The 17–22 October (1999) solar-interplanetary-geomagnetic event: Very intense geomagnetic storm associated with a pressure balance between interplanetary coronal mass ejection and a high-speed stream

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[1] Using observations from the Advanced Composition Explorer (ACE) magnetic field and plasma experiments, we investigate the magnetic, thermal, and dynamic pressure balance in the border of a high-speed stream (HSS) and an average-speed interplanetary coronal mass ejection (ICME) observed on 21–22 October (1999). We believe that the HSS compressed the ICME and intensified its internal southward magnetic field, resulting in a very intense geomagnetic storm, with peak Dst of −237 nT. In solar cycle 23 this was the only event, out of 18 very intense geomagnetic storms, i.e., peak Dst < −200 nT, which was caused by such a mechanism. We also address the solar origin of this very intense geomagnetic storm, using combined solar data from three different sources: a ground-based source, coronal hole maps from the National Solar Observatory (NSO) at Kitt Peak, and two satellite-based sources, eruption activity from the Extreme Ultraviolet Imaging Telescope (EIT) and coronal mass ejection observations from the Large Angle and Spectrometric Coronagraph (LASCO), both aboard the Solar and Heliospheric Observatory (SOHO). A coronal hole is evident just beside (to the east of) the active region from which an average-speed coronal mass ejection lifted off on 17–18 October (1999). This was the only possible solar origin of the 21–22 October interplanetary geomagnetic event.

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1. Introduction

[2] High-speed streams, originating in coronal holes, are often observed following interplanetary coronal mass ejection (ICME), at 1 AU [*Klein and Burlaga*, 1982]. One of the most important effects of the interaction between these two structures is the intensification of the internal ejecta field in its rear part, due to compression, leading to a strong geomagnetic perturbation if this intensified magnetic field is pointing southward [*Burlaga et al.*, 1987; *Bothmer and Schwenn*, 1995; *Fenrich and Luhmann*, 1998; *Dal Lago et al.*, 2001, 2002].

[3] In solar cycle 23, 18 very intense geomagnetic storms, i.e., peak negative Dst < −200 nT, have been observed, according to the data available at the World Data Center for Geomagnetism (WDC), from Kyoto. *Dal Lago et al.* [2004] have studied nine of these events, observed from January 1996 to April 2001, and they have found that almost all of them were associated with fast coronal mass ejections observed by the Large Angle and Spectrometric Coronagraph (LASCO), aboard the Solar and Heliospheric Observatory (SOHO), and they took, on average, 50 hours or fewer to travel from the Sun to the Earth. Also, sheath compressed southward B fields were the most important interplanetary causes of these very intense magnetic storms, present in nearly all events. The most impressive exception to this set of very intense storms was the 21–22 October 1999 one. An average-speed CME, with an expansion speed of 546 km/s, was the only observed solar origin of this interplanetary-geomagnetic disturbance. It took 73.5 hours to travel from the Sun to the Earth, as many CMEs which are not so much geoeffective do. Thus from solar observations, it was certainly not a "threatening CME," in geoeffective terms.

[4] In this work we present a study of the 17–22 October (1999) solar-interplanetary event, which was associated to a very intense, peak Dst = −237 nT, magnetic storm. We present an analysis of pressure balance between the ICME observed on 21–22 October and the HSS following this

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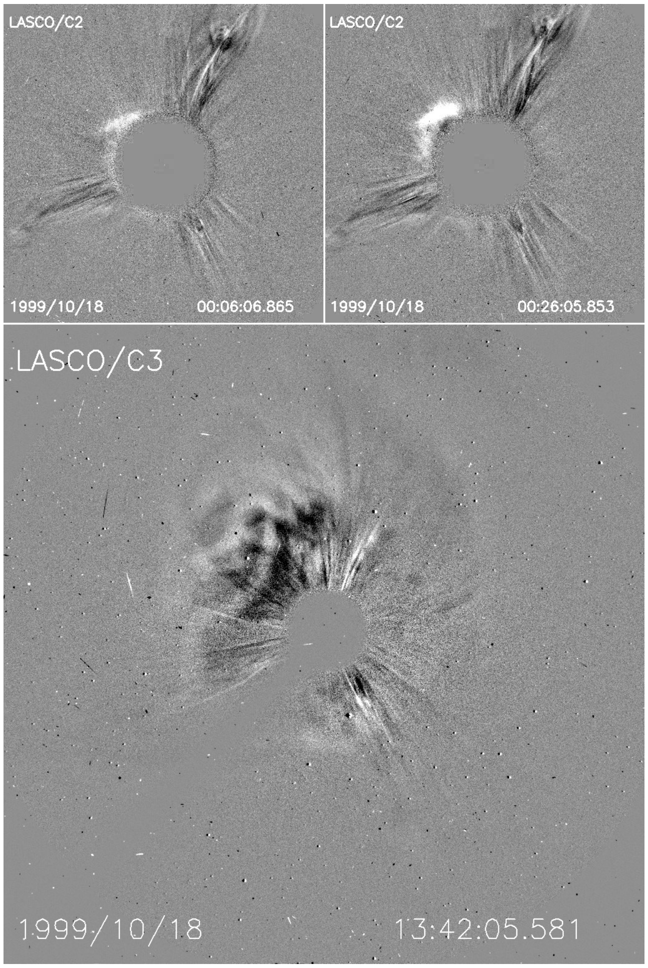

Figure 1. (top) LASCO C2 and (bottom) LASCO C3 running difference images of the 18 October (1999) coronal mass ejection.

ICME. We start our study presenting an analysis of the solar origins of these interplanetary structures using combined data from different instruments, both space and ground based, to try to find out how an average-speed CME could cause such an intense geomagnetic disturbance. After April 2001, nine other very intense geomagnetic storms have been observed; however, a detailed solar-interplanetary analysis of these events has not yet been done. Our preliminary inspection of the interplanetary structures associated with these nine events reveals that none of them has had similar southward Bz intensification via pressure balance as the October 1999 event.

2. Solar Origin of the 21–22 October (1999) Disturbance

[5] On 18 October 1999, at 0006 UT, LASCO C2 observed an Earth-directed coronal mass ejection at position angle (PA) ~45, which evolved to a halo in LASCO C3 instrument, as shown in Figure 1. Using the same methodology of *Schwenn et al.* [2005], we measured a CME expansion speed of 546 km/s for this event. According to the SOHO LASCO CME catalog (CDAW Data Center), the plane-of-sky speed of this CME at PA40 was 247 km/s. This was an average-speed CME, as many others observed during the last ~9 years of LASCO observations.

[6] The Extreme Ultraviolet Imaging Telescope (EIT 195) observed an eruption during the last hour of 17 October on the east side of the solar disk, mostly in the northern solar hemisphere, centered approximately at the heliographic position N05E37. Another EIT eruption was also observed at approximately the same time, centered approximately at the heliographic position S37E12. Since the CME erupted to the northeast in the LASCO/C2 images, we correlated the first described eruption with the CME. These EIT events can be seen in Figure 2, which shows two running difference EIT 195 images, on 17 October, one at 2236 UT without any eruption, and other at 2324 UT showing the eruptions as dark features.

[7] The National Solar Observatory (NSO/KP) coronal hole map, derived from He I 1083nm observations, from 17 October clearly reveals a positive coronal hole (CH) close to the site of the first above described EIT 195 eruption observed on 17 October, as shown in Figure 3. This CH persisted for several days. Combining the observations from EIT 195 in Figure 2 from 17 October, at 2324UT with the NSO/KP coronal hole map of 17 October, one can easily see that the positive coronal hole was sitting beside the EIT 195 eruption site, more precisely to the east, as shown in Figure 4. Since the Sun rotates from east to west, this configuration of CH, EIT eruption and CME is favorable to an interplanetary scenario in which the Earth is intercepted by an interplanetary CME followed by a high-speed stream. The positive sign in the CH indicates that the magnetic field is pointing away from the Sun, and the associated high-speed stream should have negative B_x and positive B_y magnetic field components, considering a GSM coordinate system.

3. The 21–22 October (1999) Interplanetary Event

[8] Close to the Earth, at L1, an interplanetary shock was detected by ACE magnetic field and plasma instruments on 21 October (1999), at 0134 UT, as shown in Figure 5, 73.5 hours after the first appearance of the related CME in the LASCO C2 field of view. The driver of this shock is clearly an interplanetary ejecta, or ICME, which can be distinguished from the normal solar wind by its intense magnetic field, of the order of 20 nT throughout the most part of

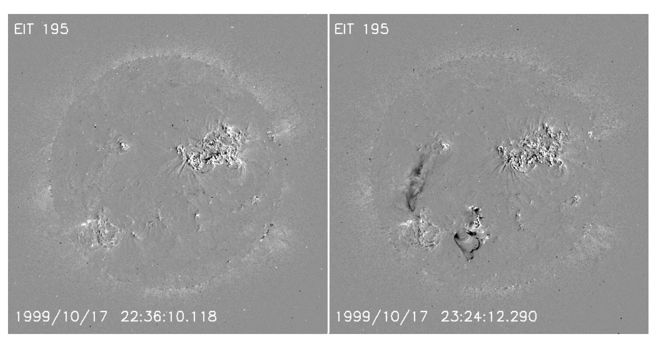

Figure 2. EIT running difference images of the eruption during the last hour of day 17, in October 1999. Another eruption in the southern solar hemisphere is also visible in the image, but this one was not related with our event.

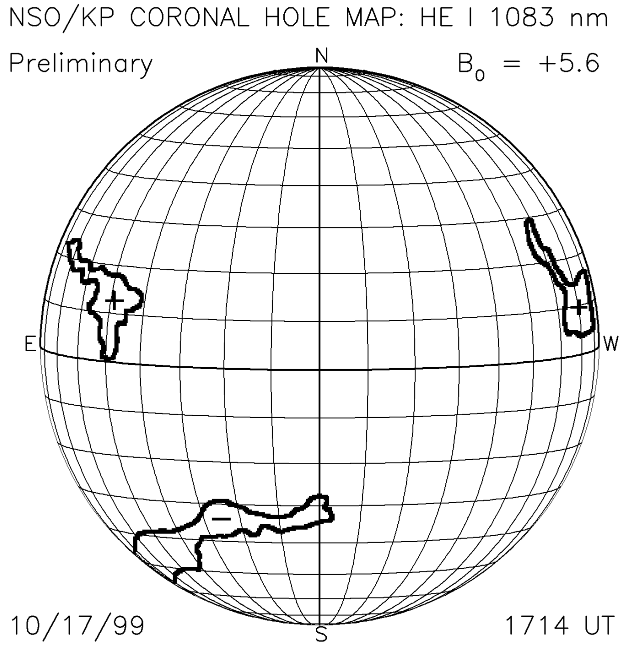

Figure 3. NSO/KP coronal hole map from 17 October. A positive polarity coronal hole can easily be identified.

21 October, and its low beta (∼0.1), shown in the fifth panel of Figure 5. We consider that the start of the ejecta is at 0358 UT of 21 October, where the sheath's high number density drops to low values (less than ∼20 part./cm^3). Our determination of the start of this ejecta is different from the one proposed by *Zhang et al.* [2003] (at 1500 UT of 21 October) because our analysis was based on the plasma beta and B field characteristics, as discussed above, which follows the criterion summarized by *Neugebauer and Goldstein* [1997]. Toward the end of this ejecta, an increase of the magnetic field intensity is observed, starting at 0230 UT of 22 October, reaching a peak value of 37 nT, almost twice the average ICME B intensity. Such an increase was decisive to cause the very intense geomagnetic storm of 22 October because in this rear part of the ejecta the magnetic field was pointing southward, reaching a peak negative value of −31 nT. In fact, when inspecting visually the B_z profile toward the end of the ejecta, one can easily find an abrupt change in the magnetic field behavior after 0230 UT of day 22, where an intensification of the order of 10 nT is present. It is important to state that it is not clear whether this ejecta is a "magnetic cloud" or not, according to the criteria of *Burlaga et al.* [1981] because the direction of the magnetic field does not rotate smoothly. Between 2 to 3 hours after the start of this negative B_z increase, Dst index also changed its slope, decreasing more rapidly, going from −109 nT to the peak value of the storm of −237 nT, as can be seen in the bottom panel of Figure 5. The time lag of 2–3 hours between peak southward B and peak Dst is consistent with the study of *Vieira et al.* [2004], in which they have found that this time lag ranges from 2 to more than 15 hours in the case of compressed B fields. The time delay between the arrival of the ICME at ACE and Dst peak is 27 hours, which is consistent with *Zhang et al.* [2003] study.

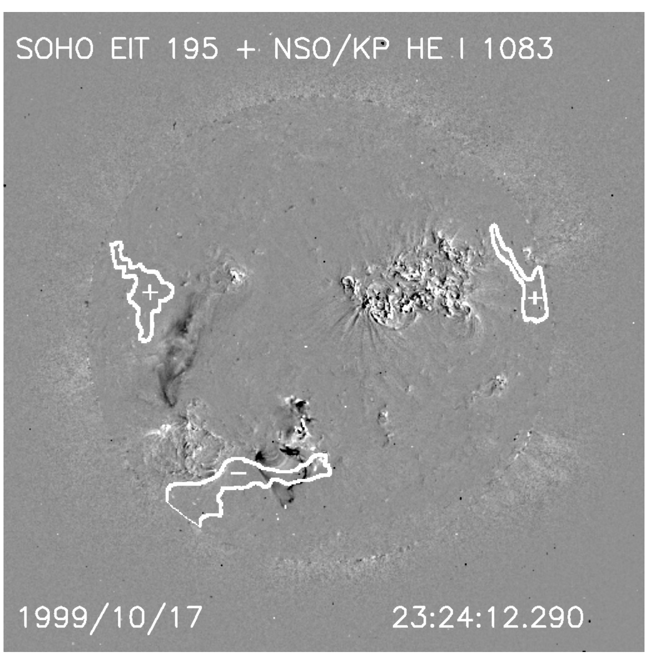

Figure 4. Combined observations from SOHO/EIT 195 and NSO/KP coronal hole map from 17 October 1999.

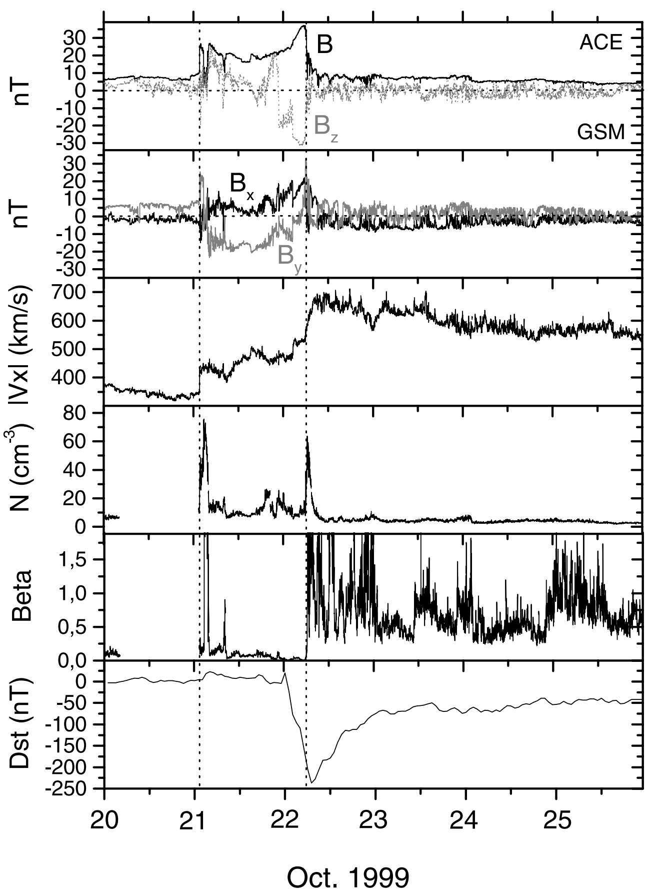

Figure 5. From top to bottom, magnetic field intensity B and its B_z component, B_y and B_x components, solar wind velocity and density, and the Dst index.

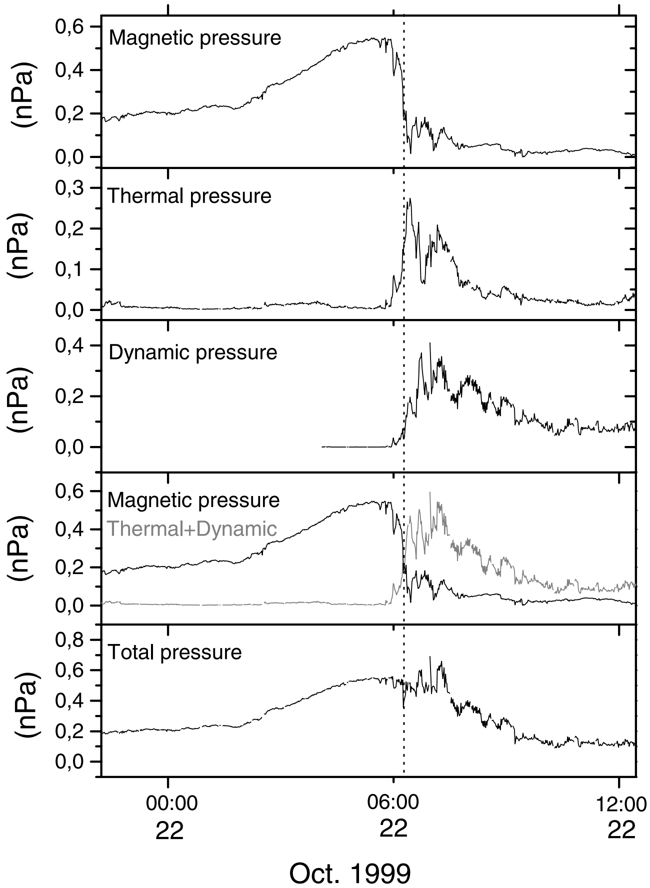

Figure 6. From top to bottom, magnetic pressure, thermal pressure, dynamic pressure, magnetic and thermal + dynamic pressures, and total pressure (magnetic + thermal + dynamic pressures), in the interface of the interplanetary ejecta and the high-speed stream observed on 22 October 1999.

[9] The important question that we are interested in is related to what might have caused such an increase in the magnetic field of this ICME in its rear part. A first possible explanation to this increase is simply the fact that the ejecta already had this magnetic field profile (with the increase towards the rear portion) since its eruption from the sun. However, inspecting more carefully, at 0615 UT of 22 October (second vertical dotted line in Figure 5), the magnetic field drops abruptly around 10 nT. We define this point as the end of the interplanetary ejecta, or ICME.

[10] Immediately after the ICME ends, a high-speed stream can be identified. In approximately 1 hour, the speed raises from ∼540 km/s inside the ICME to ∼700 km/s in the interface between the ICME and the HSS. In this same interface, the number density jumps from less than 20 part/cm^3 to a peak of the order of 60 part/cm^3. The interaction between the HSS and the ICME can be another explanation for the magnetic field increased intensity observed inside the ICME, and consequently, the cause of the very intense magnetic storm of 22 October (1999). We shall investigate this hypothesis in more detail.

[11] As mentioned previously in the introduction, many works have proposed that pressure balance may cause distortions/compression in the magnetic field profile of interplanetary ejecta (or magnetic clouds). Interplanetary ejecta structures are normally low beta; thus inside them, magnetic pressure (Pb = B^2/8PI) dominates over the thermal pressure (Pk = NkT). In the interface between an ICME and a HSS, temperature and density increase, causing the thermal pressure to increase as well. These two aspects can be observed in the two top panels of Figure 6, which show from top to bottom, the magnetic pressure and the thermal pressure in the interface (dotted vertical line) between the ICME and the HSS of 22 October (1999), respectively. One can see that these two pressures do not balance, being the thermal pressure approximately half the magnetic pressure in this interface.

[12] We looked for this "missing" pressure, which could account for a pressure balance between the ICME and the HSS, and the only additional pressure available was the dynamic pressure caused by the relative speed between the two structures. We consider the fact that in a very short time interval (∼1 hour) the velocity increased from ∼540 km/s (ICME speed) to ∼700 km/s (HSS speed), indicating that the HSS is dynamically compressing the ICME. In order to quantify this, we considered a frame moving with the final ICME speed, which is approximately 540 km/s and used the following expression for calculating the dynamic pressure:

$$P_{dyn} = \left(1/2\right).\ N.\ m_p.\ V_r^2 \qquad (1)$$

where "N" is the plasma number density, "m_p" is the proton rest mass, and "V_r" is the plasma speed relative to a frame moving at 540 km/s. The result of this calculation is shown in the third panel of Figure 6, and it clearly shows an amount of dynamic pressure exerted by the HSS, which is of the same order of magnitude of the HSS's thermal pressure. The last two bottom panels of Figure 6 show all these pressures, i.e., magnetic, thermal, and dynamic, added together. In more details, the fourth panel, from top to bottom, clearly shows that the ICME's magnetic pressure is actually of the same order of magnitude of the thermal + dynamic HSS's pressure. The fifth panel of Figure 6 shows the "total pressure," which in this case is magnetic + thermal + dynamic pressures, and, apart from some oscillations, a smooth balance can be observed in this interface.

4. Summary and Conclusions

[13] We have presented a study of the 17–22 October (1999) solar-interplanetary-geomagnetic event. This event was related to a very intense geomagnetic storm, i.e., peak Dst < −200 nT, on 21–22 October (1999). This disturbance was associated with an average-speed SOHO/LASCO CME, of 546 km/s, observed on 18 October (1999), unlike other very intense storms observed in the last solar cycle, which were related to fast CMEs. Combined observations from SOHO/EIT 195 and NSO/KP coronal holes maps revealed the proximity of an eastward positive coronal hole and an EIT eruption, both observed on the 17 October, closely related to the 18 October SOHO/LASCO CME. ACE plasma and magnetic field instruments show a interplanetary shock on 21 October, driven by an interplanetary ejecta, or ICME, both followed by a high-speed stream, all

very consistent with the solar observations of a CH, EIT eruption, and a CME event. This ICME had a particular characteristic, which is an increase of its magnetic field intensity in its rear portion, almost doubling its magnitude. Also, of particular interest in terms of the geoeffectiveness is the fact that this increased magnetic field was pointing southward and was the interplanetary origin of the very intense storm. An analysis of pressure balance between HSS and ICME shows that the interaction between them may be related to the intense southward ICME magnetic field, and hence the cause of the 22 October (1999) very intense geomagnetic storm.

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