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Solar flare of 15 February 2011 and its geomagnetic effects

R P Kane

Instituto Nacional de Pesquisas Espaciais (INPE), C P 515, São Jose dos Campos, 12245-970 SP, Brazil

E-mail: kane@dge.inpe.br

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The link between solar flares and geomagnetic storms is: Solar flare, associated coronal mass ejection (CME) leading to the subsequent interplanetary CME (ICME) which follows and engulfs the Earth and its geo-effectiveness due to a large negative Bz component of the ICME magnetic field B. During the giant flare of 15 February 2011, the last link, namely a substantial negative Bz, was absent and hence, only a very weak geomagnetic storm resulted.

Keywords: Solar flare, Geomagnetic storms, Interplanetary coronal mass ejection

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1 Introduction

Sunspots are caused by very strong magnetic fields on the Sun. Sunspots usually appear in pairs, one spot leading and the other following. The two spots have opposite magnetic polarities, joined by vertical loops. Due to the differential rotation of the Sun at different latitudes, the sunspot magnetic fields are twisted. When the tangled fields reach a breaking point, like a rubber band that snaps when wound too tight, huge bursts of energy are released as the field lines reconnect. This leads to solar flares and coronal mass ejections (CMEs).

On 15 February 2011, a very large solar flare occurred at 01:44 hrs UT, peaked at 01:56 hrs UT and disappeared at 02:06 hrs UT. It was the first of sunspot cycle 24 (September 2009 onwards) and probably the largest in recorded history. Popular reports which appeared in the website Valentine Day Solar Flare: (http://journeytothestars.wordpress.com/2011/02/25/valentines-day-solar-flare/) indicated that the geomagnetic effects of this flare were negligibly small.

2 Solar flares and associated geophysical effects

Chapman & Bartels[1] noticed that solar flares were followed by geomagnetic storms after a few tens of hours and suggested that charged particles from the Sun, rather than electromagnetic radiation, were responsible. The reasons for these remained unknown until 1950s when ideas about solar wind evolved. Biermann[2] argued that the turning of comet tails, always away from the Sun, implied that some solar radiation was impinging on the comet tail all the time. Soon after, Parker[3,4] formulated a rigorous theory of solar wind which envisaged that with temperatures of million degrees or more, the solar corona must expand and a continuous flow outwards must result with speeds of about 200-300 km s^{-1}. Further, this flow would be so powerful that the modest permanent dipole field of the Sun (about 1 Gauss) would be stretched out in the solar equatorial plane. Thus, the interplanetary space was not a vacuum but full of magnetized plasma. Also, since the Sun was rotating, the plasma would come out as an Archimedes spiral. Whereas, Parker concentrated on quiet-time solar wind, Gold[5] investigated the aspect of storm-time variations. He proposed that the impact of solar wind on Earth´s environment would be to contain Earth´s magnetic field in a restricted region which he called magnetosphere, which would be further compressed during stormy conditions. Satellite data in early 1960s (refs 6-7) confirmed the existence and characteristics of solar wind, quiet as well as enhanced. Soon after, Tousey[8] discovered CMEs which were often associated with solar flares. While in transit to the Earth´s orbit, these CMEs get considerably modified and acquire new characteristics, which may be different from that of the original CME. These modified forms are termed interplanetary CMEs (ICMEs) and these are the ones which engulf the Earth and are relevant for the evolution of geomagnetic storms.

A comparison of the satellite data with ground data showed that even when the Earth seemed to be engulfed by an interplanetary blob ICME, the geomagnetic storm did not always occur. A measure of geomagnetic storm is the disturbance storm time index (Dst), obtained by superposing the geomagnetic H component at three geographical locations 120° longitude apart[9]. Since diurnal effects are thus eliminated, only isotropic H variations remain. During storms, Dst drops considerably below the zero level, as much as 500-600 nT in extreme cases. However, it was noticed that Dst remained almost zero in some events. A closer scrutiny of the interplanetary data showed that the magnetic field *B* in the interplanetary blob was of crucial importance. Resolved into three components, B_x along the Sun-Earth line, B_y perpendicular to B_x in the plane of Earth´s orbital plane around the Sun, and B_z perpendicular to both B_x and B_y. The B_z component, parallel to the Earth´s rotation axes around itself, was of key importance. A positive B_z (pointing northward) was ineffective while a negative B_z (pointing southward) was the most effective; larger the negative B_z, larger the Dst depression (negative *Dst*). Dungey[10] explained the puzzle in a simple way. When B_z is negative, reconnection occurs at the daytime magnetopause between the terrestrial magnetic field and the southward B_z 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 law) 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). Thus, the geomagnetic storm process is well explained. With B_z negative of about 25-30 nT, Dst(min) occurs in a range of 200-600 nT. True, the Dst/*Bz* plot showed a scatter[11], but all these were severe storms [negative Dst(min) exceeding 200 nT].

3 Flare of 15 February 2011

A solar flare has one direct effect, namely, a direct transmission of electromagnetic radiation which is unaffected by magnetic fields and affects parts of the Earth which are facing sunward. In the case of the solar flare of 15 February 2011 at 0200 hrs UT, the regions in daylight were in Asia. A press report said, "The China Meteorological Administration reported that the solar flare had jammed shortwave radio communications in southern China". It said the flare caused sudden ionospheric disturbances (SID) in the atmosphere above China, the official Xinhua news agency reported.

Complete data from satellites are available on the website http://omniweb.gsfc.nasa.gov/form/dx1.html. Figure 1 shows a plot of the hourly values of the interplanetary parameters, viz. solar wind number density *N*, wind speed *V*, total magnetic field *B* and its B_z component. The last plot is for geomagnetic disturbance index Dst (ref. 9, data available at the website http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html). The following may be noted:

The number density *N* increased abruptly during 0000-0300 hrs UT of 18 February, heralding the arrival of the ICME blob (marked by the vertical line at 0000 hrs UT on 18 February). If the original CME erupted at the same time as the solar flare (0200 hrs UT on 15 February), the time taken by the ICME to reach the Earth was about 70 h, with an average speed of about 580 km s^{-1}. This is not a large speed, indicating that the CME was only moderate. The *N* increase disappeared by about 1200 hrs UT on 18 February and lasted for about 12 h.

The wind speed *V* was near 400 km s^{-1} on 16 and 17 February, but increased abruptly during 0000-0300 hrs UT on 18 February. 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. Higher speeds lasted for longer than the *N*.

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

The plot for the B_z component shows that for a large storm, the B_z component should have started negative at 000-0300 hrs UT on 18 February and attained large negative values, but it did not do so. Instead, it became positive for the next 12 h and then became negative but the negative magnitude was very small, less than 5 nT

The plot for the geomagnetic disturbance index *Dst* should attain large negative values when B_z turns negative. Instead, the *Dst* was initially considerably positive (+54 nT, indicating severe ram pressure), and

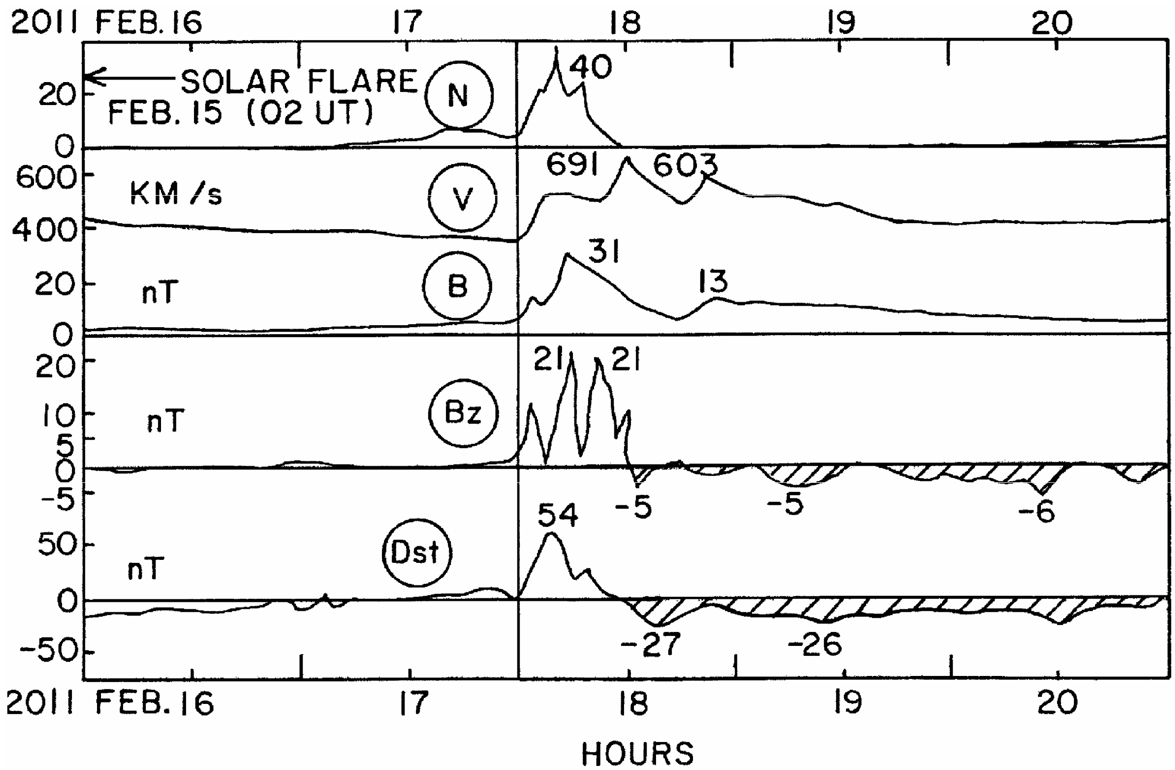

Fig. 1 — Plot of hourly values during 16-20 February 2011 for interplanetary parameters: solar wind speed *V*, total magnitude field *B* (both show the start of the disturbance at 0000-0300 hrs UT on 18 February), and the magnetic component B_z. Bottom plot is for the geomagnetic disturbance index Dst

did become negative when B_z 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; exceeding 200 nT: very severe, then Dst in the present case was in the very weak category.

Thus, even though the solar flare was one of the strongest in known history and was associated with a CME, the succeeding ICME engulfing the Earth was moderate with a magnetic field *B* reaching only 31 nT for a short time (in big storms, it reaches 50-60 nT), and its negative B_z 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).

4 Conclusions

Flares by themselves are not the cause of geomagnetic storms. The link between solar flares and geomagnetic storms is: Solar flare, associated CME, the ICME which follows and engulfs the Earth, geoeffectiveness through a large negative B_z component. It seems that in the present case of the very strong solar flare of 15 February 2011, the last link, namely, a substantial negative B_z, was mostly broken and hence, a very weak geomagnetic storm resulted. Effects of this storm on ionosphere and cosmic rays are under study.

Acknowledgements

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