Interplanetary shocks unconnected with earthbound coronal mass ejections

T. A. Howard and S. J. Tappin

School of Physics and Astronomy, University of Birmingham, Edgbaston, UK

Received 22 March 2005; revised 15 June 2005; accepted 23 June 2005; published 23 July 2005.

[1] An associated study by Howard and Tappin (2005) identified 7 Earthbound forward shocks (of which 3 were geoeffective) which were not connected with any detectable coronal mass ejection activity along the Sun-Earth line. This largely unexplored result lends evidence to the fact that some large interplanetary transients are not detected by coronagraphs. This letter explores two possibilities for the formation of the interplanetary foreward shock, namely Corotating Interaction Regions (CIR) or Erupting Magnetic Structures (EMS). Data from EPAM, SWEPAM and MAG on board ACE provided details of the interplanetary shock and associated energetic ions along the Sun-Earth line, while evidence of magnetic field reorientation at the Sun was investigated using EIT on board SOHO, the GOES network and ground-based Hα and radio telescopes. No evidence was found to associate 6 of the shocks with CIRs, although we were uncertain about one event, and in each case evidence of chromospheric activity at the Sun was detected between the estimated onset time of the transient and the arrival of the shock at ACE. The nature of this surface activity included X-Ray ($\geq$C5.0) and Hα flares, associated Type III and Type II radio bursts and disappearing filaments. These results lead to the proposal that EMS are the likely source of some interplanetary transients. **Citation:** Howard, T. A., and S. J. Tappin (2005), Interplanetary shocks unconnected with earthbound coronal mass ejections, *Geophys. Res. Lett.*, *32*, L14106, doi:10.1029/2005GL023056.

1. Introduction

[2] Interplanetary forward shocks along the Sun-Earth line have long been associated with activity at the Sun. It is generally accepted that these shocks, and their subsequent geomagnetic activity enhancement [*Gonzalez and Tsurutani*, 1987; *Gosling et al.*, 1990, 1991; *Echer et al.*, 2004] are caused by halo coronal mass ejections (HCMEs) [*Sheeley et al.*, 1995; *Gosling et al.*, 1991; *Fox et al.*, 1998; *Webb et al.*, 2000, and references therein]. These are coronal mass ejections which have a component directed toward the Earth, and hence appear to encircle the occulting disk of a coronagraph as they propagate away from the Sun [*Howard et al.*, 1982].

[3] Two recent papers have identified interplanetary transients which have not been connected with HCMEs. *Cane and Richardson* [2003] conducted a survey of magnetic clouds and their associated interplanetary shocks and geoeffectiveness during the 6 year time period from 1996–2002. They found that several of their events were not connected with HCMEs, but many of these were not connected with interplanetary shocks either. Similarly, *Schwenn et al.* [2005] identified 8 interplanetary transients which they could not connect with HCMEs, but 2 of these were not connected with a shock, 4 are in fact connected with HCMEs identified in various catalogs or by careful analysis of coronagraph data, and 2 are listed in the present study.

[4] In an associated paper, *Howard and Tappin* [2005] (hereafter referred to as Paper I) conducted a survey of almost 300 forward shocks and explored both their geoeffectiveness and associated CME and flare activity at the Sun. Interplanetary shocks were connected with HCMEs observed by the LASCO coronagraphs [*Brueckner et al.*, 1995] aboard SOHO by listing each HCME observed within a physically reasonable timeframe prior to the shock arrival. This resulted in several events being connected with more than one HCME. Of the 262 shocks measured at L1 (during time periods where LASCO data were available), the vast majority of events (254, or 97%) were connected with at least one halo or partial halo CMEs observed by LASCO. There were, however, 7 events where we were unable to identify a HCME which could be associated with the interplanetary shock. The geoeffectiveness of a shock was identified according to both A_p and Dst at the time of the shock arrival at the Earth, as shown in Table 1.

[5] The objective of the present letter is to identify the source mechanism for these events, with the emphasis on the shock occurrence rather than magnetic clouds or geoeffectiveness. Two possibilities are explored.

[6] Firstly, corotating Interaction Regions (CIRs) [*Smith and Wolfe*, 1976], which occur when fast solar wind, typically from coronal holes, interacts with slow solar wind due to corotation at low latitudes, causing a region of compression. As they are regions of high pressure, they are bounded by forward and reverse waves which typically form forward and reverse shocks [*Balogh et al.*, 1999]. Such shocks are more likely to form beyond 2 AU, but the particle signatures of CIRs have been observed within 1 AU [e.g., *Möbius et al.*, 2001]. Evidence for CIRs include:

[7] 1. Energetic ions produced by the CIR are travelling sunward before and after the forward shock [*Tappin et al.*, 1994].

[8] 2. An associated reverse shock exists and is stronger than the forward shock, due to the reverse shock forming closer to the Sun than the forward shock [*Pizzo*, 1978,1980, 1982].

[9] 3. Evidence of equatorial holes near the equator. Such an organization of the corona is generally favoured near solar minimum [e.g., *Krieger et al.*, 1973].

0094-8276/05/2005GL023056$05.00

Table 1. Definition of Storm Rating

Storm Rating	A_p	Dst
Small	~30 to 60	~−80 to −60
Medium	~60 to 80	~−150 to −80
Large	≥80	≤−150

[10] Alternatively, it is conceivable that some large-scale eruptions from the Sun may be invisible to coronagraphs. CME white light intensity is a function of the density of matter within the erupting structure. Hence, a CME is only visible to a coronagraph if it contains sufficient matter for detection above the lower threshold for the instrument [*Lyons and Simnett*, 2001]. These Erupting Magnetic Structures (EMS) may provide a clue as to why flare activity occurs at the Sun with no apparent CME. The idea of EMS was first proposed by *Lyons and Simnett* [2001], who referred to very slow moving eruptions (<100 km/s) which may not be connected with prominences or flares. We refer to EMS in a different sense, and use the term to describe any large-scale magnetic field eruption from the Sun not associated with a coronal density enhancement, which therefore cannot be directly detected by coronagraphs which are currently in operation. Our definition of EMS could therefore be regarded as "invisible CMEs". An EMS would propagate through the interplanetary medium in the same manner as a CME, and may accumulate density from the solar wind in transit via the so-called "snowplow effect". With sufficient speed, an EMS could form a shock by the time it reaches 1 AU. Evidence for EMS may appear lower in the corona, such as the existence of X-Ray or EUV flares or erupting filaments in Hα. Other evidence for magnetic reconfiguration may be more subtle, such as bulk matter movement across the solar "surface" or coronal dimming [*Howard and Harrison*, 2005, and references therein].

2. Data

[11] Spacecraft data for the present study were provided by the Solar and Heliospheric Observatory (SOHO) and the Advanced Composition Explorer (ACE) spacecraft, both orbiting the inner Lagrangian (L1) point. and X-Ray data were provided by the Geostationary Orbiting Environmental Satellite (GOES) network. Solar wind and energetic particle, and interplanetary magnetic field measurements at L1 were provided by the Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) [*McComas et al.*, 1998], the Electron, Proton and Alpha Monitor (EPAM) [*Gold et al.*, 1998] and MAG [*Smith et al.*, 1998] instruments on board ACE respectively. Solar EUV data were provided by the Extreme-Ultraviolet Imaging Telescope (EIT) [*Delaboudinière et al.*, 1995] on board SOHO. Only images from the Fe XII 195 Å line (which is common at temperatures of $\sim 1.5 \times 10^6$ K) have been used in the present study. Radio and Hα activity was obtained by ground-based stations and made available via the Solar and Geophysical Database, now at http://sgd.ngdc.noaa. gov. This provided data on X-Ray and Hα flares, Radio Type II and III bursts and erupting filaments and prominences.

[12] Seven forward shocks were identified in Paper I as being unconnected with HCMEs observed in LASCO. Some details of each are listed in Table 2. These events formed the database for the present study.

Table 2. Summary the Seven Forward Shocks Identified by *Howard and Tappin* [2005] as not Associated With CME Activity Along the Sun-Earth Line

No.	Date	Time	Max. A_p	Min. Dst
1	7 April, 1998	17:00	8	−28
2	23 October, 1998	12:34	15	−52
3	18 May, 1999	00:04	27	−27
4	23 August, 1999	11:30	31	−66
5	23 August, 1999	15:04	31	−66
6	23 December, 2001	22:19	23	−55
7	9 November, 2002	18:00	17	−27

3. Results

[13] Figure 1 shows the magnetic field and energetic ion data for the event on 23 October, 1998 (Event 2 in Table 2). Data are shown for both antisunward (P) and sunward (P′) ions. Note that the peak in the antisunward ions occurs several seconds before the peak in sunward ions (indicated by the solid and dashed horizontal lines respectively) and that there is no significant increase in backstreaming ion activity beforehand. The latter peak is probably due to backstreaming ions accelerated at the forward shock. This was common for most events, although backstreaming ions were dominant for Events 4 and 5, and bi-directional flows were found for Event 7. As shown in Figure 2, the two shocks on 23 August, 1999 were preceded by an earlier shock at 07:28 UT on the same day, and the source of the backstreaming ions is likely to be from this shock.

[14] Figure 2 shows the 24 hour magnetic field variation around the times of all seven events. In only one case is there a reverse shock accompanying the forward shock; in

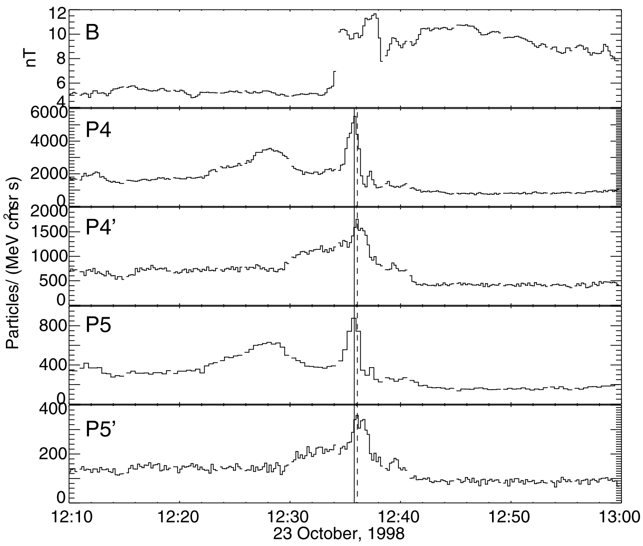

Figure 1. Magnetic field (MAG) and energetic ion (EPAM) data plotted against time for the shock on 23 October, 1998 at 12:34 UT. The energetic ion data are from the LEMS 30 (P) and LEMS 120 (P′) spectrometers on EPAM, for ions in the energy ranges of 214–337 keV (P4, antisunward), 207–336 keV (P4′, sunward), 337–594 keV (P5) and 336–601 keV (P5′). The vertical lines represent the time of the peak in the antisunward-streaming ions (solid) and the sunward-streaming ions (dashed).

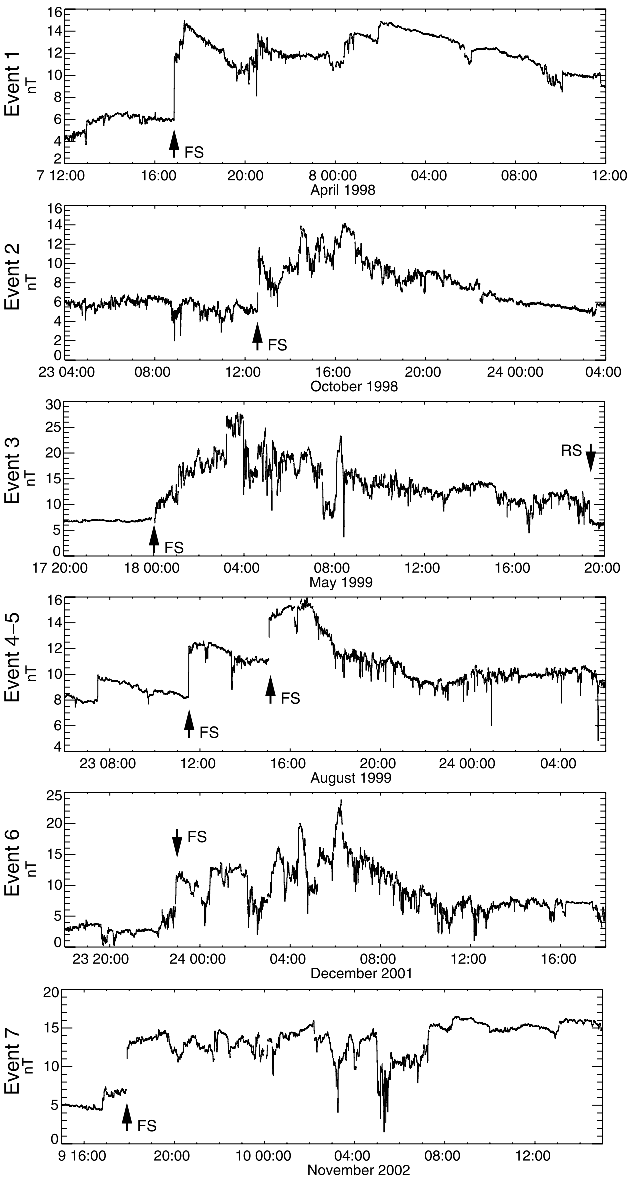

Figure 2. Magnetic field (MAG) variation for 24 hour intervals around the times of all seven events. Note that only in Event 3 is a reverse shock apparent.

all other cases the magnetic field gradually returns to the background level gradually over the course of several hours after the forward shock. In Event 3 there is a reverse shock which occurs 19 hours later at 19:20 UT, and the particle data around the time of the shock is noisy and inconclusive. EIT data shows that there is also an associated coronal hole on the solar disk. This suggests that Event 3 could have been caused by a CIR.

[15] Event 7 is the only event which shows bi-directional ion motion, which also may be evidence of a CIR. EIT data for the time around this event does show a coronal hole near the equator in the days leading up to the shock at L1, but this reached ~60° longitude in the early hours of 5 November, 2002, was close to the western limb by 9 November and is thus more likely responsible for the fast solar wind on 6 November.

[16] Figure 3 shows time lines for solar "surface" activity of each of the 7 events. The onset time of the transient was estimated using the pre- and post-shock SWEPAM measurements of the bulk solar wind speed and assuming constant propagation speed. This assumption is oversimplified, and some deceleration would probably occur [e.g., Paper I], meaning that associated "surface" events may occur after the estimated onset time range. There is clearly evidence of solar "surface" activity in all seven cases, some of which occur within the estimated onset time range. X-Ray flares $\geq$C5.0 class were observed in all 7 cases (5 with M class flares and none with X class flares), and erupting filaments occur in 5 cases. Previous work has shown a close connection between the latter phenomena and CME activity [e.g., *Munro et al.*, 1979; *Webb and Hundhausen*, 1987]. Any of these events may be an indicator of an associated magnetic eruption.

4. Discussion

[17] The physics driving an EMS is identical to that which drives a CME, i.e., a discontinuity or disturbance drives an eruption of the local coronal magnetic field. The erupting field propagates through the solar wind in the same manner as a CME, and associated "surface activity" at the Sun, such as flares or erupting filaments may occur at the footpoint(s) of the structures. If the transient travels faster

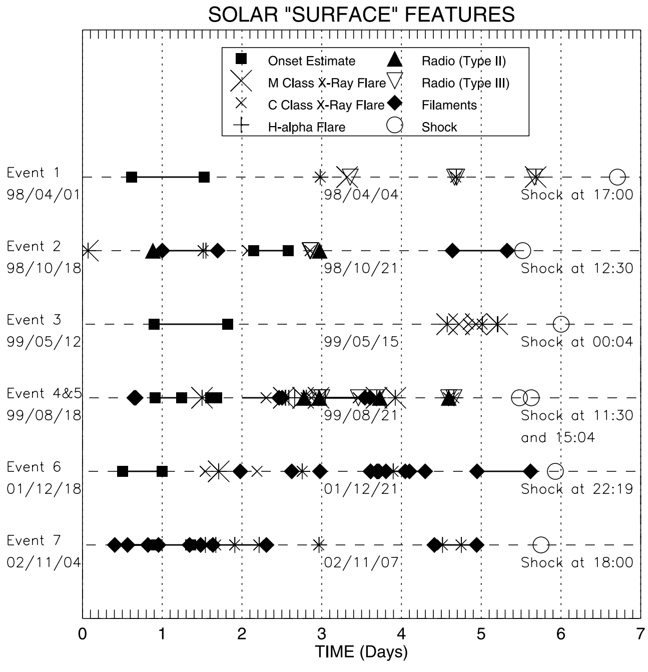

Figure 3. Time lines for solar "surface" activity of each event in the days leading up to the shock observed by ACE. In each case the beginning of a day 5–7 days before the shock is selected as a start point, and both the time of the shock and the estimated onset time range of the transient is indicated (see text). Also indicated are the onset times of X-Ray flares (Class $\geq$ C5.0) and associated Hα flares and Type III bursts. Erupting filaments, with a solid line joining their start and end times, and the onset times of Type II radio bursts are also shown.

than the local solar wind, it may form a forward shock and accumulate solar wind material in transit. The latter phenomenon has been termed the "snowplow effect". Thus, by the time it reaches 1 AU, this transient may appear identical to a shock produced by a CME, and associated geomagnetic activity is also possible for those events which are Earthbound. The difference between an EMS and a CME is that the former erupts before it had sufficient time to accumulate large amounts of coronal plasma, and is therefore invisible to coronagraphs. It should be noted that the proportion of Earthbound EMS to visible HCMEs is very small, around 3% of all events which were observed to form a shock at L1 (Paper I). It is possible that some or most EMS may not have sufficient speed to develop shocks. The results from Paper I suggested that only half of the visible Earthbound HCMEs form shocks which are detected near 1 AU

[18] We have not specifically considered the location of the chromospheric events, which may represent at least one footpoint of an EMS, but it is probable that events close to the Sun-Earth line are more likely to be connected with the shock observed at L1 [e.g., *Cane et al.*, 2000]. In each case there were several narrow ($\leq 120°$) CMEs which occurred in the days leading up to the shocks measured at ACE. These were associated with events which were not Earthbound, but it is possible that an Earthbound component of these CMEs may exist. Also, it should be noted that not all of the shocks had measurable energetic particles in EPAM.

[19] Since these events were distributed through both solar maximum and solar minimum, we may reasonably conclude that EMS rather than CIRs are the dominant cause of these interplanetary foreward shocks which cannot be associated with HCMEs.

[20] **Acknowledgments.** We thank the teams at Goddard Space Flight Center (GSFC/NASA) and Naval Research Laboratory (NRL) for their provision and maintenance of the EIT data. The Solar Geophysical Database and the GOES solar flare catalog are supported and maintained by the National Oceanic and Atmospheric Administration (NOAA) and made available courtesy of the Solar-Terrestrial Physics Division and the Space Environment Center respectively. We would also like to thank our colleagues G. M. Simnett and I. M. Robinson for useful discussions.

References

Balogh, A., J. T. Gosling, J. R. Jokipii, R. Kallenbach, and H. Kunow (1999), Corotating interaction tegions: Introduction, *Space Sci. Rev.*, *89*, 1.

Brueckner, G. E., et al. (1995), The large angle spectroscopic coronagraph, *Sol. Phys.*, *162*, 357.

Cane, H. V., and I. G. Richardson (2003), Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002, *J. Geophys. Res.*, *108*(A4), 1156, doi:10.1029/2002JA009817.

Cane, H. V., I. G. Richardson, and O. C. St. Cyr (2000), Coronal mass ejections, interplanetary ejecta and geomagnetic storms, *Geophys. Res. Lett.*, *27*, 3591.

Delaboudinière, J.-P., et al. (1995), EIT: Extreme-ultraviolet imaging telescope for the SOHO mission, *Sol. Phys.*, *162*, 291.

Echer, E., M. V. Alves, and W. D. Gonzalez (2004), Geoeffectiveness of interplanetary shocks during solar minimum (1995–1996) and solar maximum (2000), *Solar Phys.*, *221*, 361.

Fox, N. J., M. Peredo, and B. J. Thompson (1998), Cradle to grave tracking of the January 6–11, 1997 Sun-Earth connection event, *Geophys. Res. Lett.*, *25*, 2461.

Gold, R. E., S. M. Krimigis, S. E. Hawkins, D. K. Haggerty, D. A. Lohr, E. Fiore, T. P. Armstrong, G. Holland, and L. J. Lanzerotti (1998), Electron, ion and alpha monitor on the Advanced Composition Explorer Spacecraft, *Space Sci. Rev.*, *86*, 541.

Gonzalez, W. D., and B. T. Tsurutani (1987), Criteria of interplanetary parameters causing intense magnetic storms (Dst < -100 nT), *Planet. Space Sci.*, *35*, 1101.

Gosling, J. T., S. J. Bame, D. J. McComas, and J. L. Phillips (1990), Coronal mass ejections and large geomagnetic storms, *Geophys. Res. Lett.*, *17*, 901.

Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame (1991), Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, *96*, 7831.

Howard, R. A., D. J. Michels, N. R. Sheeley Jr., and M. J. Koomen (1982), The observation of a coronal transient directed at Earth, *Astrophys. J.*, *263*, L101.

Howard, T. A., and R. A. Harrison (2005), On the coronal mass ejection onset and coronal dimming, *Sol. Phys.*, *219*, 315.

Howard, T. A., and S. J. Tappin (2005), Statistical survey of earthbound interplanetary shocks, associated coronal mass ejections and their space weather consequences, *Astron. Astrophys.*, in press.

Krieger, A. S., A. F. Timothy, and E. C. Roelof (1973), A coronal hole and its identification as the source of a high velocity solar wind stream, *Sol. Phys.*, *29*, 505.

Lyons, M. A., and G. M. Simnett (2001), Erupting magnetic structures observed with SOHO/LASCO, *Sol. Phys.*, *200*, 203.

McComas, D. J., S. J. Blame, P. Barker, W. C. Feldman, J. L. Phillips, P. Riley, and J. W. Griffee (1998), Solar Wind Electron, Proton and Alpha Monitor (SWEPAM) for the Advanced Composition Explorer Spacecraft, *Space Sci. Rev.*, *86*, 563.

Möbius, E., D. Morris, M. A. Lee, G. M. Mason, B. Klecker, J. E. Mazur, M. A. Popecki, A. B. Galvin, and M. Kistler (2001), Variation of energetic He^{+}, He^{2+} and heavy ions across co-rotating interaction regions, —it Proc. Int. Conf. Cosmic Rays, 2001, 293.

Munro, R. H., J. T. Gosling, E. Hildner, R. M. MacQueen, A. I. Poland, and C. L. Ross (1979), The association of coronal mass ejection transients with other forms of solar activity, *Sol. Phys.*, *61*, 201.

Pizzo, V. (1978), A three-dimensional model of corotating streams in the solar wind: 1. Theoretical foundations, *J. Geophys. Res.*, *83*, 5563.

Pizzo, V. (1980), A three-dimensional model of corotating streams in the solar wind: 2. Hydrodynamic streams, *J. Geophys. Res.*, *85*, 727.

Pizzo, V. (1982), A three-dimensional model of corotating streams in the solar wind: 3. Magnetohydrodynamic streams, *J. Geophys. Res.*, *87*, 4374.

Schwenn, R., A. Dal Lago, E. Huttunen, and W. D. Gonzalez (2005), The association of coronal mass ejections with their effects near the Earth, *Ann. Geophys.*, *23*, 1033.

Sheeley, N. R., Jr., R. A. Howard, D. J. Michels, M. J. Koomen, R. Schwenn, K. H. Mulhauser, and H. Rosenbauer (1995), Coronal mass ejections and interplanetary shocks, *J. Geophys. Res.*, *90*, 163.

Smith, C., W. M. H. Acuna, L. F. Burlaga, J. L'Heureux, N. F. Ness, and J. Scheifele (1998), The ACE Magnetic Field Experiment, *Space Sci. Rev.*, *86*, 613.

Smith, E. J., and J. H. Wolfe (1976), Observations of interaction regions and corotating shocks between one and five AU: Pioneers 10 and 11, *Geophys. Res. Lett.*, *3*, 137.

Tappin, S. J., E. C. Roelof, and L. J. Lanzerotti (1994), Particle acceleration seen at Ulysses on 27 May 1991, *Astron. Astrophys.*, *292*, 311.

Webb, D. F., and A. J. Hundhausen (1987), Activity associated with the solar origin of coronal mass ejections, *Sol. Phys.*, *108*, 383.

Webb, D. F., E. W. Cliver, N. U. Crooker, O. C. St. Cyr, and B. J. Thompson (2000), Relationship of halo coronal mass ejections, magnetic clouds, and magnetic storms, *J. Geophys. Res.*, *105*, 7491.

T. A. Howard and S. J. Tappin, School of Physics and Astronomy, University of Birmingham, Edgbaston B15 2TT, UK. (tim@star.sr.bham.ac.uk)