ICME IDENTIFICATION FROM SOLAR WIND ION MEASUREMENTS

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Abstract. Interplanetary coronal mass ejections (ICMEs), the interplanetary counterpart of coronal mass ejections (CMEs), are most commonly identified by their enhanced magnetic field strengths and rotating magnetic field orientation. However, there are other frequent signatures in the plasma. We use a pair of these signatures, a linearly decreasing plasma bulk velocity and a cool (< 20 km s\(^{-1}\)) ion thermal speed, to identify candidate ICMEs. Many ICMEs, identified through their magnetic signatures, are also found by their ion signatures alone. However, many are not. These missed ICMEs appear not to be expanding, even when they are accompanied by leading shocks. The ICMEs with both the magnetic and ion signatures appear to be expanding as judged from either set of observations. The most clearly defined ICMEs have transit times from the Sun and growth times to the observed size that are equal. These ropes fit the paradigm of compact magnetic structures arising low in the corona and expanding uniformly in time, as they travel at constant center of mass speed toward 1 AU.

1. Introduction

Interplanetary coronal mass ejections (ICMEs) are the interplanetary manifestations of coronal mass ejections (CMEs) seen in light scattered from enhanced electron densities in the solar corona (Kahler, 1987; Hundhausen, 1988; Gosling, 1990). These structures generally accelerate in the corona to speeds above that of the ambient solar wind plasma. At 1 AU the density enhancement that marks the CME near the Sun is not so evident. Thus ICMEs are usually identified by their characteristic signature in the magnetic field, generally an enhanced magnetic field that rotates slowly over tens of hours (e.g., Gosling, 1990; Burlaga, 1991). ICMEs also have signatures in the solar wind ions and electrons. In the ion data ICMEs are often seen to be expanding, i.e., the leading edge travels faster than the rear. Furthermore, the ions and electrons are often cooler (Gosling, Pizzo, and Bame, 1973; Montgomery et al., 1974). However, cold ion temperatures appear to be a better indicator of ICMEs than electron temperatures that are more variable in ICMEs (Richardson and Cane, 1995; Richardson, Farrugia, and Cane, 1997). A more reliable indicator lies in the anisotropy of suprathermal electrons. These electrons are often found to be streaming along the magnetic field in both directions indicating connection to the Sun on both ends of the field line (Gosling et al., 1987). This latter signature is usually intermittent and this topology is not necessarily present through an entire ICME. Moreover the measurement of electrons is difficult and the needed data are often not readily available. Thus it is desirable to use ion

measurements to enhance our ability to identify and classify ICMEs. In this paper we investigate ICMEs using the signature of an expanding magnetic structure in the solar wind, one that produces a decline in the solar wind speed in the frame of the observer, accompanied by simultaneous cool ions. These two signatures have long been noted to be indicators of the occurrence of ICMEs (Gosling, 1990).

The observed speed of the solar wind is constantly changing, even when the Sun is but slowly evolving, because spatial gradients in the coronal magnetic field lead to fast and slow speeds in the solar wind (Wang and Sheeley, 1990). As the Sun rotates these regions of varying speeds are carried past an observer in space. Because the fast streams collide with the slow streams, and pile up at the interface, the signature of a stream-stream interaction is generally a rapid increase in speed and a slow decrease. The solar wind bulk speed and its ion temperature are positively correlated so that on average the fast solar wind is hotter than the slow solar wind. Thus in general the solar wind should be hotter in the high speed portion of these interaction regions.

In contrast an ICME is believed to be an expanding magnetic bottle of plasma. Since the ion bulk velocity is supersonic, the ions cannot communicate back to the Sun (a heat reservoir if communication were possible). Thus the ions in the ICME should cool as the ICME expands. This model has been confirmed with computer simulations and their comparisons with *Ulysses* data (Riley et al., 2000; Riley, Gosling, and Pizzo, 2001). We might expect to find that ICMEs consist of regions of cool solar wind whose speed decreases with time. In this study we evaluate this signature as a ICME identifier. We use the *Wind* plasma measurements (Ogilvie et al., 1995) from January 1995 to December 2001 because they have fewer data gaps than the Advanced Composition Explorer (ACE) level 2 data for the same period. The magnetic field measurements from the *Wind* instrument are also examined (Lepping et al., 1995).

## 2. Example Events

Figures 1 and 2 show events during our study period that demonstrate the plasma signature that we wish to evaluate. The first event is from February 1998 and shows a steadily ‘decelerating’ plasma from 4 February 1998 at 10:00 UT to 5 February 1998 at 22:00 UT accompanied by cool ions. Examination of the magnetic field shows an enhanced magnetic field that rotates giving a nearly smooth sinusoidal form in each of the three components. The second event is from March 2001. It also shows a ‘linear’ decrease in bulk velocity from 16:00 UT on 19 March 2002 to about 00:00 UT on 22 March 2002. Again the ion temperature is cool. The magnetic field rises and falls during this period and it rotates in direction. Again there is a clear ICME signature in the magnetic fields when the cool decelerating plasma is seen.
**TABLE I**

ICME properties.

<table>
<thead>
<tr>
<th>Start of ICME</th>
<th>End of ICME</th>
<th>Duration (hr)</th>
<th>$V_{\text{avg}}$ (km s$^{-1}$)</th>
<th>Rate of exp. ($V_{1}-V_{2}$)/$V_{\text{avg}}$</th>
<th>$V_{\text{th(avg)}}$ (km s$^{-1}$)</th>
<th>Transit time from Sun (d)</th>
<th>Time to grow (d)</th>
<th>Quality of event Larson (a)</th>
<th>Lepping (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Feb. 1996</td>
<td>16 Feb. 1996</td>
<td>09:00</td>
<td>383</td>
<td>0.143</td>
<td>17.9</td>
<td>4.53</td>
<td>5.08</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>27 May 1996</td>
<td>28 May 1996</td>
<td>10:20</td>
<td>380</td>
<td>0.179</td>
<td>19.9</td>
<td>4.57</td>
<td>4.48</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4 Feb. 1998</td>
<td>5 Feb. 1998</td>
<td>22:00</td>
<td>324</td>
<td>0.215</td>
<td>13.3</td>
<td>3.58</td>
<td>6.98</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5 Mar. 1998</td>
<td>6 Mar. 1998</td>
<td>02:00</td>
<td>330</td>
<td>0.120</td>
<td>12.3</td>
<td>5.26</td>
<td>6.25</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>2 May 1998</td>
<td>3 May 1998</td>
<td>17:00</td>
<td>527</td>
<td>0.352</td>
<td>13.5</td>
<td>3.29</td>
<td>3.33</td>
<td>4</td>
<td>2</td>
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<tr>
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<td>23 Sep. 1998</td>
<td>15:00</td>
<td>415</td>
<td>0.289</td>
<td>20.0</td>
<td>4.19</td>
<td>1.29</td>
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<td>X</td>
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<tr>
<td>25 Sep. 1998</td>
<td>26 Sep. 1998</td>
<td>10:00</td>
<td>633</td>
<td>0.154</td>
<td>16.1</td>
<td>2.75</td>
<td>4.58</td>
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<td>3</td>
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<tr>
<td>21 Feb. 2000</td>
<td>22 Feb. 2000</td>
<td>11:46</td>
<td>345</td>
<td>0.245</td>
<td>19.4</td>
<td>5.03</td>
<td>2.42</td>
<td>NR</td>
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<tr>
<td>5 Mar. 2000</td>
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<td>09:56</td>
<td>341</td>
<td>0.115</td>
<td>19.9</td>
<td>5.10</td>
<td>3.08</td>
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<td>2 Sep. 2000</td>
<td>3 Sep. 2000</td>
<td>18:16</td>
<td>411</td>
<td>0.214</td>
<td>18.8</td>
<td>4.22</td>
<td>3.84</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3 Oct. 2000</td>
<td>4 Oct. 2000</td>
<td>13:08</td>
<td>406</td>
<td>0.120</td>
<td>14.5</td>
<td>4.27</td>
<td>7.01</td>
<td>NR</td>
<td>1</td>
</tr>
<tr>
<td>6 Nov. 2000</td>
<td>7 Nov. 2000</td>
<td>15:53</td>
<td>536</td>
<td>0.166</td>
<td>20.1</td>
<td>3.24</td>
<td>4.30</td>
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<td>2</td>
</tr>
<tr>
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<td>29 May 2001</td>
<td>22:09</td>
<td>447</td>
<td>0.285</td>
<td>16.6</td>
<td>3.88</td>
<td>5.32</td>
<td>NR</td>
<td>1</td>
</tr>
</tbody>
</table>

(a) 1 – poor; 5 – excellent. (b) 1 – excellent; 3 – poor. NR – Not rated. X – identified.
3. Statistics

During the study period we found 14 events that satisfied our visual identification criteria of a linearly decreasing velocity in a cool ion flow where the proton thermal speed was less than or equal 20 km s\(^{-1}\). We measured their start and stop times, durations, average velocity, normalized rate of expansion (\(\Delta V / V_{\text{ave}}\)) and ion thermal speed. Then we calculated the transit time from the Sun at the average velocity and the time to grow to the observed dimension if the structure grew at the constant rate observed at 1 AU. These results are listed in Table I. We next examined the ICME lists on the websites of Davin Larson and Ron Lepping at
Figure 2. Magnetic field and solar wind velocity and thermal speed for the period 4–6 February 1998. Comments on caption of Figure 1 apply.

http://sprg.ssl.berkeley.edu/~davin/clouds/cloud_list.html, and http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_publ.html, respectively. We have listed their event rating in the final two columns. If the event was not classified as an ICME by them there is an X in these columns. If it was classified as an ICME but not rated (1–5 for Larson and 1–3 by Lepping), then we entered NR in the table. We note that 1 means poor to Larson and 5 excellent; 1 means excellent to Lepping and 3 means poor.

If the ICME grows linearly with distance from the Sun starting at zero size, then its growth time and transit time should be equal. Figure 3 shows three plots of these quantities: for all events; for the events common to our analysis and Lepping’s or
Larson's analysis; and for common events that were rated as good or excellent by Lepping and Larson. The straight line in the top two panels is not a fit but is the one to one correlation expected. We can see much scatter around this line in either case 1 or 2. However, in the third plot, that contains only events that might be described as classic ICMEs, there seems to be a good correlation between transit time and growth time. In order to determine if the time to travel from the Sun to the observer affects the temperature of the solar wind, we next plot the ion thermal speed versus transit time in Figure 4. We see no control in this plot. These events were all cool (our selection criterion) but the fast events were no cooler than the slow events.

Figure 3. Growth time and transit time from Sun to Wind for events in three categories: (top) all events; (middle) events with clear magnetic signature; (bottom) events classified as good to excellent ICMEs.
Figure 4. Thermal speed versus transit time from Sun to Wind for events in the three categories described in Figure 3 caption.

4. ICMEs Not Found

While Table I contains many events identified by our solar wind ion technique, at times both Larson and Lepping identified events that our technique did not identify as ICMEs. There were six events that were rated excellent/good by Larson and Lepping that did not meet our ion criteria. Each of these had warm temperatures and no significant deceleration. Figures 5 and 6 illustrate two examples of these events. The 22–24 August, 1995 event exhibits a leading shock front, a nearly symmetric rise and fall of the magnetic field, and a normal rotation of the field direction. An expanding spatially symmetric rope should appear to have an asymmetric temporal $B$ profile as it passes the observer if it has a maximum field in its center because the rise to maximum occurs faster than the fall. In this example the velocity only slowly declines and the thermal speed is at or about 20 km s$^{-1}$. The 18–20 October
event also has a leading shock but has quite a flat magnetic field profile even while the field rotates. The velocity is quite steady and the thermal speed remains at or above 20 km s\(^{-1}\). It seems that in each of these events (and the other four as well), the ICMEs simply were not expanding even though they were both associated with leading shocks.

5. Summary

We have tested a non-magnetic method of identifying ICMEs based on the declining solar wind ion bulk speed and a low ion thermal speed. These ICME indications are two of the many that have been found useful in the past. Our event identific-
Figure 6. Magnetic field and solar-wind ion velocity and thermal speed for the period 18–19 October 1995. Comments of caption of Figure 5 apply.

ations overlap with but do not exactly coincide with those identifications made principally from the occurrence of a strong, rotating magnetic field. It is possible that we could improve the detection of unusually cool events with either improved ion temperature measurements or by comparing with a measure of the expected temperature for a particular velocity of the solar wind. However, this is not the reason we missed identifying many ICMEs. Clearly some ICMEs do not expand even while they have leading shocks. Nevertheless, there are a set of ICMEs that have classic signatures, and are identified clearly by both techniques. The best defined, classic ICMEs are consistent with the structure having essentially zero thickness at the Sun and growing linearly until it propagates at nearly constant center of mass speed to 1 AU.
6. Acknowledgements

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References


