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Flows and obstacles in the heliosphere

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Abstract. The supersonic solar wind is highly variable on all time scales near the Sun but fluctuations are moderated by self-interaction as this plasma moves outward. The solar wind runs into many obstacles on its way out. The neutrals from the interstellar medium slow it down. Magnetospheres and interplanetary coronal mass ejections (ICMEs) cause shocks to form so that the flow can divert around these obstacles. Finally the solar wind is stopped by the circum-heliospheric interstellar medium (CHISM); it slows at the termination shock and then turns down the heliotail. The shocks and sheaths formed by these interactions cover scales which vary by orders of magnitude; some aspects of these shocks and sheaths look very similar and some very different. We discuss solar wind evolution, interaction with the neutrals from the CHISM, foreshocks, shock structure, shock heating, asymmetries, and sheath variability in different sheath regions.

Keywords. solar wind, shock waves, plasmas

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1. Introduction

The space age started 50 years ago with the launch of the first spacecraft above Earth's atmosphere. In those 50 years we have learned much about the planets, comets, asteroids, and the interplanetary medium. The Voyager spacecraft are now approaching the local interstellar medium and may cross into this region in roughly 10 years; they have already sampled a great deal of the solar wind/CHISM boundary region. One common feature in all the regions we have encountered are plasma flows. In particular, the heliosphere is filled with the supersonic magnetized plasma called the solar wind and the region outside the heliosphere is filled with the combination of neutrals and magnetized plasma called the CHISM. The heliosphere is filled with obstacles which affect the solar wind flow which include neutral atoms from the CHISM, planets, moons, comets, asteroids, and dust. The Sun is very dynamic which causes large variations in the solar wind and causes complex interactions within the solar wind itself. The final and largest interaction of the solar wind is that with the CHISM. The physical processes in these flows are often similar. The magnetic field and plasma are tied together since plasma can only move along, not across, the magnetic field. Neutrals are not affected by the magnetic field, so neutrals can move between plasmas and link different plasma regimes. When the plasma flows encounter a non-conducting obstacle, such as the moon or asteroids, the flow slams into the surface and is absorbed. When these flows encounter a conducting obstacle, such as a magnetosphere or another magnetized flow, the flow must divert around the obstacle since the magnetic fields cannot pass through it. If the flow is supersonic like the solar wind, a reverse shock forms upstream of the obstacle causing the flow to compress, heat, become subsonic, and divert around the obstacle. This paper discusses the evolution of the solar wind flow and compares the interactions of the solar wind with the multitude of obstacles in its path. We compare the shocks and sheath formed in front of planets, solar wind transient structures, and the CHISM. All these involve the diversion of the solar wind but at very different scales and with different flow and obstacle parameters. We will discuss the interaction of the solar wind with interstellar neutrals, compare the shocks and sheaths at these various obstacles, discuss the heating of plasma at these shocks, and discuss the asymmetries in these interaction regions.

2. Overview

Fig. 1 shows a schematic diagram of a variety of flows inside and outside the heliosphere. The top right panel shows the heliosphere, the bottom right shows a planetary magnetosphere, the bottom left shows a coronal mass ejection (CME) leaving the Sun, and the top left shows an astrosphere. In the heliosphere the solar wind flows radially outward from the Sun and the CHISM flows from left to right. The heliopause, the boundary between the solar wind and the CHISM, forms where the solar wind and CHISM pressures balance. The CHISM flows around the outside of the heliopause and the solar wind turns and flows downstream inside the heliopause. If the CHISM were supersonic, a bow shock would form in the CHISM flow upstream of the termination shock (TS) which would make the CHISM flow subsonic and allow it to divert around the heliosphere. This region of shocked CHISM flow is called the outer heliosheath; we do not know the CHISM magnetic field strength so we do not know if the CHISM is supersonic. If it were not, the CHISM flow would not need to be shocked to divert around the heliosphere. The solar wind becomes subsonic at the TS; the shocked solar wind plasma makes up the heliosheath and moves down the heliotail. Voyager 1 and 2 have both crossed the TS and in 2008 are in the heliosheath.

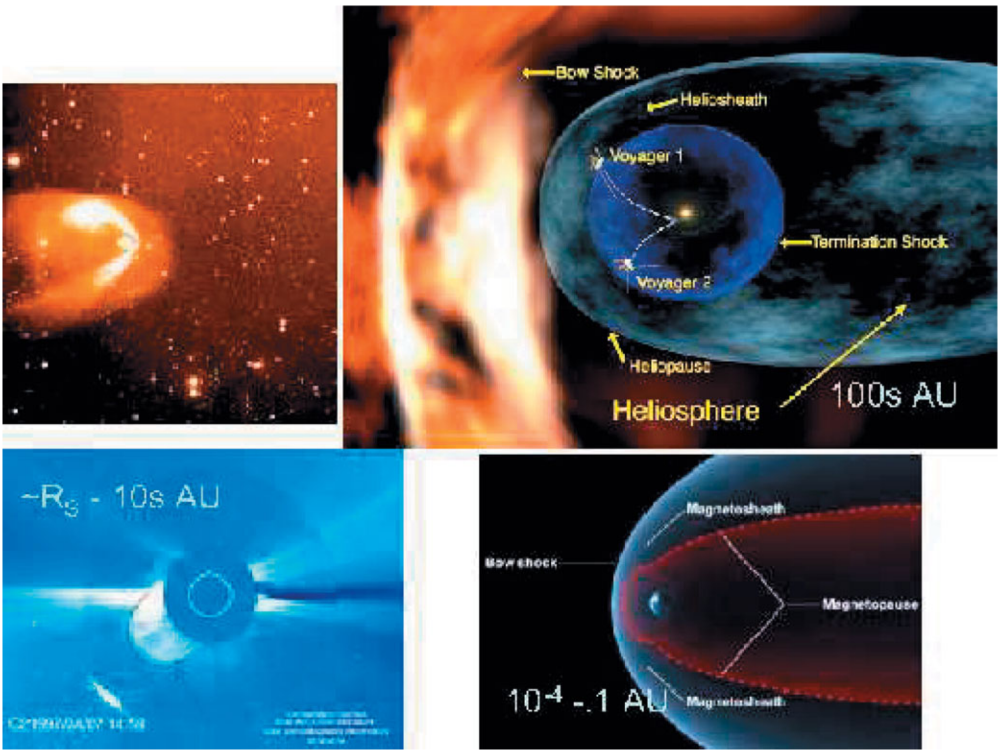

Figure 1. Examples of shocks and sheaths in the heliosphere and beyond. From top right clockwise are the heliosphere, a magnetosphere, a CME driven shock, and an astrosphere.

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Magnetospheres can be either intrinsic or induced. An intrinsic magnetosphere is one where the planet has a magnetic field strong enough that a magnetopause, the pressure balance point between the solar wind dynamic pressure and the planet's magnetic pressure, forms outside the planet. The solar wind must flow around this conducting obstacle, the magnetosphere; a bow shock forms in from the the planet and the shocked solar wind plasma in the magnetosheath is diverted around the planet. Planets without strong fields which have ionospheres have induced magnetospheres; the solar wind magnetic field cannot flow through the conducting ionosphere, but compresses the ionosphere until pressure balance is reached between the ionospheric thermal pressure and the solar wind pressure. This boundary is called the ionopause, and acts like a magnetopause in that the solar wind slows at a bow shock and then flows around the planet. CMEs are explosive events on the Sun which eject large amounts of plasma from the Sun, sometimes at very high speeds. Called interplanetary CMEs (ICMEs) in the solar wind, they are large magnetic flux ropes which maintain their connection to the Sun well past 1 astronomical unit (AU). Since they move faster than the ambient solar wind, a shock forms ahead of the ICME which allows the faster ICME to flow through the ambient solar wind. This region of shocked solar wind plasma is called the ICME sheath. The astrosphere in the upper left was observed by the Hubble Space Telescope and gives us confidence that our ideas about the heliosphere are basically correct. The CHISM is coming from the right, gets heated at the bow shock, and diverts around the astrosphere. The stellar wind comes outward, then becomes shocked and hot at the termination shock. Many similar astrospheres have been observed.

3. Solar wind evolution

The Sun is dynamic on scales from minutes to centuries. A solar cycle (11 years) of Wind data at 1 AU shows that solar wind speeds vary from 260–2140 km/s with an average of 440 km/s, densities vary from 0.1–135 cm^{-3} with an average of 7.3 cm^{-3}, and temperatures vary from 6,000 to 3,700,000 K. Over the solar cycle the configuration changes from a nearly uniform slow dense flow at solar maximum to a bi-model flow with hot tenuous solar wind at heliolatitudes above 20–30 ° and slow dense solar wind nearer the equator. The solar wind pressure changes by about a factor of 2 over the solar cycle, with minimum pressure near solar maximum, a sharp increase in the 2-3 years after solar maximum, then a slow decline until the next solar maximum. ICMEs are more prevalent near solar maximum and in the declining phase of the solar cycle. As the solar wind moves outward in interacts with itself and this variability relaxes. Fast solar wind streams run into slow streams and transfer momentum reducing variability. Fig. 2 shows daily averages and 1 AU average speeds and relative standard deviations of the speed and density versus distance. The amount of small scale variation decreases with distance as is apparent in both the daily average plots and the relative standard deviations. By 20 AU most of the daily change in speed is gone leaving only larger structures. The density relative standard deviation continues to decline with distance. The termination shock crossing is at 84 AU where the speed decreases and density increases; the relative standard deviation of density stays the same while that of the speed increases.

4. Flows and neutrals

Neutral atoms and molecules are not affected by magnetic fields and can move through the plasma. The plasma and neutrals are coupled when collisions lead to charge exchange, in which an ion gains an electron from a neutral. The ion is now a neutral and continues moving in the same direction since it is not bound by the magnetic field. The new ion (the former neutral) is bound by the magnetic field and is accelerated to the speed of the plasma. It has an initial thermal energy equal to that of the plasma flow energy. Charge exchange is an important process in both the solar wind which interacts with interstellar neutrals and in planetary magnetospheres where neutrals from a planet's moons, rings, and ionosphere interact with the plasma. In magnetospheres the magnetic field lines are connected to the planet; when a new ion is formed the energy to accelerate it comes from the planet's rotation. The accelerating force is a $J \times B$ force with the current closing along field lines and through the planet's ionosphere. If mass-loading were large enough that sufficient current can't flow through the ionosphere to accelerate the plasma to the corotation speed, then the plasma will subcorotate. Subcorotation occurs in both the magnetospheres of Jupiter and Saturn, where moons and rings produce large numbers of neutrals, many of which are ionized through charge exchange. The hot ions formed in this manner are important energy sources for these magnetospheres. The solar wind has no energy source after it leaves the Sun, so the energy to accelerate pickup ions comes from the bulk flow energy of the solar wind and the pickup ions cause the solar wind to slow down and heat up. Fig. 3 shows 101-day averages of the speeds and temperatures observed by Voyager 2 (V2) and the speeds observed at 1 AU by IMP 8. The comparison between V2 and IMP 8 speeds shows clearly that the solar wind is slowing down. In the inner heliosphere the V2 and IMP 8 speeds are very similar. The exceptions are solar minimum in 1986-87 when V2 is at a lower average latitude than IMP 8 and sees slower flow and in the 1995-97 solar minimum when V2 is at higher heliolatitudes and sees slower flow. After 1998 V2 observes consistently lower speeds than IMP 8; by 2005 this slowdown is about 60 km/s which implies the pickup ion density is about 16% of the total solar wind density. The temperature profile shows that the solar wind cools until 1986-87

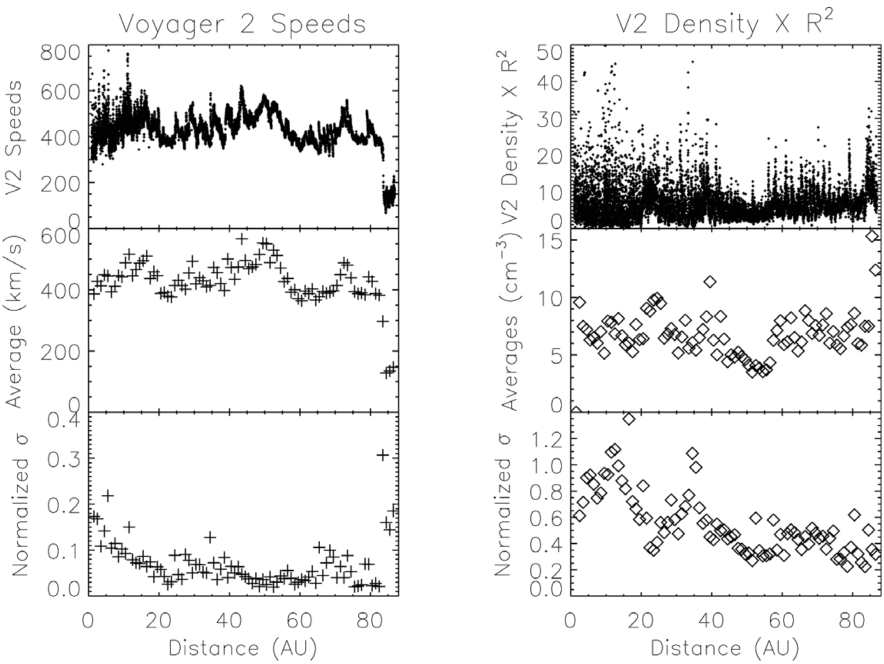

Figure 2. The panels show daily averages, averages over 1 AU, and relative standard deviations (σ/average) of the solar wind speed (left) and normalized density NR^2 (right) observed by Voyager 2.

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at about 20 AU, then the temperature increases (Richardson & Smith, 2003). The pickup ions are not measured directly so this plot shows only the thermal proton temperature. The pickup ions are formed with unstable ring distributions; magnetic fluctuations are generated when these distributions become spherical and these fluctuations heat the thermal plasma (Smith *et al.*, 2006; Isenberg *et al.*, 2005). The CHISM neutrals remove about 30% of the flow energy from the solar wind before it reaches the TS and provide almost all the energy in the thermal plasma in the outer heliosphere.

5. Shocks

Shocks form upstream of obstacles in the solar wind: magnetospheres, ICMEs, and the CHISM. These shocks all make the downstream flow subsonic so the solar wind can divert around the obstacle, but have major differences. Fig. 4 superposes plasma data from Neptune's bow shock, the TS, and an interplanetary shock. The time scales are not adjusted, but the upstream parameters are normalized to those observed at the TS. The ICME shock is from about 13 AU; ICME shocks vary depending on the speed of the CME and weaken with distance. The ICME shock is a fast forward shock; the speed, density, and temperature all increase. Speed and density jumps at ICME shocks range from very

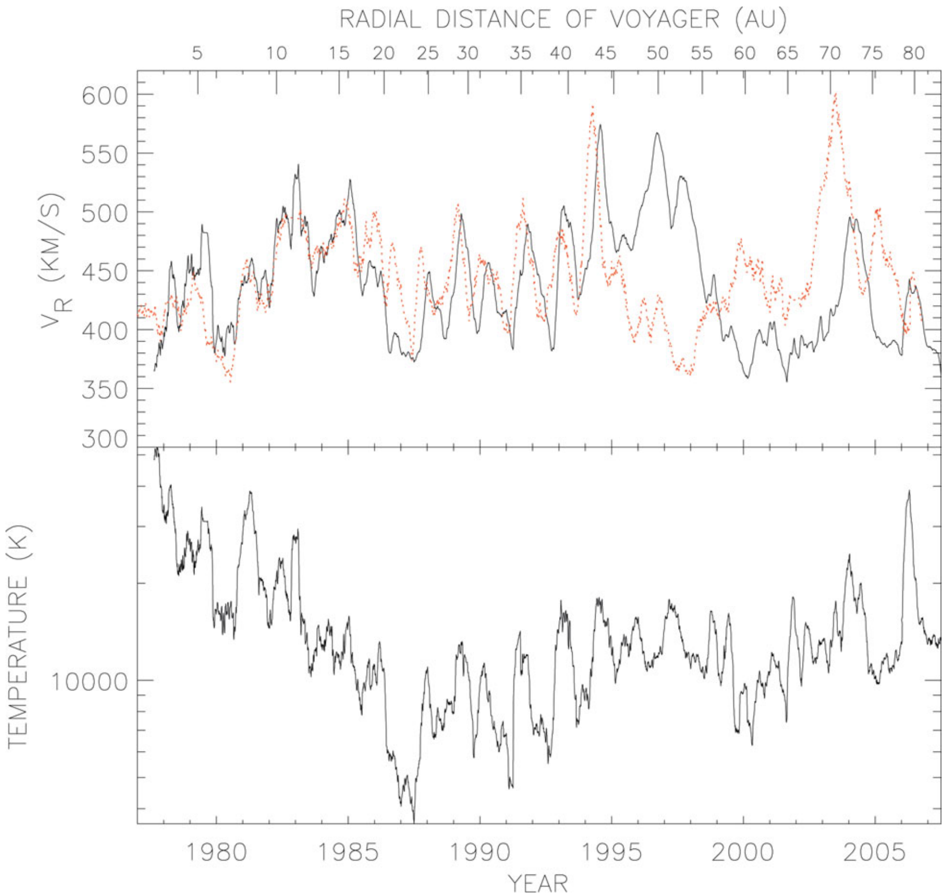

Figure 3. 51-day running averages of the solar wind speed and temperature observed by V2. The speeds measured by IMP 8 at 1 AU are superposed.

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small to a factor of 4 and the proton temperature in the strongest shocks reaches a few hundred thousand degrees. The ICME shocks propagate outward, with shock speeds up to 200 km/s faster than the solar wind flow. Planetary bow shocks and the TS are both stationary reverse shocks, so the speed drops and the density and temperature increase. Planetary bow shocks are usually supercritical, quasi-perpendicular shocks at which the speed decreases and density increases by a factor of about 4. The temperature jumps by roughly 3 orders of magnitude to a few million degrees K. Most of the flow energy ends

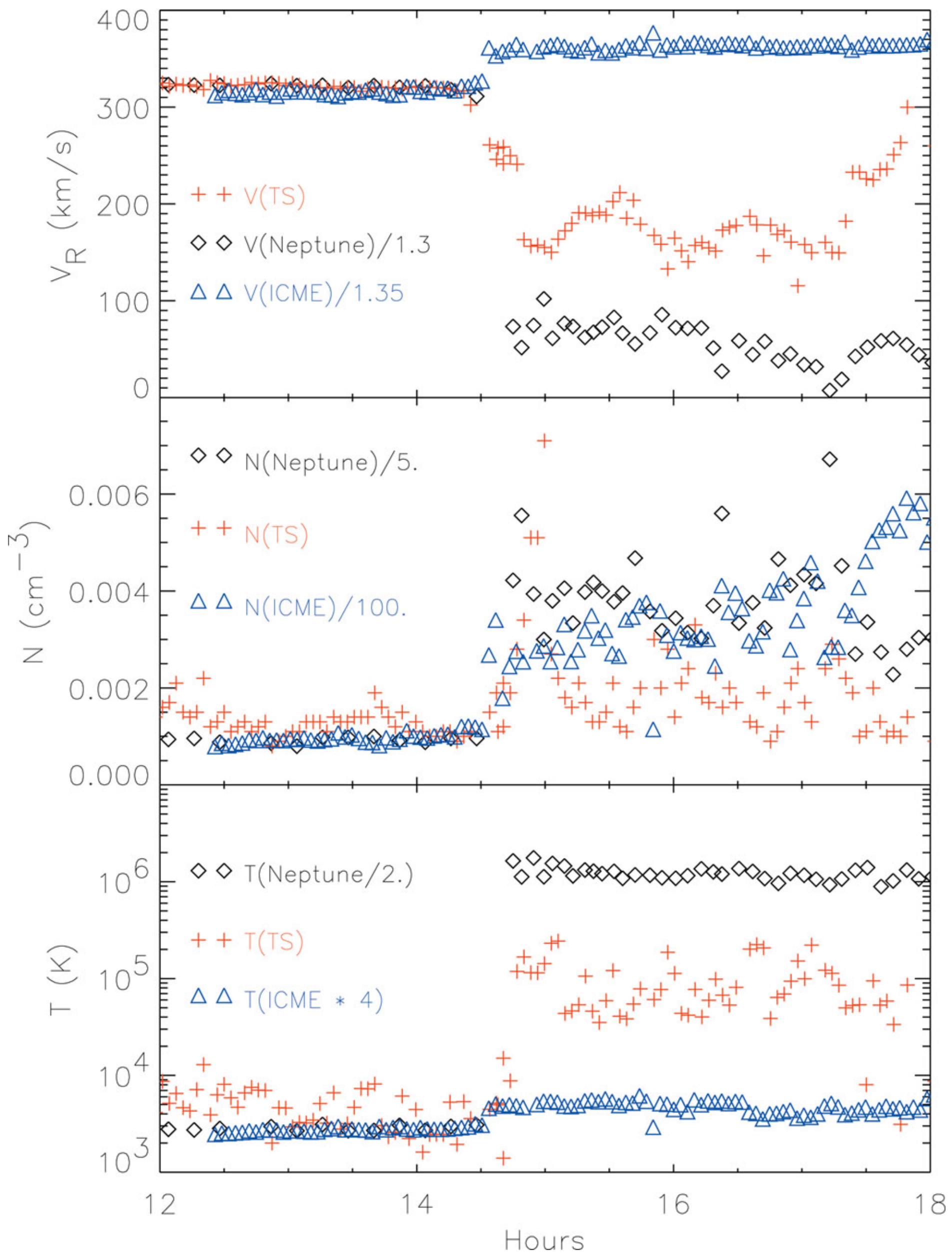

Figure 4. Shock Comparison: Neptune's bow shock, the termination shock, and an interplanetary shock. The upstream parameters are normalized to those at the TS.

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up in the thermal plasma. The TS differs from the planetary bow shocks in that the shock is weaker; the speed and temperature change by about a factor of 2, not 4, and the heating of the thermal plasma is much less at the TS. The flow in the heliosheath remains supersonic with respect to the thermal plasma. Another difference between these shocks is the downstream proton distributions. Fig. 5 shows an example of spectra observed in the Jovian magnetosheath, the heliosheath, and in an ICME sheath. At planetary bow shocks, a percentage of the ions encountering a quasi-perpendicular shock are reflected, then convected back to the shock and further heated, forming a hot proton component (Sckopke *et al.*, 1983). At Earth, the percentage of hot ions depends on the Mach number; theory predicts that the percentage of hot ions should reach an asymptotic value of 20-25% at high Mach numbers (Fuselier and Schmidt, 1994). This prediction seems valid at Earth, but Table 1 shows that Jupiter, Saturn, and Neptune often have much larger percentages of ions in the hot component, 30-60% (Richardson, 1987; 2002).

The heliosheath does not have a reflected ion component even though the TS is a perpendicular shock. The temperature of the heliosheath is much lower than that of planetary magnetosheaths, 100,000K as compared to a few million K. The available data support a picture in which the pickup ions gain most of the plasma flow energy at the TS. Zank *et al.* (1996) showed that pickup ions, not thermal ions, were likely to be reflected and heated at the TS. Gloeckler *et al.* (2005) present Voyager 1 energetic particle spectra for energies greater than 30 keV. They showed that extrapolation of these spectra to lower energies suggests that 80% of the plasma flow energy ends up in the pickup ions. Only about 15% of the plasma flow energy ends up heating the thermal plasma (Richardson *et al.*, 2008a). At the TS shock about 20% of the protons are pickup ions (Richardson *et al.*, 2008b). If the flow energy were all going into the pickup ions then these ions should have a temperature of order 5 keV. Wang *et al.* (2008) reported STEREO observations of energetic neutral atoms with energies of 6-10 keV which appear to originate near the nose of the TS (the direction from which the CHISM is flowing); these ENAs form from charge exchange of pickup ions in the heliosheath. These 6-10 keV pickup ions have thermal speeds much faster than the average plasma flow speed of 150 km/s in the heliosheath, thus the flow is subsonic with respect to the pickup ions. Thus these observations seem to form a consistent picture if the energy from the plasma flow is transferred at the TS not to the thermal plasma but to the pickup ions. ICME sheath spectra are now being investigated. Fig. 5 shows an example of an ICME sheath with two

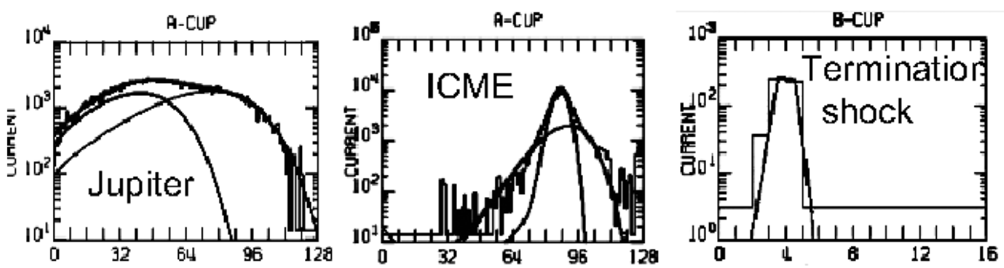

Figure 5. Spectra observed in Jovian magnetosheath, and ICME sheath, and the heliosheath The histograms are the data plotted versus a log energy scale and the curves are fits of convected isotropic proton Maxwellians to the individual components and the sum of these currents. The Jovian and ICME sheaths have hot components which comprise about 40% of the total density. The temperature of the hot component is about 9 times that of the cold component. The heliosheath spectra is well fit by a single Maxwellian distribution.Spectra observed in Jupiter's magnetosphere, an ICME sheath, and in the heliosheath. The histogram shows the measured currents and the curves the fit of convected isotropic proton Maxwellians to the data.

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proton components formed at the interplanetary shock (the proton distributions in the solar wind upstream of the shock were well fit by single Maxwellians). The temperature of the hot component is about 9 times that of the cold component. The hot particles in this sheath carry the bulk of the thermal pressure in the ICME sheath, change wave propagation speeds, and could provide seed particles for further acceleration. But this hot component is not always present in the ICME sheaths we have studied; 3 of the 10 cases we have looked at show only a single proton Maxwellian. These spectra are similar to the heliosheath spectra, which is cold and fit well by a single Maxwellian. Why some ICME sheaths have reflected ions and some don't is under investigation; possibly this difference depends on the shock parameters. As the percentage of pickup ion densities increases with distance the amount of reflected thermal ions in ICME sheaths may decrease. The one outer planet which does not show evidence of hot ions in its magnetosheath is Uranus, which is surrounded by a corona of H. This result leads us to hypothesize that there are sufficient pickup ions from interstellar gas plus the corona that thermal ions are not reflected at Uranus's bow shock.

6. Sheath size

An ICME sheath differs from that of planetary magnetosheaths in two important respects: 1) since the ICME is a long flux rope, the flow can be approximated by a 2-D flow around a cylindrical obstacle (unlike the 3-D semi-spherical obstacle posed by a magnetosphere) and 2) the ICME is expanding so interaction is not in a quasi-steady-state (like a magnetosheath or the heliosheath). The thickness of the sheath increases as the shock propagates through the solar wind ahead of the ICME. MHD models predict that the thickness of the sheath is smaller than that of a planetary magnetosphere, about 0.1 (as opposed to 0.2) times the radius of curvature of the obstacle (Siscoe *et al.*, 2007); the sheath layer is smaller because of the expansion of the ICME. The flow speeds around the obstacle are smaller than the expansion speed of the ICME, so the sheath accretes material as its size increases. ICME expansion stops at 10-15 AU (Liu and Richardson, 2004); perhaps at this distance the thickness of ICME sheaths may increase and become comparable in width to magnetosheaths.

7. Foreshocks

The particles heated at the shock can stream along the solar wind magnetic field lines into the heliosphere; this region of streaming particles is called the foreshock. At planetary magnetospheres the foreshock region is dominated by waves generated by the shock and waves generated by particles with energies of a few keV reflected and heated at the shock which move upstream. For planets only the lower energy particles encounter the bow shock again; most particles stream along field lines and remain in the solar wind. The Voyager spacecraft observed a large foreshock region upstream of the TS; this region was filled with streaming tens of keV to MeV particles (Krimigis *et al.*, 2003; MacDonald *et al.*, 2003). Both V1 and V2 first entered this region about 2.5 years before they crossed the TS. Essentially all of these particles will encounter the shock again. The foreshock region of the TS is not filled by waves as for planetary magnetospheres, perhaps because of the much higher particle energies. At planetary bow shocks the solar wind slows in the foreshock region as the plasma, waves, and streaming particles interact. At the TS, a decrease in speed is observed upstream of the shock (Richardson *et al.*, 2008b) but whether this decrease is associated with foreshock particles is not known.

Table 1. Shock and Sheath Parameters

	Jupiter	Saturn	Uranus	Neptune	ICME	TS
Distance	55-99 R_J	24-26R_S	24 R_U	35 R_N	0.4-82 AU	84-94 AU
Mach No	4-19	8-14	17.	9		8
Beta	0.4-7.	0.5-1.4	3.6	0.2		2?
V_R (km/s)	60	85	42	115		140
T (10^6 K)	5.1	4.8	2.6	3.6		0.18
N_H/N_C	0.34	0.45	0	0.48	0 - 0.5	0
T_H/T_C	6.3	7.5	0	13.0	0-10	0
$\sigma(V_R)/V_R$	0.48	0.41	2.2	0.14		0.19
σ(N)/N	0.53	0.54	0.41	0.13		0.52

8. Asymmetries

The sheaths of planets, ICMEs, and the heliosheath may all be asymmetric. Studies of Earth's magnetosheath show higher densities in the dawn than dusk in both data and MHD results (Paularena *et al.*, 2001) and asymmetries in the magnetopause locations (Dmitriev *et al.*, 2004). MHD simulations predict similar asymmetries in ICME sheaths driven by the angle between the solar wind magnetic field and the solar wind flow (Siscoe *et al.*, 2007). The tilted field drapes around the ICME asymmetrically, giving an east-west asymmetry in the sheath radius and thickness. The Voyager spacecraft showed that the TS is 10 AU closer in the V2 than the V1 direction (Stone *et al.*, 2008; Richardson *et al.*, 2008). Models show that CHISM field tilted with respect to the CHISM flow can produce such an asymmetry (Opher *et al.*, 2007; Pogorolev *et al.*, 2007).

9. Sheath plasmas

Sheaths are turbulent regions with variable plasma and magnetic fields. Table 1 compares the shocks and sheath variabilities at the outer planets, ICMEs, and the TS. The TS has a smaller Mach number and larger plasma beta than most of the bow shock crossings. The relative standard deviation of V in the heliosheath is smaller than in all the magnetosheaths except Neptune, which was apparently encountered during a time of very steady solar wind. Planetary bow shocks and magnetopauses, and thus the magnetosheaths, move in and out with changes in solar wind pressure causing large motions and speed variability in the magnetosheaths. The heliosheath is a much larger region which responds more slowly to solar wind changes. Large merged interaction regions, high density and magnetic field regions formed when ICMES merge, may be able to move the TS outward several AU (Zank and Mueller, 2003) and V1 Low-energy Charged Particle Experiment data suggest that the heliosheath plasma was moving inward following the TS crossing (Decker *et al.*, 2005), but variability would be expected to be much less, and is observed to be less, away from the TS. The density variation, however, is very similar in the magnetosheaths and in the heliosheath. This similarity suggests similar changes occur in the planetary bow shocks and TS, either motions of the shock surface or temporal variability in shock structure. The TS speeds calculated for the two complete TS crossings observed TS speeds are 90 km/s when the TS moved out past V2 and 70 km/s when the TS moved inward past V2; these speeds are comparable to the speeds of planetary bow shocks; the average speed of Earth's bow shock, for example, is 85 km/s (Formisano *et al.*, 1973). Flow angles are much more variable in magnetosheaths than in the heliosheath data measured to date. The EW flow angle has remained fairly constant in the heliosheath. Part of this lesser variability results from V2 traversing only the inner edge of the heliosheath. The flow is expected to rotate as the heliopause is approached and this rotation has been observed on V1 (Decker *et al.*, 2007).

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10. Summary

Shocks and sheaths are ubiquitous features of the Universe. Comparison of these features at ICMEs, planets, and the heliosphere boundary show both similarities and differences. The planetary and TS shocks are stationary reverse shocks whereas the ICME shock is a fast forward shock. The magnetosheath and heliosheath are in quasi-steady state while the ICME sheath accretes material and are thinner than the other sheaths. These are high-Mach number shocks; the planetary bow shocks (except Uranus) and most ICME sheaths have two populations of thermal ions, including a hot population presumably reflected at the shock. At the TS, most of the flow energy goes into the existing hot component, the pickup ions. All of these sheaths are asymmetric with asymmetries driven by a non-zero angle between the shock normal and the flow velocity which leads to asymmetric draping of the field around the obstacle. The heliosheath speeds and flow angles are much less variable than those in magnetosheaths, but the density variations are similar.

11. Acknowledgments

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