ICMEs at very large distances

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Abstract

This paper reviews recent work on the observations and evolution of interplanetary coronal mass ejections (ICMEs) in the outer heliosphere. Several case studies are shown following ICMEs or their preceding shocks from 1 AU to Voyager 2 at large (>50 AU) distances. Low temperature/speed ratios and high helium abundances have been used to create lists of ICMEs. We combine lists from the inner (0.3–5.3 AU) and outer (1–30 AU) heliosphere to perform a statistical study of ICME evolution. ICMEs expand, on average, by a factor of 5 in width between 1 and 10–15 AU, then maintain a constant width as they move beyond 15 AU. The density and magnetic field decrease more rapidly in ICMEs than the solar wind, consistent with ICME expansion. The temperature, however, decreases less rapidly in ICMEs despite their expansion, indicating that ICMEs are preferentially heated. At solar maximum, ICMEs interact with the ambient solar wind to form large pressure pulses in the outer heliosphere with correlated speed, density, and magnetic field increases.

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1. Introduction

This review describes our current knowledge of interplanetary coronal mass ejections (ICMEs) at distances beyond 1 AU. ICMEs originate as CMEs at the Sun (Gosling, 1990; Neugebauer and Goldstein, 1997). CMEs on the Sun are the progenitors of the ICMEs observed by spacecraft in the solar wind (Gosling et al., 1995; McAllister et al., 1996; Riley et al., 2003; Reisenfeld et al., 2003). Many ICMEs are not initially in equilibrium with the ambient solar wind, because their speeds and/or internal pressures are different from those in the solar wind; these ICMEs must evolve with distance. Studies by Burlaga and coworkers found that magnetic clouds, a subset of ICMEs, expand in the inner heliosphere and persist to at least 11 AU (see Burlaga (1995) and references therein). ICMEs often occur in clusters since a major active region can be the source of many ICMEs; even at 1 AU it is common to see interacting ICMEs and by the time ICMEs reach the outer heliosphere multiple interactions have often occurred.

While ICMEs are sometimes obvious features in 1 AU observations, many ICMEs are difficult to identify with certainty (Neugebauer and Goldstein, 1997). At larger distances, the effects of ICME and solar wind evolution and ICME interactions with the ambient solar wind and other ICMEs compound this difficulty. This paper discusses methods of identifying ICMEs, the evolution of ICMEs, and the effects ICMEs have on the heliosphere at large distances.

2. ICME identification

The list of ICME characteristics at 1 AU is large: low temperature/speed ratios, small magnetic fluctuation levels, low plasma beta (the ratio of thermal to magnetic
pressure), energetic ion counterstreaming along magnetic field lines, suprathermal electron counterstreaming along field lines, large He/H ratios, enhanced minor ion relative abundances, above average charge states for minor ions, preceding forward shocks, magnetic fields that are enhanced in field strength and smoothly rotating, and Forbush decreases (Gosling, 1997; Neugebauer and Goldstein, 1997 and references therein). Unfortunately, none of these characteristics is necessary and few (if any) are sufficient to identify an ICME (Richardson and Cane, 1993; Cane and Richardson, 2003). To further complicate the choosing of ICME boundaries, these characteristics can be intermittent within ICMEs.

ICME identification is even more difficult in the outer heliosphere, both because some characteristics of ICMEs are blurred through interaction with the ambient solar wind and because currently available instrumentation precludes observation of some characteristics. The best characteristics for tracing ICMEs into the outer heliosphere are those not affected by stream interactions, such as the elemental abundance ratios as well as the relative charge state abundance for a given element; for the Voyager spacecraft, the best measurable signature is the helium/proton ratio (Paularena et al., 2001). The alpha-to-proton density ratio rarely exceeds 0.08 except in an ICME (Goldstein et al., 1998).

Several ICMEs have been traced from the inner to outer heliosphere using enhanced He/H ratios as a tracer (Paularena et al., 2001; Richardson et al., 2002). Fig. 1 shows an example of an ICME observed at Earth by Wind, at 5.2 AU by Ulysses, and at 58 AU by Voyager 2 (Richardson et al., 2002). These spacecraft were separated by 200° longitude, so they observed different parts of the ICME (or perhaps different ICMEs from the same active region). The ICME data from the three spacecraft in Fig. 1 are aligned in time to facilitate comparison. At 1 AU, Wind observed an enhanced He/H ratio, 10–15%, for about 1.5 days beginning on 25 September, 1998. The ICME was part of a region of enhanced internal pressure (magnetic plus thermal pressure) centered on the leading edge of the ICME. The ICME reached Ulysses about 16 days later (10 October, 1998) and an enhanced He/H ratio was observed for about 5 days; the expansion was driven by the high internal pressure. The total pressure was roughly in equilibrium with the ambient solar wind plasma. The bottom panel shows the Voyager 2 He/H ratio enhancements which began 24 June 1999 and persisted about 5.5 days, so little additional expansion of the ICME occurred beyond Ulysses. The arrival time at Voyager 2 is consistent with the time predicted by a 1-D MHD propagation model including pick up ions, so we are confident these are the same ICME.

Another method of tracing ICMEs outward is to follow the shocks which lead these events outward. The Bastille day CME of July 14, 2001 was ideal in that Earth and Voyager 2 were at nearly identical heliolongitudes (for description of this event see http://science.nasa.gov/headlines/y2000/ast14jul_2m.htm). Several shocks were observed at Earth; a 1-D MHD model used to trace the event outward predicted these shocks would merge by a few AU, then the shock would decay in strength with increased radial distance (Wang et al., 2001a,b). Voyager 2 saw the shock in January 2001, within a few days of the expected time and with the predicted speed jump. The shock was the leading edge of a merged interaction region (MIR) which caused a decrease in the cosmic ray flux (Burlaga et al., 2001).

In October 2001 a shock stronger than the Bastille day event was observed by Voyager 2. Tracing back to 1 AU, the origin of this shock was a roughly 3-week series of events in April/May of 2001 (Wang and Richardson, 2002). The data from 1 AU were used as input to the 1-D MHD model. The model predicted the ICMEs from this region would merge to form one large shock which would reach Voyager 2 at 63 AU. The model timing was accurate to within a few days and also predicted a speed jump very similar to that observed. The MIR behind this shock also caused a decrease in the cosmic ray flux.

The October/November 2003 events were observed by multiple spacecraft at 1 AU, at Ulysses, at Cassini, and at Voyager 2 (Richardson et al., 2005; Burlaga...
et al., 2005). These events were composed of multiple CMEs which produced multiple ICMEs moving outward at many heliolongitudes. Thus the spacecraft all saw ICMEs from the same set of activity, but likely different combinations of ICMEs. Voyager 2 observed enhanced He/H ratios tens of days downstream from the shock, verifying that this plasma was composed of ICMEs. Voyager 1, however, saw no evidence of these events suggesting they did not form a true global MIR (GMIR).

3. Statistical studies

Large data bases of ICMEs are needed to study ICME evolution. Shocks are easily identified for such a study, but the actual ejecta behind the shock can be hard to identify and many shocks are not driven by ICMEs. For those that are ICME driven, behind the shock is a sheath region of shocked solar wind and compressed ejecta eroded from the leading edge of the ICME, followed by the ejecta. In the case of multiple ICMEs merging together ejecta, solar wind, and sheath are interspersed and to some degree mixed, merged, and processed.

The He/H ratio can be used to identify ICMEs; Wang and Richardson (2001) found 56 events in the Voyager 2 data where the He/H density ratio was over 0.1 for at least 12 h. These ICMEs varied in frequency with the solar cycle, were clustered in time, and had higher speeds, lower temperatures, and higher magnetic fields than the surrounding solar wind. The problem with using this ratio to identify ICMEs, however, is that only a small percentage of ICMEs have He/H ratios this large.

The temperature/speed ratio has proved useful for identifying ICMEs out to 30 AU (Wang and Richardson, 2004). At 1 AU, the criteria for identifying an ICME is that the observed temperature be less than 50% of the expected temperature (Richardson and Cane, 1995), where the expected temperature is a function of the solar wind speed (Lopez and Freeman, 1986). By including a radial temperature gradient (deduced empirically from the observations), the temperature criterion can be extended to locations far from Earth (Liu et al., 2005; Wang and Richardson, 2004). Stream interactions, including shock formation and propagation, will tend to dissipate many ICME signatures. Countering these effects, the expansion of ICMEs will help to maintain their low temperatures.

Fig. 2 shows an example of an ICME at 11 AU; the characteristics are similar to those of many ICMEs identified in the Voyager 2 data. The figure shows the ICME boundaries and the solar wind parameters. The ratio of \( T/T_{\text{ex}} \), the primary criteria for identifying possible ICMEs, is shown in the bottom panel and is well under 0.5 in the ICME. The decrease in speed across the ICME is another common characteristic. The speed decrease suggests the ICME is still expanding. The density in ICMEs beyond 1 AU is often smaller than in the ambient solar wind, in contrast to at 1 AU where densities in the ICMEs are roughly equal to those in the solar wind (Crooker et al., 2000). The magnetic field is usually the same in the ICME as in the ambient solar wind, again in contrast to 1 AU where \( B \) is higher within the ICME. The behavior of \( N \) and \( B \) are both consistent with ICMEs expanding with distance.

A search of the Voyager 2 data inside 30 AU found 145 probable ICMEs (Wang and Richardson, 2004). Merged ICMEs were counted as a single event. Fig. 3 shows the distribution of ICMEs with time, the total amount of solar wind plasma comprised of ICMEs, and the sunspot number. The number of ICMEs is larger from 1978 to 1983 then after that; lower numbers of ICMEs are expected at solar minimum as the CME rate also decreases. ICMEs at larger radial distances are probably less likely to be detected. The expansion of ICMEs, coupled with the solar cycle dependence, results in as much as 40% of the solar wind being comprised of ICME material in the descending phase of the solar cycle near 15 AU. At 1 AU, about 15% of the solar wind is ICME material near solar maximum (Gosling et al., 1992); expansion of the ICMEs increases this percentage at larger distances.
We combine the results of two studies of the radial evolution of ICMEs. Liu et al. (2005) used data from Helios 1 and 2, Wind, ACE, and Ulysses to study ICME evolution. These spacecraft provided data from between 0.3 and 5.4 AU. They used a strict criteria to select ICMEs; the temperature had to be less than 50% of the expected temperature ($T/T_{\text{ex}} < 0.5$) and the He/H ratio had to be above 8%. Magnetic field and other plasma parameters were used to help pick the ICME boundaries. Wang and Richardson (2004) used Voyager 2 data to study ICMEs out to 30 AU. They used the temperature criteria augmented with other plasma parameters and magnetic field data to choose ICME boundaries. They cut their study off at 30 AU for 2 reasons. Magnetic field data are not routinely available after 30 AU to assist in the choosing of ICME boundaries and the increasing pressure due to pickup ions likely makes the temperature criteria less reliable.

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The identification of large numbers of ICMEs allows study of ICME evolution in a statistical sense. We mention above evidence for ICME expansion. Fig. 4 shows this expansion by comparing ICME widths at radial distances from 0.3 to 30 AU, where we have combined the Liu et al. (2005) and Wang and Richardson (2004) ICME lists. The widths are obtained by multiplying the ICME duration by the average plasma speed in the ICME. In the inner heliosphere, widths increase with distance out to about 15 AU; beyond this distance the widths are roughly constant. The best linear fit to the ICME width inside 15 AU is shown by the solid line.

The largest widths are observed near 15 AU, then decrease. These results agree qualitatively with the case study shown in Fig. 1; ICMEs expand in the inner heliosphere until they reach equilibrium with the background solar wind, then maintain a constant width. The average expansion factor is large, from 0.4 at 1 to about 2 AU beyond 10 AU, a factor of 5. Some of this expansion may result from merging of ICMEs; work to simulate the expansion process is in progress.

The expansion of ICMEs should lead to different rates of change in solar wind parameters inside and outside ICMEs. Fig. 5 uses the combined ICME list to show the radial variation of the proton density, radial speed, proton temperature, and magnetic field magnitude of the solar wind. The diamonds show the average values within each ICME. The best fits to the ICME data and the ambient solar wind are shown by the solid and dashed lines, respectively. We have not adjusted the parameters to account for the different heliolatitudes of the spacecraft nor have we attempted to normalize between spacecraft. Most of the data are from within 10° of the helioequator, with the exception of Ulysses ICMEs which are observed at up to 66°. Even small heliolatitude differences can be important near solar minimum when latitudinal gradients in plasma parameters are large, but ICMEs are few near solar minimum and we ignore these effects.

The top panel shows the proton density versus distance. The fits to the data show that the density within ICMEs decreases faster than that in the ambient solar wind. This result is consistent with ICME expansion, but the density decrease is not as large as the factor of 5 increase in width would suggest.

The speeds are about the same inside and outside ICMEs. The magnetic field magnitude, shown in the bottom panel, also decreases more rapidly in the ICME plasma than in the ambient solar wind. But again, the
decrease is not as rapid as the factor of 5 increase in width would predict. We note that the magnetic field magnitude is consistent with Parker's equations.

The third panel shows the proton temperature, which we discuss last as it does not behave even qualitatively as expected. The expansion of the ICMEs should lead to adiabatic cooling of the ICME plasma. Instead, the temperature cools less rapidly inside ICMEs than in the ambient solar wind. The temperatures inside ICMEs are much lower than in the solar wind, since low temperature is a selection criteria for the ICMEs. The ICMEs must be heated as they move outward; we are investigating possible heating mechanisms. We note that the radial dependence of the temperature found in the inner heliosphere (<5.2 AU) by Liu et al. (2005) was flatter ($R^{-0.32}$) than that given here ($R^{-0.72}$). The $R$ dependence in the data shown here is driven by the Voyager data; these differences need to be further investigated.

4. Effects on the outer heliosphere

The case studies show some of the effects on the outer heliosphere; shocks propagating outward can energize particles and the MIRs following these shocks can produce barriers to inward cosmic ray transport. Recent solar wind data from Voyager 2 has shown a new phenomena; the creation of solar wind structures with correlated speed, density, and magnetic field increases (Richardson et al., 2003). Fig. 6 shows these structures; they recur on time scales of about half a year and persist 30–60 days. This new regime began with the shock in October 2001 and continues to the present time. Superposed on these structures in the last half of 2003 is an increase in speed apparently driven by coronal holes at low solar latitudes (Burlaga et al., 2005). These variations produce factor of ten dynamic pressure changes. These changes should drive motions of the termination shock; Zank and Muller (2003) show that the recovery time of the shock from a MIR is larger than the time between the observed pressure pulses, so these pulses should keep the outer heliosphere in a constant state of disequilibrium. Using ACE data at 1 AU as input to a 1-D MHD model which includes pickup ions, Richardson et al. (2003) recreated the correlations observed at solar maximum. These pulsations are a result of long-time scale solar wind evolution of the ICMEs interacting with the ambient solar wind.

Another effect of these pulsations is to modulate the cosmic ray fluxes. The cosmic ray fluxes are modulated by the magnetic field strength, increasing when $B$ is low and vice versa (Burlaga et al., 1985, 2003; Burlaga, 1995). The bottom panel of Fig. 6 shows the >70 MeV/nuc counting rates from the Voyager 2 cosmic ray subsystem (CRS). The cosmic ray intensities decrease at each of the pulses in the plasma/magnetic field strength. As these structures propagate beyond the termination shock they will eventually reach the heliopause. The interactions of these MIRs with the region beyond the heliopause are
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