Mem. S.A.It. Suppl. Vol. 9, 75

Memorie della
Supplementi

Angular size of Coronal Mass Ejections deduced from Energetic Particle Observations

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Abstract. The angular size of coronal mass ejections (CME) moving around the Sun - Earth direction, which are likely to cause space weather disturbances, are not easily determined by direct observations. Here we develop a method to correlate the CME semi size with the observation of solar energetic particles (SEPs), which are often associated with CME and flares. These energetic particles propagate through the interplanetary medium, where relevant levels of magnetic turbulence are found. We study the magnetic connection from the Earth to the solar corona by means of a numerical simulation in which turbulence levels and solar wind velocities obtained from web based data sets are used. The simulation results are compared to solar flare observations contained in the GOES catalogue for the years 1996, 1997, 1998, following solar minimum. For this data set, we find that SEPs can reach the Earth when the difference in the heliographic longitudes of the flare and of the magnetic foot point of the Earth is 25-30 degrees at most. On the other hand, the angular semi width of magnetic field line random walking in the solar wind from the Earth to the solar corona is found to be typically 6-10 degrees. The difference between the two estimates corresponds to a flare-associated CME shock with longitudinal semi size of 20-25 degrees. This estimate is in good agreement with previous mean size estimates from the Solar Maximum Mission coronograph/polarimeter.

Key words. Sun: coronal mass jections – Solar wind: turbulence – Sun: flares

1. Introduction

Solar corona and/or solar wind ions are accelerated in a short time up to energies of 10 MeV–1 GeV, in coronal mass ejection (CME)-driven shock waves or in strong solar flares. These particles propagate along the magnetic field lines of the solar wind and can enter in the Earth's magnetosphere, passing across the magnetopause. Enhanced fluxes of solar energetic particles (SEPs) represent a hazard for spacecraft operations, as many failures already indicate, for navigation systems and for manned spaceflight.

Considerable uncertainity remains on the size and location of the energetic particle source, as well as on the details of parallel and perpendicular transport of particles (Dalla et al. 2003; Zhang et al. 2003). The bundle of solar wind magnetic field lines intersecting the Earth's magnetopause does not simply follow the Parker spiral, but spreads out in space because of magnetic field irregularities (Belcher

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& Davis 1971; Bavassano et al. 1982). Indeed, it is well known that low frequency magnetic fluctuations induce a random walk of magnetic field lines which can be viewed as a magnetic field line diffusion (Jokipii & Parker 1969; Rechester & Rosenbluth 1978; Kota & Jokipii 1995; Zimbardo et al. 1995, 2000; Pommois et al. 2001a).

We perform a Monte Carlo simulation to study the magnetic connection between the Earth and the solar corona (at the level of the solar wind source surface), and compare the position of this magnetic "foot point" with that of the corresponding flare. This simulation is tailored to each specific event by using the observed values of solar wind velocity and of magnetic fluctuation level. To this end, we have analyzed web-based datasets to extract information on the flare site and class, on the solar wind velocity and magnetic turbulence level, and on the intensity of the observed SEP fluxes in the different energy bands.

2. Internet datasets and numerical study

The present analysis is limited to a period after the solar minimum in 1995, in order to minimize the uncertainty in the large scale magnetic structure of the solar wind. A catalogue of 42 events for 1996, 1997 and 1998 has been compiled by using experimental observations from data centers on Internet (Ippolito et al. 2005). For the flare date and time, position on the solar disc, and class, the Goes spacecraft catalogue has been used (ftp.ngdc.noaa.gov/STP/SOLAR-DATA/).

For the solar wind velocity and magnetic field, and for the SEP fluxes, data from the Omniweb at the National Space Science Data Center has been used (nssdc.gsfc.nasa.gov/omniweb/).

Magnetogramms at the solar wind source surface at $r = 2.5R_\odot$ were obtained by the Wilcox Solar Observatory (http://sun.stanford.edu/~wso/wso.html).

We trace a magnetic field line in the heliosphere by integrating the field line equations for the average magnetic field $B_0(\boldsymbol{r})$, which corresponds to the usual solar wind field in spherical coordinates (r, ϑ, φ) (radial distance from the Sun, latitude, azimuth)

$$\begin{cases} \langle B_r \rangle = B_{r\mathrm{E}} \left(\frac{r_\mathrm{E}}{r} \right)^2 \\ \langle B_\vartheta \rangle = 0 \\ \langle B_\varphi \rangle = -B_{r\mathrm{E}} \left(\frac{r_\mathrm{E}}{r} \right)^2 \frac{\Omega\, r}{V_\mathrm{SW}} \cos\vartheta \end{cases} \tag{1}$$

where $B_{r\mathrm{E}}$ is the radial component of the solar wind magnetic field at the Earth, $r_\mathrm{E} = 1$ AU, Ω is the solar rotation rate (26 days), and V_SW is the solar wind speed. In the presence of magnetic turbulence, a fluctuating term $\delta\mathbf{B}$ has to be added to the rhs of the above equations (Pommois et al. 2001b).

The comparison between the flare positions, the magnetic footpoint of the Earth and the SEP data shows that (Ippolito et al. 2005):

i) 6 out of 10 SEP events are observed in connection with X class flares;

ii) no SEPs are observed in connection with flares on the East side, even of X class; the western longitudes of the flares for which SEPs are observed range from W15 to W82;

iii) for the considered data set, enhanced fluxes of SEPs are observed when the longitude separation between the flare site and the Earth magnetic foot point (computed with the average field only) is at most 30°.

In order to assess the influence of turbulence on the Sun-Earth magnetic connection, we integrate Eq. (1) for many field lines ($\sim 10^5$) using the values of $\delta B/B$ obtained from the web, starting from the Earth's magnetopause, that is from a circle with estimated diameter of 40 R_E, and reaching the solar wind source surface at $r \sim 3R_\odot$. Then, we compute the contour levels of the distribution of field lines from the Earth to the arrival points in the solar corona. These contour levels represent the probability density of magnetic connection with the Earth.

The magnetic field line positions are plotted in heliographic latitude and longitude, on the background of the magnetic field maps at the source surface of the solar wind, as computed by the Wilcox Solar Observatory. Figure 1 shows the relative position of the flare site and the "foot point" area for a sample event, corresponding to the X class flare

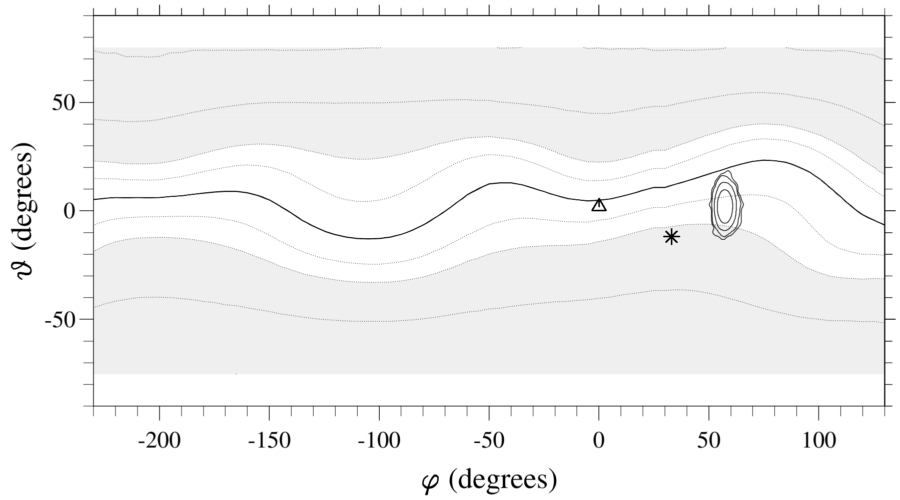

Fig. 1. Flare position (asterisc) and contours representing the magnetic footpoint of the Earth (solid lines) projected onto the magnetic field map at the solar wind source surface, for event 21 on November 4, 1997. The Earth position is indicated by a triangle.

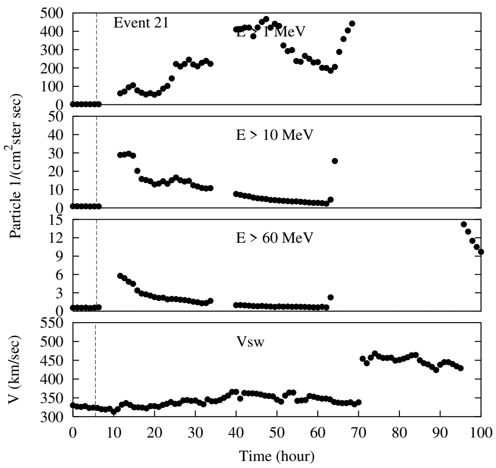

Fig. 2. Energetic particle time profiles and solar wind speed for event 21. The flare time is indicated by the vertical dashed lines.

of November 4, 1997. The energetic particles time profile for energies $E > 1$ MeV, $E > 10$ MeV, $E > 60$ MeV, and the solar wind speed from Imp8 are shown in Figure 2. The strong increase in the energetic particle fluxes after the flare time (and after a gap in the particle data) indicates that the acceleration region is larger than the distance between the flare site and the magnetic footpoint of the Earth, see Figure 1. Other events are shown in Ippolito et al. (2005).

These figures allow us to evaluate the extent of the propagation due to field line random walk: considering the semi-width at half-height of the probability density, corresponding to the first contour in Figure 1, this yields about ±6°–10° in longitude, and about ±10°–15° in latitude (the exact value depending on the turbulence level found during each event).

The presence of a shock accelerating particles, expecially after strong flares, constitutes the "current paradigm" for gradual SEP events (Reames 1999; Dalla et al. 2003). In such a case, the result of a 6°–10° longitudinal width for the field line random walk, together with the finding, reported above, that SEPs are observed on Earth when the azimuthal separation between the flare and the nominal foot point is at most 30°, gives an estimate maximum angular (azimuthal) half-size for the particle acceleration region of about 20°–24°. This is consistent with previous estimates of the average sizes of CME shocks of 47° (Hundhausen 1993), which were obtained by analysis of the images of the coronograph/polarimeter flown on the SMM spacecraft. This also agrees, as a typical size, with the shock latitudinal extent that can be inferred from Figure 2 of Dalla et al. (2003): in that figure, it can be seen that energetic particles reach the spacecraft when the latitudinal separation is less than about 20°–25°. The agreement of the typical CME shock sizes obtained from different studies supports the interpretation of the SEP data in terms of shock acceleration.

3. Conclusions

We have studied the magnetic connection from the Earth to the solar corona, taking into account the observed magnetic turbulence level and the measured solar wind speed, for a set of 42 flares taken from the Goes X-Rays catalogue for the period 1996–1998. We find that SEPs can reach the Earth when the difference in the heliographic longitudes of the flare and of the nominal magnetic foot point of the Earth is 25°–30° at most. The numerical simulation shows that the magnetic foot area has a longitudinal half-width of 6°–10°, and a latitudinal half-width of 10°–15°. ¿From this gap, we can obtain an estimate angular (azimuthal) half-size for the particle acceleration region of about 20°–24° (Ippolito et al. 2005). This agrees with previous estimates of the average CME shock size of 47°, obtained by analysis of SMM data (Hundhausen 1993). Although very large CME shocks (∼ 180°) are also observed, this "typical" size can be useful for a quick assessment of the risk generated by strong flares. Further study is needed to correlate the inferred CME shock size to the observations of Moreton waves by the Extreme ultraviolet Imaging Telescope (EIT) on SOHO, which also give an estimate of the CME size.

Acknowledgements. G.Z. thanks Ester Antonucci for useful suggestions. This work is financially supported by the Italian MIUR (Cofin 2002), by the Center for High Performance computing (HPCC) at the University of Calabria, and by the European Union Research Training Network 'Turbulence in Space Plasmas'. Numerical calculations have been performed in the framework of HPCC.

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