RELATING NEAR-EARTH OBSERVATIONS OF AN INTERPLANETARY CORONAL MASS EJECTION TO THE CONDITIONS AT ITS SITE OF ORIGIN IN THE SOLAR CORONA

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ABSTRACT

A CME was detected on January 20, 2004. We use solar observations and near-Earth *in situ* data to identify the CME source event and show that it was a long duration flare in which a magnetic flux rope erupted, taking overlying coronal arcade material along with it. We show that signatures of both arcade and flux rope material are identifiable in Cluster and ACE data, indicating that the magnetic fields changed little as the material travelled to the Earth. Consequently, the related magnetospheric storm might have been predicted from solar remote sensing data.

1. Introduction

Interplanetary Coronal Mass Ejections (ICMEs) leave the Sun with plasma content and magnetic field orientation that depend on their site of origin. Earth-directed events are often associated with magnetic storms, typically when they have flow velocities ≥ 500 km/s and a southward magnetic field component (GSE, $B_Z < 0$). Reliable prediction of storms requires estimation of, at least, CME direction, open angle, speed and the ability to infer the existence of $B_Z < 0$ near Earth. While the evolution of magnetic field orientation in transit is predicted by e.g. Cargill and Schmidt, 2002, observations are required to quantify the changes in a systematic manner. Meantime several previous studies e.g. Bothmer and Rust, 1997, Webb et al., 2000, McAllister et al., 2001, Leamon et al., 2002, Mandrini et al., 2005, have examined the relationship between the plasma and magnetic field conditions at the solar launch site and the nature and magnetic topology of the resulting magnetic cloud. In this paper we examine an ICME that originates in a non-sigmoidal active region. The magnetic configuration observed near the Earth is well matched to the pre-ejection coronal topology, in contrast to some of the earlier results above.

2. Observations

In the period from 20:00 UT on 19-JAN-04 to 10:00 UT on 20-JAN-04, several large flares originated from the active region AR0540 located at S14W36. The decay of the region then led to a significant reduction in activity. A significant shock was observed near-Earth in the solar wind flow on 22-JAN-04 following a six day period in which no shocks were detected. We examine the relationship between the shock and its likely associated flare and CME from AR0540.

2.1 Solar Observations

During the interval in question, three significant flares that might have been related to the near-Earth shock of 22 January, came from AR0540. They are labeled A, B and C on the GOES light curves in Figure 1. Event A is an impulsive C-class flare, event B is a long duration event while flare C is a complex three phase M-class event.

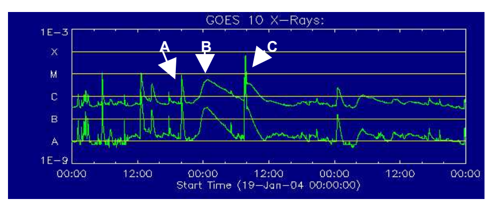

Figure 1. GOES light curve showing flaring activity from AR0540. Events labeled A, B and C may be associated with the shock detected near Earth on 22-JAN-04.

In order to determine which flare was related to the ICME, we sought to estimate travel times of the ICME and the related shock. Flare A had an associated metric Type-II burst observed at Culgoora. From the radio data and an appropriate density model, we estimated a shock speed of ~ 450 kms^{-1}. Flare B had a related halo CME, but no metric type II emission. There is an indication of a shock in

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WIND/Waves data (Type II burst, see Figure 2, M.L. Kaiser, private communication). Flare C had three distinct phases. We associate Flares Ci and Cii with two metric Type II radio bursts observed at Culgoora, with estimated shock speeds of ~ 550 kms^{-1} and ~ 850 kms^{-1}. A non-halo CME was detected by SOHO-LASCO-C2 at 08:30 UT.

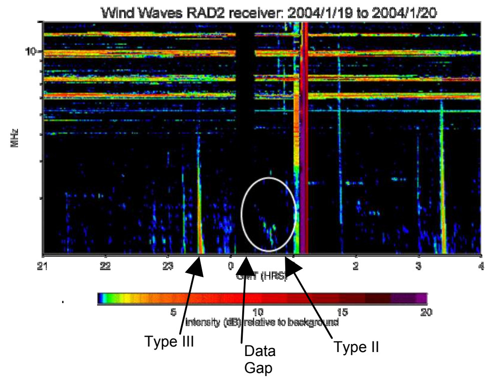

Figure 2. Data from the Wind/Waves receiver. A possible D/H Type II burst associated with flare B is apparent following a data gap.

Long duration flares are assumed to occur following reconnection of sheared arcade fields beneath a rising CME. They often involve a filament eruption. EIT images of flare B are shown in Figure 3. In this case no filament eruption was observed. The diverging flare ribbons and the persistent formation of flare loops connecting them (i.e. reforming arcades, Figure 3 left) support the reconnection picture. EIT difference images, where two extended dimming regions appeared NE and SW of the active region (Figure 3 right), may be interpreted as the footprints of magnetic field lines which expanded in the CME. Reconnection of sheared arcade fields can be expected to generate a flux rope, as observed later near Earth (see Section 3), whether or not a flux rope was present in the pre-CME configuration (e.g. Forbes and Isenberg, 1991; Antiochos et al, 1999). The chirality of a pre-existing flux rope is unaffected. MDI magnetogram data were used to identify the magnetic inversion line. Inspection of the magnetic polarity either side of it (> 0 to the SE, < 0 to the NW) and the orientation of the arcade loops relative to the line, shows that the axial field of the flux rope was ~ NNE-SSW oriented (Martin and McAllister, 1997). The shear angle between the arcade loops and the inversion line suggests that the active region, and so also the flux rope, has a left handed twist; unexpectedly for a southern hemisphere case (Pevtsov and Balasubramaniam, 2003). The erupting flux rope is expected to carry away material associated with the overlying E-W oriented arcade field lines.

A single image from a sequence of LASCO C2 observations is shown in Figure 4. It is clear from the movie sequence that this is a halo CME though with some bias towards southerly expansion. It is therefore a likely to be geo-effective and so we have examined the features of flare B in some detail.

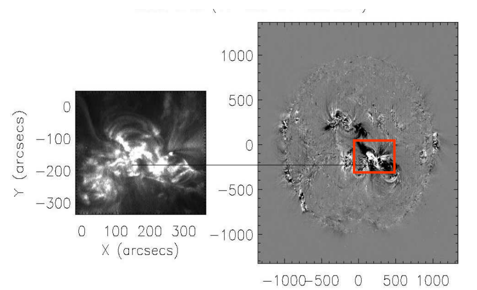

Figure 3. EIT 195 Å image of Flare B showing (left) coronal arcade loops and (right) EIT difference image showing "dimming regions".

In addition, the LASCO images show an apparent interaction between the CME and a streamer structure to the East of it (Figure 4). MDI magnetograms and sequences of EIT images demonstrate that the open streamer magnetic field lines have opposite polarity to the neighbouring arcade field lines. As the overlying arcade was forced to expand during the flux tube eruption, it is possible that the arcade magnetic field could have reconnected with the streamer magnetic field.

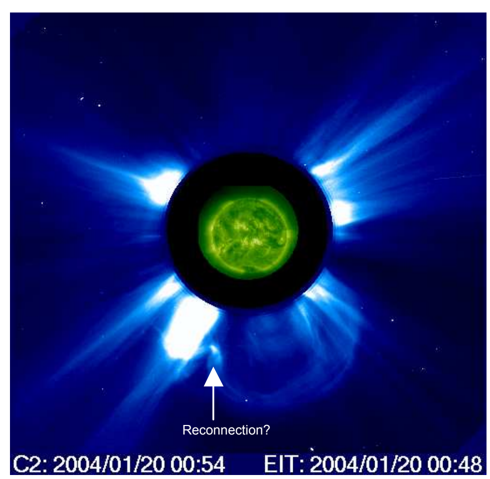

Figure 4. LASCO C2 coronagraph image on January 20 at 00:54 UT, showing the halo CME. Note its apparent interaction with the streamer (bottom left).

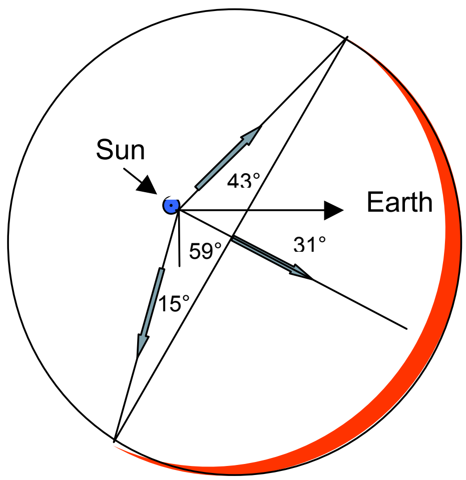

Figure 5. Cone model for a halo CME (Michalek et al. 2003). Estimation of CME speed (V ~ 910 km/s), cone axis orientation and location of origin were obtained by using LASCO first/last detections of CME crossings of the limb.

In the absence of a well-defined near-Sun shock signature for Flare B, we applied the cone model of Michalek et al., (2003) to the halo CME. The derived parameters are shown in the schematic diagram of Figure 5. We estimated that the angle between the CME cone symmetry axis and the sky plane was $\gamma \sim 60^0$, the cone opening angle was $\alpha \sim 150^0$ and the CME velocity $V_B \sim 910$ kms^{-1}. The cone symmetry axis lies at ~ 20^0 to solar N-S such that the first detection in LASCO C2 occurred in the solar SW quadrant

Table 1lists the flare starting times and for each flare provides two estimates of the shock arrival time at Earth; T_1 for travel at the estimated near-Sun speed, $V_{Coronal}$ and T_2 for travel at the speed measured by Cluster near Earth, $V_{E.}$ = 740 km/s – see next section. We conclude that shocks from Flares A and C must arrive too late, while a shock from Flare B can arrive at Cluster at the observed time of 01:35 UT on 22 January. We conclude that the source of the shock observed at Earth was the halo CME associated with the long-duration flare that began at 23:08 UT on January 19, in AR 0540.

Table 1. Event Timings

Flare	T (UT)	T_1 (UT)	T_2 (UT)
A	19 Jan 19:54	23 Jan; 15:55	22 Jan; 03:54
B	19 Jan 23:08	21 Jan; 21:15	22 Jan; 07:54
Ci	20 Jan 07:30	23 Jan; 10:42	22 Jan; 15:24
Cii	20 Jan 07:40	22 Jan; 08:22	22 Jan; 15:36
Ciii	20 Jan 08:00	n/a	22 Jan; 15:54

2.2 Near Earth Observations

At ~ 01:35 UT on January 22nd 2004, the Cluster spacecraft located at (15.0, -11.1, 5.2) R_E GSE in the solar wind, measured a strong interplanetary shock, followed by a 7 hour interval of compressed solar wind plasma (referred to below as "sheath"), and then by the leading edges of the coronal ejecta (Figure 6, upper panels). After a further ~2 hours, the ejecta magnetic field turned southward and remained so for 24 hours, while the flow speed remained above 500 kms^{-1}. Such conditions favour the occurrence of a geomagnetic storm, and a storm was indeed observed with provisional minimum Dst of -149 nT at 14:00 UT. The ACE spacecraft, located at (229.8, -40.6, 22.1) R_E GSE detected the same phenomena ~37 minutes earlier. Cluster later moved downstream of the terrestrial bowshock and so did not provide unbroken coverage, but ACE recorded the entire event (Figure 6, lower panels). No shocks were seen at ACE during the preceding 6 days.

The shock characteristics were examined using the four Cluster spacecraft, which were in a tetrahedral configuration, roughly 200 km apart. The magnetometer data time resolution (22 vectors s^{-1}) was sufficient to clearly identify the differing shock arrival times at the four spacecraft. Assuming the shock front was locally planar, a simple four-spacecraft timing analysis provides an estimate of the shock normal vector and velocity. The sunward shock normal direction was *n* = (0.91, -0.31, -0.29) GSE which is tilted at a cone angle of 25° to the Sun-Earth line. The (anti-sunward) shock speed along this normal is V_E = 740 km/s. The shock is quasi-perpendicular (_$_{BN}$ = 80°) and supercritical with an Alfvén Mach number of 5.6.

The sheath plasma exhibited the same composition as the solar wind, but density, temperature and magnetic field strength were higher than solar wind levels. PEACE electron spectrometer data shows unidirectional suprathermal electrons with pitch angle α = 180° in the solar wind and sheath, consistent with electrons streaming away from the Sun on open magnetic field lines. The sheath material flowed predominantly anti-sunward, but the flow was inclined at ~5º (reducing over time) to the solar wind, tilted towards +*z* and to a lesser extent +*y* GSE. The shock motion and sheath flows suggest that the main body of the ICME passed by the Earth some distance away in the [–*y*, –*z*] GSE direction.

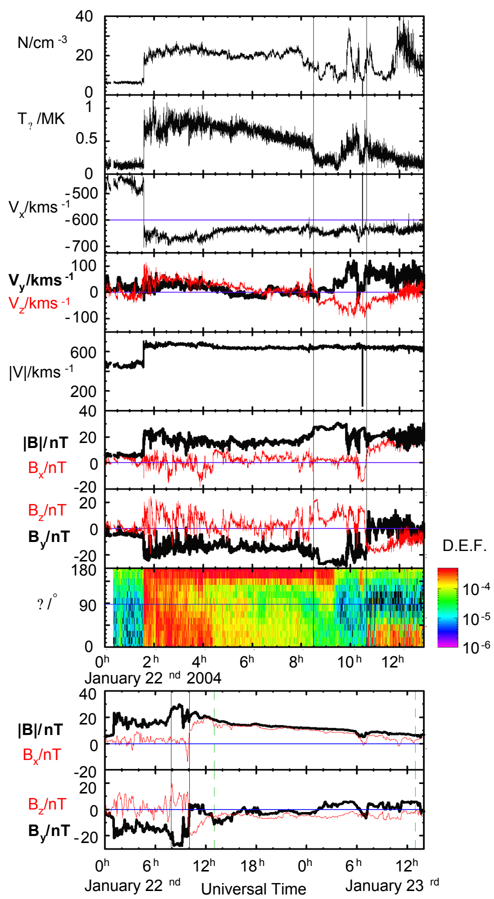

Figure 6. The upper plot panels show Cluster data. From the top: CIS-HIA ion number density, perpendicular temperature, and bulk flow velocity; FGM magnetic field vector; PEACE suprathermal (~130 eV) electron differential energy flux vs. pitch angle [ergs/(cm^2 s sr eV)]. The lower plot panels show ACE MAG magnetic field vector.

The last sheath material passed Cluster at ~08:30 UT, followed by plasma of coronal origin, as indicated by the high He^{2+}/H^+ ratios which were elevated over solar wind levels for a further 28 hours. Between ~ 08:30 and ~10:40 UT, the magnetic field lay in the *y*-*z* plane, mainly on –*y* GSE but with a small +*z* component, and its magnitude |*B*| was elevated above sheath levels (Figure 6, between solid vertical lines). Suprathermal electrons were observed with α = 180°, suggesting that these are open field lines. Within the interval 09:50 to 10:20 UT, was a region of depressed |*B*|, associated with two distinct regions of higher density and temperature plasma, coinciding with suprathermal electrons with 60º < α < 120º, perhaps locally pitch angle scattered in this region of higher plasma β as proposed by Crooker et al (2003). During the corresponding interval observed upstream at ACE, SWICS data show O^{7+}/O^{6+} ratios a factor 20 above solar wind levels. These observations are consistent with the spacecraft sampling a region of trapped coronal plasma. Following this period, the magnetic field swings to the anti-sunward, and fluxes of 120º < α < 180º electrons (and also >10 keV protons) appear at Cluster, which we interpret as foreshock particles from the terrestrial bowshock.

Between 10:36 and 10:48 UT the magnetic field rotated to a predominantly [+*x*, –*z*] GSE direction. A minimum variance analysis indicated a tangential discontinuity, in which the magnetic field rotates through 180° in a plane with the normal (0.83, -0.22, 0.51). We interpret this as due to a current sheet separating two distinct plasmas of coronal origin. Note that the plane is tilted northwards at ~30° to the GSE y-z plane, which is not consistent with lying on a simple spherical expansion front. Cluster (foreshock electrons notwithstanding) and ACE data (not shown) confirm that a bi-directional suprathermal electron signature began at this point and persisted thereafter throughout the interval discussed in this paper.

Cluster re-entered the magnetosheath at ~ 16:30 UT, however ACE data suggest that the predominantly sun-pointing ICME magnetic field configuration persisted for about a day, during which time the flow speed dropped, the density declined and the magnetic field weakened, as is typical for an expanding ICME. Minimum variance analysis from January 22, 13:00 UT to January 23, 13:00 UT (Figure 6 lower, between dashed vertical lines) shows α ~180° rotation in a plane with normal along the minimum eigenvector (+0.11, +0.17, –0.98). The magnetic field vector shows a steady B_Z < 0, a B_X > 0 that gradually weakens, and a B_y that fairly steadily transforms from < 0 to > 0. We interpret this as a crossing of a flux rope, in which the core field is directed North to South (N-S) and is surrounded by a magnetic field with a left-handed twist. The spacecraft passes to the West (–ve y GSE) side of the axis. As there is no magnetic field peak during the crossing, the spacecraft may be far from a core axial field if one exists. Preceding this interval, between 10:40 and 13:00 UT, $|B|$ appears enhanced relative to the trend of the next 24 hours; $B_y \sim 0$, $B_x > 0$ and B_z is strongly negative. Bi-directional electrons are seen here, so we believe that this interval belongs to the flux rope, although the magnetic field direction is unexpected. We tentatively attribute its differing character to the effects of compression and possibly other interactions (e.g. reconnection) as the flux rope pushes against the upstream plasma.

3. Relating Solar and Near-Earth Observations

The cone model of the CME implies a central axis directed along [$-x$, $-y$, $-z$] GSE, and a hemispherical shock front. The Cluster determination of a shock surface moving anti-sunward, towards [$+y$, $+z$] GSE and measured sheath flows in the same sense are consistent with such a picture, and thus support the model.

For the EIT image of flare B shown in Figure 3 (left), we can deduce the related magnetic field configurations from simultaneous SOHO MDI magnetogram data. As described in section 2.1, the fields associated with the E-W directed coronal arches and with the underlying fluxrope configuration along the active region neutral line are as indicated in Figure 7. Thus

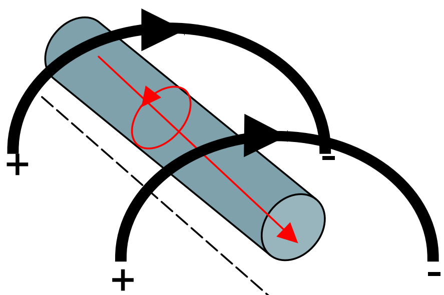

Figure 7. Magnetic configurations for the flare of 19 January, 2004 at 23:08 UT.

in the interplanetary ejecta, we expect to see first the appearance of an E-W and later a twisted NNE to SSW oriented magnetic structure. This is indeed apparent in the data of Figure 6 and in the ACE magnetic field data shown in Figure 8.

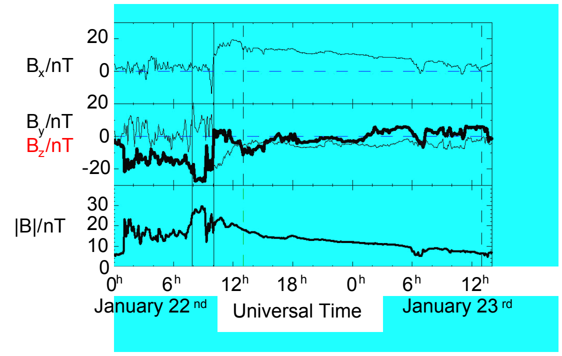

Figure 8. Magnetic field measurements made at ~ 10^6 km from Earth. The two intervals used for minimum variance analysis are indicated by the vertical solid and dashed lines.

Cluster and ACE data show that the ICME material during the first 2 hours after the sheath passes has a coronal composition, and a magnetic field which was stronger than in the sheath, oriented primarily along $-y$ GSE, i.e. solar E-W, and with a distinct +z GSE component,. We identify this as magnetic flux from overlying arcade material, and suggest that the strong magnetic field is due to compression between the expanding flux rope and the upstream solar wind/sheath. The denser, hotter (~ 0.5 MK) ions, and the high O^{7+}/O^{6+} ratios indicative of higher altitude coronal plasma seen during this period may be the signatures of overlying arcade plasma that has been carried along with the ICME. The observation of anti-parallel-only rather than bi-directional electron fluxes during this period can be understood if the overlying arcade field lines did reconnect with streamer field lines to the East of the arcade, creating open field lines rooted in the corona only in the West. Evidence of an interaction between the magnetic field of the CME and the oppositely directed field lines of the neighboring streamer is indicated in Figure 4.

We interpret the 24 hour period (starting January 22, 13:00 UT) of ACE data with consistent IMF $B_Z < 0$ and $B_X > 0$ as the spacecraft passing through the flux rope which emerged with the CME. We infer that the spacecraft passed to the west of the rope axis, as expected if the main body of the rope maintained its coronal ~ NNE-SSW orientation. The flux tube axis determined using ACE data lies N-S, i.e. slightly inclined relative to the coronal orientation, suggesting a local distortion of the flux rope, or else reflecting error margins in our analysis. The difficulties of fully characterizing an ICME flux rope using single spacecraft data are highlighted by Riley et al., 2004.

4. Conclusions

We report a study in which we unambiguously identify the coronal source region and flare event that produced a halo CME which, now as an ICME, was detected *in situ* by Cluster and ACE. The source event was a long duration flare, which is expected to be related to the eruption of a magnetic flux rope. The eruption carried with it overlying coronal arcade plasma from the active region involved in the long duration flare. The expectation is confirmed by magnetic field and plasma signatures in the ICME which closely match their coronal counterparts, apparently having changed little while traveling from Sun to Earth. The resulting geomagnetic storm may have been predictable from knowledge of the original coronal magnetic field configurations. However the ability to achieve this sort of prediction will depend on the development of a full understanding of the possible interactions of the CME magnetic fields with those of the solar wind and the interplanetary medium.

5. References

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