In the case of automatic detection to recognize a CME, besides brightening, a radial velocity signal must be

observed (Robbrecht and Berghmans, 2004). At the flanks of CMEs brightening can be caused by compression of coronal plasma and can be recognized as an eruption in SOHO/LASCO catalog but not in the automatic detection method. This means that widths included in the LASCO catalog are systematically larger in comparison with these included in the CACTus catalog. The projection effect of CMEs width are difficult to evaluate. Therefore, our study will concentrate on the projection effect impacting velocities. In the last panels the distributions of longitudes of source location are shown. Longitudes of source location are distributed over all possible values. However, it appears from the figures that the majority of events are at mid-longitudes, away from both limbs.

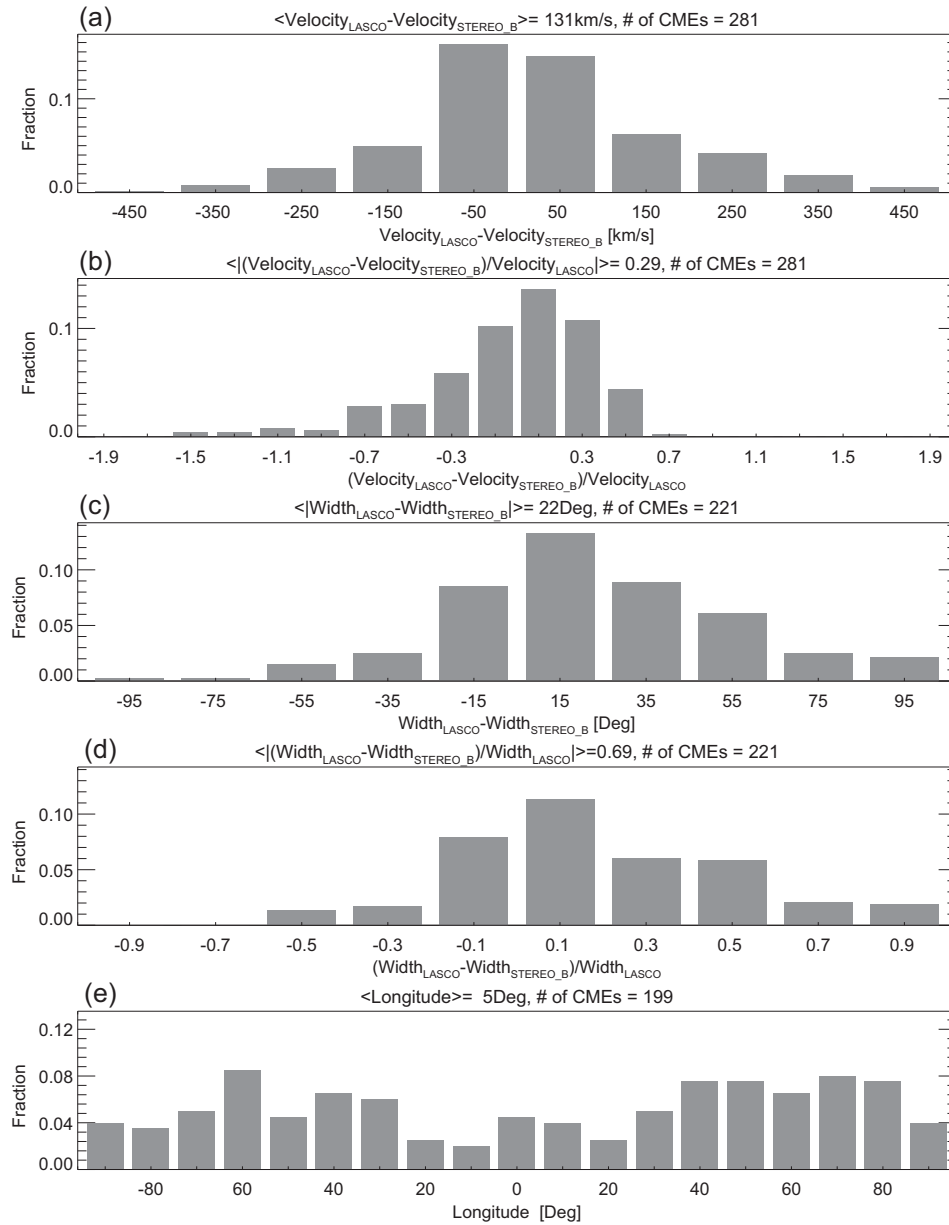


Fig. 2. Distributions of differences between the basic attributes of CMEs (velocity, relative velocity, width, relative width) included in the SOHO/LASCO and CACTus catalogs for STEREO B (panels a–d) and distributions of longitude of their source location (panel e, June–October 2011).

It is evident that due to projection effects the basic attributes of CMEs should systematically change with longitude or angular distance of source location of CMEs from the center of the Sun. Therefore, it seems that plotting these attributes versus the angular distance from the center of the Sun should demonstrate projection effects. With two independent telescopes, we can even try to estimate how this effect affects the basic attributes of events. Fig. 3 displays velocities of CMEs, obtained from both satellites, versus angular distance of source location from the center of the Sun. The angular separation was obtained, using spherical trigonometry, from longitudes and latitudes of the flare locations. Panel (a) shows exactly velocities from both telescopes versus the angular distance from the center of the Sun visible from the position of the Earth. Dotted

and dashed lines are linear fits to SOHO/LASCO and STEREO datasets, respectively. We observe weak trends confirming the existence of projection effects. The speeds determined from SOHO/LASCO observations systematically increase along with the distance from the disk center and those for STEREO decrease. Panel (b) shows the same data except that for STEREO observations, the source location of an explosion was shifted as if the center of the Sun was observed from the position of the STEREO satellites (the source longitude were shifted by 90°). Now, we observe almost identical changes of velocities with distances from the disk center for both datasets. Linear fits almost overlap. These results show that the velocities observed with these instruments are affected by projection effects. Nevertheless, the real CME velocities are not

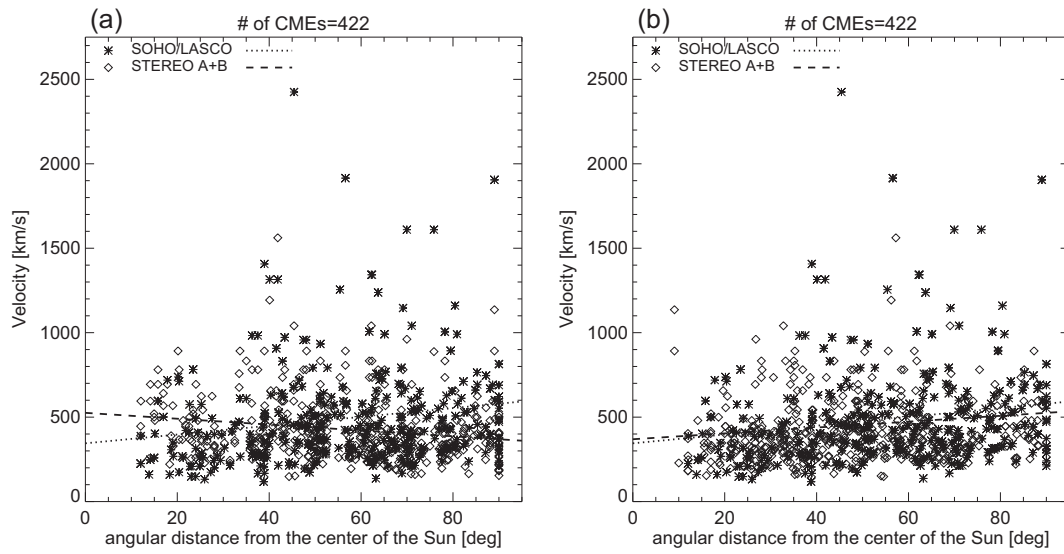


Fig. 3. Scatter plot of velocity of CMEs, obtained from both satellites, versus angular distance of source location from the center of the Sun (stars are for SOHO/LASCO and diamonds for STEREO A and B datasets). The angular separation was obtained, using spherical trigonometry, from longitude and latitude of the flare location. Panel (a) shows exactly velocities, from both telescopes, versus the angular distance from the center of the Sun visible from the position of the Earth. Dotted and dashed lines are linear fits to SOHO/LASCO and STEREO datasets, respectively. Panel (b) shows the same data except that for STEREO observations, the source location of an eruption was shifted as if the center of the Sun was observed from the position of the STEREO satellites (the source longitudes were shifted by 90°).

constant but randomly spread over a wide range of values, so there is not a significant relationship between the source locations and velocities of events. From this figure it is evident that this approach cannot be used to estimate projection effects. Therefore, in order to more accurately estimate the projection effect, in the further part of our considerations we will refer to the difference in velocity for individual CMEs.

3.2. Velocity projection effect versus width of CMEs

It is obvious that projection effects must be mainly dependant on width and source location of CMEs. Fig. 4 shows the absolute value of the relative differences between velocities versus width of CMEs determined for the SOHO/LASCO catalog (panel (a)). Additionally, in panel (b), average values of the absolute value of the relative difference between these velocities determined in 20° bins are displayed. As it was to be expected, the projection effect can be the most significant for narrow and less important for wide events. The dashed line (Panel (a)) shows approximate limit on the maximal relative velocity difference for respective widths. The formula for this upper limit is:

$$y = 0.0044 * x + 1.6, \quad (1)$$

where y is the absolute value of the relative difference between velocities and x is the width of CME in degrees. And the solid line (Panel (b)) shows a general trend reflecting the importance of projection effects with the width of CMEs. This relation is described by the formula:

$$y = -0.00034 * x + 0.31, \quad (2)$$

where y is the average value of the absolute value of the relative difference between velocities determined in 20° bins and x is the width of CME in degrees. As shown in Fig. 4, the projection effect depends on width of CMEs. The projection effect in the case of narrow CMEs (width $< 30^\circ$) may cause significant change in CMEs velocities up to one and a half times of their velocity included in the SOHO/LASCO catalog. Only very wide CMEs (width $> 200^\circ$) have smaller projection effects. In the figure, we did not include halo CMEs because even their approximate widths are unknown. It is also worth mentioning that very similar result (not included in the manuscript) were obtained for widths determined for STEREO spacecrafts.

3.3. Velocity projection effect versus source location of CMEs

Angular distance of source location of CMEs from the center of the Sun is the second parameter having a direct effect on projection effects. Fig. 5 shows the relative difference between velocities versus the longitude of source location of CMEs (panel (a)) and versus the angular distance of the source location from the disk center (panel (b)). The results presented on both panels are very similar. We can only notice that on panel (b) the source locations are systematically shifted towards larger angles. For this panel, we do not observe practically the ejections located in the center of the solar disk. This is due to the fact that in this case we have included additional latitude of source location. As expected, projection effects, from the point of view of SOHO/LASCO coronagraphs, is the most significant for CMEs originating from the disk center. For the limb events

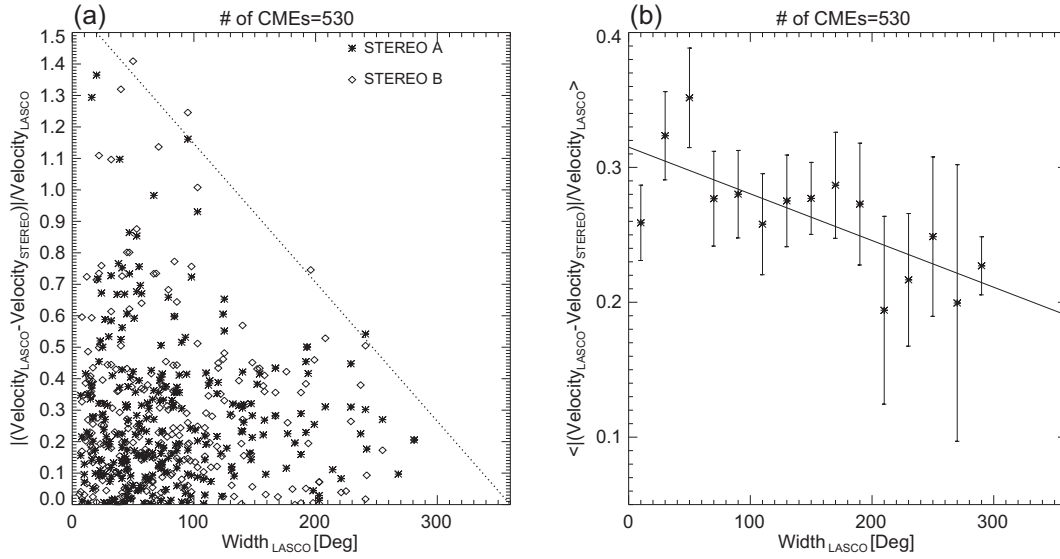


Fig. 4. Scatter plots of the absolute value of the relative difference between velocities versus width of CMEs recorded in the SOHO/LASCO catalog (Panel (a)). Stars and squares are for the differences between SOHO/LASCO and STEREO A and SOHO/LASCO and STEREO B, respectively. Dashed line shows approximate limit on the maximal relative difference between velocities. Panel (b) shows average values of the absolute value of the relative difference between velocities obtained in 20° bins together with standard deviations. Solid line is a linear fit to data points.

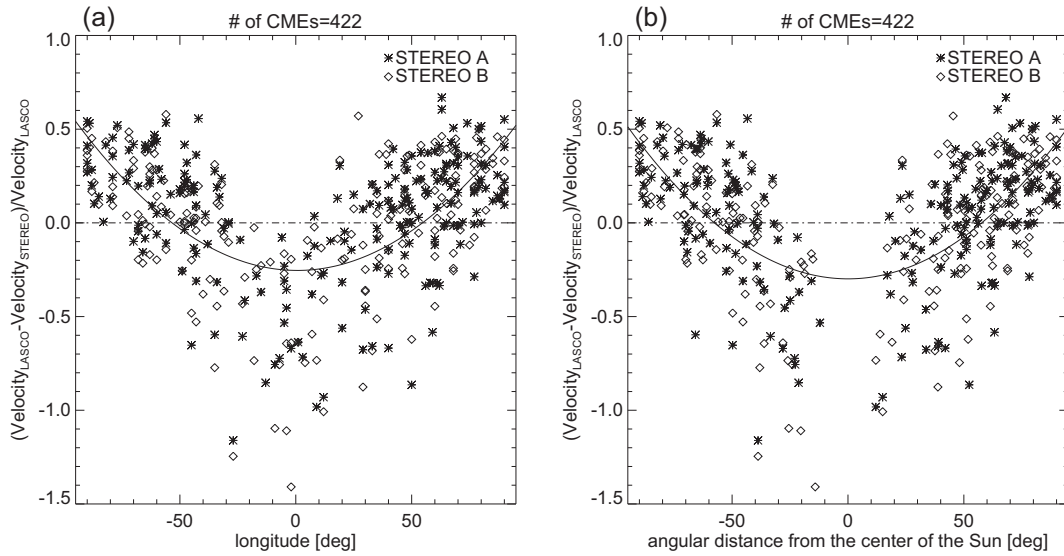


Fig. 5. Scatter plot of the relative difference between velocities versus longitude of source location of CMEs. Stars and squares are for the differences between SOHO/LASCO and STEREO A and SOHO/LASCO and STEREO B, respectively. Continuous line are quadratic fits to data points. Dashed lines divide figures for areas where SOHO/LASCO velocities are larger (above this line) or smaller than STEREO velocities (below this line).

($|\text{angular distance from the disk center}| > 70^\circ$) this effect disappears. We may clearly state that from the point of view of the Earth projection effects decrease with increasing angular distance from the center of the Sun. In this frame of reference for STEREO observations the opposite trend is observed. This opposite behaviour is only caused by reference system. In fact STEREO data are subject to the exact same projection effects as LASCO. The continuous lines show quadratic fit to the data points. The formula for this fit is:

$$y = -0.252934 - 0.00011 * x + 0.000086 * x^2, \quad (3)$$

for the longitude of source location and

$$y = -0.298703 - 0.0000059 * x + 0.000089 * x^2, \quad (4)$$

for the angular distance of source location from the disk center, where y is the relative difference between velocities and x is the respective angle in degrees. It may be used to correct the projection effect for velocities of CMEs. Dashed lines divide figures for areas where SOHO/LASCO velocities are larger (above this line) or smaller than STEREO velocities (below this line). From the point of view of space weather our attention should be focused on halo CMEs

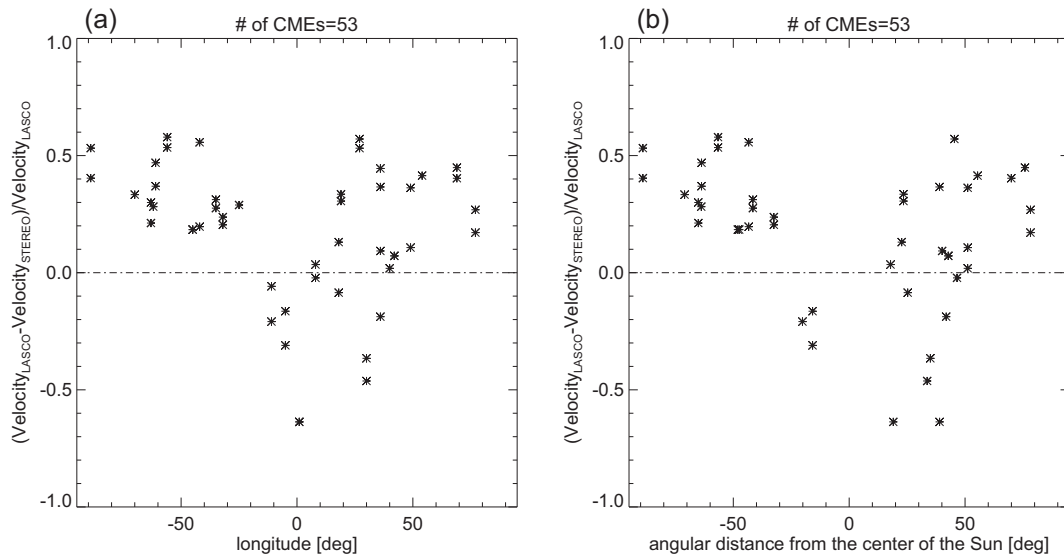


Fig. 6. Scatter plot of the relative difference between velocities versus longitude of source location and angular distance from the center of the Sun of halo CMEs. Stars and squares are for the differences between SOHO/LASCO and STEREO A and SOHO/LASCO and STEREO B, respectively. Dashed lines divide figures for areas where SOHO/LASCO velocities are larger (above this line) or smaller than STEREO velocities (below this line).

since they are responsible for the severest geomagnetic storms. Fig. 6 shows the relative difference between velocities versus longitude (panel (a)) of source location and angular distance from the center (panel (b)) of halo CMEs. As expected, the projection effect, from the point of view of SOHO/LASCO coronagraphs, is the most significant for events originating close to the disc center. Its impact diminishes rapidly as longitude increases. For halo events having source location farther from the disk center ($|\text{longitude}| > 40^\circ$) this effect disappears.

For a few halo CMEs, near the disk center (within longitude 50°), we observe larger speeds in comparison with speeds obtained from STEREO coronagraphs. This unexpected observation may result from imprecise determination of source location of eruptions. Our considerations are based on the location of associated flares. The flares are much more compact phenomena compared to the very energetic halo CMEs. The CMEs are associated with plasma expulsions from a large volume in the corona. This makes it difficult to clearly determine their source location. This explanation is confirmed by the comparison of the results presented on the panels (a) and (b). As we can see this unexpected effect is not so significant in the case when we also included the latitude of source location not only the longitude (Panel (b)).

4. Summary and discussion

In the study we evaluate the projection effect which affects coronagraphic observations. We concentrated on the SOHO/LASCO coronagraphs because they are the main tools for CME detection since 1995. For this purpose we employed two additional STEREO coronagraphs observing the Sun in quadrature. Therefore, we considered

all CMEs recorded by SOHO/LASCO and STEREO/SECCHI coronagraphs during the period of June–October 2011.

Firstly, we have shown that both data bases are consistent in the considered period of time. This allowed us to compare the basic attributes of CMEs included in both data bases. However, when comparing the results of these two missions, we must also remember that they have different field of views. SOHO/LASCO coronagraphs have a range of up to 32 solar radii and STEREO coronagraphs only up to 15 solar radii. This fact may in particular affects the determination of CME speeds. It seems, however, that this is not essential for our research. A detailed analysis of the velocity changes of CMEs with the distance from the Sun, which we performed for a sample of events, has revealed that they reach the maximum speed before the distance of 15 solar radii from the Sun. So that both instruments, despite different field of view, should record similar speed of CMEs.

It was demonstrated that observations of CMEs included in the SOHO/LASCO catalog are subject to the projection effect. It is consistent with the previous studies (Gopalswamy et al., 2000; Burkepile et al., 2004; Sheeley et al., 1999; Leblanc and Dulk, 2000). Fig. 4 demonstrated that STEREO coronagraphs, like other coronagraphs, also are subject to similar effect. This effect on, average, is equal about 130 km s^{-1} or 0.3 in absolute or relative values, respectively.

We also shown that this effect significantly depends on the width and longitude of source location of CMEs (Fig. 4). It can be very significant for narrow events (width $< 30^\circ$) and it can be neglected only for very wide events (width $> 200^\circ$). Depending on width of CME we provided upper limit for the projection effect.

We also evaluated dependence of projection effects on longitude of source location. It was demonstrated that projection effects could be very significant for events originating from the disk center. It systematically decreases with increasing longitude of source location. Only halo CMEs origination close to disk center ($|\text{longitude}| < 40^\circ$) are subject to the projection effect.

We demonstrated that this method cannot be used to determine projection effect for width of CMEs. Unfortunately, both considered catalogs have different method to determine width of CMEs so their comparison is not conclusive.

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Very narrow coronal mass ejections producing solar energetic particles

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ABSTRACT

Aims. Our main aim is to study the relationship between low-energy solar particles (energies below 1 MeV) and very narrow coronal mass ejections (“jets” with angular width $\leq 20^\circ$).

Methods. For this purpose, we considered 125 very narrow coronal mass ejections (CMEs) from 1999 to 2003 that are potentially associated with low-energy solar particles (LESPs). These events were chosen on the basis of their source location. We studied only very narrow CMEs at the western limb, which are expected to have good magnetic connectivity with Earth.

Results. We found 24 very narrow CMEs associated with energetic particles such as ions (protons and ^3He), electrons, or both. We show that arrival times at Earth of energetic particles are consistent with onset times of the respective CMEs, and that in the same time intervals, there are no other potential sources of energetic particles. We also demonstrate statistical differences for the angular width distributions using the Kolmogorov–Smirnov test for angular widths for these 24 events. We consider a coherent sample of jets (mostly originating from boundaries of coronal holes) to identify properties of events that produce solar energetic particles (velocities, widths, and position angles). Our study presents a new approach and result: very narrow CMEs can generate low-energy particles in the vicinity of Earth without other activity on the Sun. The results could be very useful for space weather forecasting.

Key words. Sun: coronal mass ejections (CMEs) – Sun: activity – Sun: particle emission

1. Introduction

The first coronal mass ejection (CMEs) was detected in the 1970s with the Orbiting Solar Observatory (Tousey 1973). CMEs are episodic large expulsions of magnetized plasma from the Sun that involve significant disturbances in the solar wind, and if they are directed toward Earth, can be potential sources of geomagnetic activity and harmful to advanced technology. Energetic CMEs can generate geomagnetic storms and solar energetic particles (SEPs; Gopalswamy et al. 2007). Understanding the mechanism by which SEPs are accelerated is a long-standing problem in solar physics (Cliver 2009). There is evidence for particle acceleration by two different processes: a flare reconnection process, and a CME-driven shock. Large SEP events are usually but not always associated with large flares and CME-driven shocks (Gopalswamy et al. 2015). Flare and shock processes both contribute to the particle flux, but the relative contribution from them is unclear (Cliver 2009; Klecker et al. 2007).

The timescales for CME eruptions are from several minutes to several hours (Hundhausen et al. 1994). A wide diversity of expulsions are observed, but the events may be divided into at least two categories: normal and narrow CMEs. The normal CMEs mostly originate from closed magnetic structures such as erupting flux rope systems, consisting typically of a three-part structure: a leading front, a dark cavity, and a bright core (Crifo et al. 1983).

The first narrow structures were detected in 1985 (Howard et al. 1985). Very narrow CMEs are defined as events whose angular width is 20° or less. This choice of an apparent

angular width is quite arbitrary: the real difference between the types is that the very narrow CMEs have an elongated jet-like shape, whereas the normal CMEs resemble closed loops. These differences may indicate different mechanisms of initiation of the two CME types. The CME width distribution appears to be a featureless power law (Robbrecht et al. 2009), which suggests that there is only one basic mechanism.

Observations made with the Solar and Heliospheric Observatory (SOHO) mission’s Large Angle and Spectrometric Coronagraphs (LASCO) suggest that very narrow events themselves originate from either coronal holes (jet-like CMEs) or streamers (blob-like CMEs). The blob-like CMEs can be divided into two groups: structured and unstructured. Faster (above 400 km s^{-1}) and narrower jets (angular width less than 5°) usually originate from coronal holes (St. Cyr et al. 1997) although jets can sometimes be caused by other magnetic processes (Kahler et al. 2001) while continuous slow (300 km s^{-1}) outflows are observed from streamers, and these events are similar to the solar wind. A mechanism for blob ejection and plasma sheet formation has been proposed in which a stretched helmet-streamer loop reconnects with neighboring open field lines in the vicinity of the cusp (Wang et al. 1998).

Kahler et al. (2001) found an impulsive SEP event observed by the Wind spacecraft on 2000 May 1 that was associated with an impulsive flare and also with a narrow CME. This result assumed a flare is necessary to produce SEPs at 1 AU, and Kahler et al. (2001) did not provide detailed information (e.g., velocities, widths, and position angle) for the event. The 2000 May 1 CME event has a position angle (PA) of 323° , a

width of 54° , and a velocity of 1360 km s^{-1} (Wang et al. 2012). The angular width is sufficiently wide to exclude this CME from our group of very narrow CME events, according to our definition. Nitta et al. (2006) investigated the solar origin of impulsive SEP events generated by flares. They also demonstrated that these events were associated with CMEs with a range of different widths. Wang et al. (2012) surveyed the statistical properties of a set of 1191 solar electron events observed by the WIND 3DP instrument over one solar cycle (1995 through 2005). For a subset of the events, they also surveyed the accompanying low-energy ion emissions, which are highly enriched in ^3He . They started from solar electron events and examined the possible association with Geostationary Operational Environmental Satellite (GOES) SXR flares, CMEs, and type II and III radio bursts. This sample includes a set of narrow CMEs with some overlap with the events we consider here, but nine very narrow SEP events in our group of events are not listed by Wang et al. (2012). This may be attributed to the different selection methods.

In comparison to previous studies, we concentrate on very narrow CMEs (“jets”) to show that such events (without other activity on the Sun, i.e., without flares) are able to produce low-energy solar particles (LESPs). It is possible that very narrow CMEs may be a source of low-energy SEPs because they are expected to be triggered in open magnetic structures, which may allow the energized particles to escape. During solar activity maximum, coronal holes migrate from the poles to the equator and may then generate very narrow CMEs (jets) that are magnetically connected to Earth. We excluded the solar minimum as a period useful to investigations because large and stable streamers appear at the solar equator during solar minimum. Such magnetic structures produce only “blobs” (narrow but very slow CMEs). Therefore, SEPs produced by jets from coronal holes can only be detected during solar maximum. We here study very narrow CMEs around the maximum of solar cycle 23 (1999–2003).

In comparison to previous investigations, in the first stage we consider a coherent sample of jets (mostly originating from the boundaries of coronal holes) to identify properties of events that produce SEPs (velocities, widths, and PAs). This is a new approach and scientific goal.

This paper is divided as follows. The data used for this study are described in Sect. 2. A data analysis is performed in Sect. 3. In Sect. 4 we present the results of our analysis, and the conclusions are discussed in Sect. 5.

2. Data

For our analysis we used two databases: LASCO images, and the time series from the Advanced Composition Explorer (ACE) particle detector. The data for our study were taken from the SOHO/LASCO CME catalog. The list of CMEs in the catalog is compiled using images from the LASCO coronagraphs on board SOHO¹. In our study we concentrated on fast and narrow CMEs originating close to the solar equator on the west side. These narrow CMEs can produce SEPs recorded near Earth. From the period of time 1999–2003, we selected events for which the central PAs are between 255° and 285° (the central PA is defined as the mid-angle with respect to the two edges of the CME in the sky plane and is measured anticlockwise from the solar north pole), the angular widths are equal to or below 20° , and the speeds are above 400 km s^{-1} . We consid-

ered only narrow CMEs originating from the western hemisphere close to the solar equator. The motivation is that these events are likely to have good magnetic connectivity with Earth and so can generate energetic particles that are likely to reach Earth (McCracken 1962). Figure 1 presents a typical example of a considered jet ejection. The left panel displays the image from the Soft X-ray Telescope (SXT) on board the Yohkoh satellite. On the right side we show the running-difference image from the LASCO C2 coronagraph. The Yohkoh/SXT image at 02:01 UT shows the X-ray jet with a flare brightening at the jet base. This eruption is observed in the later four images. This event has a width of 12° and a speed of 610 km s^{-1} . Similar X-ray structures were also observed, in Yohkoh or Extreme ultraviolet Imaging Telescope (EIT) images, for other considered ejections.

The Electron, Proton, and Alpha Monitor (Gold et al. 1998; EPAM) on board the Advanced Composition Explorer (ACE) mission provides information about energetic particles appearing in the vicinity of Earth. ACE contains ten instruments, but only the EPAM detector is used for our study. It is important to note that the ACE satellite is placed outside of the Earth’s magnetosphere, so that it only registers particles from the interplanetary medium. We used the EPAM Level 2 Data, which show ions in five channels (46–67 keV, 115–193 keV, 315–580 keV, 795–1193 keV, and 1060–1880 keV) and electrons in four channels (between 38–53 keV, 53–103 keV, 103–175 keV, and 175–315 keV).

3. Data analysis

LESPs can be produced by different phenomena (e.g., flares and shocks). In the study we must be very careful to associate LESP events with narrow CMEs. For this purpose, for all considered CMEs, we applied the special procedure we describe below. We performed our study around the maximum of solar cycle 23 (1999–2003). As mentioned, the analysis was limited to fast (with speeds above 400 km s^{-1}) and very narrow (a width of 20° or less) CMEs that were potentially magnetically connected to Earth (PAs between 255° and 285°). To ensure that a given ejection was really magnetically connected to the Earth, we inspected Yohkoh/SXT and SOHO/EIT images and searched for signatures of eruption from the limb of the solar disk. Additionally, we restricted the study to narrow events that are not a part of another CME. The selection criteria also include the requirement that there are no other west-limb CMEs in the LASCO images with times consistent with production of an SEP in the search-time window, or for some time before. This makes us confident that a given LESP event was not associated with a shock generated by another CME. For example, for the very narrow CME in our list that occurred on 2003 Jan 23 at 02:54, the ACE data show an increase in the 38–53 keV flux after ≈ 30 min, and an increase in the 175–315 keV flux after ≈ 15 min. This is consistent with the narrow CME at 02:54 producing the SEP event, and we do not observe other activity from the west limb in the four hours before. Hence we associate the narrow CME with the SEP event. Our study includes a very representative sample.

For the considered period of time, we found 125 events that fulfilled these requirements. If narrow CMEs originating from the western hemisphere fulfil these conditions, they might be expected to produce an SEP event. To test this hypothesis using data from ACE, we searched for fluxes of energetic particles associated with our sample of narrow CMEs. To determine

¹ https://cdaw.gsfc.nasa.gov/CME_list/

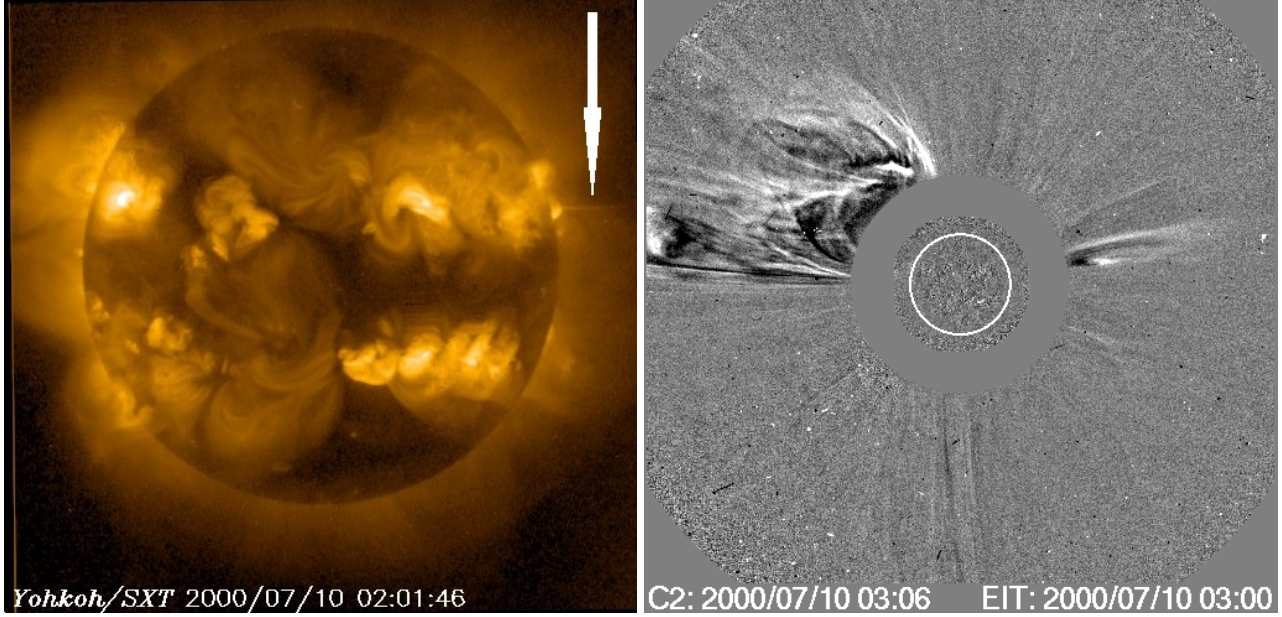


Fig. 1. Example of a jet ejection. *Left panel:* X-ray jet (Yohkoh/SXT) on 2000/07/10 at 02:01. *Right panel:* this jet is later observed in the LASCO C2 coronagraph at 03:00.

Table 1. Travel time for protons and electrons with energies covered by the ACE detectors.

Particle	Channel	Energy ranges (keV)	Maximum travel time (h)	Median travel time (h)	Minimum travel time (h)	Difference between max and min travel times (h)
e ⁻	(DE1)	38–53	0.46	0.42	0.39	0.07
e ⁻	(DE2)	53–103	0.39	0.33	0.30	0.09
e ⁻	(DE3)	103–175	0.30	0.27	0.25	0.05
e ⁻	(DE4)	175–315	0.25	0.23	0.21	0.04
Ion	(P1)	46–67	17	15	14	3.0
Ion	(P3)	115–193	11	9.3	8.3	2.7
Ion	(P5)	315–580	6.4	5.5	4.7	1.7
Ion	(P7)	795–1193	4.1	3.7	3.3	0.8
Ion	(FP6')	1060–1880	3.5	3.0	2.6	0.9

whether our narrow CMEs were associated with low-energy solar particles, we estimated their travel times to Earth. Energetic particles move along spiral magnetic field lines (the combination of the outward motion of the solar wind and solar rotation), so we assume that to reach Earth, they have to travel a distance equal to 1.2 AU. The solar wind blows radially outward, carrying with it the solar magnetic field, and it produces a classical Archimedean spiral magnetic field (the Parker spiral). The propagation distance 1.2 AU was calculated based on a slow solar wind speed of about 400 km s^{-1} , which was assumed because the slow solar wind appears to originate from a region around the Sun's equatorial belt (Feldman et al. 2005).

The travel time was estimated using the energy of the particles. We calculated travel times for ions (protons and ^3He) and electrons observed by ACE in different energy ranges, using the relativistic formulas for protons and electrons. The estimates are presented in Table 1. The table shows the ranges of energies for respective detectors (Cols. 2 and 3), the respective travel times (Cols. 4, 5, and 6) and the differences between minimum and maximum travel times (Col. 7). For each channel the minimum travel time is calculated for the maximum energy, the maximum travel time is calculated for the minimum energy, and the median travel time is calculated for the median energy. For the five chan-

nels for ions and for the two channels for electrons, we obtained graphs from ACE data. Then, according to Table 1, we checked whether during the respective time frames the channels showed a visible increase in the flux above the noise level. To ensure that our methods were reliable, we required detection of LESP in at least in two channels. It is important to mention that we assumed free-streaming propagation of the energetic particle. The SEPs along the way interact with interplanetary magnetic irregularities undergoing cross-field diffusion and changes in their kinetic energy (Dalla et al. 2013; Zank 2014).

Figure 2 shows the flux of electrons in the 38–53 keV and 53–103 keV energy ranges on 14 December 2001. From the time of observation of a narrow event at the Sun and using Table 1, we expect to see an increase in the electron flux after ≈ 20 – 30 min for these channels. The very narrow CME on 14 December 2001 occurred at 23:30. In the ACE data, a peak well above the noise at $\approx 00:00$ on 2001 Dec 15 is visible, which is in the expected time window. The intensity level for the event is $> 2 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ in the 38–53 keV band and $> 2 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ in the 53–103 keV band.

4. Results

4.1. Events producing energetic particles

We found 24 LESP that are associated with narrow CMEs. We considered only the very narrow events for which we observe an increase in the particle flux in at least two channels. These events are presented in Table 2. In the first three columns we present the number of the event, and the date and the time of CME appearance in the LASCO field of view. We have marked 15 events with asterisks that are also included in Wang et al. (2012). The next two columns give the onset time for the CME obtained from linear and quadratic fits to height-time points based on data in the SOHO/LASCO catalog. Parameters characterizing the CMEs (PA, angular width, and speed) are shown in Cols. 6, 7, and 8, respectively. Column 9 contains the location of the very narrow CMEs established on the basis of EIT images. We determined these locations using different

Table 2. Properties of 24 very narrow CMEs generating low-energy SEPs.

	Date	Time of appear. (UT)	Onset 1 (UT)	Onset 2 (UT)	Central PA (deg)	Angular width (deg)	Speed (km s ⁻¹)	Location	Radio bursts III type DH/metric	e ⁻	³ He-rich us/Wang	B0 (deg)
1	1999 Sep 15*	05:06	04:14	04:17	277	14	518	N14W95	04:30/04:23	Yes	Yes/Yes	+7.22
2	2000 Jul 10	02:26	01:42	01:41	285	12	610	N20W80	-/-	Yes	Yes/-	+3.88
3	2000 Aug 07*	12:30	11:30	11:43	278	13	581	N14W85	12:10/11:31	Yes	Yes/Yes	+6.25
4	2000 Oct 02	07:27	06:28	06:40	262	20	1036	N05W95	06:50/06:45	No	Yes/-	+6.64
5	2000 Oct 04	04:06	03:19	02:37	261	13	597	N01W87	03:50/03:41	No	Yes/-	+6.54
6	2001 May 01	11:54	11:07	11:17	272	19	667	S01W90	11:54/11:22	Yes	Yes/-	-4.11
7	2001 Dec 14*	23:30	22:47	22:54	269	7	463	S10W83	23:30/22:53	Yes	No/No	-0.92
8	2001 Dec 17*	03:30	02:53	03:03	264	6	812	S01W85	03:10/03:02	Yes	Yes/Yes	-1.15
9	2002 Oct 05	12:30	11:55	12:03	272	20	723	N05W80	no data/11:49	Yes	Yes/-	+6.52
10	2002 Oct 06*	06:30	05:42	05:54	266	10	860	N10W84	06:00/05:51	Yes	Yes/Yes	+6.46
11	2002 Oct 06*	15:54	15:07	15:19	269	16	792	N10W84	15:30/-	Yes	Yes/Yes	+6.43
12	2002 Oct 06*	20:06	19:17	19:18	268	12	642	N10W84	19:35/18:54	Yes	Yes/Yes	+6.42
13	2002 Oct 07*	00:30	00:02	23:51	269	12	759	N10W90	00:20/00:13	Yes	Yes/Yes	+6.41
14	2002 Oct 07*	06:06	05:28	05:33	272	10	724	N12W90	05:45/05:20	Yes	Yes/Yes	+6.40
15	2002 Dec 14*	09:30	08:50	09:00	272	6	697	N03W80	09:06/09:03	Yes	No/No	-0.81
16	2002 Dec 26	14:54	14:13	14:18	255	19	872	S14W91	-/-	Yes	No/-	-2.34
17	2003 Jan 22*	08:54	07:44	08:00	278	18	565	S10W70	07:54/07:50	Yes	Yes/Yes	-5.22
18	2003 Jan 23*	02:54	02:20	02:25	272	12	785	S10W80	02:25/02:22	Yes	Yes/Yes	-5.29
19	2003 Aug 15	02:06	01:36	01:31	262	8	814	S08W91	01:50/01:46	No	No/-	+4.63
20	2003 Oct 03*	15:10	14:16	14:30	273	8	417	N06W91	14:40/14:11	Yes	No/Yes	+6.61
21	2003 Oct 03*	20:56	20:11	-	261	8	643	S10W90	20:20/20:07	Yes	No/Yes	+6.60
22	2003 Oct 04*	13:31	13:05	13:11	273	17	1425	N06W91	13:31/13:11	Yes	Yes/Yes	+6.56
23	2003 Oct 04	21:54	21:35	21:38	285	20	1050	N06W91	21:45/21:32	Yes	Yes/-	+6.55
24	2003 Oct 05	01:31	00:55	00:40	276	16	895	N06W95	01:20/01:07	Yes	Yes/-	+6.54

Notes. We have marked 15 events with asterisks that are included in Wang et al. (2012).

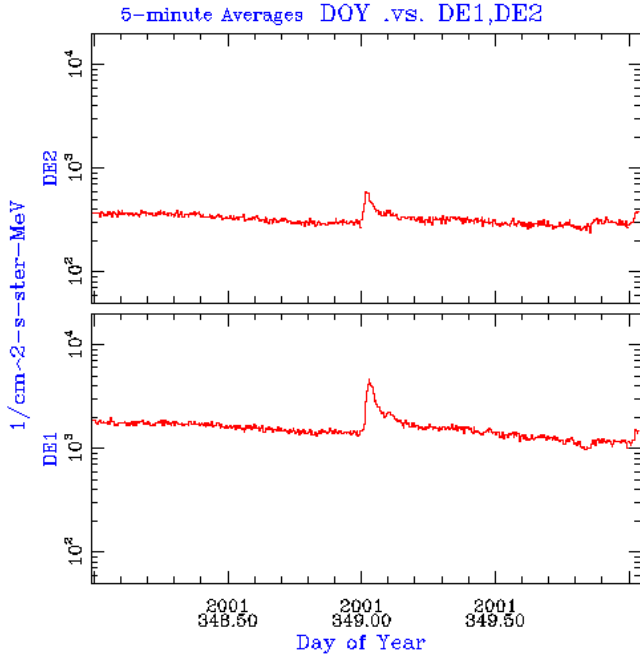


Fig. 2. Five-minute averaged solar particle flux. Electron flux in the ACE EPAM Level 2 data in the 38–53 keV and 53–103 keV energy ranges on 14 December 2001.

ejection signatures. For events ejected behind the limb, the approximate longitudes are presented. Knowing the solar rotation rate, we estimated the longitudes of the active area that the respective CMEs are associated with. Column 10 provides the onset times of associated III type radio bursts in decameter-hectometer (DH, based on WIND data) and meter wavelengths (from the Solar Geophysical Data). In the case of two events, we did not identify any radio

emissions. We also checked these databases for type II bursts. We found no type II radio bursts associated with these narrow events.

Columns 11 and 12 give information about the types of particles that are generated by the events, that is, electrons and ³He-rich particles, respectively. The abundance of ³He was determined based on data from the Ultra Low Energy Isotope Spectrometer (ULEIS) particle instrument on board ACE. ULEIS measures ion fluxes from He through Ni from about 20 keV nucleon⁻¹ to 10 MeV nucleon⁻¹. It covers both suprathermal and energetic particle energy ranges. Additionally, we provide information about ³He-rich events obtained by Wang et al. (2012). Almost all SEP events are ³He rich. This indicates that reconnection produces the energetic particles (Nitta et al. 2015; Bucik et al. 2016). Only six extremely narrow events included in our studies were not ³He-rich events. In the last column, we show B0-angles representing the heliographic latitude of the central point of the solar disk. This angle varies from -7°.23 to +7°.23 and represents the inclination of the Sun’s equatorial plane with respect to the ecliptic. This parameter influences the magnetic connectivity of CMEs (Gopalswamy et al. 2013; Gopalswamy & Mäkelä 2014). When it is positive or negative for a north or south CME source location, it improves the magnetic connectivity. This parameter can be important in our study because we consider very narrow events. Only for three CMEs, taking into account source locations, is the magnetic connectivity weaker (4 December 2002, 15 August 2003, 3 October 2003). For the remaining events, this parameter improves the magnetic connectivity of the considered CMEs.

We assumed that a given particle flux is associated with a given CME if the particle travel time is consistent with the appearance times for the SEP event at Earth. Table 2 shows that only five CMEs generate fluxes of both electrons and ions at ACE. Sixteen CMEs produce only fluxes of electrons, and three

events produce only energetic ions. One of the SEP events, on 4 October 2003, is associated with a flare at 13:09 (N06W91). In comparison to previous studies (e.g., Wang et al. 2012) our procedure is very restrictive. If we cannot observe an increase in particle flux well above the noise level, or if any case is uncertain, we mark “no” in Table 1.

To prove that associations between the narrow CMEs and SEPs are real, we conducted an additional test. We chose at random 30 narrow and isolated events with PAs excluding their magnetic connection to Earth. These events were not likely to produce SEPs near Earth. If in our study an accidental coincidence between SEPs and the very narrow CMEs was possible, we should also find energetic particles for these events. We did not find any SEPs associated with these CME events, however. This result clearly proves that our considerations are correct.

We checked different databases for X-ray flares associated with our events. Only two of the SEP events were associated with flares. The first occurred on 26 December 2002 at 14:38 (S14W91, B5.1), and the second occurred on 4 October 2003 at 13:09 (N06W91, C2.5).

We also evaluated CME speed profiles. The considered events are very fast and mostly reach high speeds ($>600 \text{ km s}^{-1}$) very close to the Sun (20 events). This velocity is enough to generate interplanetary shocks (Gopalswamy et al. 2001). For 4 events, which have only a few height-time points in the LASCO field of view, the velocity determination close to the Sun is ambiguous. Of the considered CMEs, 75% decelerate in the LASCO field of view.

The considered SEP events are mostly ^3He -rich. This means that magnetic reconnection is involved in particle acceleration (Nitta et al. 2015). On the other hand, the associated CMEs attain high speed early and can produce shocks, although of very small width. Probably both these mechanisms, magnetic reconnection and shocks, must be effective to generate SEP events.

4.2. Statistical analysis of narrow CMEs

Only 19% (24) of the 125 narrow CME events we identified produced energetic particles. It is interesting to compare the properties of the narrow CMEs that do and that do not produce energetic particles. The CME samples are statistically different. All CMEs producing SEPs are limb events (longitude close to 90°) that were located very close to the solar equator. The CMEs without SEPs can be located much closer to the solar center: about 20% of them have a longitude lower than or equal to 70° . The presence of type III radio bursts is an indicator of energetic electrons in the solar corona. For 21 (90%) SEPs events we found associated type III bursts. In Fig. 2 we show the velocity distributions of CMEs that produce (dashed line) and that do not produce SEPs (solid line). The diagrams suggest that the SEP events are associated with fast narrow CMEs. The narrow CMEs with SEPs have a median speed that is 100 km s^{-1} faster than narrow CMEs without associated SEPs.

The second most important parameter characterizing CMEs is their angular width. In Fig. 3 we show the angular width distribution of CMEs that produce SEPs (dashed line) and that do not produce SEPs (solid line). The diagrams suggest that SEP events are more likely to be produced from slightly wider CMEs. It is important to note that energetic particles are observed to be generated by CMEs with an angular width larger than or equal to 6° .

To estimate the probability that the two sets of data (narrow CMEs with SEPs, and narrow CMEs without SEPs) are drawn from the same distribution, we performed a Kolmogorov-

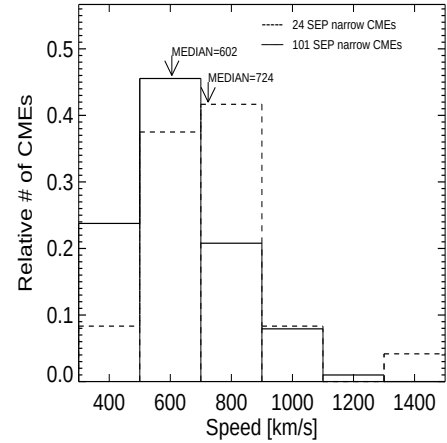


Fig. 3. Velocity distribution for narrow CMEs associated with SEPs (dashed line) and without SEPs (solid line).

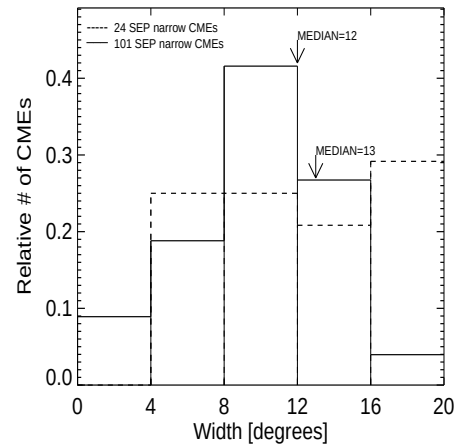


Fig. 4. Angular width distribution for narrow CMEs associated with SEPs (dashed line) and without SEPs (solid line).

Smirnov (K-S) test (Press et al. 1992) on the distributions shown in Figs. 3 and 4. For the speed distributions (Fig. 4), the K-S test result is $p = 0.3$ (p is the computed probability at the 0.05 significance level), and for the width distributions (Fig. 3), the result is $p = 0.01$. Hence there is no evidence for a statistical difference between the velocity distributions, but there is evidence for a difference between the width distributions.

Finally, in Fig. 5 we consider PA distributions for the two CME samples. This parameter is very important because to be geoeffective, narrow CMEs must originate close to the solar equator. The distributions are very similar. The narrow SEP events have PAs between 255° and 290° . If CMEs are really associated with SEP events, they must be magnetically connected to Earth. This means that the narrowest events producing SEPs should exactly originate in the regions closest to the solar equator. In Fig. 5 we present PA distributions, but only for CMEs with an angular width smaller than 8° . The CMEs producing SEPs originate only from PAs between 261° and 279° , but CMEs without SEPs originate from significantly wider ranges of PAs (249° – 285°). This means that the PAs of CMEs producing SEPs are correlated with their widths (with a correlation coefficient equal to 0.33). The correlation coefficient is not significant, but we recall that wider CMEs (width $\geq 8^\circ$) producing SEPs can originate from the entire range of PAs, but only the narrowest events are limited to start exactly from the equatorial region.

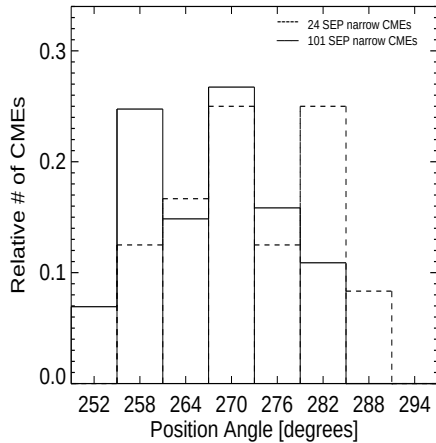


Fig. 5. PA distribution for narrow CMEs associated with SEPs (dashed line) and without SEPs (solid line).

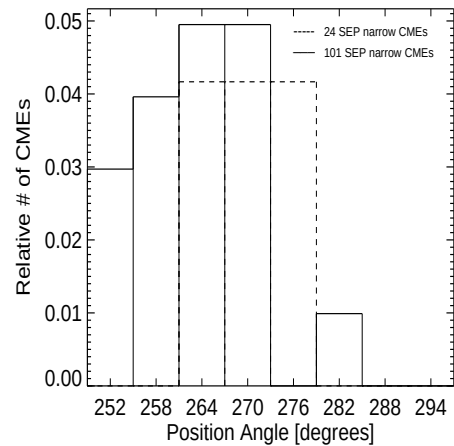


Fig. 6. PA distribution for narrow CMEs associated with SEPs (dashed line) and without SEPs (solid line). Only CMEs with an angular width smaller than 8° are shown.

5. Summary and discussion

We considered the possibility that LESP might be produced by very narrow CMEs. For this purpose, we investigated narrow CMEs around the maximum of solar cycle 23 with PAs between 245° and 295° , corresponding to CMEs that are more likely to produce SEPs that are able to reach Earth. Using data from the EPAM instrument on board the ACE satellite, we found 24 (19% of all the considered events) low-energy solar particle fluxes that we associated with narrow CME events. The association between very narrow CMEs and energetic particles was based on the consistency between estimates for particle travel times from the Sun and the appearance times for the SEP events at Earth. To ensure that these associations are real, we considered only isolated narrow CMEs without any additional energetic phenomena on the Sun. To ensure that associations between the narrow CMEs and SEPs are real, we conducted an additional test. We chose at random 30 narrow and isolated events with PAs that excluded a magnetic connection to Earth. These events were not likely to produce SEPs near Earth. If in our study an accidental coincidence between SEPs and the very narrow CME appeared, we should also find energetic particles for these events. We did not find any SEPs associated with these CME events, however. This result clearly demonstrates that our considerations are correct.

Additionally, we performed a statistical analysis of the narrow CMEs. We separately considered the narrow CMEs associated with energetic particles and those without energetic particles. We demonstrated a statistical difference for the angular width of the SEP-related events in comparison to the other narrow events. This suggests that these events constitute a separate group of very narrow CMEs that are sufficiently powerful to produce energetic particles that can be detected at Earth. We demonstrated that the velocity distributions for CMEs without SEPs that are associated with SEPs are very similar. However, the latter are on average about 100 km s^{-1} faster than CMEs without associated SEPs. Additionally, we showed that CMEs producing SEPs show a correlation between their PAs and widths.

We demonstrated that narrow CMEs can generate energetic particles in the vicinity of Earth. This new result may be impor-

tant for space weather forecasting. Admittedly, low-energy particles are less dangerous for astronauts, but they are harmful for satellites. Our study presents a new approach and set of results, and confirms that very narrow CMEs can generate low-energy particles without other activity on the Sun.

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Oświadczenie

Ja, niżej podpisana: Katarzyna Bronarska (nr indeksu: 1007139), doktorantka Wydziału Fizyki, Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego, oświadczam, że przedłożona przeze mnie rozprawa doktorska pt. „Goeffectiveness of Coronal Mass Ejections” jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem doktora hab. Grzegorza Michałka. Pracę napisałam samodzielnie. Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami). Jestem świadoma, że niezgodność niniejszego oświadczenia z prawdą ujawniona w dowolnym czasie, niezależnie od skutków prawnych wynikających z ww. ustawy, może spowodować unieważnienie stopnia nabytego na podstawie tej pracy.

Kraków, dnia

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