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Longitudinal Distribution of Solar Flares and Their Association with Coronal Mass Ejections and Forbush Decreases

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Abstract Major Hα solar-flare events of high optical importance have been employed to study their heliographic distribution in longitude around the Sun for the period of 2001 to 2006. A statistical analysis was performed to obtain their relationship with halo/partial-halo CMEs and Forbush decreases (Fds) of cosmic-ray intensity. Our analysis indicates that 63% of the solar flares associated with halo CMEs and Fds occur in the western hemisphere and of 37% of such flares occur in the eastern hemisphere. Similarly, we found that nearly 60% of the solar flares associated with partial- halo CMEs and Fds occur in the western hemisphere and the rest (40%) occur in the eastern hemisphere. Finally, we conclude that the flares in association with CMEs and located in the western hemisphere of the solar disk are more effective in producing Fds. The magnitudes of Fds are observed to be higher when in association of halo CMEs. A slight excess in the eastern hemisphere is found for both the halo and partial-halo CMEs.

Keywords Cosmic rays · Neutron monitors · Solar flares

1. Introduction

The occurrence of a solar flare on the Sun is considered to be one of the events that release a vast amount of matter and radiation in a short interval. We can also identify the

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location of active regions producing major solar flares by using Hα observations. The distribution of major flares on the solar disk and their association with other solar and interplanetary phenomena play an important role in the process of cosmic-ray modulation. One of the solar-flare related sporadic variations in cosmic-ray intensity is the so-called Forbush decrease (Fd): a sudden decrease in cosmic-ray intensity followed by a gradual recovery. These decreases are associated with intense solar flares, high-speed solar wind streams, and perturbation in the interplanetary magnetic field (Iucci *et al.*, 1979). Barnden (1973) found that the descending phase of some Fds exhibits a clear two-step structure, which is located inside the associated interplanetary disturbances. Iucci *et al.* (1979) showed that the interplanetary perturbation generated by type IV radio bursts reduces the comic-ray intensity in a cone-like region defined by spiral interplanetary magnetic fields.

The maximum cosmic-ray modulation is observed between 0° and 40°W of the meridian plane crossing the flare site. Iucci *et al.* (1986) noted that an asymmetric perturbation trailing the shock from a solar-flare event is the cause of the longitudinal asymmetry of two-step Fds. Belov *et al.* (2001) related Fds with interplanetary and geomagnetic activities. On the other hand the east-west distribution of major solar flares has been studied by Badruddin and Yadav (1982), and they found an almost equal distribution of solar flares in both the eastern and western hemispheres of the Sun. Yadav *et al.* (1983) have also reported the absence of east-west asymmetry. They have used the major solar flares observed for the period of 1955 to 1979. The existence of east-west asymmetry is therefore not well established and rather controversial. Recently, Tang and Le (2005), using flares exceeding the GOES C1 level, found a slight excess in the western hemisphere for the period of May 1996 to May 2005. A number of investigators have studied the distribution of flares around the solar disk and their association with Fds (Hatton, 1980; Shrivastava, 2003; Shrivastava and Singh, 2005). It has been reported that the major solar flares are usually followed by large geomagnetic disturbances and cosmic-ray short-term decreases (Garde *et al.*, 1983). Jain *et al.* (1983) have reported that major solar flares occurring between 60°E and 30°W of the solar disk are usually followed by Fds. They have used the events of major solar flares for the period of 1975 to 1979. In recent years coronal mass ejections (CMEs) along with major solar flares are investigated as the source of cosmic-ray modulation process (Shrivastava, 2003; Shrivastava, Singh, and Tiwari, 2005). Recently a number of researchers (Cane, Richardson, and Von Rosenvinge, 1996; Cane, Richardson, and Wibberenz, 1997; Cane, 2000; Shrivastava and Singh, 2005) have discussed Fds in relation with CMEs. CME related cosmic-ray decreases mostly originate from shocks or ejecta (Cane, 2000). Very energetic CMEs will create shocks which are strong enough on their fronts to cause cosmic-ray decreases.

In this study, major solar flares and their heliographic distributions in longitude are studied along with halo and partial-halo CMEs. Association of these two categories of CMEs with solar flares and their effects on cosmic-ray decreases are studied for the period of 2001 to 2006, which covers the descending phase of solar cycle 23.

2. Data Analysis

In the present investigation, major Hα solar flares have been selected for the period of 2001 to 2006. The selection is made from the list of routinely published solar flares in the *Solar Geophysical Data* (Prompt Report). All the major solar flares which have optical importance ≥ 1 have been noted. Only those Hα solar flares which are found to be associated in time either with CMEs or with both CMEs and Fds have been taken into account in this study.

Table 1 East-west heliographic distribution of solar flares in different categories.

Combinations (2001 – 2006)	East	West	Total	Percent East	Percent West	Asymmetry $A = 2(E - W)/(E + W)$
SF + halo CMEs	98	125	223	43.9%	56.1%	−0.24
SF + partial-halo CMEs	119	154	273	43.6%	56.4%	−0.27
SF + halo CMEs − Fd	66	71	137	48.2%	51.8%	−0.073
SF + partial-halo CMEs − Fd	85	104	189	44.9%	55.1%	−0.20
SF + halo CMEs + Fd	32	54	86	37.2%	62.8%	−0.51
SF + partial-halo CMEs + Fd	34	50	84	40.5%	59.5%	−0.38

CMEs are considered as associated with solar flares if these are within a ± 1 day window. To relate these solar flares with the occurrence of Fds, possible time lags of $+1$ to 3.5 days have been considered. Different combinations of solar flares and Fds for the period of 2001 to 2006 and their longitudinal distribution are given in Table 1. The Fd events are sorted out from the hourly plots of cosmic-ray intensity from the Prompt Report of *Solar Geophysical Data*. All Fd events with magnitude $\geq 3\%$ (at the Kiel neutron monitor station) which occur at at least two other stations beside the Kiel station are selected. When the data from Kiel are not available, we use the data from another station, which have nearly the same cut off rigidities as the Kiel station. We have considered the onset date/time and the magnitude (in percent) of Fds.

3. Results and Discussion

It is well known that the cosmic-ray intensity, particularly at neutron monitor energies, varies with an 11-year period in anti-phase with the solar activity cycle (Shrivastava, Shukla, and Agrawal, 1993; Singh, Nigam, and Shrivastava, 1996). Generally the solar activity cycle is represented by sunspot numbers. Beside sunspot numbers, the solar flare is another solar feature that indicates the solar activity. We are interested in the location of active regions producing major solar flares. Shrivastava (2003) reported that the major solar flares occurring in the zones between 15°N to 30°N and between 0°E to 30°E are more effective in producing cosmic-ray Fds. Recently Shrivastava and Singh (2005) reported that the flares occurring in the zone 0°W – 40°W are more effective in producing Fds for solar cycle 22. However, in solar cycle 23 the zone 10°E to 60°W is found to be effective in producing Fds.

In this analysis, we have extended our previous work to recent periods and adopted a slightly different approach than as used in earlier works (Shrivastava and Singh, 2005; Shrivastava, 2005). Figure 1 shows the heliographic distribution in longitude of all major flares on the solar disk which are also associated with halo CMEs for the period of 2001 to 2006. The flare location has been summed up to 10° bins. It is noted that an almost equal number of flares occurred in both the eastern and western hemispheres. Similarly Figure 2 shows such solar flares associated with partial-halo CMEs during the period of 2001 to 2006. Figures 1 and 2 show that the distributions of major solar flares are identical on both the eastern and western hemispheres. However, slight increases are seen in the western hemisphere.

Now, all the major solar flares that are associated with halo CMEs or partial-halo CMEs are divided into two groups; the first group, which is not associated with an Fd, and the second group, which is associated with an Fd. Figure 3 shows the heliographic distribution

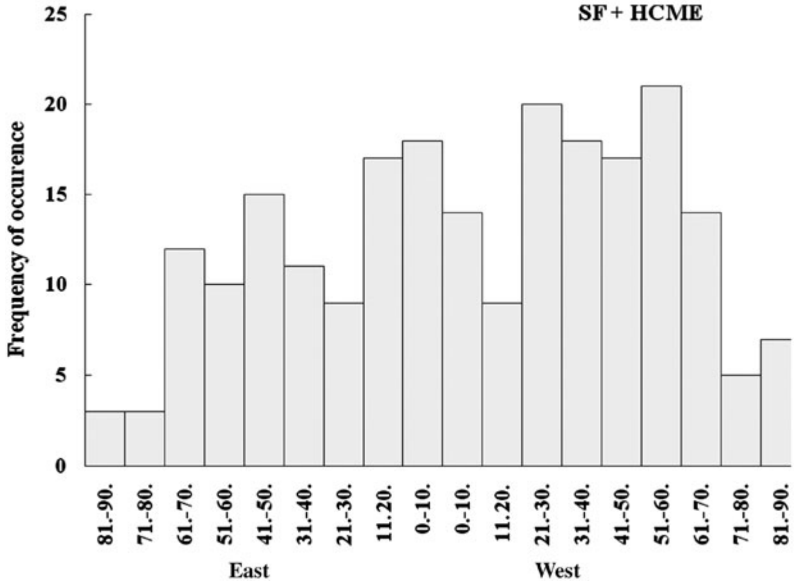

Figure 1 The heliographic distribution in longitude of all Hα flares in association with halo CMEs (± 1 day window) on the solar disk for the period of 2001 – 2006.

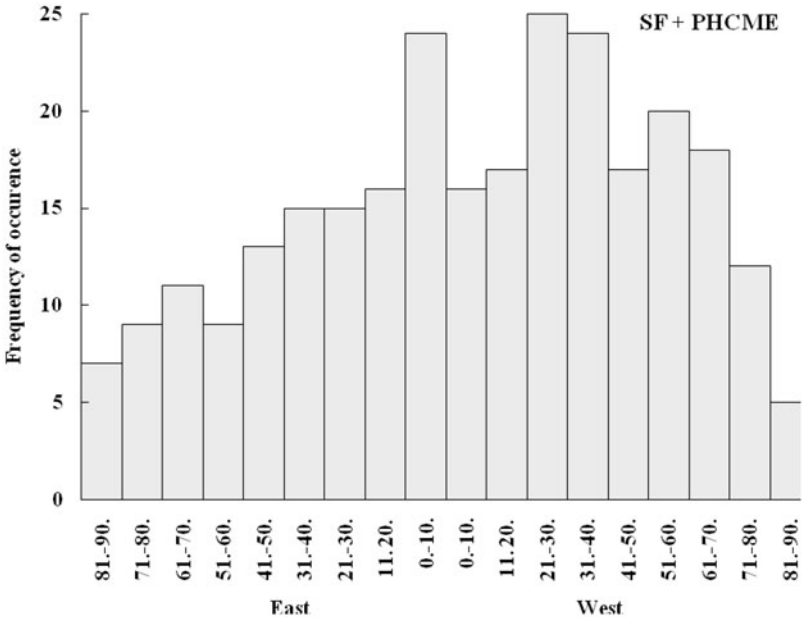

Figure 2 The same as Figure 1 but for partial-halo CMEs instead of halo CMEs.

in longitude of major flares on the solar disk, which are associated with halo CMEs but not associated with Fds for the period of 2001 to 2006. Out of 137 such flares, 71 flares

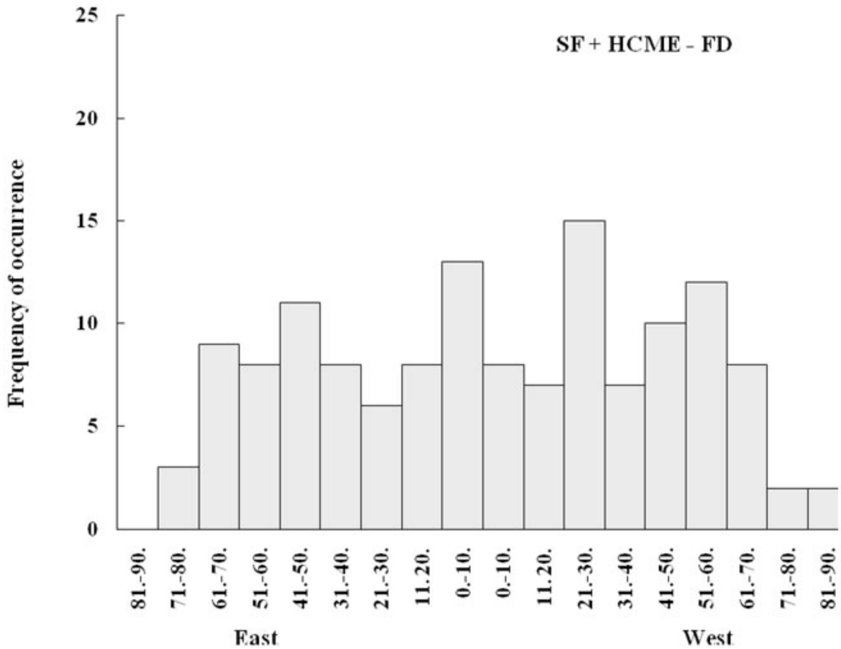

Figure 3 The heliographic distribution in longitude of Hα flares in association with halo CMEs (± 1 day window) and without associated Fds on the solar disk for the period of 2001 – 2006.

are found in the western hemisphere and 66 flares are found in the eastern hemisphere. Similarly, Figure 4 shows the distribution of solar flares in the case of partial-halo CMEs instead of halo CMEs. In this way it can be inferred that an almost equal number of major solar flares in association with halo CMEs or partial-halo CMEs but not associated with Fds occurs all over the solar longitudes.

Further, we have extended our analysis to observe the influence of solar flares in association with CMEs and Fds for the entire interval of studies. During this study, 46 Fds are found in cosmic-ray intensity variation having a decrease of magnitude of $\geq 3\%$. Out of 223 solar flares, 86 flares are found to be associated with halo CMEs and Fds. Similarly, 84 flares are found to be associated with partial-halo CMEs and Fds. Figure 5 shows the distribution of solar flares associated with halo CMEs and also with Fds. It is seen from Figure 5 that more flares occurred in the western hemisphere in comparison to the eastern hemisphere. Namely about 63% (54 out of 86) are found in the western hemisphere, while only about 37% (32 out of 86) flares are found in the eastern hemisphere. Similarly, we observe such results for partial-halo CMEs as seen in Figure 6; about 60% (50 out of 84) flares are found in the western hemisphere, while about 40% (34 out of 84) flares are found in the eastern hemisphere.

The magnitude of Fds is also one of the factors that show the importance of solar/interplanetary sources. To consider the magnitude of Fds, we have calculated the average magnitude in interval of 10°. The average magnitudes are derived only for those Fds that are associated with solar flares and halo/partial-halo CMEs. To depict the magnitude distribution of Fds magnitudes in relation with halo CMEs and solar flares on the solar disk, the heliographic distribution in longitude is shown in Figure 7. It is apparent from Figure 7 that the frequency distribution is almost similar in both hemispheres. However, the east-

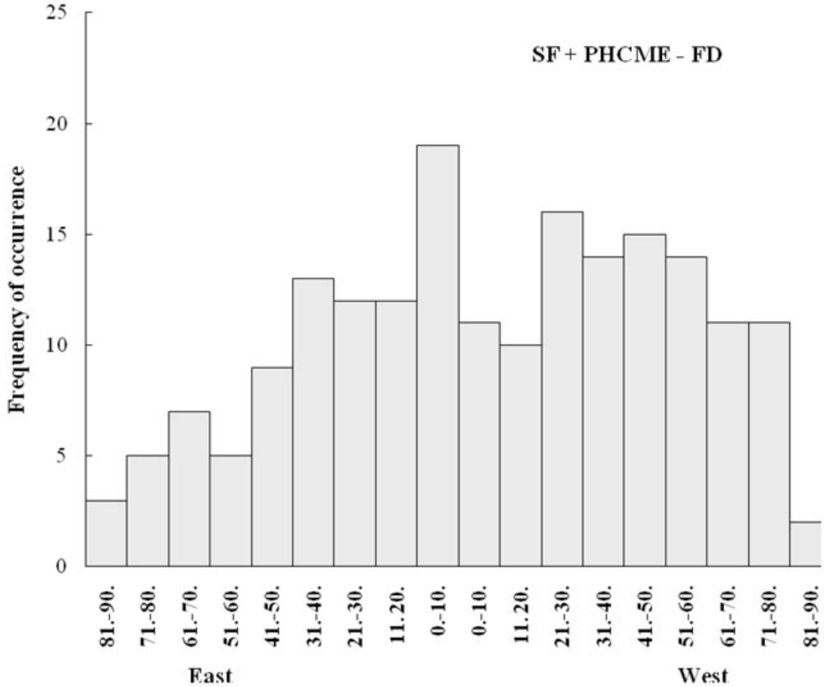

Figure 4 The same as Figure 3 but for partial-halo CMEs instead of halo CMEs.

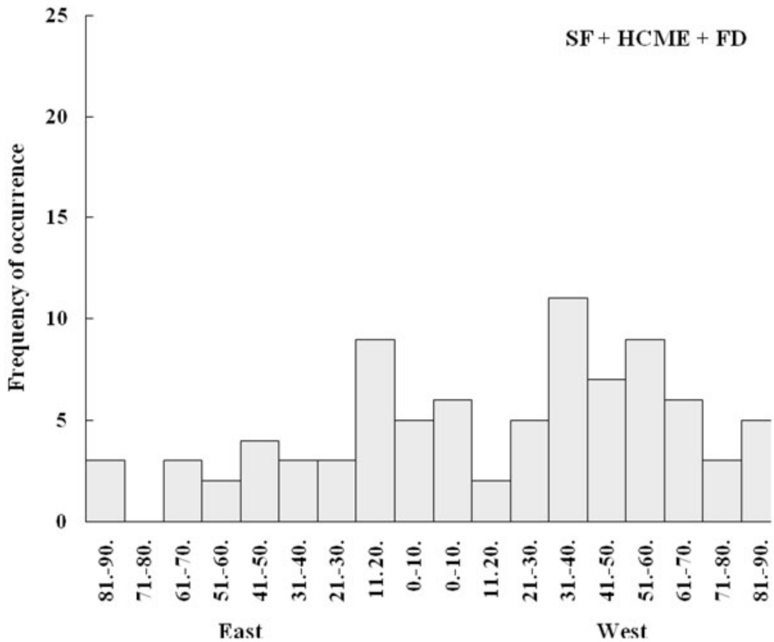

Figure 5 The heliographic distribution of Hα flares in association with halo CMEs (± 1 day window) and Fds on the solar disk for the period of 2001 – 2006.

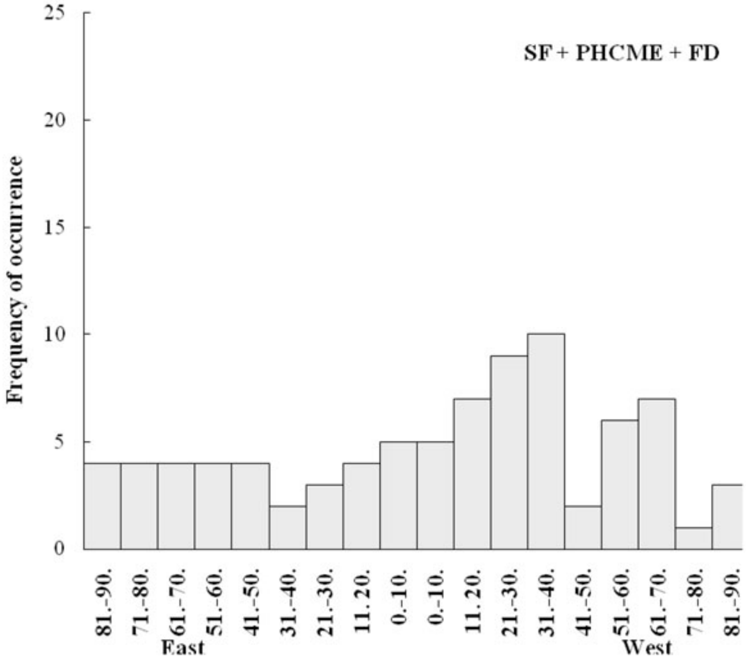

Figure 6 The same as Figure 5 but for partial-halo CMEs instead of halo CMEs.

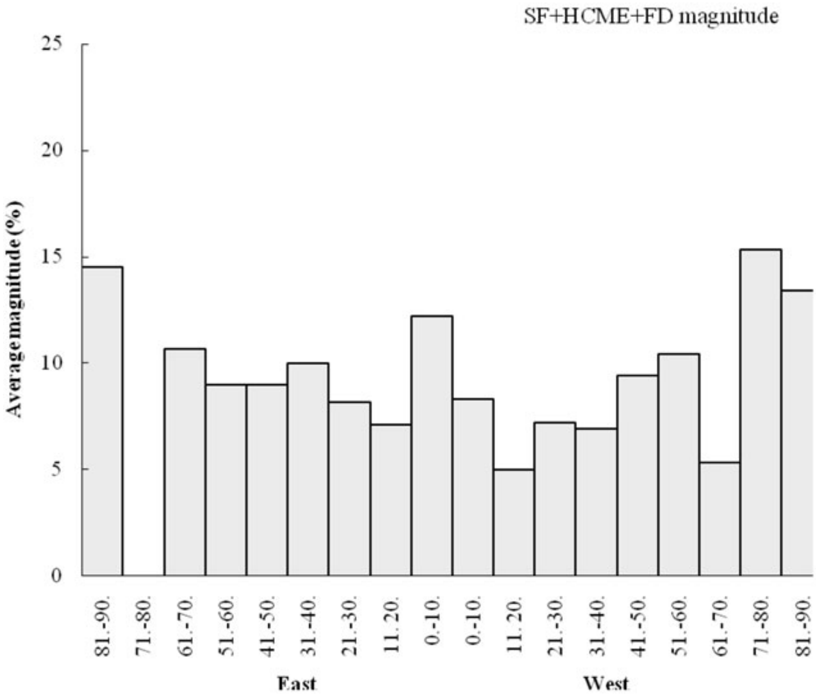

Figure 7 The heliographic distribution in longitude of the magnitude of Fds that are associated with Hα flares and halo CMEs (± 1 day window) on the solar disk for the period of 2001 – 2006.

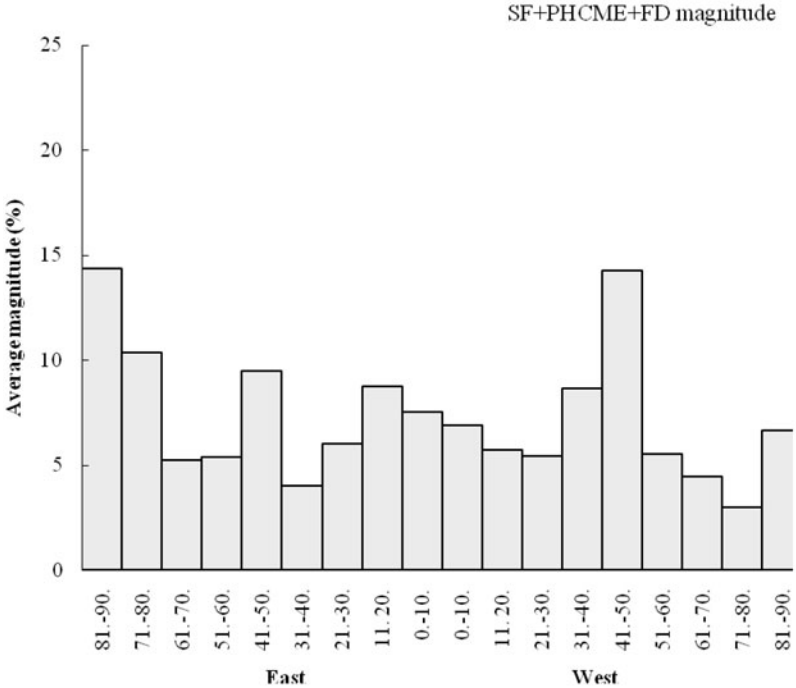

Figure 8 The same as Figure 7 but for partial-halo CMEs instead of halo CMEs.

ern hemisphere shows a slightly larger frequency. Likewise, we observe similar results for partial-halo CMEs, as seen in Figure 8. The average magnitudes of Fds for the eastern and western hemispheres are calculated as 10.08 and 9.04, respectively. Similarly the average magnitudes for partial-halo CMEs are 7.9 and 6.7, respectively. It is remarkable from the analysis that the average magnitude is found to be lower for partial-halo CMEs in comparison to halo CMEs. This result on the magnitude of Fds is in agreement with the earlier observations (Yoshida and Akasofu, 1965). Yoshida and Akasofu (1965) reported that solar particle events from the western hemisphere caused more Fds than those from the eastern hemisphere. However, the magnitude of Fds is generally larger for those flares occurring in the eastern rather than the western hemisphere of the Sun.

The percentages of events associated with Fds are higher in the western hemisphere, as given in Table 1. On the basis of this analysis, we can infer that the majority of solar flares occurring in the western hemisphere of the Sun are more effective in producing Fds. Fds have recently been explained as being due to the shielding of cosmic-ray particles by shock fronts produced by intense solar flares (Lockwood, 1971). Kaushik and Shrivastava (2000) proposed that Fds are due to perturbations in the interplanetary medium caused by shock waves. It is also believed that at the time of an explosive solar flare, gas is ejected from the flaring region of the Sun in the form of a plasma cloud and when the plasma cloud arrives at the Earth it produces a decrease in cosmic-ray intensity.

A simultaneous occurrence of multiple CMEs will produce a shock front or magnetic field discontinuity and will provide the mechanism for the initial reduction of the cosmic-ray intensity at the Earth. For such a tangential discontinuity the momentum balance equation in three dimensions can be written (Shrivastava, Singh, and Tiwari, 2005)

$$\mathrm{d}/\mathrm{d}r\left(4\pi r^3\rho\right) = 4\pi r^2(\rho_o V_{od} - \rho V_d),$$

where ρ is the particle density inside and ρ_o is the density outside the CME cloud and V_d and V_{od} are the particle drift velocities in the two regions, respectively. B and B_0 are the interplanetary magnetic fields in two regions. For the maximum rate of decrease we put $\mathrm{d}\rho/\mathrm{d}r = 0$ and then we find

$$(\rho/\rho_o)\cdot(V_{od}/V_d) = (\mathrm{d}B_o/B_o)/(\mathrm{d}B/B) = \mathrm{d}B_o/\mathrm{d}B$$

neglecting the shock-front velocity relative to the particle drift velocity and putting $B_o \approx B$. From satellite data on the interplanetary field, we have a gradient $\mathrm{d}b2B_o/\mathrm{d}B \approx 0.3$, which is reasonable. Such a tangential discontinuity produces a massive decrease in the cosmic-ray intensity behind the front.

4. Conclusions

In this work, we have determined the distribution of solar flares on the solar disk and their association with CMEs and Fds. The following conclusions can be drawn from our study.

i) Major Hα solar flares in association with partial-halo, or halo CMEs are found to be almost equally distributed all over the heliographic longitude. However, slightly large numbers of solar flares in association with partial-halo CMEs are evident in the western hemisphere.

ii) Solar flares in association with partial-halo CMEs or halo CMEs occurring in the western hemisphere are found to be more effective in producing Fds than the flares in the eastern hemisphere.

iii) Halo CMEs in association with major solar flares are found to be more effective in producing Fds in comparison to partial-halo CMEs.

iv) The average magnitudes of Fds are found to be slightly larger in the eastern hemisphere in comparison to the western hemisphere.

v) The magnitudes of Fds are found to be high in association with halo CMEs in comparison to partial-halo CMEs.

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