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Interplanetary Coronal Mass Ejections During 1996-2007

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Abstract: Interplanetary coronal mass ejections are the interplanetary manifestations of coronal mass ejections observed by coronagraphs near the Sun. Their associated effects include the generation of upstream shocks which may accelerate energetic particles, short-term (Forbush) decreases in the galactic cosmic ray intensity, unusual energetic particle flows, and geomagnetic storms. We summarize some of the properties of ICMEs observed during solar cycle 23.

Introduction

Interplanetary coronal mass ejections (ICMEs), the interplanetary manifestations of coronal mass ejections (CMEs) at the Sun observed by coronagraphs are associated with many characteristic features [1]. These characteristics, which are not necessarily observed in every case, include: abnormally low solar wind proton temperatures; solar wind ion charge state and compositional anomalies; the generation of shocks upstream of fast ICMEs which may be important accelerators of energetic particles; short-term (Forbush) decreases in the galactic comic ray intensity; unusual energetic particle flows, including bidirectional flows at keV to GeV energies; plasma wave generation; and the production of geomagnetic storms. ICMEs may also play a role in long-term cosmic ray modulation.

Primarily in view of their consequences on energetic particles, we have made several studies of ICMEs in the vicinity of Earth and at 0.3-1 AU from the Sun using observations from near-Earth spacecraft and Helios 1 and 2 [e.g., 2, 3, 4]. These include [3] the compilation of a "comprehensive" list of ICMEs passing the Earth since 1996, the beginning of solar cycle 23, which we continue to update (the current version is available from the authors). The ICME identifications are based on solar wind plasma, magnetic field, and composition data, and energetic particle observations which, in addition to providing information on particle modulations and unusual particle flows which may be indicative of passing ICMEs, can help to associate a shock/ICME with a specific solar event based on the intensity-time profile.

Figure 1 shows an example of solar wind plasma, magnetic field and energetic particle observations (from ACE and IMP 8) in the vicinity of a shock/ICME in the near-Earth solar wind in April 2001. The green line marks passage of the shock, while the ICME is delineated by purple lines. Several ICME signatures are evident: Abnormally low proton temperatures are indicated by the black shading in the T_p panel which denotes when $T_p < 0.5\ T_{exp}$, where T_{exp} is the temperature expected for normally-expanding solar wind (the expanding ICME cools more rapidly than the ambient solar wind). T_{exp} is inferred from the observed solar wind speed based on the V_{sw}-T_p correlation found in normal solar wind and is overplotted in red. Enhancements in solar wind ion charge states (e.g., O^7/O^6, mean Fe charge) measured by ACE/SWICS and indicative of higher coronal temperatures in the CME source regions are also evident. The expected value for O^7/O^6, based on compositional variations in the normal solar wind, is overlaid in red (see [4] for

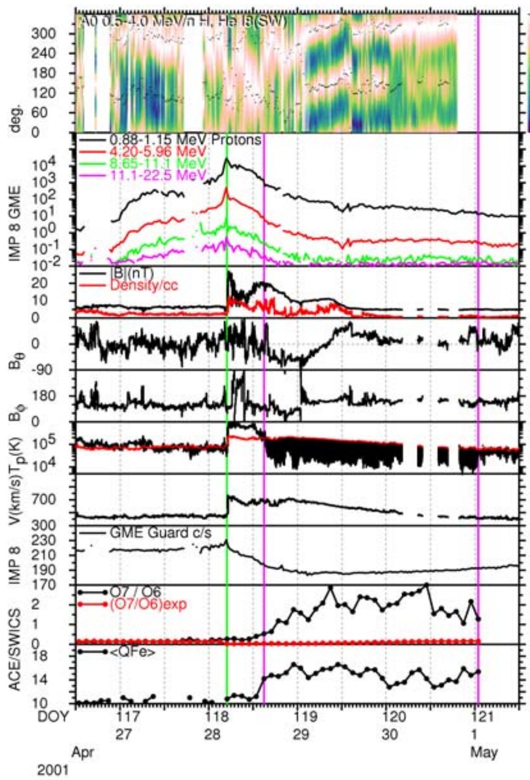

Figure 1: Energetic particle, and solar wind plasma and magnetic field data associated with a shock and ICME in April 2001.

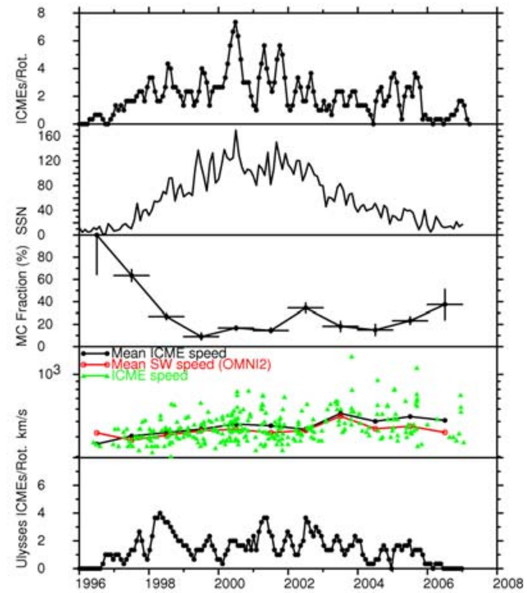

Figure 2: ICME rate/solar rotation at the Earth, monthly sunspot number, fraction of ICMEs that are magnetic clouds, mean ICME and solar wind speeds with speeds of individual ICMEs at 1 AU overplotted, and the ICME rate/rotation at Ulysses, since 1996.

further discussion). The cosmic ray depression commencing at the shock is illustrated here by the counting rate of the anti-coincidence guard of the Goddard particle instrument on IMP 8. The top panel shows 0.5-4 MeV proton anisotropies in the solar wind frame measured by this instrument. The intensity (normalized to the maximum value in a given 15-minute interval) is plotted vs. viewing direction (GSE coordinates) such that particles arriving from the direction of the Sun (or an approaching shock) along the Parker spiral (~315º) have higher intensities towards the top of the panel while sunward-flowing particles (~135º) lie below center. Black dashes are aligned with or opposite to the local magnetic field direction. In addition to a flow reversal from anti-solar to sunward close to shock passage in the particle enhancement peaking at shock passage, bidirectional field-aligned particle flows can clearly be identified within the ICME, indicative of particles trapped on or mirroring along predominantly closed field lines in the ICME. This event was associated with a 1006 km/s halo CME at 1230 UT on April 26 related to a 2B/M7.8 flare at N17ºW31º.

Using similar observations, we have identified ~300 ICMEs that passed the Earth during 1996-mid 2007. The top panel of Figure 2 summarizes the ICME rate/solar (Carrington) rotation, averaged over 3 running rotations. The monthly sunspot number is plotted in the second panel. Although the ICME rate broadly follows solar activity levels, there is not a close correlation with sunspot number. Rather, the ICME rate maintains a general level of ~2/rotation during much of the period with occasional intervals of enhanced rates associated with periods of exceptionally high solar activity (such as July, 2000, early-2001). The ICME rate shows some evidence of quasi-periodic variations that are consistent with the ~150 day "periodicity" previously reported in various energetic solar data sets [3, 5]. The ICME rate has remained relatively high during the late declining phase of the solar cycle. Nevertheless, observations of low ICME rates during much of

2006, and during 2007 to date suggest that the rate is approaching that seen in 1996 during the last solar minimum.

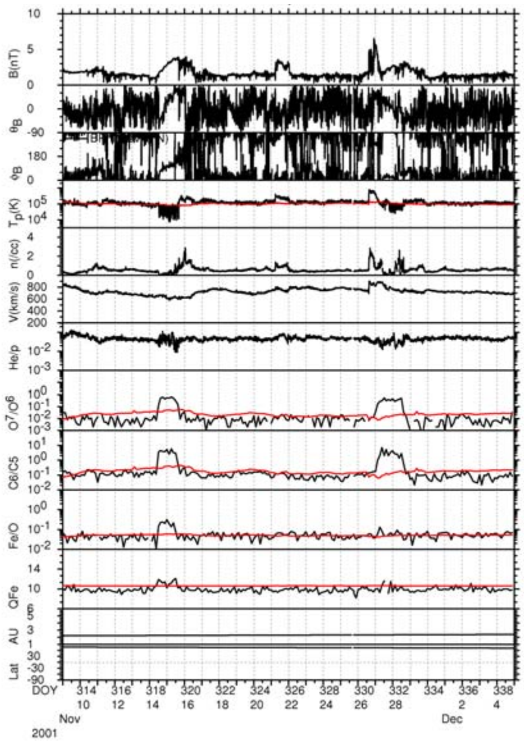

Figure 3: Ulysses solar wind magnetic field, plasma, and composition data showing two ICMEs in high-latitude, high-speed solar wind flows. Expected values of T_p and comositional/charge state parameters are overlaid in red.

We have previously noted [6], based on observations during this and the previous two solar cycles, evidence of a solar-cycle dependence in the fraction of ICMEs that have the characteristics of "magnetic clouds", i.e., an enhanced magnetic field strength with a smooth, slow rotation in field direction and low proton temperature. A MC fraction of 30% is frequently quoted. However, we suggest that the fraction is dependent on the phase of the solar cycle, with the fewer ICMEs around solar minimum having a higher incidence of MCs than around solar minimum (third panel of Figure 2). The observations up to 2006 show only a hint of the increase in the MC fraction expected with a return towards solar minimum conditions.

Another ICME parameter showing an interesting variation during this cycle is the in-situ ICME speed (Figure 2, panel 4). Average speeds have increased by around 100 km/s, from ~400 to 500 km/s. We also show speeds of individual ICMEs. At least two factors may contribute to this solar cycle variation. One is the increase in average solar wind speeds, also shown in the figure (from the OMNI2 data set), since ICME speeds tend to converge towards the ambient solar wind speed. Another factor is the tendency for fast ICMEs (and fast CMEs at the Sun) to occur following solar maximum in this cycle. An unusual number of exceptionally fast shocks/ICMEs have been observed in this cycle, even during the late declining phase, compared to recent cycles (some fast events are absent in Figure 2 because of plasma instrument issues). The prevalence of exceptionally fast transient events and associated strong shocks may help to account for the predominance of solar energetic particle events dominated by shock acceleration during the second half of cycle 23 compared with the first half [7]. The shock/ICME in Figure 1 produced a modest geomagnetic storm of Dst = -47 nT. Around 90% of the ~100 storms in 1996-2005 with Dst < -100 nT were associated with ICMEs and/or the upstream sheath of shocked plasma [8].

ICMEs at Ulysses

We have applied similar analyses to observations during the Ulysses mission, launched in October, 1990 to explore the solar wind within ~5 AU of the Sun extending up to high heliolatitudes. The proton temperature T_p, and hence T_{exp}, varies both with V_{sw} and heliocentric distance (R). We estimate $T_p = (502V_{sw}\text{-}1.26\times10^5)/R^{0.98\pm0.06}$, i.e., $T_p \sim R^{-1}$, using T_p(small) observations from the SWOOPs instrument made in 1990-2006. Composition and charge state data are available from the SWICs instrument on Ulysses. As at 1 AU, we infer expected values for these parameters from their V_{sw}-dependence. Since composition/charge states are determined by conditions at the Sun, they do not vary with spacecraft location.

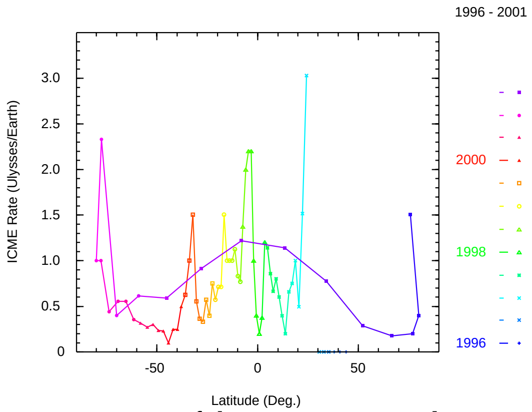

Figure 4: Ratio of the ICME rates at Ulysses and Earth during 1996-2001 as a function of time and Ulysses heliolatitude.

Figure 3 shows two ICMEs observed by Ulysses at 2 AU, 80ºN in high-latitude high-speed flows. The ICMEs are readily identified by their anomalies with respect to expected values overlaid in red, including $T_p < T_{exp}$, and enhancements in C^6/C^5 O^7/O^6, Fe/O, and $<Q_{Fe}>$. Using solar wind plasma and magnetic field data and plasma composition/charge states, we have identified ~280 probable ICMEs during the Ulysses mission up to 2006. The bottom panel of Figure 2 shows the 3-rotation running average ICME rate at Ulysses. Despite the excursions of Ulysses in heliocentric distance and latitude, the ICME rate is essentially similar to that at Earth, at ~1-2/rotation for much of the solar cycle (see also [9]). Figure 4 shows the rotation-to-rotation variation in the Ulysses ICME rate divided by that at Earth for 1996 to 2001 (indicated by the color of the graph) as a function of Ulysses heliolatitude. During this period, Ulysses made a slow transition from northern to southern latitudes encompassing aphelion, followed by a fast latitude scan at perihelion in 2001. Again, although there are similar rates at each location, the decrease in the relative rate at Ulysses at mid-latitudes, followed by a recovery at the highest latitudes suggests that there may be a separate population of ICMEs at high latitudes unrelated to that seen at low latitudes, though this requires further investigation.

Summary

The ICME rate in 2006-2007 is approaching that of the previous solar minimum. Throughout cycle 23, the ICME rate may be characterized as ~2/rotation with brief enhancements associated with occasional periods of exceptionally high solar activity. ICME rates at Ulysses are similar to those at Earth, and there is an indication of a separate population of ICMEs seen at high latitudes.

Acknowledgments

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