Heliographic distribution of bright solar flares and association of Forbush-decreases with flares and coronal mass ejections

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Received 17 April 2007; revised 29 January 2008; accepted 22 April 2008

Major solar flare events have been selected to study the heliographic distribution of solar flares during solar cycle 23. The occurrence of Forbush decreases (FDs), bright solar flares; solar flare index, coronal mass ejections (CMEs), average solar magnetic field and solar wind velocity have been studied for the period 1996-2006. It is found that the solar flare index in northern and southern hemisphere represents the cumulative activity of solar flare in both hemispheres. Though, the bright solar flares are equally distributed in the entire solar region, majority of the bright solar flares responsible for FDs (≥ 4% magnitude) are located in the north-east region of the solar disk. Out of 41 FDs, 88% are found to be associated with halo (central position angle ≈ 360°) and partial halo (central position angles ≥ 120°) CMEs (coronal mass ejections) and 55% with bright solar flares of importance ≥ 1B. The abrupt increase in average solar magnetic field and solar wind velocity has also been found to be a necessary condition for producing FDs. The occurrence of non-recurrent type FDs are more frequent than recurrent type FDs. In latitudinal distribution, northern hemisphere is more dominant than the southern hemisphere in producing FDs. It is also found that eastern hemisphere is more effective as compared to western hemisphere to produce FDs in longitudinal distribution during the aforesaid period.

Keywords: Solar flares, Coronal mass ejections, Forbush decreases, Solar cycle

PACS No.: 96.60.Qe; 96.60.Ph

1 Introduction

A solar flare originated from the solar atmosphere is referred to as a major solar event and an impulsive phenomenon that releases vast amount of matter and energy in a short interval. Flares also often occur in association with CMEs (coronal mass ejections) but they are not assumed to be instigator of mass ejections. Flares are believed to be generated by the heating results from reconnection of field lines. Usually the solar flares associated with CMEs are of long duration and also associated with meter wavelength type II and particularly, type IV radio bursts. Large Forbush decreases (FDs) are caused by fast CMEs, which may also be associated with specific solar flares. The FDs are frequently recorded near solar maximum but it may occur throughout the solar cycle. A number of investigators have studied the distribution of solar flares around the sun and some reported the combined effect of bright solar flares and CMEs responsible for the short-term decreases in galactic cosmic ray intensity. Recently, the northern hemisphere has been reported to be dominant in general during the rising phase of cycle 23. The dominance of northern hemisphere shifted towards the southern hemisphere after the solar maximum. During CMEs, a large amount of matter propels out from the sun's outer atmosphere. These episodic expulsions of mass and magnetic fields from the solar corona into the interplanetary medium may have masses of the order of $10^{15}$ g and may liberate energies up to $10^{30}$-$10^{32}$ ergs. The CMEs are the result of a large-scale rearrangement of solar magnetic field and they are often observed as an eruption of twisted magnetic field from the solar atmosphere. Out of various types of CMEs, the halo CMEs are more likely to impact the Earth and incident at right angle to Earth-Sun line. The FDs in cosmic ray intensity are often associated with CMEs and interplanetary CMEs (ICMEs). The FDs are observed as transient depressions in the galactic cosmic ray intensity, characterized by a sudden onset, reaching a minimum within about a day and followed by a more gradual recovery phase typically lasting up to several days.
These decreases are most likely produced by perturbations in the interplanetary magnetic field and particle flow, which propagate away from the sun. It is also found that the depth of a FD is dependent on the helio-longitude of the active region, which ejects the associated CMEs. The depth of FDs is larger when the associated CME originates near solar meridian and the vast majority of Forbush events are caused by CMEs originated within 0-50 deg helio-longitude. The FDs are basically of two types, non-recurrent and recurrent. Non-recurrent decreases are caused by transient interplanetary events, which are related to mass ejections from the sun. They have a sudden onset, reach maximum depressions within about a day and have a more gradual recovery. Recurrent decreases have a more gradual onset, more symmetric in profile and are well associated with co-rotating high speed solar wind streams.

In the present paper, an attempt has been made to study the heliographic distribution of bright solar flares and association of FDs with flares and CMEs. The aim of this study is to find out the active regions of the solar disk, which is responsible to produce FDs during 1996-2005. The dominance of flares occurring in different quadrants has also been investigated during 1996-2005, which is more effective in producing FDs.

2 Data analysis

For the present study the authors have sorted out the major solar flares (optical importance $\geq 1 B$) and cosmic ray intensity Forbush decrease (FDs) recorded by Calgory (cut-off rigidity $R_c \approx 1.09$ GV) neutron monitor during the period 1996-2006 (Solar Geophysical Data Prompt and comprehensive reports). To study the spatial distribution of flares with respect to heliographic latitude and longitude, the number of observed flares has been calculated in the interval of 10 deg (see Table 1). To see the association of FDs with solar flares and/or CMEs, possible time lags of 1-4 days (travel time depending on the solar wind plasma velocity from source region to interplanetary region near Earth) have been considered. The FDs are classified as non-recurrent, showing sudden onset and recurrent if onset is gradual. The association of solar flares and CMEs responsible for cosmic ray intensity decreases $\geq 4\%$ during the period 1996-2006, has also been investigated. Further the association of FDs with different classes of CMEs has been analyzed according to their position angle, namely class A (those that occur with position angle in the range of 150-300 deg) and class B (those that occur with position angle in the range 0-150 deg). The CMEs data have been taken from the website http://cdaw.gsfc.nasa.gov/cme list. The solar magnetic field intensity data (Average) and solar wind velocity have been taken from the “Omni website”.

3 Results and discussion

Solar active regions have been identified by location of major solar flares, which eject vast amounts of energy and matter from solar atmosphere and affect the cosmic ray intensity. The occurrence of solar flares in northern and southern hemispheres along with solar flare index is shown in Fig. 1(a). This figure shows that the solar flare index in northern and southern hemisphere effectively represents the occurrence of solar flare in both hemispheres. A distribution of solar flares (with interplanetary magnetic field, IMP $\geq 1 B$) occurred around the solar disk during the period 1996-2006 as shown in Table 2. This table shows that the number of major solar flares is slightly more in northern hemisphere or in western hemisphere as compared to southern or

<table>
<thead>
<tr>
<th>Events</th>
<th>Num. of events</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD + P.H.CME + H.CME</td>
<td>22</td>
<td>53%</td>
</tr>
<tr>
<td>+ LARE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FD + FLARE</td>
<td>1</td>
<td>2%</td>
</tr>
<tr>
<td>FD + CME</td>
<td>14</td>
<td>35%</td>
</tr>
</tbody>
</table>

Table 1—number of observed flares/CMEs and their associated FDs

Fig. 1(a)—Relation between solar flare index along with the solar flare
eastern hemisphere respectively, as shown in Fig. 1(b). From this figure, it is also evident that most of the flares are produced in the 10-30 latitudinal and longitudinal belt, which is in accordance with the results reported earlier. No bright solar flares have occurred beyond 50° in northern or southern hemisphere.

The heliographic distribution of solar flares (IMP ≥ 1B) in quadrants area of the solar disk is depicted in Fig. 2(a)-(e). The distribution of type 1B flares is observed equal over the solar disk (see Fig. 2(a). It is also evident from Fig. 2(b) and (c) that the occurrence of flares (type 2B and 3B) is more in northern hemisphere as compared to southern hemisphere, whereas, the type 4B solar flares are found to occur in south-east region of solar disk [see Fig. 2(d)]. Figure 2(e) reveals that the total number of bright flares occurred slightly more in northern hemisphere as compared to southern hemisphere. The number of solar flares during increasing and decreasing phase of solar activity is shown in Fig. 2 (f) and (g), which shows that the occurrence of bright solar flares is maximum in northern hemisphere.

<table>
<thead>
<tr>
<th>Hemisphere</th>
<th>No. of Events</th>
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<tr>
<td>Northern</td>
<td>284</td>
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<tr>
<td>Southern</td>
<td>255</td>
</tr>
<tr>
<td>Eastern</td>
<td>263</td>
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<tr>
<td>Western</td>
<td>276</td>
</tr>
<tr>
<td>Total</td>
<td>539</td>
</tr>
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</table>

Table 2—Solar flares distribution (IMP ≥ 1B) around the solar disk during 1996-2006

Fig. 1(b)—Latitudinal distribution of bright solar flare (≥ 1B) during 1996-2006

Fig. 2—(a) 1B type; (b) 2B type; (c) 3B type; (d) 4B type and (e) total distribution of bright solar flare (%) in quadrants during 1996-2006; also (f) increasing phase distribution during 1996-1999 and (g) decreasing phase distribution during 2001-2005
during increasing phase and in southern hemisphere during decreasing phase of solar cycle 23.

The yearly occurrence of flares from 1996 to 2006 along with sunspot number is shown in Fig. 3. It is evident from this figure that the occurrence of flares follows the solar cycle with maximum number observed in the year 2000-2001 during the maxima of solar cycle 23. Out of different types of CMEs, 33 partial halo CMEs have been found to be responsible for FDs. Furthermore, partial halo CMEs according to their position angle have been classified into two categories (class A and B) and it is found that out of 33 CMEs, 16 falls into the category of class A (position angle 200-300 deg) and the rest in class B (position angle 50-150 deg) during the period of 1996-2006. It is also found that the partial halo CMEs having angular width in the range 90°-180° in both classes, are more effective in producing FDs. Out of 41 FDs, 27 events have been found to be non-recurrent and 14 events are recurrent. The association of FDs with flares and/or CMEs has been shown in Table 1. This table shows that majority of CMEs are responsible for producing FDs in comparison to flares. The distribution of flares responsible for FDs is shown in Table 3. It is found that only those flares are effective in producing FDs, which have occurred in 10-30° of longitudinal and latitudinal regions (see Table 3).

The distribution of all types of bright flare and total flares in different quadrants are shown in Fig. 4(a)-(d). These figures show that the majority of flares (type 1B, 2B and 3B) occurred in north-east region and are responsible for FDs during the aforesaid period. The solar magnetic field (Average) and solar wind stream (Velocity) with the occurrence of FDs is shown in Table 4. It is found that, in most of the cases the average magnetic field strength and solar wind velocity has been found to be enhanced at the time of FDs, which shows the clear relationship

![Image](image_url)

**Fig. 3—Occurrence of bright solar flare (≥ 1B) along with sunspot number during 1996-2006**

<table>
<thead>
<tr>
<th>Type 1B Solar Flare Distribution (FDs Associated)</th>
<th>20-30</th>
<th>30-40</th>
<th>40-50</th>
<th>50-60</th>
<th>60-70</th>
<th>70-80</th>
<th>80-90</th>
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<tr>
<td>0-10</td>
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<td>1</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
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<td>2</td>
<td>2</td>
<td>1</td>
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<th>30-40</th>
<th>40-50</th>
<th>50-60</th>
<th>60-70</th>
<th>70-80</th>
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<td>2</td>
<td>3</td>
<td>8</td>
<td>0</td>
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<th>Type 1C Solar Flare Distribution (FDs Associated)</th>
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<th>40-50</th>
<th>50-60</th>
<th>60-70</th>
<th>70-80</th>
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<tr>
<td>10-20</td>
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<td>11</td>
<td>14</td>
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<tr>
<td>W</td>
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<td>9</td>
<td>12</td>
<td>5</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>5</td>
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between FDs and interplanetary conditions. The occurrence of FDs with increasing and decreasing phase along with solar cycle is depicted in Fig. 5. This figure shows that the FDs follow the solar cycle except in 2004. The modulation of cosmic rays is a complex combination of outward convection by solar wind, inward diffusion due to scattering of magnetic field irregularities, adiabatic cooling, curvature and heliospheric neutral sheet drifts. It is expected that due to the configuration of the heliospheric magnetic field, cosmic ray particles will drift from the polar regions down to equatorial regions when the heliospheric magnetic field is directed outward in the northern hemisphere of the heliosphere.

The FDs are isotropic variations, as the cosmic ray particles recorded by ground based stations are collected equally from all sides by neutron monitors. When solar flares or coronal mass ejections or both are ejected from the solar surface and move towards

### Table 4—Solar magnetic field (average) and solar wind stream (velocity) with the occurrence of FDs

<table>
<thead>
<tr>
<th>Date</th>
<th>% of FD</th>
<th>Avg. Mag. Field., nT</th>
<th>SW Velocity, km/s</th>
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<td>8 Apr. 4</td>
<td>9.2</td>
<td>322</td>
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<tr>
<td>2 May 6</td>
<td>19.2</td>
<td>793</td>
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</tr>
<tr>
<td>24 Sep 11</td>
<td>17.7</td>
<td>839</td>
<td></td>
</tr>
<tr>
<td>Year 1999</td>
<td>23 Jan 5.5</td>
<td>16.5</td>
<td>638</td>
</tr>
<tr>
<td>18 Feb 5</td>
<td>14.4</td>
<td>673</td>
<td></td>
</tr>
<tr>
<td>19 Aug 4</td>
<td>6.8</td>
<td>641</td>
<td></td>
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<tr>
<td>12 Dec 6.5</td>
<td>9.6</td>
<td>608</td>
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<tr>
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<td>10.7</td>
<td>505</td>
</tr>
<tr>
<td>21 May 5</td>
<td>6.5</td>
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</tr>
<tr>
<td>8 Jun 7</td>
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<td>772</td>
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<tr>
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<td>7.0</td>
<td>758</td>
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<tr>
<td>17 Sep 7.5</td>
<td>25.3</td>
<td>666</td>
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<tr>
<td>28 Oct 5.5</td>
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<td>6 Nov 8</td>
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<td>Year 2001</td>
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<tr>
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<td>9.9</td>
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<td>15 May 8</td>
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<tr>
<td>Year 2006</td>
<td>14 Dec 20</td>
<td>11.9</td>
<td>955</td>
</tr>
</tbody>
</table>
the Earth, the shielding effect of magnetosphere starts to get disturbed. Therefore, FDs are more frequently observed during maximum solar activity. It is also proposed that the shock wave production due to magnetic linear blast wave is a principal operating mechanism, which reduces the cosmic ray intensity on Earth\(^{19}\). Associated with flares and/or CME, the resulting sudden injection of the fast solar wind pushes the slower, steady wind forwarded into a blast wave with a shock front. The FDs are caused by CMEs and flare associated interplanetary shock. The faster flare associated CMEs decelerate close to the Sun, whereas other CMEs accelerate\(^{21}\).

The CMEs in comparison to solar flares have been found more to be effective due to higher kinetic energy of CMEs than those of flares\(^{22}\). The coronal waves propagating in the northern hemisphere are very fast and dimming extended over the entire southern hemisphere\(^{23}\). It is found that the solar flares originated on the western limb of the sun do not have much effect on either the interplanetary magnetic field (IMF) or on the geomagnetic field. There is a general correlation between the sunspot number and the frequency of solar flares formation, but the major flare events do not necessarily occur at sunspot maximum. Some flares that produce the most marked effects near Earth are formed while the sunspot group is decaying.

4 Conclusions

Based on the analysis discussed as above, the following conclusions are drawn.

The occurrence of bright solar flares is maximum in northern hemisphere during increasing phase and in southern hemisphere during decreasing phase of solar cycle 23 in both hemispheres.

Though the occurrence of total bright flares and type 1B solar flares are equally distributed in the solar regions, the occurrence of type 2B and 3B solar flares is found to be more in northern hemisphere as compared to southern hemisphere. During solar cycle 23, the type 4B solar flares are found to occur in south-east region of solar disk, in which 67% are responsible to produce FDs.

Although, the bright solar flares occurring in north-east region are more effective in producing FDs, the type 4B major flares responsible for FDs have occurred in south-east region. The bright solar flares originated from 0°-40° in north region, 10°-40° in south region, 0°-40° in east region and 10°-40° in west regions have been found to be more effective in producing FDs.

As much as 88% FDs are found to be associated with coronal mass ejections (halo and partial halo CMEs) and 55% FDs are found to be associated with bright solar flares.

Out of total FDs, 66% are non-recurrent and the remaining of recurrent type. Non-recurrent FDs are found to be associated with fast CMEs, while recurrent ones with slow CMEs.

The angular width of partial halo CMEs (FDs associated) has been observed in the range of 90-180 deg in both classes.

The average solar magnetic field and solar wind velocity are found as a necessary condition for producing FDs.

The occurrence of FDs during increasing phase and decreasing phase almost follows the solar cycle except in 2004.

References