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The in-situ manifestation of solar prominence material

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Abstract. Coronal mass ejections observed in the corona exhibit a three-part structure, with a leading bright front indicating dense plasma, a low density cavity thought to be a signature of the embedded magnetic flux rope, and the high density core likely containing cold, prominence material. When observed in-situ, as Interplanetary CMEs (or ICMEs), the presence of all three of these signatures remains elusive, with the prominence material rarely observed. We report on a comprehensive and long-term search for prominence material inside ICMEs as observed by the Solar Wind Ion Composition Spectrometer on the Advanced Composition Explorer. Using a novel data analysis process, we are able to identify traces of low charge state plasma created during prominence eruptions associated with ICMEs. We find that the likelihood of occurrence of cold material in the heliosphere is vastly lower than that observed in the corona but that conditions during the eruption do allow low charge ions to make it into the solar wind, preserving their expansion history. We discuss the implications of these findings.

Keywords. coronal mass ejections, prominence, solar wind, etc.

1. Introduction

Coronal Mass Ejections (CMEs) occur as a result of a rapid reconfiguration of the coronal magnetic field following destabilization of the magnetic field on the Sun. This reconfiguration via magnetic reconnection explosively ejects large quantities of material, magnetic field, and energy out of the corona and into the heliosphere (Klimchuk *et al.*, 2001). The in-situ manifestation of CMEs are called Interplanetary Coronal Mass Ejections (ICMEs), which strongly influence space weather and the interaction of the Sun with the near-Earth space environment (Gosling *et al.*, 1974; Webb and Howard, 1994; Howard *et al.*, 1997).

The physics responsible for CME eruption have yet to be fully resolved. However, the majority of CMEs observed remotely at the Sun are associated with filament eruptions (e.g., Gopalswamy *et al.*, 2003; Webb & Hundhausen 1987; Munro *et al.*, 1979), in which the filament is lifted out of the Sun's gravitational well and can become embedded in the CME (e.g., Webb & Hundhausen 1987, and references therein). Filaments are cool (T$\sim$$10^4$ K) quasi-stationary structures in the low corona which sit over magnetic neutral lines. They form in locations with high plasma density, where radiative cooling strongly affects the plasma (Karpen & Antiochos 2008). In these regions, low-charge ions ((He^+, O^+, O^{2+}, C^{2+}, etc.) and neutral atoms are likely to contribute to a significant portion of the local material.

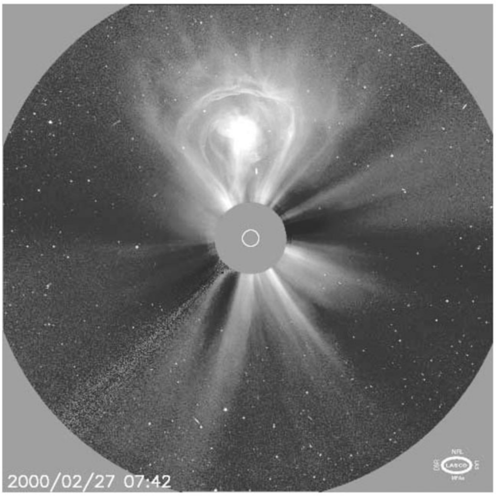

Figure 1. A CME with a clear three-part structure launches off the northern limb of the Sun and is observed by SOHO LASCO. The bright front rings the top of the exploding bubble, with a less dense cavity contained within. The bright central region is the core which is thought to contain the cold remnants of the erupted filament. Adapted from Riley *et al.* (2008).

As a CME erupts, it lifts filament and possibly flare material out of the low corona and carries it into the heliosphere along with the solar wind. The filament material plays a key role in forming the three-part structure commonly observed in coronagraph images as shown in Figure 1. The "bright front" is formed as the faster moving CME interacts with the ambient solar wind ahead of the ejecta. As the front forms, a low density region is left behind, forming the "cavity" which likely contains stronger magnetic fields ejected from low in the corona (Lynch *et al.*, 2004; Low 1994). The trailing feature of the three-part structure is the dense "core", consisting of cool filament plasma, which is thought to occupy a small fraction of the volume of the CME.

Based on the fact that ∼70% of CMEs observed near the Sun exhibit this three-part structure (e.g., Gopalswamy *et al.* 2003; Webb & Hundhausen 1987; Munro *et al.* 1979), one might expect to find frequent evidence of the same three-part structure in ICMEs observed in the heliosphere. However, this structure is rarely observed in-situ and presents an observational puzzle (Zurbuchen & Richardson 2006, and references therein). In fact, ICMEs typically exhibit only two of the three structures, with the front appearing as a density pile up ahead of the low density, magnetically dominated cavity, often with flux-rope type topology. The core, containing filament material, is rarely reported to be present.

In-situ, one would expect the core to be identifiable based on the presence of usually low charge states, indicating cool electron temperatures associated with the filament, low in the corona where the charge states are frozen into the plasma. Observations by the SOHO Ultra-Violet Corona Spectrograph (UVCS; e.g., Raymond 2002) show these low charge states and temperatures in the low corona, however, in-situ measurements with ion spectrometers have not revealed the same ubiquitous signatures. In order to preserve the filament's low charge state ions during their expansion out of the corona, plasma heating from the eruption must be ineffective at further ionizing the filament material.

It has been established that the vast majority of ICMEs exhibit high charge states, reflecting elevated coronal electron temperatures in the source region of the CME (Lepri *et al.* 2001; Henke *et al.* 2001; Richardson & Cane 2004). It is thought that the heating

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responsible for these elevated charge states is driven by energy released during magnetic reconnection, possibly in flaring regions. (Lepri & Zurbuchen 2004; Reinard 2005; Rakowski *et al.* 2007). In fact, nearly all ICMEs exhibit bimodal charge state distributions with contributions from hot plasma and solar wind-like plasma (Gruesbeck *et al.*, 2011). This "mix" of plasma is also seen in remote-sensing observations from UVCS, although the cool contribution is often observed remotely to be far cooler than the typical solar wind type temperatures, and resembles the filament type cold plasma. Why then, do we not frequently see this cold plasma in the heliosphere?

Early observations with electrostatic analyzers did reveal the rare presence of cold ions in the solar wind associated with observations of ICMEs. Schwenn *et al.* (1980) and Zwickl *et al.* (1982) found 3 ICMEs over an 8 year period with enhanced He+. Zwickl *et al.* also found evidence for low charge states of heavy ions (Fe^{5+}, O^{2+}, and C^{4+}), although the measurement techniques at that time were not able to unambiguously determine the ions' identities. Until recently, only 2-3 more events were identified in in-situ observations (Burlaga *et al.* 1998; Skoug *et al.* 1999), with Gloeckler *et al.* (1998) presenting the first unambiguous determination of the presence of a range of cold ions, as measured with the Solar Wind Ion Composition Spectrometer (SWICS) on the Advanced Compsoition Explorer (ACE).

We review the first systematic search for cold ions originating in filament material embedded within ICMEs in this paper. A more in depth discussion of this study can be found in Lepri and Zurbuchen (2010). We utilize ACE SWICS data and capitalize on the ion retrieval algorithms that isolate and characterize charge states down to C^{2+}, O^{2+} and Fe^{4+} using observational techniques that significantly limit contributions from background noise sources. We report that the presence of low charge state material inside of ICMEs is more common than previously thought, but much more rare than expected based on remote observations.

2. Measurements

SWICS on ACE is a time-of-flight (TOF) mass spectrometer. Particles enter the instrument through an electrostatic analyzer (ESA) which selects ions based on their energy per charge (E/Q). After exiting the ESA, they pass through the TOF telescope and deposit their energy (E) in solid state detectors (SSDs). This technology can be used to uniquely identify a wide range of ions (from He to Fe) in the solar wind (Gloeckler *et al.*, 1998). Combining the ion's E/Q, E and TOF allows the the mass, charge and speed of an ion to be independently calculated. Integrating over one or more cycles in integer multiples of 12 minutes, one can obtain the velocity and charge state distribution of the thermal solar wind in the E/Q range of 0.5 - 60 keV/e as it passes the spacecraft. For this analysis we examine the charge state distributions calculated with 2-hour time resolution– long enough to provide sufficient counting statistics for reliable C, O and Fe charge states. More detail on the methods used to calculate the charge states can be found in Von Steiger *et al.* (2000), Lepri *et al.* (2001), Lepri and Zurbuchen (2004, 2010).

In general, the typical unperturbed solar wind exhibits charge states consistent with the 1MK corona, with the main ion contributors being H^{+}, He^{2+}, C^{5+}, O^{6+} and Fe^{10+} in the slower, equatorial solar wind as shown in the green histograms in Figure 2. Most ICMEs are characterized by elevated charge states, including significant contributions from O^{7+} and Fe^{16+} and higher as shown in the red histograms in Figure 2 (e.g. Lepri *et al.*, 2001, Lepri and Zurbuchen, 2004 and Zurbuchen and Richardson, 2006). These high charge states set ICME-associated solar wind apart from the nominal solar wind state, as the high charge states reflect temperatures ~4-5MK in the source regions. As a

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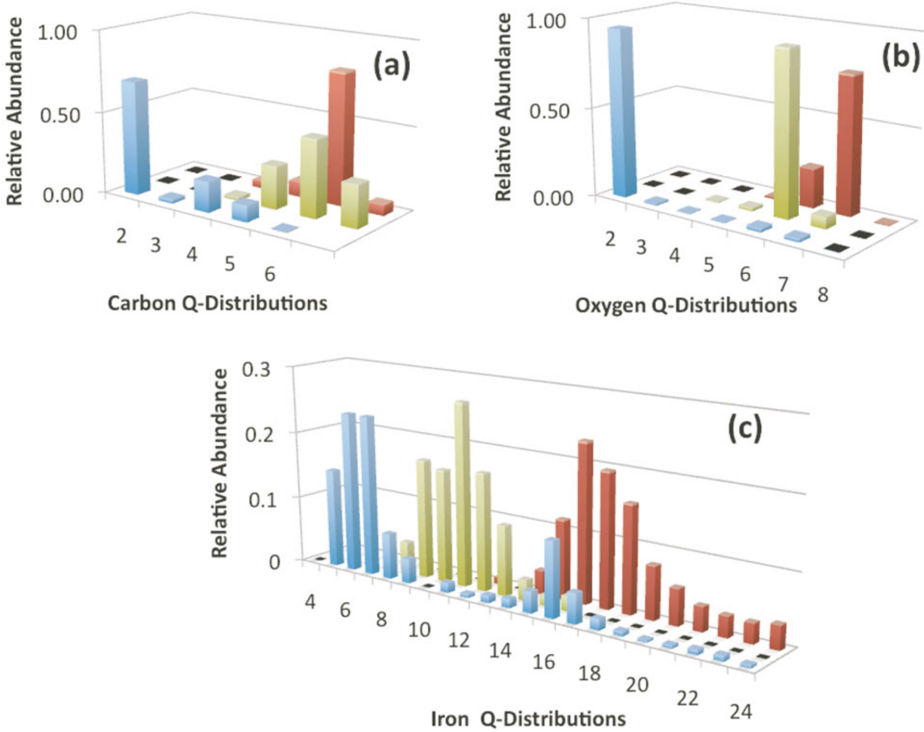

Figure 2. Charge state distributions measured by ACE/SWICS for C, O, and Fe for three different scenarios: a cold ICME (in blue), normal solar wind (in green), and a hot ICME (in red). Adapted from Lepri and Zurbuchen (2010).

result, these elevated charge states are excellent identifiers of ICME material in-situ. In the event that an ICME is characterized by unusually low charge states (shown in the blue histograms in Figure 2), as in the May 1-2, 1998 event first reported in Gloeckler *et al.* (1999), these low charge states can be observed simultaneously with contributions from the high charge states more typically associated with ICMEs.

3. Cold ICMEs

In order to mine a decade long range (1998-2008) of the ACE/SWICS data set for cold ICMEs, we compare periods with enhanced abundances of low charge state ions with known near-Earth ICME periods (as identified by Richardson and Cane (2010)). A stringent set of criteria for C, O, and Fe are established to identify periods with cold material and reduce the number of false positives due to local sources of low charge ions (e.g. comets, planetary sources). In order to identify intervals with enhanced contributions from low charge states, using 2-hour data from ACE/SWICS, we calculate relative abundances of $\frac{C^{2-3+}}{C_{Tot}}$, $\frac{O^{4+}}{O_{Tot}}$ and $\frac{Fe^{4-7+}}{Fe_{Tot}}$. We calculate the mean value of these ratios across the mission as well as the standard deviation. We then search for periods where all three ion ratios are greater than one standard deviation above their mean values, thus ensuring we are finding significant enhancements of solar origin. We include an additional criteria to eliminate further confusion from false positives by requiring the ion speed to be within 15% of the solar wind speed, in line with expectations for heavy ions in the

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solar wind (see Hefti *et al.*, 1998 for more details). To summarize, the criteria used to identify low charge state intervals are as follows:

$$\frac{|\Delta V|}{V} < 0.15$$
$$\frac{C^{2-3+}}{C_{Tot}} > 0.034$$
$$\frac{O^{4+}}{O_{Tot}} > 0.009$$
$$\frac{Fe^{4-7+}}{Fe_{Tot}} > 0.121$$

Using these highly constrained criteria, we find 11 events with significant contributions from low charge state ions during the 10 years surveyed, all of which correlate with ICME periods. An example of one event, 20-22 May 2005, is shown in Figure 3. Panels (a), (b) and (c) show the proton density, temperature and velocity from ACE/SWEPAM, respectively. Panel (d) shows the magnetic field magnitude which becomes enhanced just inside the leading edge of the ICME, denoted by the solid vertical red line. Charge state distributions of Fe, O and C are shown in Panels (e), (f), and (g); the color bars represent the relative density of individual charge states in the given 2-hour time interval. The charge states deviate from their normal behavior inside the front boundary of the ejecta, shifting to higher charge states. They return to normal, lower charge states after the trailing boundary passes, as is denoted by the dashed red vertical line, although there are periods where the charge states appear nominal inside the ejecta as well. In fact, the second half of the ejecta is dominated by charge states of Fe similar to the nominal solar wind with another minor contribution from the high charge states during this period. The period dominated by enhanced low charge state ions is highlighted in yellow around noon on 20 May 2005.

Of the 284 ICMEs which were observed by ACE at L1 during the observation period, only 4%, or 11 events, contained cool material. In order to investigate whether these events were related with filament eruptions that were swept into the expanding CMEs, we reviewed EIT 195Å movies and examined observations from the Mauna Loa Solar Observatory, looking for erupting or disappearing filaments. 90% of the events that have LASCO CME counterparts were associated with erupting filaments, thus lending credibility to the idea that this cold material originated inside of ICMEs. The 11 low charge state events identified in the 10-year span of data indicate that these events are at least an order of magnitude more frequent than previously measured. With less restrictive criteria, we may find these numbers are much higher. An examination of the location of the low charge material within the 11 events does not reveal spatial ordering within the ICMEs.

Gilbert *et al.* (2012) went on to include the singly charged particles in his analysis of the same cold ICMEs and found that the 11 events identified in Lepri and Zurbuchen (2010) also included contributions from the lowest charge states, including C+ and O+. In general, when these singly charge ions were included in the analysis, the events tended to last on average 20% longer than reported using the more restrictive criteria laid out in Lepri and Zurbuchen (2010).

4. Ionization Models

Ionization models can be utilized to understand how cold material is preserved within some ICMEs. Gruesbeck *et al.* (2011) found success modeling the ionization and recombination of observed bimodal charge states in ICMEs assuming rapid heating of a dense plasma ($>10^9$ cm^{-3}) followed by adiabatic cooling during expansion out of the corona. This scenario is similar to what is expected during flares and successfully reproduced

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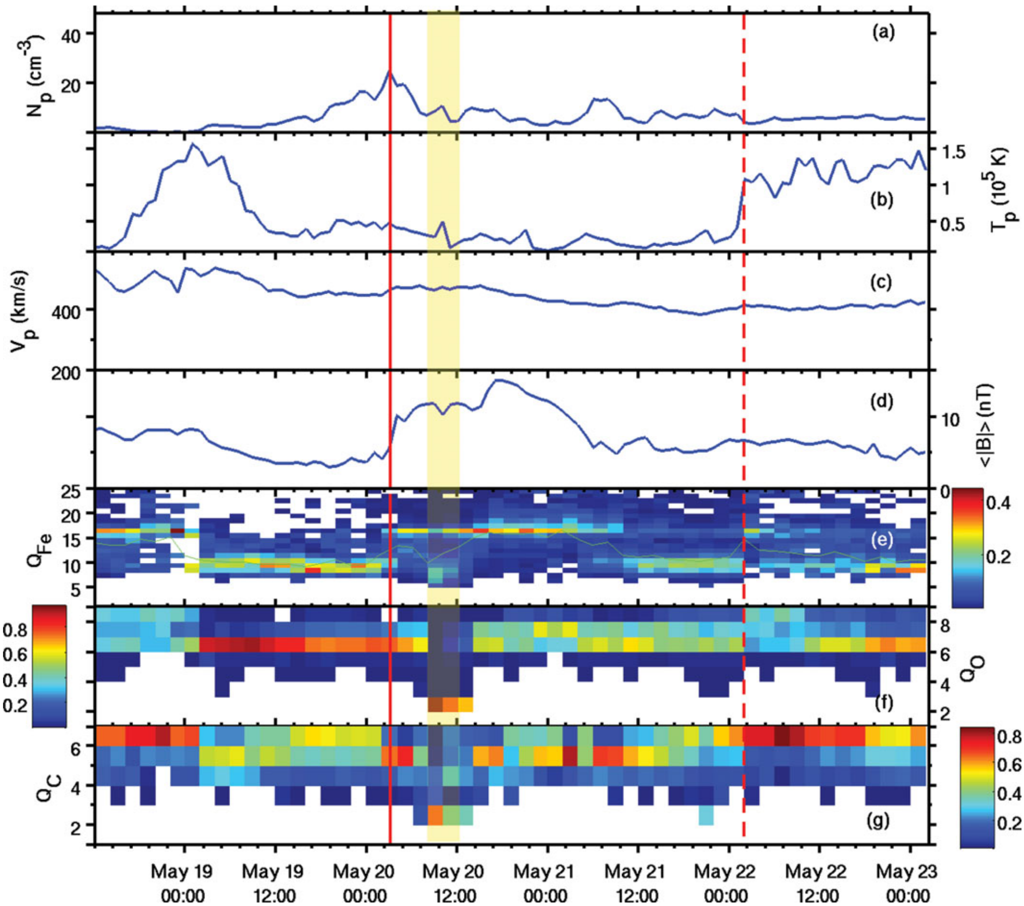

Figure 3. Solar wind plasma parameters and solar wind ion charge state distributions for an ICME associated with cold material (shaded in yellow in all panels). Panels are as follows: (a) Solar wind density, (b) Solar wind temperature, (c) Solar wind speed, (d) Solar magnetic field strength, (e) Fe charge distribution, (f) O charge distribution and (g) C charge distribution. Adapted from Lepri and Zurbuchen (2010).

Fe charge state distributions that had peaks at both Fe^{10+} (nominal solar wind) and Fe^{16+} (hot ICME solar wind). Gruesbeck *et al.* (2012) considers the challenges presented in explaining the simultaneous presence of both high charge state and low charge state material as is seen in the 11 events described above. Using the same ionization model as in the 2011 paper, they test two theories for the creation of the observed bimodal charge state distributions, with both very low and high charge states observed concurrently. They find that while a rapidly heated single dense plasma that subsequently cools adiabatically can produce bimodal charge state distributions for Fe as in the 2011 paper, they fail to produce the bimodal charge state distributions of C and O, especially failing to capture the low charge state peaks. However, by combining two different plasmas, which start off at the same temperature but which undergo different heating profiles, they were able to successful recover the observed bimodal charge state distribution. In this model, one plasma is rapidly heated to very high temperatures ∼3MK, similar to flare heated plasma, while the other plasma is an order of magnitude denser ($>10^{10}$ cm^{-3}) and is heated to much lower temperatures ∼100,000K representing the filament material. The key here is that the cooler plasma, due to its high density, has a chance to recombine to even lower charge states than the initial charge states before freezing into the solar wind. The best match of the observed charge state distributions is obtained with a mass-dependent mixing ratio model for the cold and hot plasma. This result is not unexpected as lower mass ions tend to freeze-in closer to the Sun while higher mass ions freeze farther out in the corona (out to $\sim 4R_s$). These results support the idea that disparate parts of the ICME can mix as magnetic reconnection rearranges the plasma during the eruption, allowing prominence plasma to mix with flare plasma during the eruption. Gruesbeck *et al.* (2012) suggests that this type of mixing supports the breakout model of CME eruption, in which reconnection allows the plasma to mix along field lines (Antiochos *et al.* 1999).

5. Summary

Despite the frequent association of filament eruptions with CMEs at the Sun, a dearth of in-situ evidence of such a linkage exists in the heliosphere. While the survey of Lepri and Zurbuchen (2010) increases the known number of ICMEs with prominence material embedded within by more than a factor of 4, questions still remain as to why these observations are so infrequent. Ionization model results suggest that in order to preserve the low charge state plasma a very dense cold plasma ($>10^{10}$ cm^{-3}) must initially be heated to temperatures ~100,000K and then given time to recombine further as it transitions toward the freeze-in point. It may be likely that the fraction of ICME mass filled with filament material is very low, thus lowering our probability of observing it with a single spacecraft. The low number of in-situ observations may also indicate that most filaments expand more rapidly or may be further heated during eruption, erasing the low charge state signatures of the filament by the time it freezes-into the solar wind.

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