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Cosmic ray Forbush decreases after the giant solar flare of 15 February 2011

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A very strong X-ray solar flare occurred at about 0200 hrs UT on 15 February 2011. It was associated with a coronal mass ejection (CME) but the CME was not very strong and its interplanetary CME (ICME) took about 70 h to reach the Earth. Also, the ICME blob had a moderate, short-lived magnetic field *B,* so the resulting cosmic ray Forbush decrease (FD) was weak. The *Bz* component was only slightly negative, so the resulting geomagnetic storm magnitude *Dst* was negligibly small. Thus, this giant solar flare had very poor geo-effectiveness indicating that large flares need not necessarily lead to significant storm effects on Earth, particularly in the early part of a sunspot cycle when overall solar activity would be weak.

Keywords: Forbush decrease, Solar flare, Coronal mass ejection (CME), Geomagnetic storm, Cosmic ray

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1 Introduction

When a solar flare occurs, it is generally accompanied by a coronal mass ejection (CME)[1]. If the CME is strong (velocities exceeding 1000 km s^{-1}) and ejected in a wide angle, its modified form interplanetary CME (ICME), reaching the Earth´s orbit around the Sun, may engulf the Earth and cause disturbances. For geomagnetic storms to occur (large negative *Dst)*[2], an additional requirement is that the magnetic field *B* in the ICME blob (magnetic bottle region characterized by enhanced number densities, large velocities and large magnetic fields)[3] engulfing the Earth should have a substantial negative *Bz* component. This was explained by Dungey[4]. When *Bz* is negative, reconnection occurs at the daytime magnetopause between the terrestrial magnetic field and the southward *Bz* component of the interplanetary field. When the field lines are swept back in the geomagnetic tail, a neutral point is formed through which the solar wind gets an entry into the magnetosphere. Low energy particles spiral around the stretched geomagnetic field lines and impinge on the terrestrial atmosphere in the polar region causing enhanced aurora. High energy particles rush towards the Earth but are deflected around the Earth (Fleming's right hand rule) in circular orbits in the equatorial plane forming a ring current at several earth radii, which causes large geomagnetic field reductions at the ground (negative *Dst*). With *Bz* negative, of about 25-30 nT, *Dst(min)* can occur in a range of 200-600 nT.

CMEs (generally associated with strong solar flares) do not have a direct effect on terrestrial environment. The effect comes through the ICME blobs (modified form of CME during their transit in interplanetary space) when these engulf the Earth. Besides geomagnetic storms (caused only if the blob has a substantial negative *Bz* component of magnetic field), ICME blobs also cause modulation (decreases) in the extra-galactic cosmic ray (CR) flux impinging on the Earth. These are known as Forbush decreases (FD). For a substantial FD magnitude, the magnetic structure of the ICME blob should be extensive and the magnetic field *B* strong enough (several tens of nT) to repel and deviate the CR flux considerably[5]. (Note that for FD, only the total magnetic field *B* in the ICME blob is relevant. The negative *Bz* component has no relevance for FD, though negative *Bz* component has full relevance for geomagnetic storms). Before the occurrence of a FD, sometimes solar energetic particles (SEP) are produced in the solar flare region (http://www.lpl.arizona.edu/SummerSchool07/lectures/jokipii/Jokipii1.pdf) and these cause ground level events (GLE) seen as abrupt increases of CR intensity before the Forbush decreases[6,7].

On 15 February 2011 at 01:56 hrs UT, a very large X-ray solar flare occurred, the first of sunspot cycle

24 (September 2009 onwards) and one of the largest in recorded history of X-ray flares. As such, very large geophysical changes were expected, but nothing much seems to have happened (reported in http://journeytothestars.wordpress.com/2011/02/25/valentines-day-solar-flare/; http://www.astronomy.com/~/link.aspx?_id=8ad8f193-856f-4dc4-95af-9041b930be40; http://www.nasa.gov/mission_pages/sunearth/news/News021411-xclass.html). There were auroras in the polar region. The China Meteorological Administration reported that the week's solar flare activity caused sudden ionospheric disturbances in the atmosphere above China and jammed short-wave radio communications in the southern part of the country (http://phys.org/news/2011-02-huge-solar-flare-radio-satellite.html). However, there were virtually no geomagnetic effects.

In the present communication, results about CR neutron monitor intensity changes (Forbush decreases) during 16-20 February 2011 have been reported.

2 Data and plots

The data used are for the chain of eight cosmic ray neutron monitors operated by the Bartol Research Foundation, USA (http://neutronm.bartol.udel.edu/). Table 1 gives the station details.

Figure 1 shows the plots of the percentage hourly values of the eight neutron monitor intensities for the period 16-21 Feb 2011. The following may be noted:

(i) The top plot is for the neutron monitor at Thule (77°N). A few oscillations of 0-1% are present all through but there was no big increase. Thus, no solar energetic particles (SEP) were produced to cause a ground level event (GLE). The Forbush decrease started at about 0000-0300 hrs UT on 18 February (see the arrow). Since the flare occurred at about 0200 hrs UT on 15 February, there was a delay of about 3 days (72 h). So, if the CME occurred at about the same time as the solar flare, its transit time to reach the Earth as ICME was as large as 72 h indicating an average speed of about 580 km s^{-1} which is not very high. Thus, this was a weak event.

(ii) After starting, the Forbush decrease (FD) reached the maximum depression in about 6 h (see the second arrow). The maximum depression was 4.1% and is mentioned in Table 1.

(iii) The further plots are for neutron monitors at other locations in descending order of northern latitudes (40°N for Swarthmore), while the last two plots are for McMurdo and South Pole in the southern hemisphere (Antarctic region). The FD started at about 0000-0300 hrs UT on 18 February (shown by arrows) for all the locations, but the minima occurred after 6-9 h later (shown by arrows), as one proceeded from North to South.

(iv) The recovery was slow with about 1% depression still remaining even at the end of 21 February (4 days). This indicates that even though the ICME passed over the Earth, the magnetic field in the region farther away from Earth in the anti-sunward direction was still effective in modulating CR arriving at Earth.

Table 1—Details of the eight cosmic ray neutron monitors

Station	Latitude	Longitude	Forbush decrease, %
Thule	76.5°N	68.7°W	4.1
Inuvik	68.4°N	133.7°W	5.0
Fort Smith	60.0°N	111.9°W	4.7
Nain	56.5°N	61.7°W	4.2
Peawanuck	55.0°N	85.4°W	4.8
Swarthmore	39.9°N	75.4°W	4.4
McMurdo	77.9°S	166.6°E	4.5
South Pole	90°S		5.0

The FD magnitudes are in the range 4-5% with no consistent latitude dependence. Magnitudes less than 4% are considered low. Cane *et al.*[8] considered FDs only of 4% or larger. Grading FDs roughly: 0-4% as very weak; 4-8% as weak, 8-12% as moderate; and exceeding 12% as severe, the present event is in the weak category.

When an ICME engulfs the Earth, geomagnetic storms occur, if there is a substantial negative Bz component of interplanetary magnetic field B. Press reports said that there was negligible geomagnetic activity in the present event because the negative Bz component was not there. To check this, the interplanetary parameters, viz. solar wind speed V, magnetic total field B and its component Bz have been plotted in the bottom part of Fig. 1 (data from http://omniweb.gsfc.nasa.gov/form/dx1.html). The following may be noted:

(i) The wind speed V was near 400 km s^{-1} for 16 and 17 February, but increased abruptly during 0000-0300 hrs UT of 18 February, heralding the arrival of an ICME blob. This is the same time as the commencement of the cosmic ray Forbush decreases, as expected. The speed increased to 691 km s^{-1} by 1200 hrs UT and then decreased back to about 400 km s^{-1} by the end of 19 February indicating exit of the ICME blob.

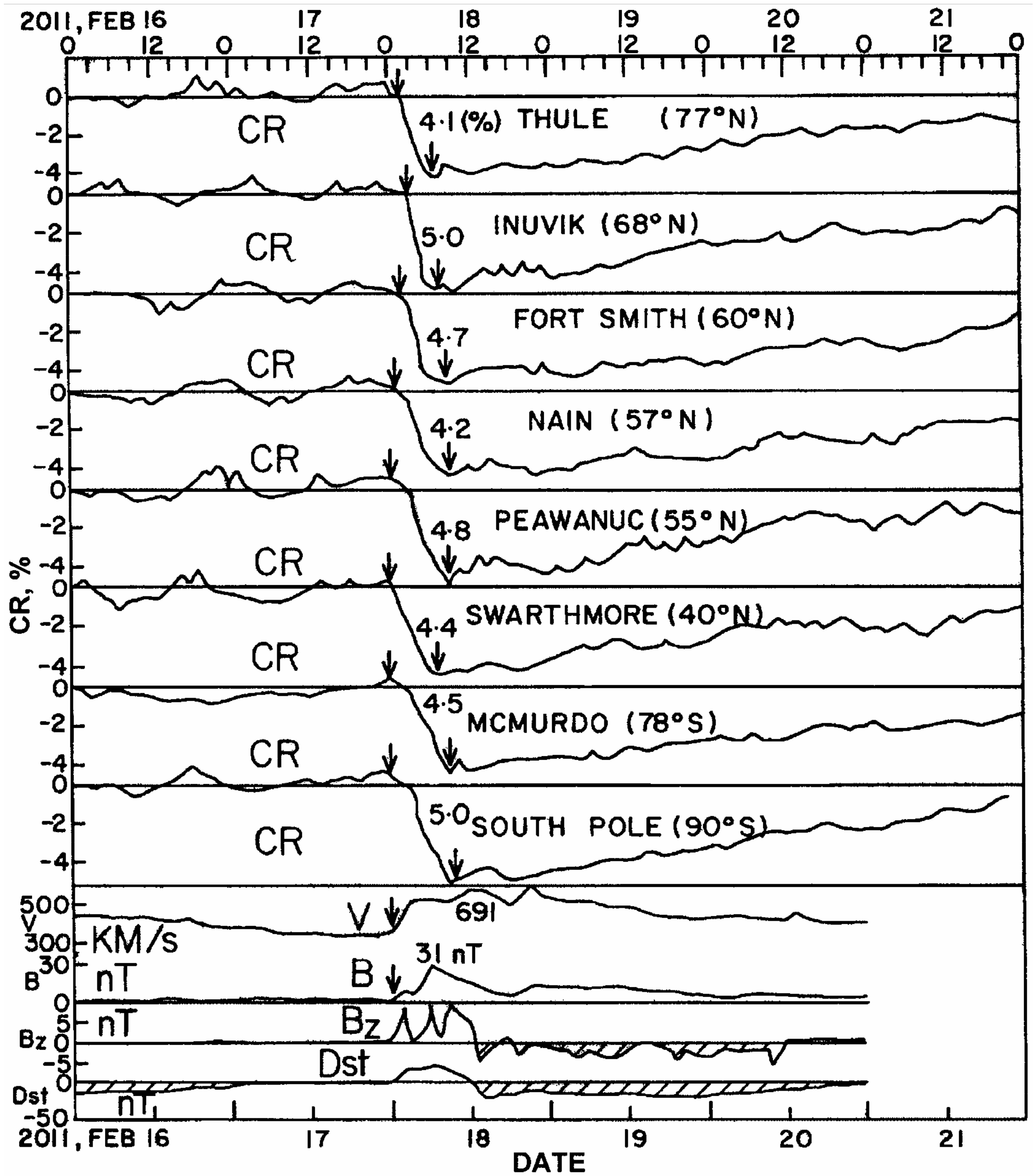

Fig. 1—Plot of hourly values during 16-21 February 2011 [upper plot: Cosmic ray neutron monitor counts (percent) for eight neutron monitors at different latitudes; first arrow shows the start of a FD (Forbush decrease) at about 0000-0300 hrs UT of 18 February; second arrow shows the maximum depression at about 0600-0900 hrs UT of 18 February; lower plot: Interplanetary parameters: solar wind speed *V*, total magnitude field *B* (both show the start of the disturbance at 0000-0300 hrs UT of 18 February), and the magnetic component *Bz;* bottom plot is for the geomagnetic disturbance index *Dst*]

(ii) The next plot for total interplanetary magnetic field *B* shows a similar pattern, namely started increasing at 0000-0300 hrs UT of 18 February, but reached a peak value of 31 nT in the next 6 h and then declined rapidly.

(iii) The third plot is for the *Bz* component. For a large storm, the *Bz* component should have started negative at 0000-0300 hrs UT of 18 February and attain large negative values but it did not do so. Instead, it became positive for the next 12 h and then became negative but the magnitude was very small, less than 5 nT.

(iv) The fourth plot is for the geomagnetic disturbance index *Dst* (Ref. 2) which should attain large negative values when *Bz* turns negative. Instead, the *Dst* was initially positive, and did become negative when *Bz* turned slightly negative (shaded portions), but the negative *Dst* magnitudes were very small, less than 50 nT. If negative *Dst* is graded as: 0-50 nT very weak; 50-100 nT weak; 100-150 nT moderate; 150-200 nT severe; and exceeding 200 nT very severe, the *Dst* in the present case was in the very weak category.

Thus, even though the X-ray solar flare was one of the strongest in known history and was associated with a CME, the succeeding ICME engulfing the Earth was weak with a magnetic field *B* reaching only 31 nT for a short time (in big storms, it reaches 50-60 nT), and its negative *Bz* component was negligibly small, less than 5 nT (in big storms, it reaches more than 25 nT). As a result, the geomagnetic *Dst* was negligibly small, less than 50 nT (in big storms, negative *Dst* exceeds 200 nT).

Whereas for large *Dst*, a large negative *Bz* component is crucial; for CR FDs, the *Bz* has no significance whatsoever. What matters is the total interplanetary magnetic field *B* structure around the Earth. This may be represented by large *B* values, but it was found that the *B* magnitudes observed near the Earth by the satellite were not proportional to FD magnitudes (correlation less than 0.5)[9]. Also, even in severe storms, the *Dst(min)* magnitudes were poorly correlated with FD magnitudes[9].

3 Conclusions

A very strong X-ray solar flare occurred at about 0200 hrs UT on 15 February 2011. It was associated with a coronal mass ejection (CME), but the CME was not very strong. Its modified form ICME took about 70 h to reach the Earth (a strong ICME takes about 20 h or even less). Also, the ICME blob had a moderate magnetic field, only about 30 nT lasting for a short time (strong blobs have magnetic fields exceeding 50-60 nT); so the resulting Forbush decrease (FD) was weak, only about 4-5% strong FDs often exceed 10%. The *Bz* component was only slightly negative, less than 5 nT (strong storms have negative *Bz* exceeding 25 nT); so the geomagnetic storm magnitude *Dst(min)* was negligibly small, less than 50 nT (strong storms have negative *Dst(min)* exceeding 200 nT). Thus, this giant solar flare had very poor geo-effectiveness indicating that large flares need not necessarily lead to significant storm effects on Earth. It may be noted that in the early part of a sunspot cycle (as at present when cycle 24 started in 2009), overall solar activity is weak. So, though strong flares may occur in localized regions, the general environment would not be favourable for strong CMEs.

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