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STATISTICAL ANALYSIS OF SOLAR EVENTS ASSOCIATED WITH STORM SUDDEN COMMENCEMENTS OVER ONE YEAR OF SOLAR MAXIMUM DURING CYCLE 23: PROPAGATION AND EFFECTS FROM THE SUN TO THE EARTH.

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Abstract. From the list of 32 SSCs over the year 2002, we performed a multi-criteria analysis based on propagation time, velocity comparison, sense of the magnetic field rotation, radio waves to associate them with solar sources, identify their causes in the interplanetary medium and then look at the response of the terrestrial ionized and neutral environment to them. The complex interactions between two (or more) CMEs and the modification in their trajectory have been examined using joint white light and multiple-wavelength radio observations. The structures at L_1 after the 32 SSCs are regarded as Magnetic Clouds (MCs), ICMEs without a MC structure, Miscellaneous structures, CIRs/SIRs, and shock-only events. In terms of geoeffectivity, generally CMEs with velocities at the Sun larger than 1000 km.s-1 have larger probabilities to trigger moderate or intense storms. The most geoeffective events are MCs, since 92% of them trigger moderate or intense storms. The geoeffective events trigger an increased and combined AKR and NTC wave activity in the magnetosphere, an enhanced convection in the ionosphere and a stronger response in the thermosphere.

Keywords: Sun: CME, Solar Wind: ICME, Earth: SSC, geoeffectiveness

1 Introduction

We focus on the year 2002, a period of maximum solar activity. We propose a novel, multidisciplinary, and statistical approach to the whole chain of processes from the Sun to the Earth (Sun, L_1, magnetosphere, ionosphere, thermosphere) in order to study the geoeffectiveness of solar events (for a full description see Bocchialini et al. (2017)). In contrast to previous statistical or case studies, the starting point is neither the coronal mass ejections (CMEs) emission at the Sun, nor the value of the min(Dst) index used to evaluate the intensity of the geomagnetic storm, but the storm sudden commencements (SSCs): near-Earth signatures produced by shocks impinging on the magnetosphere and followed by geomagnetic activity. This study then aims first to associate an SSC with a possible source at the Sun (Fig. 1), and then to characterise the propagation of solar events along the entire chain from the Sun to the Earth. It exploits existing catalogs and observations of SSCs, solar activity,

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solar wind at L_1 (Fig. 2 left), magnetosphere/magnetopause, and the coupled ionosphere/thermosphere system (Fig. 2, right), using available space borne (SOHO, Wind, ACE, Cluster, Geotail, CHAMP) and ground based measurements for radio waves, geomagnetic indices and ionospheric measurements (SuperDARN).

2 Relationships between SSCs and the CMEs at their Origin

Before looking for the solar origin of the observed SSCs, we first associate SSCs to their origin at L_1, starting with the Observatori de l'Ebre/ISGI list of the 32 SSCs detected during 2002. The 32 SSCs are linked to 31 perturbations observed at L_1, two SSCs being associated with the same event. Those 31 events, relying on our observations and on existing catalogs, are identified as: 12 Magnetic Clouds (MCs), 6 Interplanetary Coronal Mass Ejections (ICMEs, non MCs), 5 CIR/SIRs, 4 miscellaneous (Misc.) or not well characterised structures and 4 isolated shocks events. On the other hand, we consider halo and non halo CMEs that have a visible source on the Sun, taken in a temporal window of 5 days before an SSC.

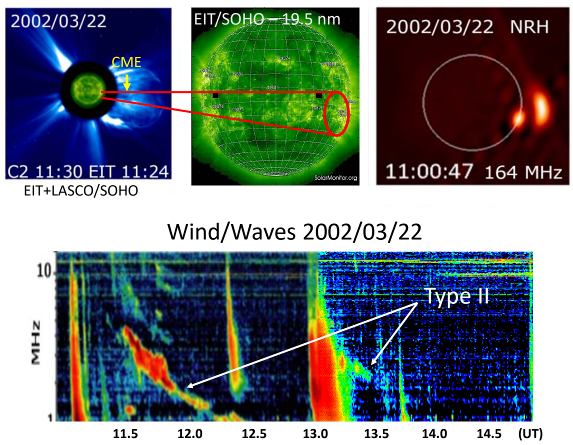

Fig. 1. Exemple of March 22, 2002. Top: Composite of EIT/SOHO image at 19.5 nm inside the LASCO C2 f.o.v showing a CME (left), EIT/SOHO image at 19.5 nm showing the source of the CME (middle), radio signature at 164 MHz measured by the NRH (right). Bottom: Dynamic spectrum from *Wind*/WAVES.

In order to further investigate the SSC/L_1 signatures/CME associations, we consider four criteria:

- propagation considerations based on the ballistic model,
- estimations from the drag-based model (DBM, (Vršnak et al. 2013)),
- radio emissions as signatures of acceleration processes linked to solar sources, and
- the compatibility of the flux rope chirality observed at L_1 with the location of the solar source. This criterion only applies to MCs.

As a first approach we start with the ballistic model and a time window to account for propagation uncertainties. In addition, we also use the drag-based-model (DBM) and calculate the drag coefficient. 85 % of the leading CME show a DBM coefficient $0.11 \times 10^{-7} < \gamma < 2.2 \times 10^{-7}$ km^{-1}, included in the range predicted by Vršnak et al. (2013) between 0.1×10^{-7} and 100×10^{-7} km^{-1}. Both mean and median values are not far from the commonly used value in the model of 0.2×10^{-7}km^{-1}, which validates the resulting association between most L_1 events and their solar source.

As a result, we can associate 28 SSCs to 44 CMES, out of an original list of 60 CMEs. The 3 SSCs with no solar source identified are due to events followed by SIR/CIRs at L_1.

The statistical analysis of the 44 CMEs, including 21 halo CMEs possibly responsible for the 28 SSCs leads to the following results:

- We confirm that the solar sources of these 44 CMEs are active regions (AR), mainly located in the central part of the disk, with filament in 60 % of the cases. The presence of a filament indicates that the magnetic

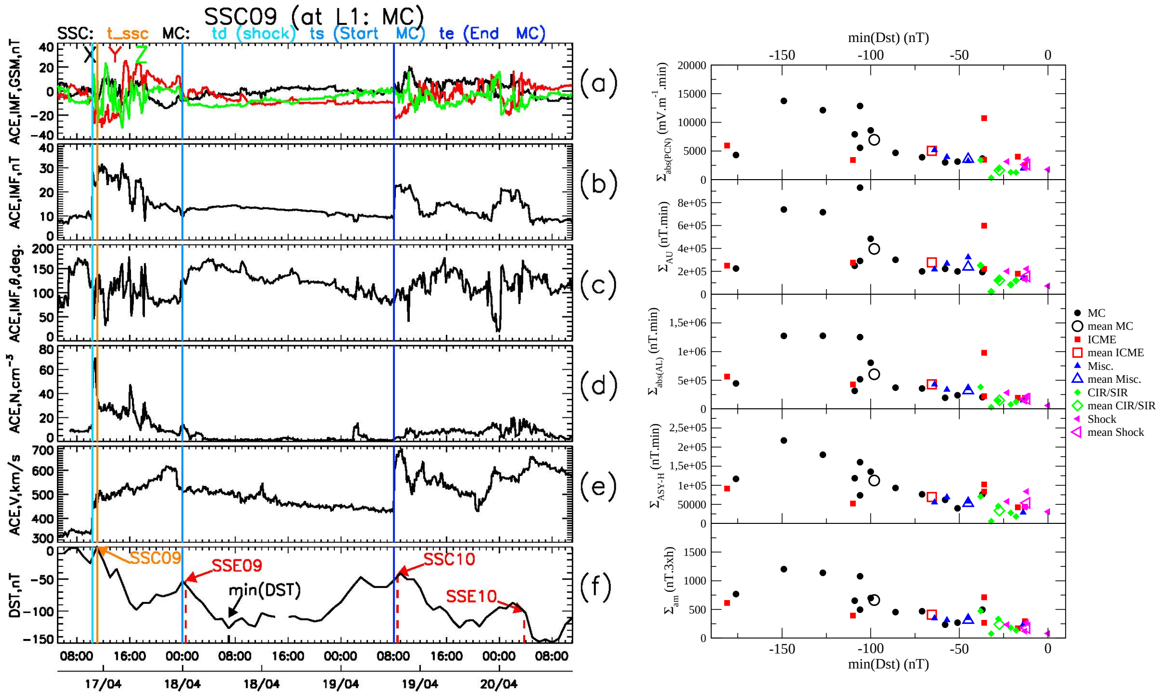

Fig. 2. Left: Observation at L_1 (ACE data) of an example of an MC together with ground-based observations of the Dst-index, on 17 April 2002. The IMF is described in the three top panels by its three components in the GSM coordinate system (a), the IMF intensity (b), and the IMF inclination with respect to the Z-axis (c). The solar-wind properties are described in the next two panels by its density (d) and velocity (e). The simultaneously observed variations of the Dst-index are displayed on the bottom panel along with the indication by dashed lines of the other SSC observed during the time window, the SSE events (see text) and the min(Dst) associated with the SSC09 event. Right: Minimum of Dst as a function of integrals of different indices over event duration (from top to bottom: PCN, AU, AL, ASY-H, am), for all events.

field of the region is strongly sheared which is a good indicator of destabilisation and eruption. CMEs are associated with small, medium, large X-ray flares with no preferences.

- In 54 % of the cases (15/28 SSCs), a single CME is related to one SSC and in 46 % of the cases, 2 CMEs at least are related to one SSC. Twenty-one are halo CMEs *i.e.* 75 % of the 28 halo CMEs –with a visible source on the Sun referenced in 2002– induce an SSC in the Earth environment, most of the time the faster the more geoeffective. According to the CDAW list, more than 500 front-side non-halo CMEs were recorded in 2002 (1.5 per day on average). Half of them are front-side and only 23 (5%) could be associated with an SSC.

- Radio observations allowed us to classify the events at the Sun in three categories, the largest group gathers events displaying Type IV radio emissions. The presence of the Type IV burst component that we call B (a long-duration radio continuum detected in a frequency range typically from decimetric to decametric wavelengths), which is physically linked with the development of the CME current sheet, is statistically the most important factor for SSC prediction. Taking only this B-components (observed by ground base instruments, and forming the first radio group) would have led in the present study to predicting 85 % of the SSC-led events with a minimum value of Dst less than -30 nT. A second group assembles the four events related to shocks only at L_1. *Wind*/WAVES observed only four Type IV radio emissions in 2002; those correspond to CME–SSC associations that are related to an MC. Globally, 25/31 events are associated with a Type II event, which is indicative of electrons accelerated by a shock.

Our analysis also underlines the importance of joint white-light and multi-wavelength-radio observations, in particular of the radio imagery, for revealing and explaining the complex interactions between different CMEs or between a CME and the ambient medium.

Most shocks observed in 2002 at L_1, either isolated or part of other events, cause an SSC. This is the case for 80 % of the 35 IP shocks listed by Gopalswamy et al. (2010). Conversely, only 5 out of 41 CIRs/SIRs reported by Jian et al. (2006) in 2002 were associated with SSCs, and for 3 of them there are no CME candidates.

For 28 SSC-led events observed at L_1, a plausible solar source is identified. Concerning MCs and ICMEs, different catalogs and studies exist. We identified a common core of 11 MCs and of 10 non-MCs ICMEs listed by respectively 3 (2) or more studies. All 11 MCs (100 %) and 6 ICMEs (60 %) caused SSCs. There is no obvious correlation between the solar source properties and the L_1 categories.

Finally, we emphasise that 14 of the 28 associations mentioned above fulfil all the relevant criteria for the considered category (*i.e.* 4 criteria for the MCs, 3 for the other categories). In particular, the criterion based on the ballistic velocity is not satisfied in 7 cases. These mismatching cases result not only from the complexity of the ICME velocity evolution during its propagation (interaction with the ambiant solar wind and/or with other ICME) but also from the lack of direct observation of the radial velocity along the Earth–Sun direction.

3 Propagation between the Sun and L_1

The propagation in the ambient medium from the Sun to L_1 is an important source of uncertainties due to the acceleration/deceleration of CMEs.

We calculate the propagation delay from the Sun to L_1 using different simple propagation models (Huttunen et al. 2005; Schwenn et al. 2005; Vršnak et al. 2013) for shock propagation (25 events) and for the ICME and MC propagation (18 events). We compare the results with our observations. There are roughly as many negative as positive delays. Half of them are longer than ± 14 hours, which is considered as the uncertainty of the models. These statistics are not improved by restricting the event base to halo CMEs or to isolated CMEs.

The results demonstrate the need for a reliable propagation tool to properly relate an ICME observed at L_1 and a CME detected within the five days preceding their arrival at L_1.

4 Geoeffectiveness

The geoeffectiveness is first discussed as a function of the minimum in Dst-values, generally used as an indicator of the storm strength (intense, -200 nT $<$ min(Dst) ≤ -100 nT; moderate, -100 nT $<$ min(Dst) ≤ -50 nT). The analysis of the SSC-related events in 2002 shows that:

- If the CME velocity $V_\odot$ is larger than 1000 $\mathrm{km\,s^{-1}}$ there is a greater probability to trigger moderate or intense storm. No particular rule is found with the nature of the CME source (halo or not, single or multiple, flare class), but the most geoeffective events are associated with Type IV radio bursts.

- The most efficient storm drivers are MCs, followed by ICMEs: 11 out of the 12 (92 %) MCs cause storms (7 intense and 4 moderate). The 2 other intense storms that follow an SSC were caused by ICMEs.

- The 3 most geoeffective MCs induce a sudden secondary event (SSE) with a magnetic signature similar to an SSC.

- Among the 6 moderate storms that follow an SSC, 4 are due to MCs and 2 to the so-called miscellaneous events. Our statistics differ from those of Echer et al. (2013) who reported that the interplanetary structure (CIRs and pure high-speed stream) are responsible for 30 % of these storms, ICMEs being the second major cause. Our study shows that when the storm is preceded by an SSC, the main driver of moderate storms remains globally ICMEs (including MCs, non-MCs, and Misc.).

- The presence of a southward IMF component and its duration are generally considered as favorable conditions for geomagnetic activity. In order to account for it, we computed a normalised and time-integrated parameter ($B^*_{z<0}$) and we found that this is a good indicator of the potential geoeffectiveness of a solar-wind structure.

- For geoeffective ICMEs (11 MCs and 2 non-MCs) triggering intense and moderate storms, we separate the effects of their sheath and central core. These statistics are limited but globally, the central core is responsible for the minimum values of the Dst. We note that for events related to intense storms, the sheath plays an important role in about half events and that this role becomes dominant for three (33 %) events since it results in the most negative min(Dst). The sheaths causing intense storms show limited variations and low values of the β parameter ($0.4 < \beta < 0.75$ and of the Alfven Mach number $3.6 < M_A < 6.5$).

For each of the 31 SSC-led events, we considered different indices for which we computed the time integral of their absolute value, from the shock arrival time until the time of the final recovery of Dst. The results are plotted with respect to min(Dst) in Figure 2 (right) *i.e* polar cap (PCN), auroral zone (AU, AL), low-latitude (ASY-H), and sub-auroral latitude (am). The integrated indices follow some kind of slope increasing with decreasing values of the min(Dst) and reach a kind of plateau for min(Dst) < -100 nT.

The analysis of the perturbations at L_1 and their associated geomagnetic response enabled us to estimate the power that the solar wind provided to the Earth's magnetosphere by means of two coupling functions: we find that their correlation with the different magnetic indices remains relatively weak. The function proposed by Newell et al. (2007), $[\frac{d\Phi_{MP}}{dt}]$, might better account for the effect of the magnetic field within the discontinuity that hits the Earth's environment. The Akasofu parameter (Perreault & Akasofu 1978), $[\epsilon_3]$, correlates with mid-latitude and global indices better than does $\frac{d\Phi_{MP}}{dt}$, whereas the later correlates best with auroral indices.

Finally, the response of the magnetosphere – ionosphere – thermosphere system is expectedly enhanced with the geomagnetic activity level. Among them, we emphasise the following issues:

- A combined NTC and AKR wave activity develops in the magnetosphere during ICMEs (MCs, non-MCs and Misc.), suggesting the presence of acceleration processes over a large sector of the plasma sheet. Conversely, this effect appears more local for most CIRs/SIRs or Shock-only with the enhancement of only one of these emissions.
- All events associated with strong and moderate storms induce a thermospheric storm, mostly identified by a significant enhancement of the night time neutral density. This occurs during most ICMEs. Conversely, CIRs/SIRs and Shock-only have almost no impact on the thermosphere.

5 Concluding remarks

The most striking results of our combined analysis of the full chain between Sun and Earth ionised and neutral environment concern well-observed MCs in 2002, all of them being associated with SSCs; 11/12 MCs are associated with radio emission of Type IV and induce intense or moderate storms; the CMEs at their origin being not necessarily a halo CME, nor a unique CME source. The effects of the 9 intense magnetic storms of our study (7 MCs and 2 ICMEs) are seen both in the ionosphere and in the thermosphere.

The statistical results point out the difficulty of identifying the relevant parameters measured at the Sun to be able to forecast the arrival time of a CME at the Earth, and to estimate its probability of impacting the Earth, despite the use of a multi criteria analysis combining velocities, radio wave analysis and - when appropriate - chirality. The development of a reliable propagation tool is required to find the link between ICMEs observed at L_1 and the (halo) CMEs detected within the five days preceding their arrival at L_1.

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