Chapter 10

Large Scale Interplanetary Physics

Aims and Learning Outcomes

The **Aims** of this lecture are to relate coronal/solar activity and large scale structures to corresponding phenomena in the solar wind. This sets the stage for study of planetary magnetospheres, space weather, and the outer heliosphere. It also connects our study of solar physics with the rest of the solar system.

Expected Learning Outcomes. You are expected to be able to

- Understand the physics and phenomenology of the heliospheric current sheet.
- Explain the relationships between coronal and solar wind phenomena involving the magnetic field, plasma velocity, density, and slowly-varying coronal X-rays.
- Explain the origin and characteristics of corotating interaction regions (CIRs).
- Identify shocks in solar wind data and estimate their speeds.
- Explain the origin and characteristics of shocks and CMEs in the solar wind.

10.1 The heliospheric current sheet

At lowest order the large scale magnetic field of the Sun can be represented as a dipole tilted relative to the rotation axis, ignoring for the moment the contributions due to active regions and other localized regions. Consider the effects of outflow of the solar wind plasma and of rotation. Physically, both effects tend to distend the field lines near the equator, where the flow is approximately perpendicular to the magnetic field lines, due to the flow tending to drag the frozen-in magnetic field with it. Added to those effects are those of magnetic pressure and tension (see Section 2.5). The magnetic pressure $B^2/2\mu_0$ acts only perpendicular to the magnetic field, while the magnetic tension acts to straighten bent magnetic field lines. These four effects are calculated quantitatively and self-consistently in Figure 10.1, which displays the results of MHD simulations of solar wind outflow for a dipolar magnetic field imposed at the photosphere and [e.g., Pneuman and Kopp, 1971]. Note that the polar magnetic field lines have been pulled slightly more "open" by the plasma outflow (due to the magnetic tension force) while the closed field lines near the equator have been strongly affected (both by the outwards convection and the magnetic pressure), having been pulled out into a current sheet. Inspection of Ampere's Law (3.13) show that this current flows perpendicular to the page. This current sheet is known as the "heliospheric current sheet". The axis of the current sheet, where the normal magnetic field strength is very small, is known as the "magnetic neutral line". A similar process occurs at the top of more localized coronal loops and helmet streamers.

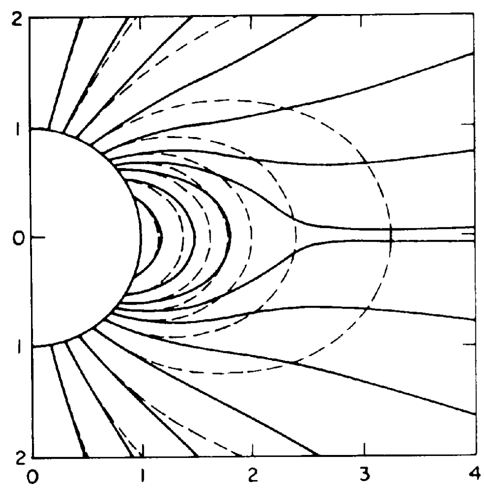

Figure 10.1: A dipole source of magnetic field is imposed at the photosphere and the MHD equations are used to construct the magnetic field lines in the cases with (solid lines) and without (dashed lines) a self-consistent solar wind outflow [Pneuman and Kopp, 1971].

Digressing for a moment, note that current sheet/neutral line configurations like Figure 10.1 involve field lines that are almost anti-parallel near the neutral line. If plasma flows or stresses cause these field lines to come together then the magnetic energy can be released in a process called "magnetic reconnection". The favoured models for solar flares and terrestrial substorms involve magnetic reconnection, as discussed in Lectures 9 (Section 9.3.2), 13, 14 and 15.

The heliospheric current sheet persists into the outer heliosphere and is responsible for both local and global phenomena in the solar wind. Moreover, for a uniform plasma density at the base of the corona, easier escape of the plasma particles will cause the plasma density on open field lines to be smaller (and the outflow speed larger) than on closed field lines at the same distance from the Sun. This concentration of plasma in the solar equatorial band is expected to produce higher levels of thermal X-rays and other emission (Figure 10.2), as indeed observed.

Neither the solar rotation axis nor the effective dipole axis are perpendicular to the ecliptic plane. Accordingly, the Sun's rotation causes the heliospheric current sheet to move up and down at a fixed observer's position, with associated changes in the plasma density and the direction (towards/away) of the magnetic field (Figure 10.3). This wavy pattern of the current sheet is sometimes referred to as the "ballerina skirt" effect. Localized coronal magnetic configurations can also be expected to modify the position and properties of the heliospheric current sheet.

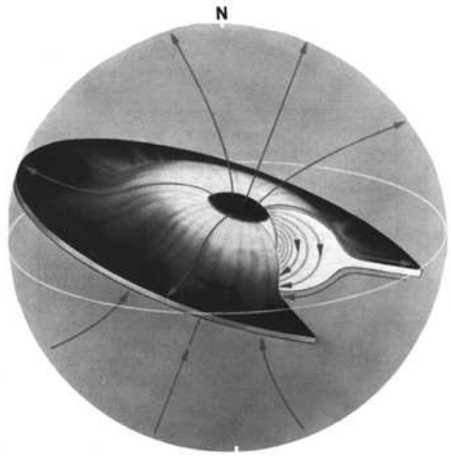

Figure 10.2: An artist's sketch of the plasma structure and magnetic configuration expected near the solar equator [Hundhausen, 1972].

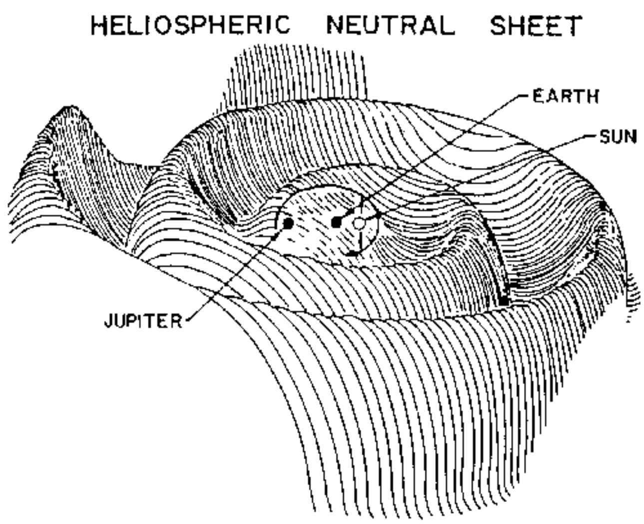

Figure 10.3: The "ballerina skirt" ripples predicted on the heliospheric current sheet [Dryer, 1998].

10.2 Correlations between coronal and solar wind properties

X-ray pictures of the Sun from SMM (Solar Maximum Mission), Yohkoh and SOHO show the existence of both large scale (e.g., coronal holes and the equatorial plasma belt) and small scale (e.g., active regions) structure in the corona. These magnetic and plasma structures can be expected to have counterparts in the solar wind, as they indeed do.

Figure 10.4 [Severny et al., 1970; Cravens, 1997] compares the disk-averaged component of the solar magnetic field away from (positive) or toward (negative) the Sun with the corresponding time-lagged and averaged solar wind magnetic field. Three important results are apparent. First, the large scale solar field strength is well correlated with the solar wind field strength in both direction and (scaled) amplitude. This supports the corona being the source of the solar wind magnetic field. Second, the solar wind field varies at the solar rotation period (approximately 27 days). Third, distinct, long-lasting intervals of uniform solar wind field direction exist, called "sectors" (Figure 10.5).

Figure 10.6 shows that these magnetic properties are also associated with the solar wind speed and detailed plasma structures in the corona [e.g., Hundhausen, 1972]. Each pair of figures is for a given Carrington rotation (or rotation of the Sun). The lefthand figures show contours of the the coronal X-ray brightness overlaid with the direction of the photospheric magnetic field outward from or inward to the Sun (+ or -, respectively). Note the primarily equatorial band of intense X-ray emission, as expected from Figure 10.2, and the wavy nature of the current sheet. Positive field directions lie primarily northward of the equatorial band. The righthand figures show time variations in the speed of the solar wind measured in situ at 1 AU.

A number of important results are apparent in Figure 10.6. First, major variations exist in the speed of the solar wind, organised into so-called "fast" and "slow streams". Second, fast solar wind streams are associated with times when the Earth is at latitudes poleward of the heliospheric current sheet. These are times when a coronal hole has moved to low heliolatitudes. Third, a given stream carries a magnetic field with the polarity (outward or inward) corresponding to the field orientation of the coronal source region. Fourth, these associations between the coronal and solar wind magnetic field and the solar wind speed are repeatable from solar rotation to solar rotation, albeit with variations on several timescales. These variations include small changes due to localized, small-scale and fast time scale coronal structures, while there are also changes associated with large scale evolution of the corona itself. The overall conclusion here is that fast solar wind streams are associated with coronal holes and open field regions of the corona while slow streams come from the closed field regions primarily concentrated near the equatorial (or streamer) belt.

The Ulysses spacecraft recently finished its second set of passes over the Sun's north and south poles in a polar orbit. Its results allow direct testing of the above interpretations (and investigation of changes with the solar cycle). Figure 10.7 shows the solar wind speed, magnetic polarity, and coronal brightness as a function of time and heliolatitude [McComas et al., 1998]. Clearly, the polar regions do correspond to high solar wind speed and low density while the equatorial regions correspond to slow, relatively dense solar wind speed. Moreover, regions with fast and slow streams correspond to relatively low heliolatitudes where slow streams can leave closed field regions. Finally, the magnetic field shows the expected change in polarity expected at the heliospheric current sheet.

Two final remarks concerning fast and slow solar wind streams. First, the number and significance of fast and slow solar wind streams varies with the solar cycle:

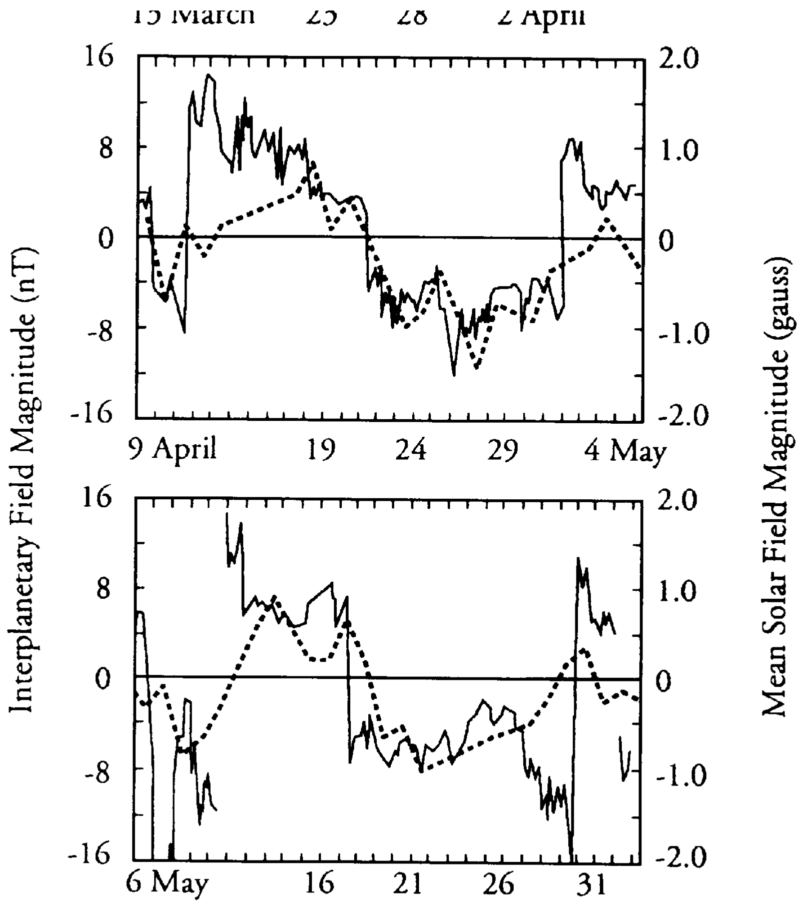

Figure 10.4: The time-averaged away/toward the Sun (positive/negative) components of the magnetic field in the solar wind (solid lines) are compared with the disk-averaged away/toward component of the photospheric magnetic field (dashed lines) [Severney et al., 1970].

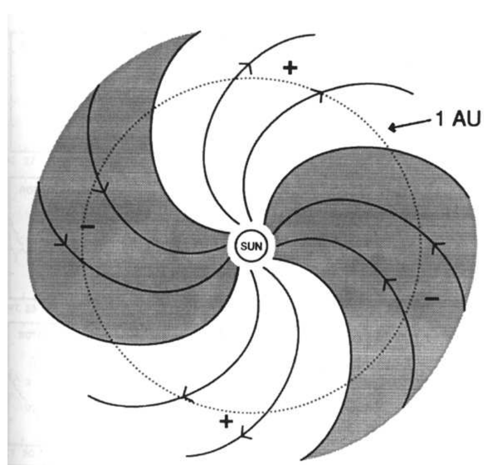

Figure 10.5: Illustration of sectors of magnetic field lines with different polarities [Cravens, 1997].

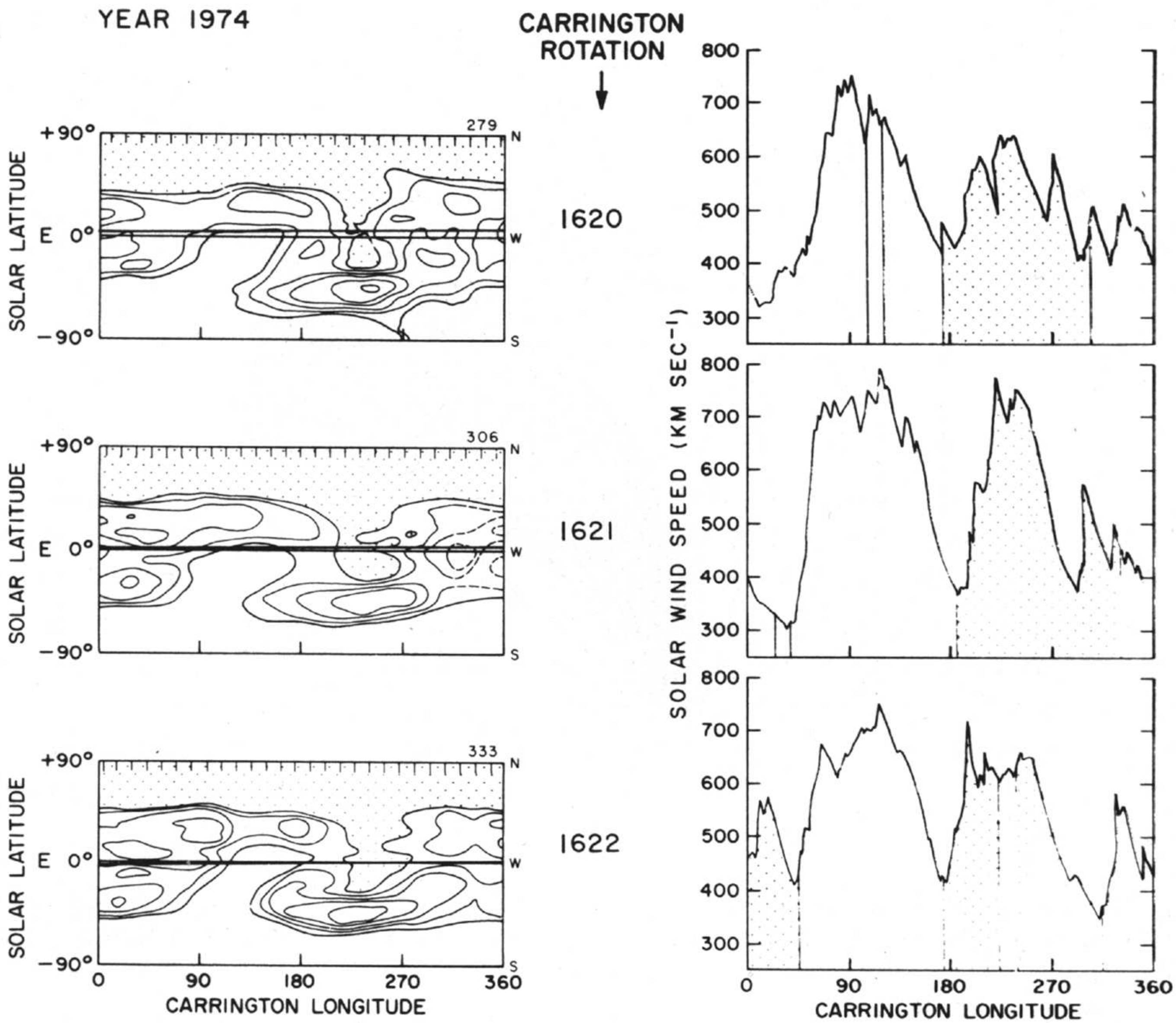

Figure 10.6: The lefthand figures show contours of the X-ray brightness of the corona and the sense of the vertical component of the coronal magnetic field direction. The righthand figures show the solar wind speed and the polarity of the radial component of the solar wind magnetic field. Adapted from Hundhausen [1972].

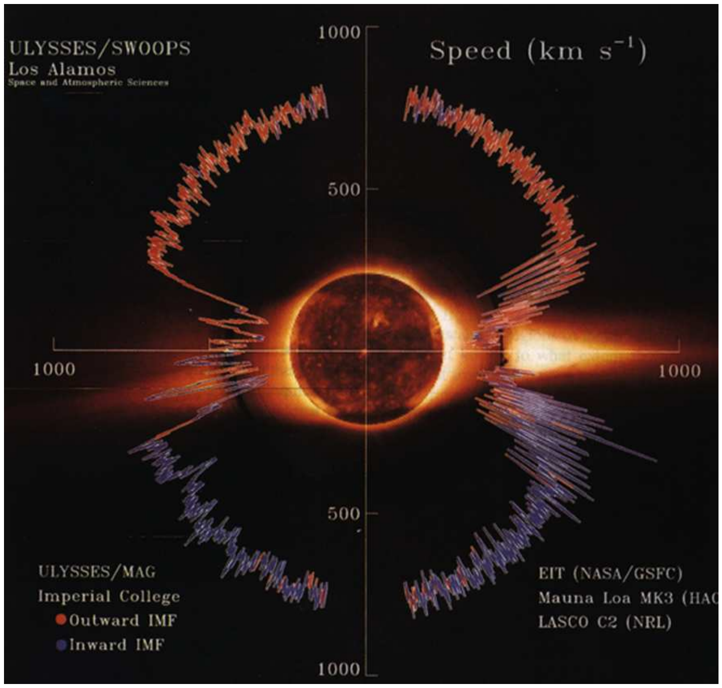

Figure 10.7: Colour illustration of the solar wind speed and the sense of the magnetic field's radial component observed as a function of heliolatitude by the Ulysses spacecraft [McComas et al., 1998].

more long-lived fast streams are present during the declining phase of the solar cycle (e.g., near solar minimum as sunspots move towards the equator) as coronal holes expand in size. Second, numerous other plasma properties depend on whether the stream is fast or slow, including the temperature and detailed composition of the plasma and the plasma waves present.

10.3 Co-rotating Interaction Regions: interactions between fast and slow streams

The previous section showed that a fixed observer relatively close to the solar equatorial plane will observe successive fast and slow solar wind streams during much of the solar cycle. What interactions are there between these streams? Obviously, there must be interactions because plasma from the fast stream will catch up with and overtake plasma from the slow stream. Figure 10.8 [Hundhausen, 1972] shows the qualitative predictions of this scenario: formation of a compression region in the rear of the slow stream, the likely formation of a shock emanating from the compression region (most likely two, as discussed below), and a rarefaction region at the rear of the fast steam, all with characteristic variations in the plasma and field variables. Intuitively it can be seen that these interaction regions will have spiral shapes that may wrap multiple times around the Sun. These regions are called "co-rotating interaction regions" or CIRs since they corotate with the Sun.

Co-rotating interaction regions are not always bounded by shocks. The reason is that shock formation occurs due to the nonlinear steepening of waves, thereby requiring several nonlinear steepening times to elapse before a shock is formed. Since most CIRs do not have shocks at 1 AU but have steepened into shocks by 2 AU,

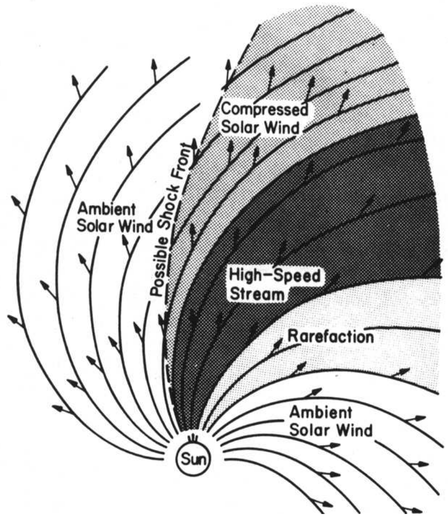

Figure 10.8: Schematic illustration of a fast stream interacting with a slow stream [Hundhausen, 1972].

empirically the nonlinear steepening time must be of order 4 days. (*Exercise: why?*) One reason why two shocks are eventually formed at a CIR is due to symmetry about the pressure enhancement caused by compression and entraining of the slow wind ahead of the fast stream (Figure 10.9 [Gosling, 1996]): shocks are driven away from the pressure increase in both directions, resulting in a so-called "Forward-Reverse shock pair" in which the forward shock propagates away from the Sun while the reverse shock propagates towards the Sun but is carried out with the solar wind flow.

Figure 10.10 [Hundhausen, 1973; Gosling, 1996] displays the results of 1-D MHD simulations of this process. Note the formation of a pressure increase which drives forward and reverse shocks with the formation of a characteristic two step increase in the flow speed with a subsequent slow fall-off to the slow speed (in the rarefaction region). At first sight this two-step profile is inconsistent with both the forward and reverse shock being fast mode shocks. However, this is a reference frame effect: in the frame of the reverse shock the upstream speed (undisturbed fast stream at later times) is greater than the downstream speed (earlier times). In fact, the Rankine-Hugoniot conditions for mass flux across the shock in the shock frame (equation 5.17) can be used with the observed upstream and downstream flow speeds to calculate the shock speed U_{sh}; i.e.,

$$\frac{v_{obs}^{up} - U_{sh}}{v_{obs}^{down} - U_{sh}} = \frac{n_{down}}{n_{up}} \ . \tag{10.1}$$

It is emphasized that the reverse shocks are still convected outwards from the Sun, despite attempting to propagate Sunwards.

Figure 10.11 [Smith, 1985] shows the observed evolution of a CIR from 1 AU to 4.2 AU. Note the evidence for magnetic field and plasma compression at 1 AU (lower panels), but an absence of shocks there, which had evolved to a good example of a forward-reverse shock pair and CIR by 4.2 AU (upper panels). As the shocks convect out, however, the forward and reverse shocks move apart and weaken (due to energy losses associated with heating, compressing, and changing the velocity of the downstream plasma). Eventually the forward and reverse shocks from neighbouring CIRs cross one another, tending to smooth out the plasma again (However,

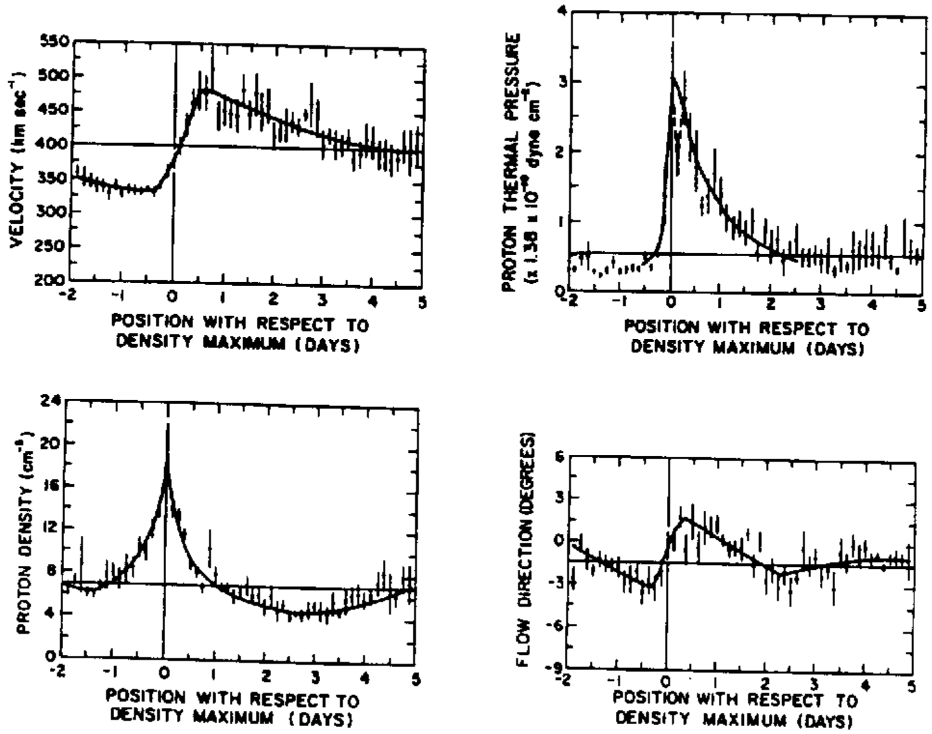

Figure 10.9: Superposed-epoch analysis of the plasma parameters for CIRs [Gosling et al., 1996]. Note the well defined pressure pulse and compression region in the modified portion of the slow stream.

shock weakening prevents this.). These and similar events can be compared with the results of MHD simulations: Figure 10.12 [Gosling et al., 1976; Pizzo, 1985] illustrates the very good agreement between observation and theory available using only MHD.

Figure 10.13 illustrates the winding up of CIRs (and the Archimedean spiral) at large heliocentric distances, where they are clearly likely to have important effects on the plasma. The shock waves and associated structures of CIRs are important in numerous ancillary ways in the solar wind. For instance, CIRs dissipate the energy in fast streams by slowing and heating the plasma, while the magnetic compression regions and turbulence associated with shocks can scatter cosmic rays. Moreover, particles can be accelerated at the CIR shocks. The shocks and most of the plasma structure of CIRs are merged together and primarily smoothed out beyond about 20 AU. Only the magnetic compression regions tend to persist into the outer heliosphere beyond 20 AU. These effects are discussed more in Lectures 11 and 20.

10.4 Travelling interplanetary shocks and CMEs

Co-rotating interaction regions and their associated shocks are not the only transient phenomena in the solar wind. Data from the LASCO coronagraph on SOHO makes it clear that many transient releases of matter occur from the Sun, some but not all in association with solar flares. Historically the primary evidence for shocks in the corona and solar wind came from type II solar radio bursts (whose drift speeds appeared small enough to be associated with a shock moving at the Alfven or fast mode speeds) and from the "Sudden Storm Commencement (SSC)" component

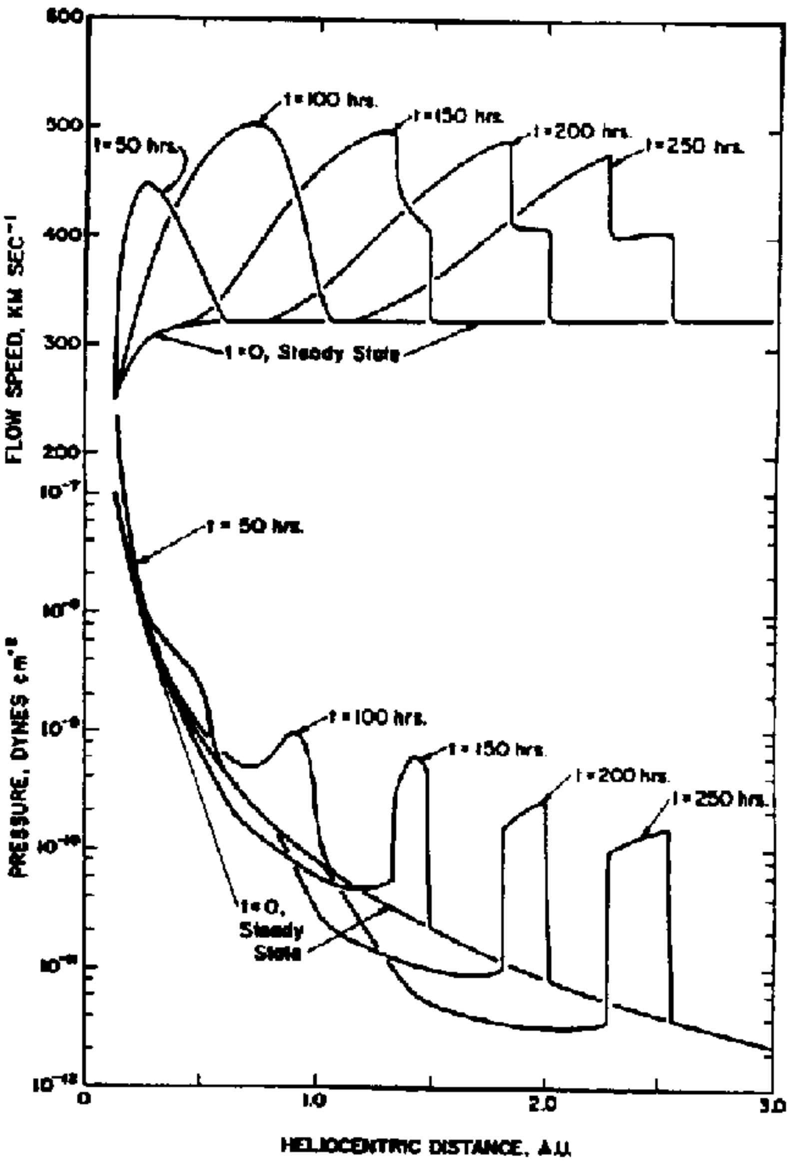

Figure 10.10: Evolution towards a CIR state of a high temperature region imposed at the inner boundary of the solar wind [Hundhausen, 1973]. Note the development of shocks, a pressure pulse, and the characteristic two-step increase and decay of the solar wind speed.

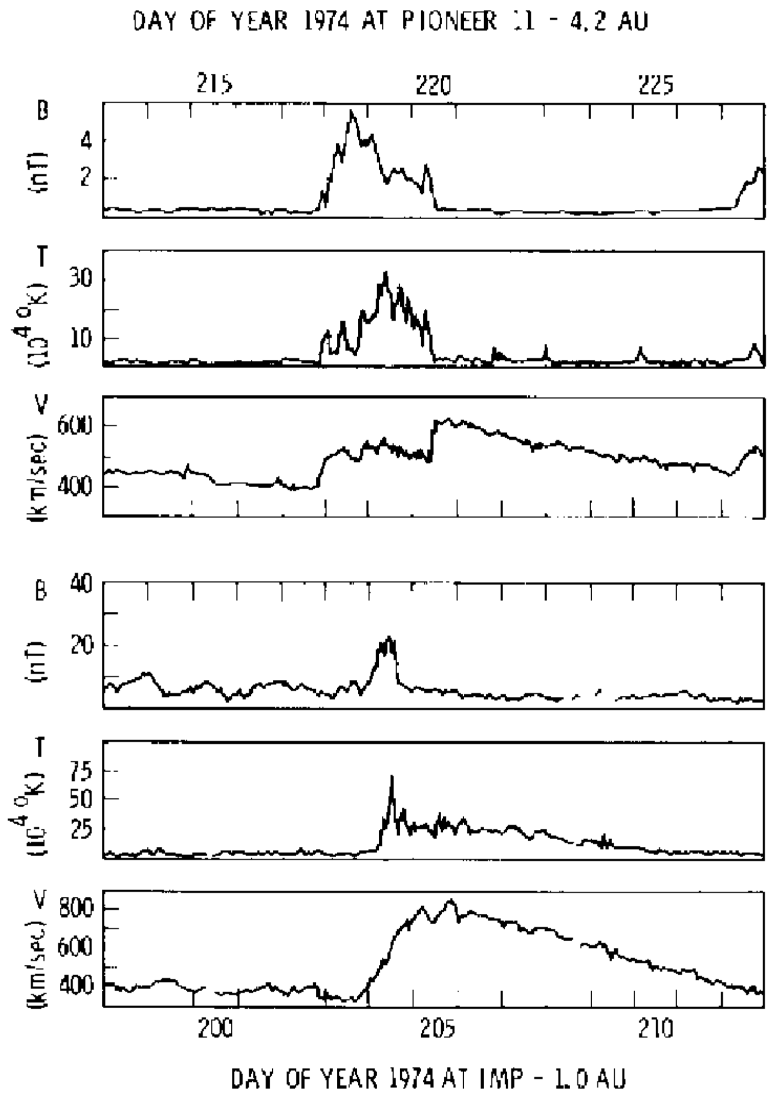

Figure 10.11: Figure from Smith [1985] described in the text.

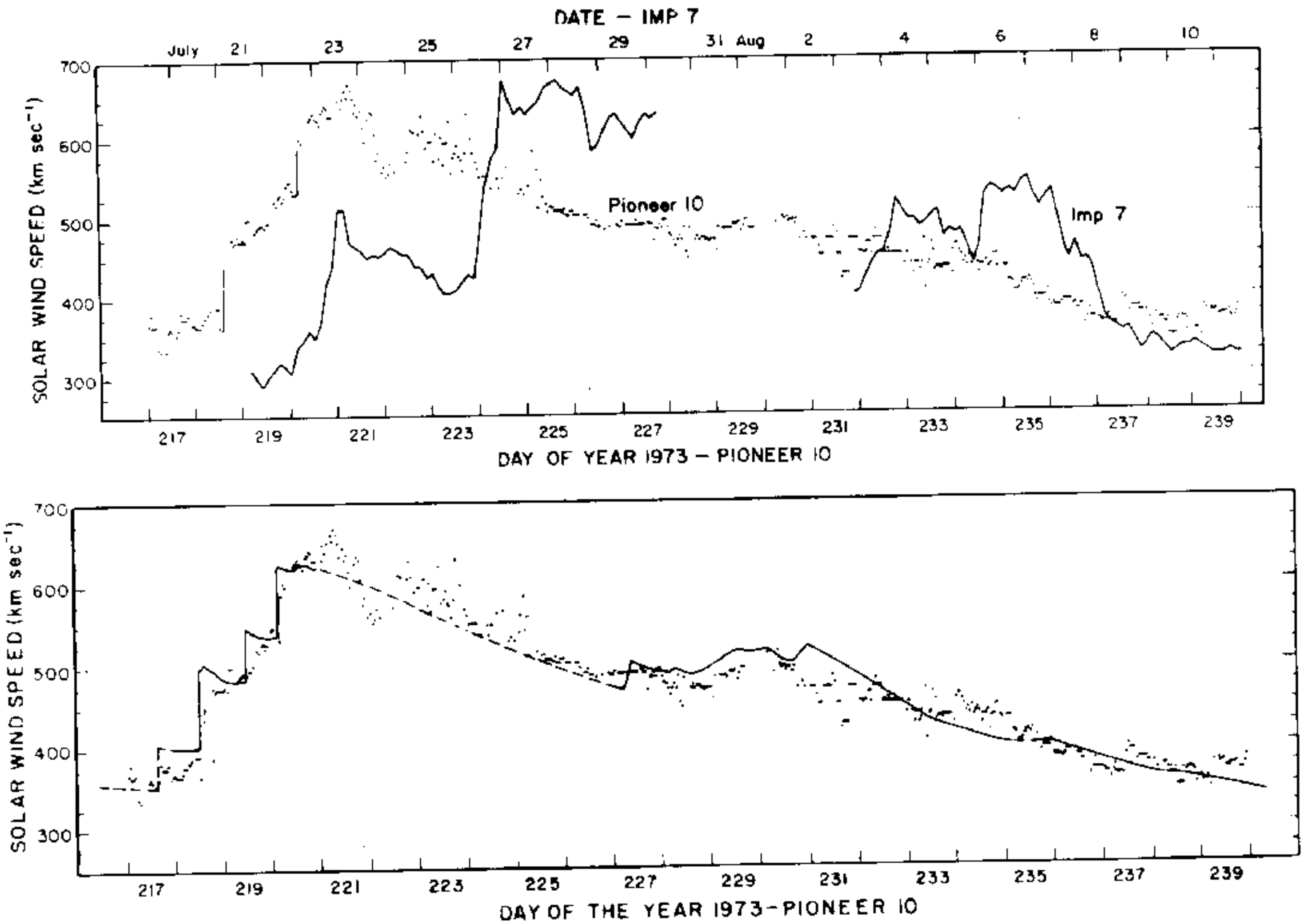

Figure 10.12: The top panel shows time profiles of the solar wind speed observed by IMP 7 near 1 AU and by Pioneer 10 near 4.5 AU. The bottom panel compares the solar wind speeds measured by Pioneer 10 with those predicted by a 1-D MHD code using the IMP 7 data as input. Very good agreement is evident [Gosling et al., 1976].

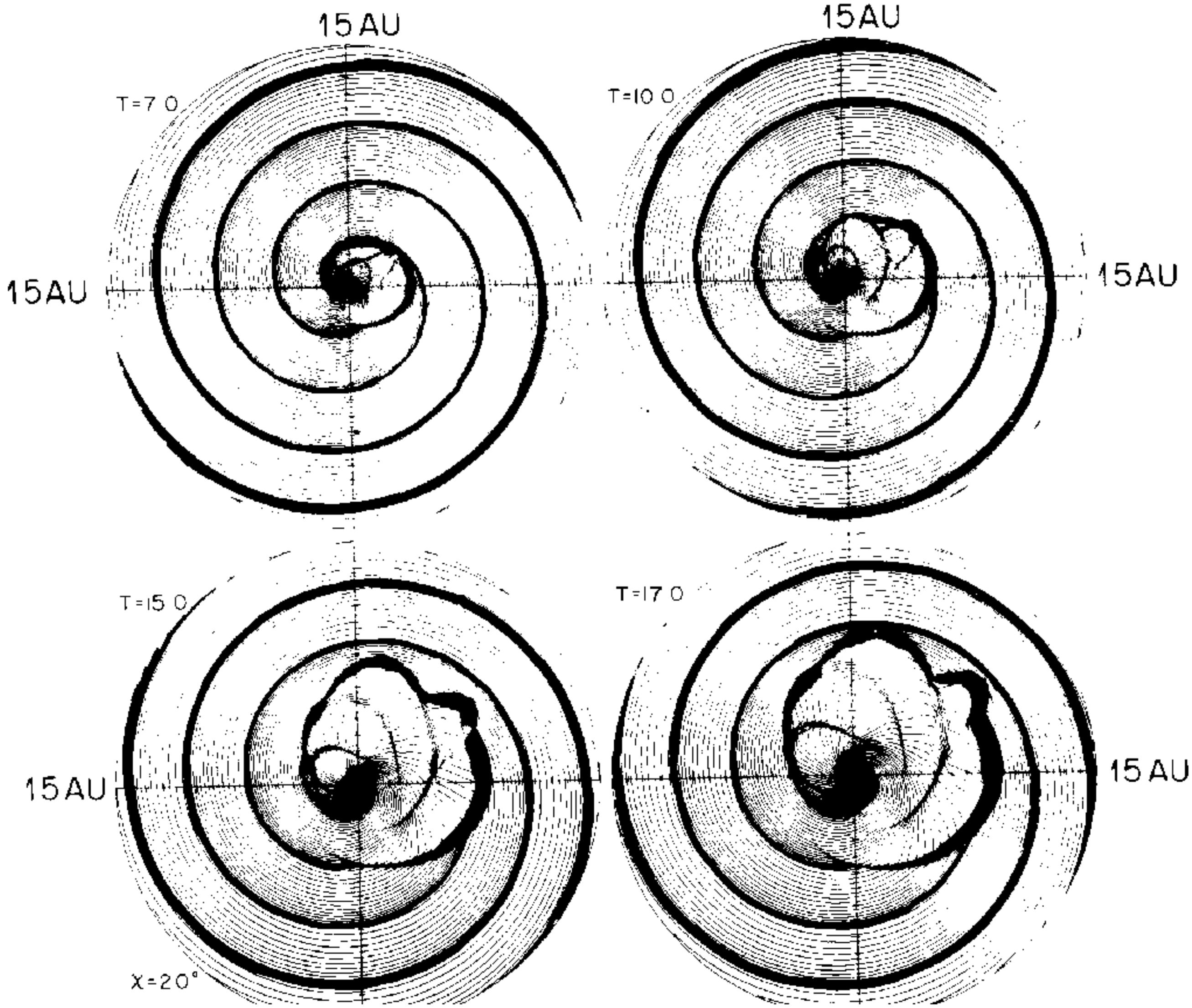

Figure 10.13: MHD simulation of (1) high speed streams which cause the development of CIR structure and (2) the propagation of transient shocks which also modify the CIR structure (bottom two panels particularly) [Akasofu and Hakamada, 1983].

of geomagnetic activity. Until recently it was thought that some shocks observed in the solar wind were associated with blast waves initiated by flares and others were driven ahead of plasma clouds ejected from the Sun ("coronal mass ejections or CMEs"). Now, however, the current belief is that all non-CIR interplanetary shocks are associated with CMEs.

The basic situation is illustrated in Figure 10.14 [Cravens, 1997]: a dense, fast, magnetized loop or cloud of plasma is ejected from the Sun, moving like a piston into the pre-existing solar wind and creating a compression region bounded by a forward shock. The CME/magnetic cloud often has a force-free configuration

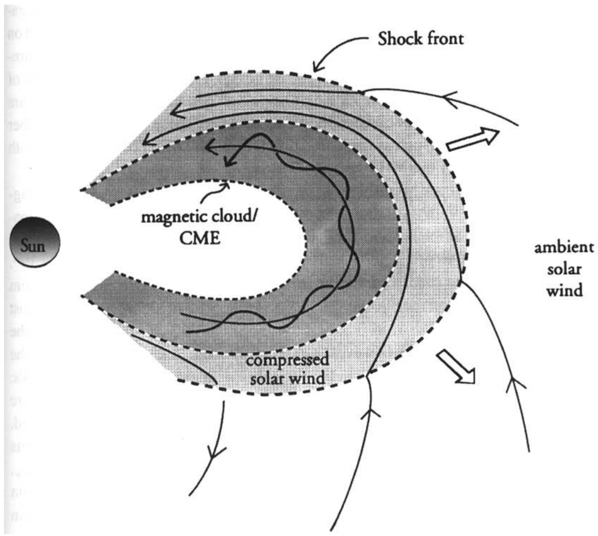

Figure 10.14: Schematic of a coronal mass ejection in the form of a magnetic cloud [Cravens, 1997] with a shock.

and may remain magnetically connected to the Sun even beyond 1 AU; its plasma composition and characteristics are often very different from the pre-existing solar wind. Figure 10.15 shows the plasma and magnetic field data for one CME event observed near 1 AU. Note the forward shock, the compression of the plasma density and magnetic field, and the slow rotation of the magnetic field vector inside the magnetic cloud itself (this is a characteristic of a force-free field configuration).

Arguing by analogy with the two shocks associated with the pressure pulse in CIRs, one might expect that CMEs would also drive a reverse shock, at least beyond 1 AU. Figure 10.16 shows that this is the case [Gosling, 1996]. Similar to CIR shocks, travelling interplanetary shocks also accelerate particles and generate enhanced plasma waves and radio emissions.

Travelling interplanetary shocks and CME's affect Earth's "space weather" environment in a number of ways. First, the change in magnetic field across the shock causes a time-varying EMF which can overload transformers etc. on communication cables and power grids. Second, the large plasma pressure of the CME and compression region can significantly move the bow shock and magnetosphere Earthward, leading to major currents that can couple to the ionosphere, the ring current, and to terrestrial cables. Third, the shock can inject large numbers of energetic particles into Earth's inner magnetosphere, worsening the radiation environment for spacecraft and increasing the ring current. These effects will be discussed more in Lecture 15.

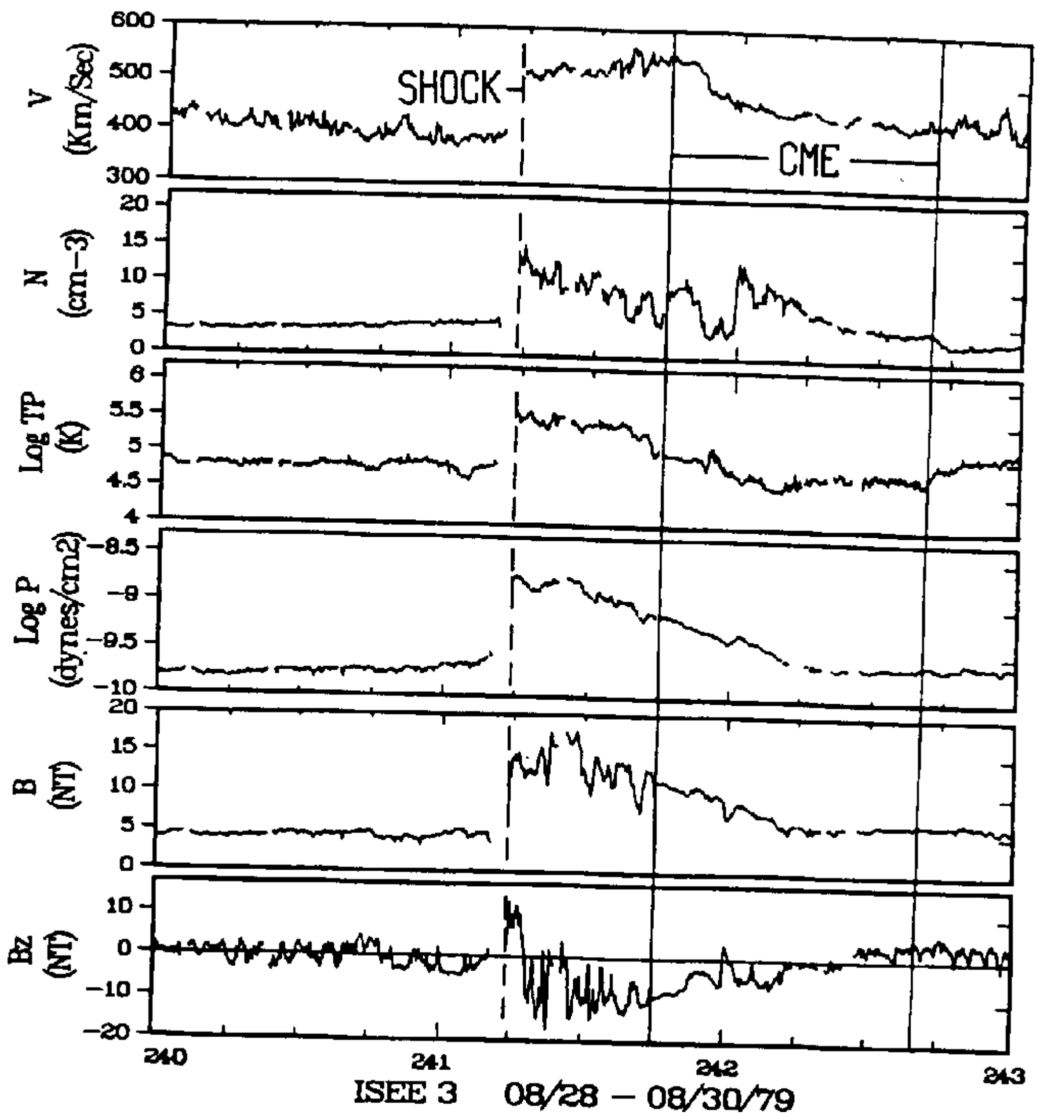

Figure 10.15: Plasma parameters of a CME and associated shock observed near 1 AU [Gosling, 1996].

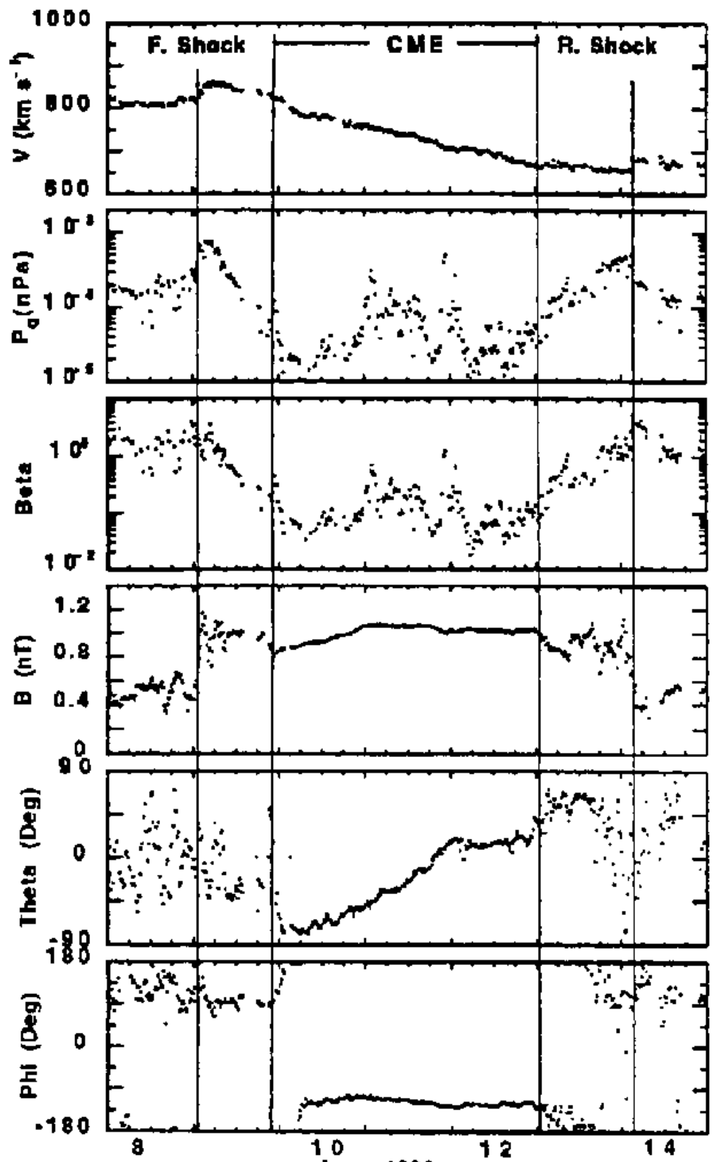

Figure 10.16: Example of a CME and associated forward/reverse shock pair observed by Ulysses near 5 AU [Gosling, 1996].

10.5 References

- Akasofu, S.-I., and K. Hakamada, Solar wind disturbances in the outer heliosphere caused by successive solar flares from the same active region, in *Solar Wind 5*, NASA Conf. Publ. CP2280, 475, 1983.
- Cravens, T., *Introduction to Solar System Plasma Physics*, Cambridge, 1997.
- Dryer, M., Solar wind and heliosphere, in *The Solar Wind and the Earth*, Eds. S.-I. Akasofu and Y. Kamide, D. Reidel, 21, 1987.
- Gosling, J.T., A.J. Hundhausen, and S.J. Bame, Solar wind stream evolution at large heliocentric distances: Experimental demonstration and the test of a model, **J. Geophys. Res**, **81**, 2111, 1976.
- Gosling, J.T., Corotating and transient solar wind flows in three dimensions, **Ann. Rev. Astron. Astrophys.**, **34**, 35, 1996.
- Hundhausen, A.J., *Coronal Expansion and Solar Wind*, Springer-Verlag, 1972.
- Hundhausen, A.J., Nonlinear model of high-speed solar wind streams, **J. Geophys. Res.**, **78**, 1528, 1973.
- McComas, D.J., et al., Ulysses' return to the slow solar wind, **Geophys. Res. Lett.**, **25**, 1, 1998.
- Pneuman, G.W., and R.A. Kopp, **Solar Phys.**, **18**, 258, 1971.
- Severney, A., J.M. Wilcox, P.H. Scherrer, and D.S. Colburn, Comparison of the mean photospheric magnetic field and the interplanetary magnetic field, **Solar Phys.**, **15**, 3, 1970.
- Smith, E.J., Interplanetary shock phenomena beyond 1 AU, in *Collisionless Shocks in the Heliosphere: Reviews of Current Research*, Eds. B.T. Tsurutani and R. G. Stone, AGU, 69, 1985.