A new parameter to define interplanetary coronal mass ejections

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Abstract

The interplanetary manifestations of coronal mass ejections, ICMEs, have many signatures in the solar wind but none of these signatures in the velocity, density, temperature, magnetic field, plasma composition or energetic particles uniquely and unambiguously identifies the occurrence of an ICME. Different investigators identify different events when confronted with the same data. Herein, we present a single physical parameter that combines information from multiple plasma components and that holds the promise of defining a beginning and an end of the region of influence ICME and an indication of the location of the encounter with the ICME relative to its central meridian. This parameter is the total plasma pressure perpendicular to the magnetic field, consisting of the sum of the magnetic pressure and plasma kinetic, or thermal pressure. It provides a vehicle for classifying the nature of the ICME encounter and, in many cases, provides an unambiguous start and stop-time of the event. However, it does not provide a start and stop-time for any embedded flux rope. This identification depends on examination of the magnetic field.

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1. Introduction

The discovery of coronal mass ejections (CMEs) with the coronagraphs en SOLWIND and Skylab was a key breakthrough in the understanding of the interconnection of solar and geomagnetic activity (Gosling et al., 1976). It soon became clear that the interplanetary manifestation of these coronal mass ejections (ICMEs) were large structures of magnetized plasmas, at least some of which took the form of twisted magnetic flux ropes (Klein and Burlaga, 1982). Prior to the launch of SOHO and even today, it was difficult to track CMEs that were launched toward the Earth. Thus, it has been difficult to unambiguously identify the causative CME and the resultant ICME. Exceptions to this were the quadrature studies comparing Helios data above the limbs of the Sun (Schatten, 1983) and Pioneer Venus data at 0.72 AU above the limbs (Linday et al., 1990), both with CME activity monitored by SOLWIND. There remains little doubt that these magnetized structures seen at 1 AU do arise from CMEs.

ICMEs themselves are still mysterious entities. While many of them take the form of magnetic ropes, many of them cannot be so interpreted (Gosling, 1990). In fact, there still is little agreement on what defines an ICME (Russell and Shinde, 2005; Zurbuchen and Richardson, 2005). There are many signatures that are associated with ICMEs, but none of them appears to be unique to ICMEs or a sufficient condition to identify an ICME. In fact, any of these signatures could be missing and, if the others were present, some observers would argue for the presence of an ICME.

We can divide the signatures of ICMEs into those in fluid parameters, and those involving either plasma composition or energetic particle distributions. There are interpretations of the meaning of these latter signatures but there is not yet a commonly accepted model.

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for the relationship of these signatures to the magnetized plasma structure that constitute an ICME. In contrast, there is a well-developed physical model for the fluid parameters even to the point of launching ICMEs and following them to Earth (Manchester et al., 2004). Thus, we feel it is most appropriate to search for a necessary and sufficient condition for the presence of an ICME in the fluid parameters of the solar wind. In particular, we examine the total perpendicular pressure in the straight-field-line approximation, in which magnetic curvature forces play no role in the calculation. In other words assuming gyrotropy, we are examining two of the three diagonal terms of the stress tensor ignoring the pressure force along the magnetic flux tubes, exerted totally by the plasma. We do this because our purpose is to construct the simplest diagnostic parameter. The total perpendicular pressure has been occasionally used in the diagnosing of ICMEs (e.g., Gosling et al., 1994a,b), but it has not been used extensively. In the following sections, we examine the use of this pressure in identifying and classifying ICMEs and demonstrate its diagnostic powers.

2. Total perpendicular pressure as an ICME identifier

A popular current paradigm of an ICME and the region affected by it is that it consists of the interaction region associated with an expanding flux rope, possibly rooted in the Sun. Thus, if a spacecraft ran directly into the center of an ICME, it would see an enhanced magnetic field and a rotating field direction. These are both related to the nature of a magnetic flux rope that may be self-balancing or force-free so that the curvature force balances some or all of the magnetic pressure gradient force. This central high field region might also be magnetically quiet as beth a low beta region in which the magnetic pressure dominates over the plasma pressure. The rope may also be expanding in cross section as the rope moves outward from the Sun. This expansion can be detected as a decreasing solar wind velocity through the ICME, with the forward part of the ICME moving faster than the rear. If the structure moves quickly enough then a leading shock will arise as the ICME pushes into the ambient solar wind. If the plasma is expanding, the spacecraft should cool, especially the ions.

If we look at each of the elements contributing to perpendicular pressure, we might see that each parameter changes at a different time and in a different way. However, if we look at the perpendicular pressure itself, we should see a coherent pattern as the spacecraft first crosses the shock, passes through the magnetic flux rope, and then out the back of the ICME into the ambient solar wind again. The spacecraft measurements should first show a sharp increase in perpendicular pressure as it crosses the shock. Behind the shock, we expect at most a weak gradient in the pressure as the spacecraft passes through the ICME's magnetosheath. Next, the spacecraft enters the magnetic obstacle. Here, the perpendicular pressure rises as it does in the Earth's magnetosphere because we do not account for the self-balancing forces in our calculation. Eventually, when the spacecraft passes the center of the rope, the pressure drops. If the rope is expanding, we would expect the perpendicular pressure to have a sharp drop at the rear of the structure as it cd at the front.

Fig. 1 shows the perpendicular pressure calculated from the magnetic field and plasma measured by Wind on November 6-8, 2000, together with the elements that go together to produce perpendicular pressure. Looking first at perpendicular pressure in the lowest panel, we see the sharp leading rise in perpendicular pressure associated with the crossing of the bow shock. Behind the bow shock the pressure is roughly constant. This might not be immediately obvious if one examines the parameters that make up the perpendicular pressure. The proton temperature jumps up at the shock and then declines slowly and then abruptly. The proton density jumps at the shock changes, remains roughly steady, then jumps, and later falls. The magnetic field jumps at the shock, grows slowly, reaches a plateau and then drops for a while. When all these are combined, the perpendicular pressure profile is rather simple in its behavior.

After the perpendicular pressure plateau, the spacecraft enters a region of slow rotation of the magnetic field and the pressure rises. We interpret this as entering the magnetic rope and the calculation that assumes straight field lines no longer gives the net outward perpendicular pressure. Eventually, the center of the rope is crossed, the pressure begins to drop, a new pressure plateau is encountered, and then the perpendicular pressure drops and returns to the original ambient conditions. We emphasize that the perpendicular pressure does not indicate where the spacecraft leaves the magnetosheath and enters the obstacle or leaves it. The profile merely identifies the region affected by the ICME.

This rope was chosen because it was a structure that was close to our ideal in an earlier study (Russell and Shinde, 2005). In that study, we used an A*, our highest rating, but there were several aspects we did not notice before examining the total perpendicular pressure. First, the duration of the event, from the shock at which it started and the shee pressure drop where it stopped have now become very evident. The event lasts about 54 h from pressure rise to pressure drop. We see that the region of decreasing solar wind velocity, the expanding region, lasts only part way through the rope. At the tail end of the rope the solar wind velocity rises as does the density. It is in this very region that there is a decrease in the perpendicular pressure. We are seeing the effect of the interaction of a fast stream approaching the ICME from the rear and accelerating the rear of the ICME. Returning to the region of declining solar
wind velocity we see that the cool protons occupy almost the same region but not quite, exactly the same region. We note that as shown in Fig. 1 the region of the flux rope and the rear of the ICME are regions of lower density than the sheath region surrounding it. Perhaps the expanding flux tube had an evacuating effect on the density as well as the obvious cooling. In short, having the context of the total perpendicular pressure profile we can begin to place the rest of the structure into proper perspective and explain physically what we are seeing.

3. Types of total perpendicular pressure signatures

We have calculated the total perpendicular pressure for all the ICMEs in the list discussed by Russell and Shinde (2005). We use this list as it includes a classification scheme based on the constituent variations of the ICME. There are a variety of signatures and we have attempted to classify them as members of one of three groups. The first group consists of events that like the event shown in Fig. 1 appear to be interpretable in terms of the standard ICME/magnetic flux rope paradigm. There is a leading pressure jump, a leading pressure plateau and a central maximum pressure decline to the background later, often with a sudden drop in pressure. Five of these ICMEs are shown in Fig. 2 in panels 34 h long. The first event (top of panel) appears to be significantly shorter than this and the fourth event significantly longer. The middle panel shows the event discussed in Fig. 1. Three of these events are A\(^+\) events, out top ranking. However, the other two events are C\(^+\) events our lowest ranking. Thus the shape of the perpendicular pressure profile is providing us new information about the ICME. We note that the peak pressure in these ICMEs ranges from about 100 to 200 pPa and represents a very significant increase over the ambient solar wind pressure that at non-event times usually is in the range 20-50 pPa.

The pressure profiles do not always exhibit a central maximum. Sometimes the central region has a fairly constant pressure and sometimes a minimum in pressure. Sometimes there is a maximum at the end of the event. This could be due to a fast stream overtaking an ICME and compressing it. It could also be due to
an expanding rope that continued expanding after its central pressure maximum had disappeared. Such over expanding structures have been reported at high latitudes by Gosling et al. (1994a,b).

We have grouped these events in a second category, group 2, and show five examples of these in Fig. 3. These five events are rated from B* to A. They are not the most classic ICMEs but they are also not the poorest examples either. The peak pressures here range from about 50 pPa to almost 500 pPa. We note that, since at 1 AU the typical dynamic pressure of the solar wind (momentum flux measured in the Earth's frame) is 1000-2000 pPa, that 500 pPa represents a significant pressure between the ambient solar wind and the moving ICME structure. We also note that, while we have taken measured parameters for the solar wind pressure and magnetic field in making these calculations, we have assumed the solar wind composition and the electron temperature are at their statistical values. During the event shown in panel four of Fig. 3 after 01 UT on January 11, 1997, a very cool and dense filament crossed Wind (Lin, personal communication. 1999) and the electron temperature was much lower than usual. Thus, the blocky pressure changes that occur when the density changes are probably not real, but the overall smooth trend is probably correct. We note that the lack of a central perpendicular pressure enhancement is consistent with the lack of a magnetic enhancement in the center of this ICME. It seems that the magnetic field does not have strong curvature in this ICME.

The last category of events, group 3, is shown in Fig. 4. These events have a rapid perpendicular pressure rise at the beginning of the event and a monotonic decay. The rise can be to very high values, over 1000 pPa. These profiles suggest the passage of a shock wave but with the arrival of no driver gas. A value of over 1000 pPa would be expected only from a very fast shock. We note that these events are all B or B* events and obtained some of their "points" for the ranking from their strong leading bow shock.

4. Discussion

Force in a magnetized plasma is governed by the stress tensor but in much of space the curvature of the magnetic field is not an important factor and we can approximate the forces by the diagonal terms. This is fortunate as with a single spacecraft it is difficult to estimate the curvature of magnetic field lines. We further concentrate our examination on the forces perpendicular to the field line as we in general have a more accurate estimate of the temperature perpendicular to the field line than along it unless we have a full three dimensional plasma detector. Fortunately, as we have attempted to demonstrate herein, the two components of pressure perpendicular to the field line behave simply and are good diagnostics of the nature of the ICME. The reason...
for this is that this diagnostic is a component of the ideal MHD approximation and should be valid wherever ideal MHD is valid. The simplicity in its signature is due to the fact that in the subsonic region behind the shock the fast mode wave smoothes pressure jumps.

The three groups of ICME signatures that we have found in the total perpendicular pressure can be interpreted in terms of the classic paradigm of a flux rope plowing through the solar wind with the aid of Fig. 5. Group 1 events are interpreted as encounters with ICMEs in which the trajectory takes the spacecraft through the magnetic structure or rope driving the interaction. In Fig. 5, that is adapted from Spreiter et al. (1966) gas dynamic model of the solar wind interaction with the Earth's magnetosphere, a group 1 trajectory carries the spacecraft through a shock into a magnetosheath with fairly constant density and pressure and then into the driving flux rope or magnetic obstacle to the flow. The apparent overpressure in our calculation of the perpendicular pressure is because we do not take into account the curvature of the magnetic field in calculating the magnetic stress. In a flux rope, as in the Earth's magnetosphere, part or all of the magnetic pressure gradient force inside the magnetic obstacle is balanced by the curvature force.

Group 2 events can be interpreted as encounters of the magnetic obstacle to the side of the obstacle. Here, the magnetic pressure is weak. There may be some twisted field reminiscent of a rope but the plasma may dominate the plasma dynamics in this region. Group 3 may be much further from the magnetic obstacle. Here, the major feature is the crossing of the shock front. The temperature and density rise at the shock but behind the shock there is no obstacle. The plasma expands, rarifies, accelerates and cools. Thus, the total perpendicular pressure drops monotonically.

To validate our physical intuition we have measured the total perpendicular pressure along five straight trajectories (outward from the Sun) through a MHD simulation of the Earth's bow shock (Wang and Raeder, personal communication, 2005). These pressure profiles are shown in Fig. 6. At the subsolar shock the pressure jumps up to 1500 pPa as much of the dynamic pressure of the flow relative to the Earth is converted to magnetic and thermal pressure. There is a weak gradient in the total perpendicular pressure that continues to slow and deflect the flow as it proceeds to the magnetopause. There is no signature in the pressure profile at the magnetopause. In the dipolar region of the magnetosphere the perpendicular pressure goes off our scale but in this region the unconsidered curvature forces are largely balancing the pressure gradient force. At $Y = 5R_E$ the behavior is largely the same but at $Y = 10R_E$ the trajectory cuts through the dusk side of the magnetosphere and the pressure profile remains monotonically. At $Y = 15R_E$, the pressure jump at the shock has dropped to about 900 pPa and shows a monotonic decay once the shock is crossed. At $Y = 20R_E$ the pressure maximum drops to about 600 pPa and is followed by a monotonic decrease. The finite (and growing with $Y$) thickness of the shock is due to a combination of the finite resolution of the MHD code, decreasing resolution away from the subsolar point and an increasingly oblique path of the trajectory through the shock. In practice, the shock would be sharp wherever it was crossed.
5. Concluding remarks

There is still little consensus in identifying ICMEs. Different authors use different criteria and prepare different lists of events. In this report we have examined a promising, single, physically-based parameter that helps identify and characterize ICMEs. This parameter is the total perpendicular pressure, consisting of the thermal pressure perpendicular to B plus the magnetic field pressure. We assume that the magnetic field lines are not twisted in this calculation and use the deviations from apparent pressure balance to identify those regions where this assumption breaks down. We approximate the electron temperature and alpha particle ratio with statistical values but this need not be the case in future investigations such as with STEREO. The profiles of total perpendicular pressure observed form a continuum of signatures, from those that appear to be taken along trajectories through the center of the magnetic flux rope to those that just graze the shock. Many of the structures have well-defined end points as well as well-defined onsets in the perpendicular pressure. At least one structure appeared to “over expand” similar to structures studied at high latitudes on the Ulysses mission.

We emphasize that this study is only an introduction to the use of this parameter in diagnosing solar wind behavior. We have begun to examine the signature of stream interactions. This signature is also quite diagnostic of the interaction but is even more so when combined with the temporal variation of the solar wind speed. Since ICMEs frequently expand, but should never be shrinking, their solar wind speed profile is declining. In contrast fast−slow stream interactions always have an increasing solar wind speed. We also plan to explore how the signature varies with heliocentric distance and latitude using additional datasets. However, until we finish this study we will not be able to determine if the signatures we have found are necessary or sufficient. Nevertheless, based on our studies to date, we believe that this simple, combined parameter has much to offer in the diagnostics of ICMEs and the solar wind in general, and encourage its use.

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