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Atmospheric electric field anomalies associated with solar flare/coronal mass ejection events and solar energetic charged particle "Ground Level Events"

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Abstract

We discuss the fair weather atmospheric electric field signatures of three major solar energetic charged particle events which occurred in on 15 April 2001, 18 April and 4 November, and their causative solar flares/coronal mass ejections (SF/CMEs). Only the 15 April 2001 shows clear evidence for E_z variation associated to SF/CME events and the other two events may support this hypothesis as well although for them the meteorological data were not available. All three events seem to be associated with relativistic solar protons (i.e. protons with energies >450 MeV) of the Ground Level Event (GLE) type. The study presents data on variations of the vertical component of the atmospheric electric field (E_z) measured at the auroral station Apatity (geomagnetic latitude: 63.8°, the polar cap station Vostok (geomagnetic latitude: −89.3°) and the middle latitude stations Voyeikovo (geomagnetic latitude: 56.1°) and Nagycenk (geomagnetic latitude: 47.2°). A significant disturbance in the atmospheric electric field is sometimes observed close to the time of the causative solar flare; the beginning of the electric field perturbation at Apatity is detected one or two hours before the flare onset and the GLE onset. Atmospheric electric field records at Vostok and Voyeikovo show a similar disturbance at the same time for the 15 April 2001 event. Some mechanisms responsible for the electric field perturbations are considered.

1 Introduction

Solar flare (SF) and solar cosmic ray (SCR) effects on variations of the fair weather atmospheric electric field (E_z) have been studied in a number of papers (Cobb, 1967; Reiter, 1969; Markson, 1971, 1978; Olson et al., 1978; Reagan et al., 1983; Goldberg, 1984; Moiseev et al., 1993; Zadorozhny et al., 1994; Sheftel et al., 1994; Rycroft et al., 2000). Solar protons of high energies (>450 MeV) lead to different changes of electric properties in the atmosphere. For example, Holzworth and Mozer (1979) and Reagan et al. (1983) reported a reduction of the vertical electric field (by up to 90%) and an increase of atmospheric conductivity at 30 km (balloon altitudes) during the great solar proton event of the Ground Level Event (GLE) type on 4 August 1972. Such a response is to be expected from the relationship between the vertical atmospheric current density j_z, conductivity σ and vertical electric field E_z:

$$j_z = \sigma E_z, \tag{1}$$

On the other hand, Holzworth et al. (1987) and Zadorozhny et al. (1994) detected an increase of the vertical component of the electric field in the stratosphere and low mesosphere with a simultaneous increase of conductivity during two other GLEs (16 February 1984 and 19 October 1989, respectively). The existence of such large stratospheric and mesospheric electric fields may be related to aerosol layers (Goldberg, 1984; Holzworth et al., 1987; Zadorozhny et al., 1994; Rycroft et al., 2000). Relativistic solar protons penetrating the atmosphere may affect the aerosol layer through ionization and ion nucleation processes (Arnold, 1982; Hofmann and Rosen, 1983; Goldberg, 1984). Shumilov et al. (1996) detected an increase in aerosol concentration up to 50% at 20 km altitude at high latitudes following the 16 February 1984 GLE. Moreover, the energetic charged particle precipitation may "short out" such existing mesospheric and stratospheric electric fields, producing either an increase or decrease of E_z (Hale and Croskey, 1979; Zadorozhny et al., 1994). In particular, in Holzworth et al. (1987), Zadorozhny et al. (1994), Zadorozhny and Tyutin (1998) and Kasatkina and Shumilov (2005) it was shown that the increase of the vertical component of the electric field strength during a GLE event is possible if the total aerosol change increases with the ion pair production rate increase more than that of the conductivity. For example, this phenomenon may be considered in the charged aerosol gravitational sedimentation physical mechanism (Aikin and Maynard, 1990; Zadorozhny et al., 1994; Zadorozhny and Tyutin, 1998).

Major GLEs are rare events. Since 1980, three major GLEs occurred in 1981, two in 1982, one in 1984, seven in 1989, four in 1990, two each in 1991 and 1992, one in 1997, three in 1998, one in the millennium year 2000, five in 2001 and two in 2003 (data available at the Oulu Cosmic Ray Station website at http://cosmicrays.oulu.fi/GLE.html.

Measurements of E_z are also rather rare. Data are available from Nagycenk in Hungary (geomagnetic latitude: 47.2°) since 2001, from Voeikovo in Russia (geomagnetic latitude: 56.1°) since 2001, from Apatity on the Kola Peninsula (geomagnetic latitude: 63.8°) from 2001 to 2002, and at the Antarctic Vostok station (geomagnetic latitude: −89.3°) from 2001 to 2002. In this paper, the results of E_z measurements are presented for three major GLEs (on 15 April, 18 April, and 4 November 2001) at different latitudes; data from Apatity, Vostok, Voeikovo and Nagycenk are presented. We are not aware of any other similar E_z data being available during 2001 from other stations.

2 Results

Only five GLEs have been detected in 2001.Unfortunately, fair weather conditions occurred only for three of them. These three events are all associated with coronal mass ejections (CMEs) according to data from the Large Angle and Spectroscopic Coronograph (LASCO) on board the Solar Heliospheric Observatory (SOHO). The solar flare and CME onset times, peak times and properties of these events are summarized in Table 1.

In Fig. 1 the E_z component at the four stations, variations of the solar X-ray intensity and of the 1-min integral fluxes of energetic charged particles above a threshold energy observed by GOES-8 (data are available at the GOES website at http://rsd.gsfc.nasa.gov/goes) are shown for the 15 April 2001 GLE event. It is seen that vertical electric field variations at Apatity became more irregular with jumps (up to ∼1000 V/m in ten minutes) approximately two hours before the GLE event onset at 14:10 UT according to the neutron monitor data (Poirier and D'Andrea, 2002) and 1.5 h before the X-ray flare of magnitude X 14. The corresponding optical flare on the Sun occurred in the region 9415 located at 20° S, 85° W at 13:19 UT (Nitta et al., 2003), at which time E_z was ∼−1000 V/m.

After the GLE event onset the electric field changed only slowly, and was generally <300 V/m. Another jump in E_z (to −1000 V/m) occurred at ∼19:40 UT at the end of the GLE event according to the neutron monitor data (Poirier and D'Andrea, 2002). We have no idea about the causes of this second spike in E_z. However, we note that, at the same time (~19:00 UT), an increase of solar proton (>1 MeV and >10 MeV) fluxes occurred. Although LASCO/C2 data show a very high background due to the main eruption at 14:06 UT, the combined EIT/C2 difference images movie shows a brightening in EIT on the West limb at 18:04 UT, most probably from the same region of the 14:06 UT event. Ejection is also seen in C2 starting between 19:00 and 19:30 UT mainly on the south, but from 20:47 UT the ejection is also seen spread all around the West limb. The second jump seen at 19:40 UT in the electric field may be related to this later event. This would also agree with the variation of the field detected at Voeikovo starting at about 19:00 UT. From Fig. 1, for the 15 April 2001 event, there are associated effects in the atmospheric electric field at middle latitudes (Voeikovo) and in the polar cap (Vostok). In general, the E_z changes started up to 2.5 h before the SF and more before the corresponding GLE event.

It is well known that local meteorological factors (wind speed, temperature) may cause considerable changes in E_z. It was carried out the analysis of the wind speed variations at Vostok and Apatity for the period investigated. It turned out that the wind speed had been nearly constant since early on 14 April 2001, typically between 5 and 6 m/s, at Vostok station. At Apatity, there was a smooth increase of wind speed on the morning 15 April 2001, but for the period of interest the wind speed was generally <5 m/s. Such wind speed values are not expected to lead to significant variations of atmospheric electric field (Daniljchenko et al., 1978). Unfortunately, there is no meteorological information at Nagycenk and Voeikovo. Therefore, a negative E_z value (−100 V/m) observed at Voeikovo in first half of day is more probably to be explained by the influence of local effects. However, considerable E_z changes observed on the background of this negative value coincide with relative E_z changes at Apatity and Vostok. We suppose these changes to be related to extraterrestrial influence strongly expressed at high latitudes. Nagycenk E_z data were taken from the tables of hourly averages determined for quiet or slightly-disturbed conditions and published in the periodically-issued Observatory Reports (Marcz and Harrison, 2003). A low mean value of E_z (~30 V/m) being typical for the station seems to be connected to a long-term downwards trend in the Nagycenk E_z (Marcz and Harrison, 2003).

Figures 2 and 3 show E_z variations at Apatity and GOES-8 data for two other major GLEs (18 April 2001 and 4 November 2001), associated with large solar flares (C2 and X1) originating from the Sun's western hemisphere (see Table 1). Again, an increase in E_z occurred approximately one hour (on 18 April) and ~20 min (on 4 November) before the flare onset, and lasted 7 and 2 h, respectively. However, it should be noted that the pre-flare increase in E_z on 18 April may be associated with the storm sudden commencement (SSC) which occurred at 00:40 UT. No E_z data from Vostok, Nagycenk and Voeikovo for 18 April and 4 November 2001.

3 Discussion

Processes of solar charged particle injection into the heliosphere are controlled by solar coronal structures. The maximum injection takes place from the region coinciding with the magnetic active region where the solar flare happened. Outside the active region the solar proton injection is much weaker. The solar flare on 15 April 2001 appeared in a region close to the western limb of the Sun where one would expect good magnetic connection between the flare site and the Earth along a spiral interplanetary magnetic field line. These solar flares are characterized by the prompt arrival of energetic particles (Gosling, 1993). For the 15 April 2001 GLE we calculated the heliolongitude of the footprint of the Sun-Earth line of force Φ using methods developed by Nolte and Roelof (1973a, b):

$$\Phi = (\Omega r / V_{sw}), \tag{2}$$

where: r is the distance between the Earth and the Sun, Ω is the angular velocity of the Sun's rotation (Ω=14.3°/day), and V_{sw} is the solar wind speed.

The result of the calculation (Φ=49.6°) and an analysis of the solar magnetic field map (Solar Geophysical Data, 2001) for the 15 April 2001 event have shown that the flare and the corresponding footprint of the Sun-Earth line of force were located within the same active region. Similar calculations for the 4 November 2001 SF/CME event show a different situation: the footprint of the magnetic line was outside the active magnetic region where the flare took place.

All three SF/CMEs are accompanied by atmospheric electric field changes at the auroral observatory of Apatity. For the 15 April 2001 event, E_z variations were detected in three different zones of magnetic latitude (polar cap, auroral zone and middle latitudes). An investigation of E_z records from Nagycenk (Hungary) (geomagnetic latitude: 47.2° N; L∼2) did not demonstrate any variations associated with GLEs, presumably a latitudinal effect (Marcz, 1976; Marcz and Harrison, 2003). It should also be taken into account that two of the GLEs considered (15 April and 18 April 2001) occurred during strong (>35% according to the auroral neutron monitor data) Forbush decreases (FDs) of galactic cosmic rays (data available at the Oulu Neutron Monitor website at http://spaceweb.oulu.fi/projects/crs). Thus the GLE effects in the atmospheric electric field at middle latitudes may be masked by FDs (Marcz, 1997).

Another interesting phenomenon is the variation of E_z observed before SF/CME onset. In some published works (Reiter, 1969; Olson et al., 1978; Kobrin et al., 1982; Moiseev et al., 1993; Goshdzhanov et al., 1993) it had been shown that solar flare precursors influenced some geophysical and meteorological parameters at the Earth before the flare onset. In particular, one or two days before the flare appearance, there may be some changes in the intensity of the H_α line, the creation of loop prominences, quasi-periodic fluctuations of radio-emission with periods of 20–200 min, and pulsations of geomagnetic field and solar X-ray emission (Moiseev et al., 1993). Olson et al. (1978) showed statistically that an increase of E_z, zonal circulation index, and atmospheric vortex intensity (VAI) were observed before solar flares. Doppler ionospheric sounding has shown that, 30–80 min before some X-ray flares, ionospheric disturbances having a specific waveform can be observed (Goshdzhanov et al., 1993).

If these effects are connected to conductivity changes of the atmosphere, they should be connected to additional ionization sources before the solar flare or CME. As a possible solar ionization agent in the "pre-eruption" phase, one may consider UV radiation from current layers (Syrovatsky, 1977; Goshdzhanov et al., 1993) and pre-CME streamers (Raymond et al., 2003), or soft X-ray emission from rising bright loops (Aurass et al., 1999; Nitta et al., 2003). For example, Syrovatsky (1977) noted the possibility of a brightness temperature increase (decrease) at radio wavelengths $\lambda<(>)0.1$ m in the current sheets (close to the weak solar magnetic field regions) several hours before the flare. Support for this has been provided by observations at 3.3 mm (Mayfield et al., 1970) and in the decameter wavelength range (Ramesh and Ebenezer, 2001; Ramesh et al., 2003). Syrovatsky (1977) also showed that energy in the C III (97.7 nm), O II (83.3–84.5 nm), Ne II (44.5–46.2 nm), Si II (120.65 nm) lines from a disturbed current sheet may be several times greater than from the undisturbed one. These conclusions have been partly supported by SOHO satellite observations of spectral signatures of CMEs associated with X-class flares and pre-CME streamers (Raymond et al., 2003).

However, it is difficult to suppose that UV and X-ray emissions are a possible source for the E_z perturbations observed, except for that on 15 April 2001 which was the only event detected during the daytime, the other two being at dawn and dusk, respectively. Analysis of the LASCO SOHO (C2) Coronograph pre-event (11:54 UT) and event (13:54 UT and 14:06 UT) images (Fig. 4, from http://lasco-www.nrl.navy.mil/cmelist.html) showed a so-called pre-CME streamer with a cavity and loop core, which appeared at 11:30 UT (approximately the time that the marked changes of E_z began) and which rapidly disrupted just before the SF/CME event itself. Such pre-CME streamers seem to appear before CME events and may be responsible for variations in UV emission and the generation of type III radio bursts excited by electron beams (Aurass et al., 1999; Bastian et al., 2001; Raymond et al., 2003). Enhancements of the energetic (>1 MeV) proton flux were observed at approximately 12:20 UT and ∼19:00 UT (see Fig. 1).

It has been reported earlier that CME-driven shocks may accelerate both protons and electrons (Haggerty and Roelof, 2002; Simnett et al., 2002; Gopalswamy et al., 2003; Kahler and Reames, 2003). Moreover, charged particle events associated with CMEs have their highest intensity below 20 MeV (Cane et al., 2003; Perrone et al., 2004). As for the 4 November 2001 SF/CME event, the ejection occurred over a large part of an S-shaped active region (Nitta et al., 2003). It had an extended "pre-eruption" phase in which the structure involved expanded on timescales of some tens of minutes (Nitta et al., 2003). It had earlier been reported that CMEs usually begin to lift off from the Sun before any substantial flaring activity has occurred (Harrison et al., 1990; Gosling, 1993).

4 Conclusions

We suppose that the E_z disturbances observed are caused by solar energetic (with energies exceeding a few MeV) charged particles (electrons and protons) associated with the CME formation. These very energetic (relativistic) particles may gain direct entry into the polar caps, or be trapped in the magnetosphere and precipitate into the atmosphere (Shumilov et al., 1993). An exception is the 18 April 2001 event, when the E_z variations seem to result from the SSC-associated particle energization which occurred at 00:42 UT on 18 April 2001 (see Fig. 2). This SSC-event was caused by the interaction of an interplanetary shock associated with the 15 April 2001 solar flare. Some studies (Blake et al., 1992; Li et al., 1993) have reported injections of electrons and protons with energies above 15 MeV into the inner magnetosphere ($2<L<3$) during such SSC-events. Goldberg et al. (1994) showed that relativistic electrons of >1 MeV can modulate the electrical properties of the middle atmosphere to altitudes below 50 km.

In general, from a physical point of view one may note that the pre-SF/CME atmospheric E_z disturbances may be explained by a number of different effects such as the different locations of the active region relative to the solar equator and limb, the relative

Sun-Earth position, conditions in interplanetary space, the state of the ionosphere and of the atmosphere at middle and high latitudes. What is clear, however, is that in a solar active region there are some changes in its magnetic state (the “precursor”, or pre-eruption, phase) before the sharp release of the energy in form of a solar flare (Mayfield et al., 1970; Syrovatsky, 1977; Ramesh and Ebenezer, 2001; Nitta et al., 2003; Raymond et al., 2003), which may also increase the electrical conductivity of the atmosphere and hence cause a reduction of E_z.

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Table 1. Flare/CME events associated with SPEs and observed by SOHO/LASCO.

Date	Flare Start (UT)	Flare Intensity	Flare Location	CME onset (UT)	SPE Start (UT)	SPE Peak (UT)	>10 MeV Proton Flux at SPE peak ($\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}$)
15 Apr 2001	13:19	X14	S20 W85	13:32	14:10	19:20	951
18 Apr 2001	02:14	C2	S20W-Limb	02:11	03:15	10:45	321
4 Nov 2001	16:03	X1.0	N06 W18	16:12	17:05	06/02:15	31 700

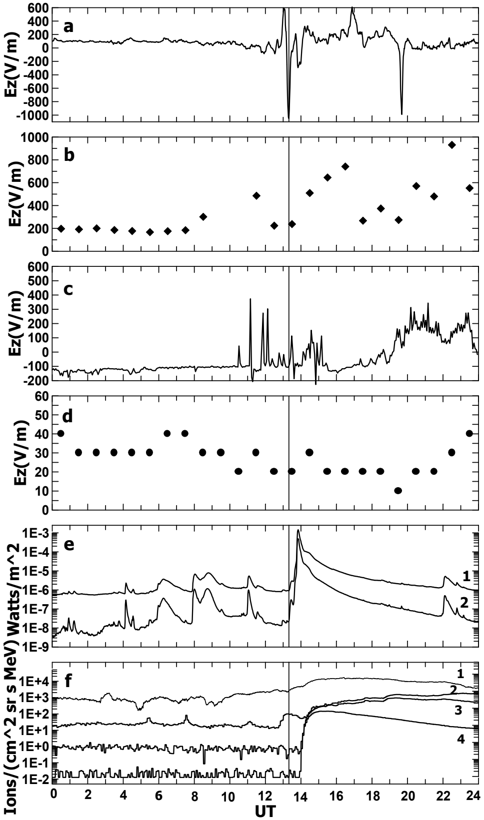

Fig. 1. For the 15 April 2001 GLE: **(a)** records of the vertical component of the atmospheric electric field (E_z) at Apatity (geomagnetic latitude Λ=63.3°); **(b)** Vostok (Λ=−89.3°); **(c)** Voeikovo (Λ=56.1°); **(d)** Nagycenk (Λ=47.2°); **(e)** GOES X-ray fluxes (1 for the 0.1–0.8 nm, and 2 for the 0.0–0.4 nm wavelength bands); **(f)** 1-min flux values of electrons with E>2 MeV−1, protons with E>1 MeV−2, protons with E>10 MeV−3, and protons with E>100 MeV−4. The moment of flare onset is shown by the vertical line at 13:19 UT.

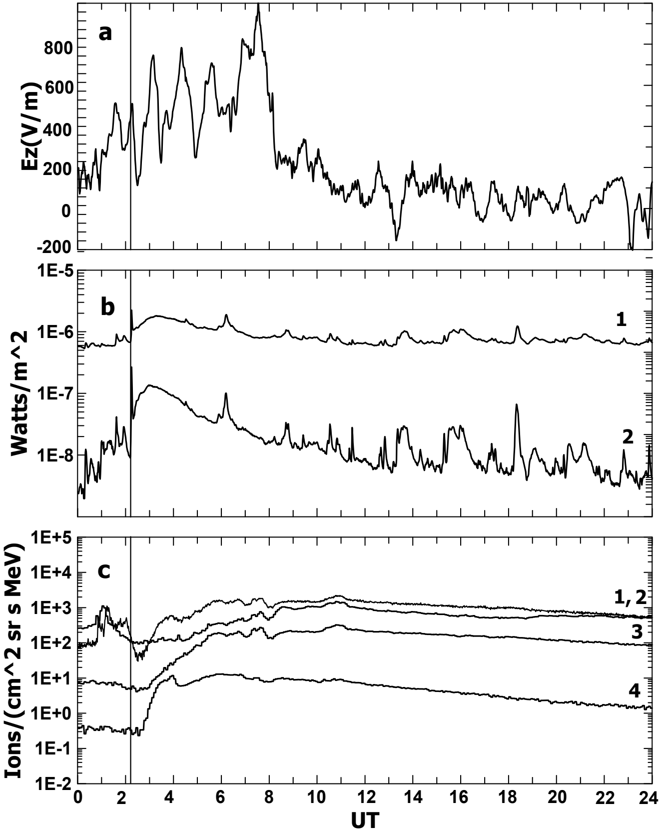

Fig. 2. For the 18 April 2001 GLE: **(a)** records of the vertical component of the atmospheric electric field (E_z) at Apatity; **(b)** GOES X-ray fluxes (1 for the 0.1–0.8 nm, and 2 for the 0.05–0.4 nm wavelength bands); **(c)** 1-min flux values of electrons with E>2 MeV−1, protons with E>1 MeV−2, protons with E>10 MeV−3, and protons with E>100 MeV. The moment of flare onset is shown by the vertical line at 02:14 UT.

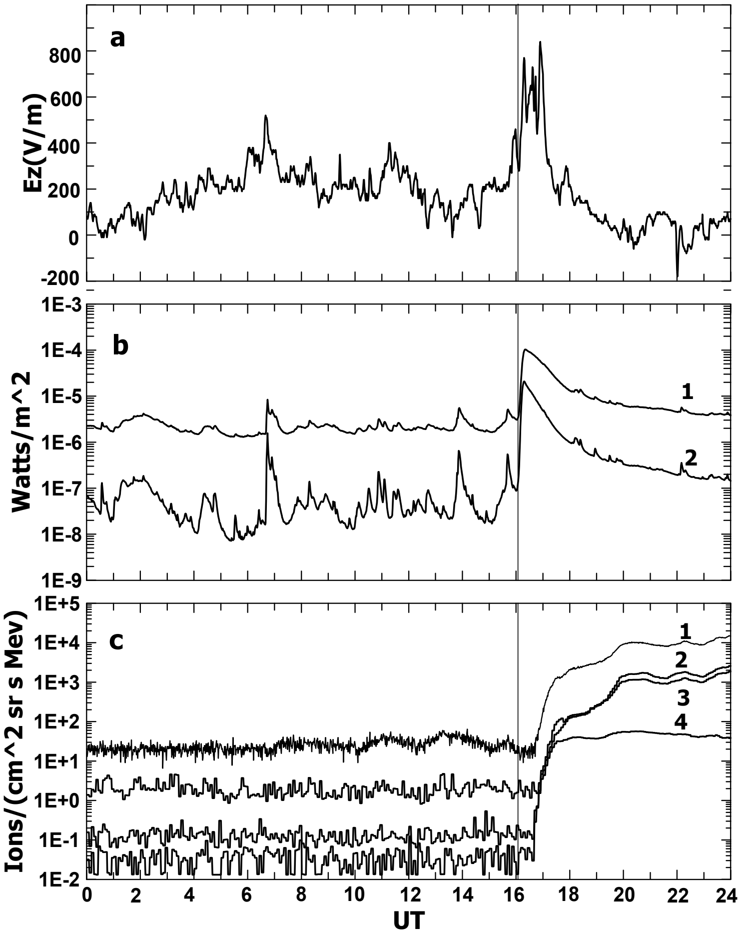

Fig. 3. The same as for Fig. 2 but for the 4 November 2001 GLE.

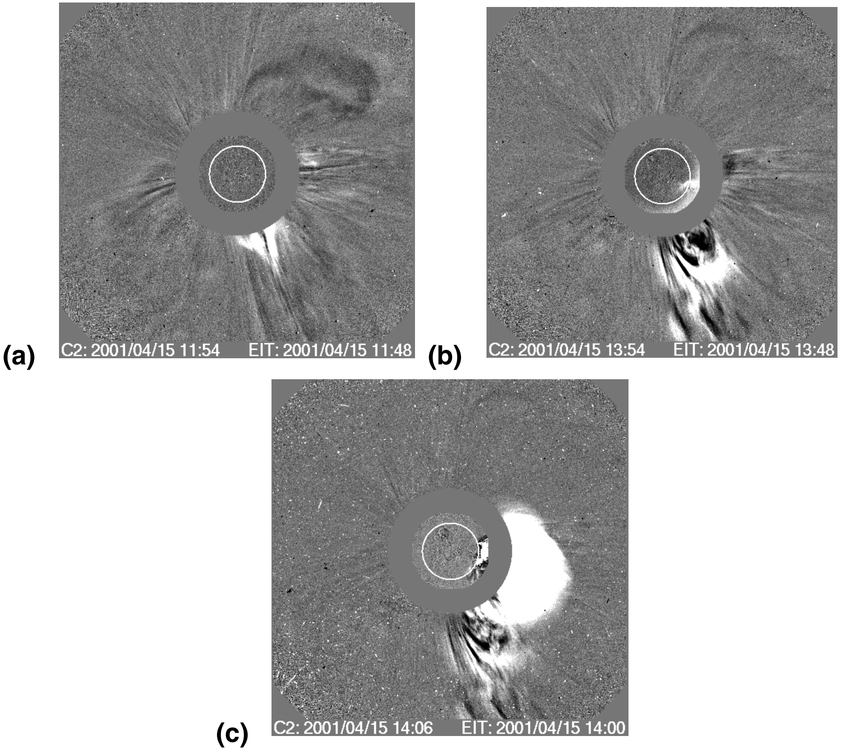

Fig. 4. Consecutive phases of the 15 April 2001 SF/CME event development evident from the data of LASCO SOHO (C2) coronograph images: **(a)** pre-event (11:54 UT), **(b)** early in the event (13:54 UT) and **(c)** peak of the event(14:06 UT).