

Interplanetary and terrestrial observations of an Earth-directed coronal mass ejection

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Abstract. In this article we report interplanetary scintillation observations at 103 and 327 MHz of an Earth-directed coronal mass ejection (CME) which occurred near the center of the solar disk at 0435 UT on May 12, 1997. The disturbance was found to have plasma density ~ 4 times more than that of the ambient plasma at a distance of ~ 0.5 AU from the Sun. The most peculiar aspect of this CME is that it appears that the disturbance moved slightly slower than the ambient medium. Solar and Heliospheric Observatory (SOHO) and interplanetary scintillation (IPS) estimates of solar wind are quite different; it appears that the difference could be due to the projection effect of the SOHO image. Though the disturbance was not very severe, its impact on Earth's environment produced a geomagnetic storm. This event was associated with a two-ribbon flare. The ionospheric effects of soft X rays from this solar flare were observed by a digital ionosonde at Ahmedabad in the form of excess ionization (~ 1200 el cm^{-3}) in the D region of the ionosphere.

1. Introduction

The phenomenon of coronal mass ejection (CME) was identified using spaceborne coronagraphs. These events are particularly interesting as they show how the Sun can be the source of interplanetary disturbances which dramatically affect the Earth [Gosling, 1993; Hundhausen, 1997 and references therein]. It is known that halo CMEs originating on the visible solar hemisphere directed toward the Earth may have the severest terrestrial consequences [Howard *et al.*, 1982]. Hudson *et al.* [1998] examined 11 “halo” CMEs using Yohkoh soft X-ray images during December 1996 to May 1997. One of

these CMEs occurred on May 12, 1997 at 12°N , 8°W on the solar corona. This was an Earth-directed CME and was associated with a two-ribbon flare [Jain *et al.*, 1997]. In this article we present and discuss the following observations of this event: (1) the effect of excess soft X rays on the D region of the ionosphere over Ahmedabad, (2) the interplanetary scintillation observations at 103 and 327 MHz wherein propagation of this CME is clearly identified, and (3) terrestrial effects of the CME such as higher geomagnetic activity. Some of these were part of a local campaign for solar-terrestrial relationship.

2. Observations

At Udaipur Solar Observatory, Jain *et al.* [1997] made high-resolution synoptic observations of solar chromosphere and photosphere in H-alpha and 6122 Å, respectively. Their time sequence showed that a filament was stretched over the active region NOAA 8038 on May 10, which was disrupted on May 11, 1997, and was not visible on May 12, 1997. A moderate two-ribbon flare (1B/C1.3) began at 0444 UT on May 12, 1997. The flare was composed of several bright/eruptive centers forming the ribbon structure [Jain *et al.*, 1997]. The ribbon structure was clear around 0449 UT, and the two ribbons appeared

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to separate from each other with a velocity of $\sim 20 \text{ km s}^{-1}$. The flare was of a relatively long duration and ended at $\sim 0620 \text{ UT}$.

Once the possibility of some activity from NOAA 8038 was indicated, a minicampaign was started using our ground based systems, namely, digital ionosonde at Ahmedabad and interplanetary scintillation (IPS) array at Rajkot. The ionosonde operates on the principle of radio sounding of the ionosphere in which pulses of HF radio waves in the range of 0.5–20 MHz are transmitted vertically upward. Depending on the plasma frequency, which varies as the square root of plasma density in the ionosphere, the different frequency radio waves are reflected from different heights and recorded as an ionogram. The ionograms have been extensively used for various studies of the ionosphere and related phenomena [Rastogi *et al.*, 1972; Reinisch and Huang, 1983 and references therein]. The minimum frequency (normally termed " f_{min} ") at which echoes are observed in the ionogram depends, among other things, on absorption present in the lower part ("D" region) of the ionosphere. The ionization density in the D region will govern the increase or decrease in absorption. The primary source of ionization in the D region is known to be solar soft X rays (1–8 Å). The temporal variation (0440–0610 UT) of soft X-ray flux (solid curve and scale on the left side in W m^{-2}) measured by GOES 9 is displayed in Figure 1 which clearly indicates ~ 15 times increase in the soft X-ray flux. The dotted curve in Figure (scale for this curve is marked on the right side in megahertz) shows

temporal variation of relative deviation in f_{min} . This shows a very clear increase in f_{min} by $\sim 0.6 \text{ MHz}$. From this it is possible to calculate the excess electron density produced by the solar X-ray flare. The excess electron density in the D region over Ahmedabad was estimated to be $\sim 1200 \text{ el cm}^{-3}$ during this event. The peak of f_{min} occurred $\sim 20 \text{ min}$ later than that of the X-ray flux. This delay is due to the response time of the local D region to the solar X-ray flux.

The associated coronal mass ejection event was observed by extreme ultraviolet imaging telescope (EIT), originating north of central solar meridian [Thompson *et al.*, 1998]. EIT was running a campaign consisting of full disk 195 Å images taken at an average cadence of a single half-resolution image every 18 min. An expanding wave front was observed emanating from a central point near or at NOAA active region 8038 at 23°N 7°W . The disturbance propagated quasi-radially. The propagation of the disturbance in the heliosphere can be monitored indirectly by interplanetary scintillation. The IPS observations of this disturbance were made at 103 and 327 MHz.

The interplanetary scintillation observations at 103 MHz were made using an IPS radio telescope at Rajkot, details of which are given by Vats and Deshpande [1994]. This was the second experiment of our local campaign. The Rajkot telescope observes the radio emission of selected compact radio sources (in the present case, 3C48) daily during local transits at Rajkot (longitude 70.8°E , latitude 22.3°N). The phenomenon of interplanetary scintillation can be understood in the following way. The radio wave front from a compact source can be assumed to be a plane wave front at sufficiently far distance. When such a wave front passes through a medium (in this case, interplanetary medium (IPM) which contains plasma density irregularities, it gets randomly modulated. Further propagation of the randomly modulated wave front to the observer (in this case the radio telescope) produces intensity scintillation. Thus interplanetary scintillation (IPS) is caused by the plasma turbulence of IPM. In this way, IPS is a technique for studying the propagation of the disturbances from ground-based observations of radio sources [Rickett 1975; Watanabe and Kakinuma, 1984]. The scintillation is measured by a statistical index S_4 , which is defined by Briggs and Parkin [1963] as the normalized root-mean-square deviation of signal intensity:

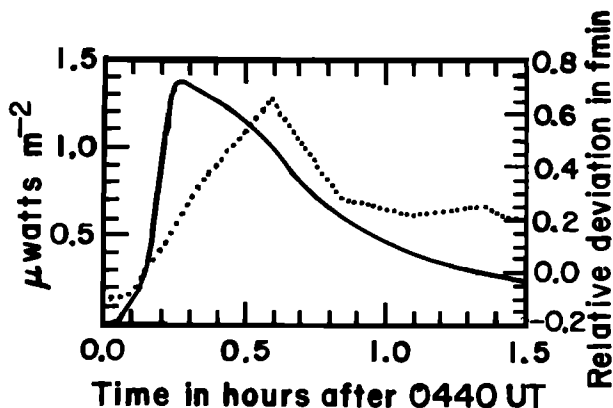


Figure 1. Temporal variation of (1) soft X-ray flux (solid curve and scale on the left side in W m^{-2}) measured by GOES 9 and (2) relative deviation for f_{min} (dotted curve and scale on right side in megahertz) measured by ionosonde over Ahmedabad.

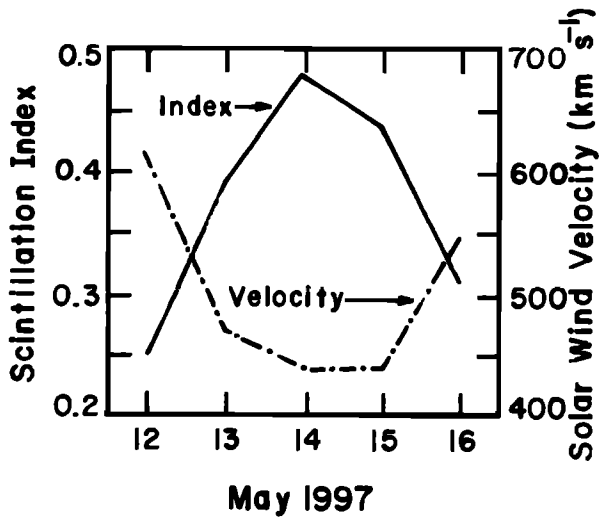


Figure 2. Variation of daily scintillation index S_4 (solid curve and scale on the left side) of a compact radio source 3C48 at 103 MHz and solar wind velocity (dash-dotted curve and scale on the right side) in km s^{-1} for the same radio source at 327 MHz.

$$S_4 = \frac{\langle (1 - \langle I \rangle)^2 \rangle^{1/2}}{\langle I \rangle} \quad (1)$$

where I represents intensity of signal strength and $\langle \rangle$ denotes average. The radio source 3C48 was observed at the local transits of the source at Rajkot before, during, and after the passage of the interplanetary disturbance of the coronal mass ejecta of May 12, 1997. The variation of scintillation index S_4 (solid curve and scale on the left side) of 3C48 is shown in Figure 2. The solar wind velocity measurements by the IPS observations of the same radio source 3C48 at 327 MHz were made by Solar Terrestrial Environment Laboratory (STELab), Nagoya University, Nagoya, Japan, and are available at their Web site (http://stesun5.stelab.nagoya-u.ac.jp/ips_data-e.html). These velocity measurements for the same period are also shown in Figure 2 (dash-dotted curve and scale on the right side). It is clear that the scintillation index and the solar wind velocity vary in opposite phase. During the passage of the interplanetary disturbance the scintillation index increased by approximately twofold from 0.25 on May 12 to 0.5 on May 14, 1997. On the other hand the solar wind velocity decreased from $\sim 613 \pm 10 \text{ km s}^{-1}$ to $\sim 438 \pm 30 \text{ km s}^{-1}$. As the IPS observations at

Rajkot and Nagoya were made at local transits of the radio source, the time difference in the observations would be around 3.5 hours. Thus the line of sight to 3C48 from Rajkot and Nagoya was passing through a close region of the IPM (both in space and time).

Using the calibration scheme of Tappin [1986], the twofold increase in scintillation index would mean a fourfold increase in density. Thus at the time of crossing the line of sight to 3C48 the blob of disturbance associated with the coronal mass ejecta had plasma density ~ 4 times more than that in the ambient medium. The ambient medium means the region where the disturbance was absent, i.e., before and after the passage of the disturbance. During the passage of disturbance, the solar wind velocity recorded a decrease; that is, the solar wind velocity was more before and after the passage of this disturbance. This indicates that the blob moved slower than the ambient medium. From the event occurrence we obtained a solar wind velocity $\sim 500 \text{ km s}^{-1}$. This conforms reasonably to the solar wind measurements by the IPS method. The increase in scintillation during the passage of the disturbance leads to an estimate that the disturbance at the point of crossing of the line of sight to 3C48 had at least 4

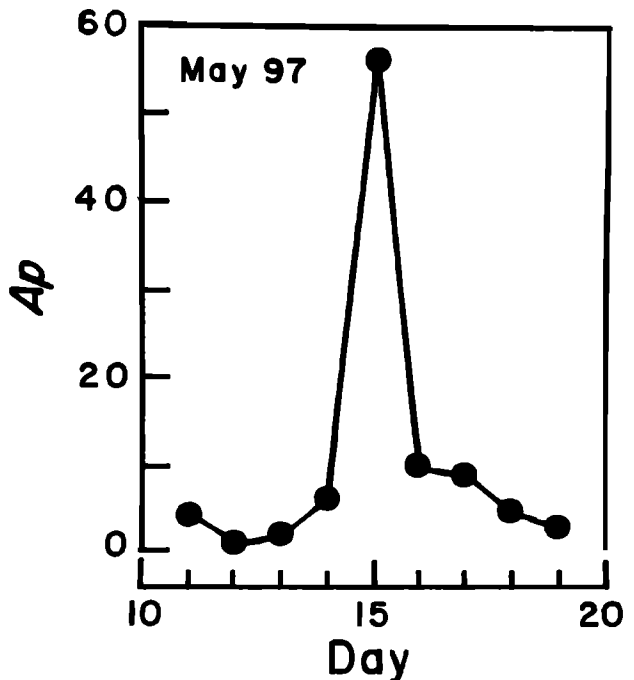


Figure 3. Variation of daily A_p values during May 10-20, 1997. The increase on May 15 indicates a geomagnetic storm.

times more plasma turbulence. The heliocentric latitude and longitude of the point of closest approach (from the Sun) to the line of sight to 3C48 on May 14, 1997, were $\sim 43^\circ$ and 49° , respectively. The solar elongation angle and the distance to the point of closest approach from the Sun were 28° and 0.47 AU, respectively. Thus a portion of the disturbance would have passed the line of sight to 3C48 ~ 2 days after it started from the solar corona and 1 day earlier than it interacted with the geomagnetic field.

The observations of geomagnetic activity in the form of daily values of planetary index A_p for May 10 to May 20, 1997, are shown in Figure 3. The A_p index was less than 10 up to May 14, 1997. On May 15 it went up to ~ 55 and again returned to low values (< 10) on May 16 and remained so up to May 19. This sudden increase in A_p index on May 15 was due to the interaction of the solar disturbance with the geomagnetic field. The geomagnetic disturbance lasted for less than a day.

3. Discussion

Several solar disturbances have been tracked by IPS observations in the past. *Hewish and Bravo* [1986] found that most of them were shells of enhanced density followed by high-velocity streams and claimed that all these originated from coronal holes. They stressed that there were no flares or filament activities on the solar disc within a suitable time interval. However, there exist several exceptions or contradictions to their findings, and many geomagnetic activities are related to filaments and flares. During the post-solar-minimum period from December 1996 to June 1997, *Webb et al.* [2000a] found that all six halo CMEs were Earth directed and were associated with shocks, magnetic clouds, and moderate geomagnetic storms at the Earth 3–5 days later. The present work supports this point of view (here the effect on the CME is seen in the interplanetary medium and terrestrial geomagnetic field after 2 and 3 days, respectively).

The event reported here has its origin in a two-ribbon flare and a halo coronal mass ejection on May 12, 1997. Velocity of the disturbance estimated by the event occurrence $\sim 500 \text{ km s}^{-1}$ is somewhat higher than the one calculated by multistation IPS method at 327 MHz ($\sim 438 \text{ km s}^{-1}$). However, this is lower than that estimated by *Plunkett et al.* [1998] using Large-Angle Spectrometric Coronagraph (LASCO) observations, namely, $\sim 613 \text{ km s}^{-1}$. They estimated

the velocity using a reasonable assumption about the geometry and a projected velocity of $\sim 250 \text{ km s}^{-1}$. These differences could be explained in two ways. One possibility is that the disturbance began from the source with a velocity $\sim 613 \text{ km s}^{-1}$ and the velocity reduced to $\sim 438 \text{ km s}^{-1}$ as it moved away in the IPM. This could give an average velocity of $\sim 500 \text{ km s}^{-1}$ as estimated by the event occurrence. However, the decrease from 613 to 438 km s^{-1} is rather large to understand theoretically.

The other possibility for the difference could be the projection of the SOHO image which could cause an error of approximately $\pm 100 \text{ km s}^{-1}$ and thus bring the two estimates closer. In fact, *Thompson et al.* [1998] reported the projected velocity as $245 \pm 40 \text{ km s}^{-1}$ which suggests that the projection effect of the SOHO image could be responsible for the difference in IPS and SOHO estimates of solar wind velocity.

Jackson et al. [1988] presented solar and interplanetary observations of the coronal mass ejection on May 7, 1979. They found that the plasma acceleration in that case was not limited only to distances within $3 R_\odot$, as is usually the case, but continued beyond the outer limit of the coronagraph view at $8 R_\odot$. The interplanetary scintillation velocity time series determined from the IPS observations of 3C48 showed a substantial increase during the passage of the May 7, 1979, coronal mass ejection. *Jackson* [1992] compared photometric and IPS observations of May 7, 1979, event and also that of April 27, 1979. The April 27, 1979, event was associated with an X1/1B flare at 20°N , 16°E on the solar surface, and the CME was found to have a motion of $\sim 700 \text{ km s}^{-1}$. *Wei and Dryer* [1991] analyzed several flare-associated shock wave events and found that all the disturbances show an enhancement of $> 50 \text{ km s}^{-1}$ in solar wind velocity (IPS measurements). In the present investigation the IPS observations of the coronal mass ejection of May 12, 1997, show an increase in the turbulence level (as seen by the time series of scintillation index (Figure 2)) and a decrease in solar wind velocity (as seen in Figure 2 by the time series of solar wind velocity). Thus the present work shows an unusual feature in that this CME (which had a density 4 times greater than the ambient medium) appeared to move slower than the ambient medium. More CMEs should be investigated in this way to substantiate these results.

The present observations also indicate that the disturbance had plasma density ~ 4 times greater than

that of the ambient medium. Thus this event had significantly less turbulence than the two cases of plasma disturbances reported by Vats *et al.* [1996] where plasma densities were ~ 16 and 36 times more than those of the ambient medium. Subsequently, as seen in Figure 3, the present disturbance produced a geomagnetic storm on May 15, 1997. This storm lasted for less than a day, whereas the two cases discussed by Vats *et al.* [1996] had geomagnetic disturbances lasting for 4 and 8 days. Thus the present disturbance was a relatively weaker one, but it displayed all the phenomena of the solar-terrestrial link. This supports the findings of Webb *et al.* [2000b] in that CMEs, not the surface activity, are the key causal link between solar eruptions and space weather at Earth.

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