A comparison of magnetosheaths, ICME sheaths, and the heliosheath

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Abstract. Sheaths are regions of compressed, heated, decelerated, and deflected flow behind a shock. We compare three types of sheath observed in the heliosphere, planetary magnetosheaths, ICME sheaths, and the heliosheath. Features common to these sheaths are plasma depletion layers, mirror mode waves, hot proton components, and asymmetries.

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INTRODUCTION

Sheaths are regions of shocked plasma between a shock and an obstacle to a supersonic flow. Two obstacles which produce quasi-stationary shocks in the solar wind are planetary magnetospheres and the local interstellar cloud (LIC). ICMEs are magnetic structures ejected from the Sun, sometimes at high speed. Shocks form ahead of high-speed ICMEs. ICMEs expand with distance, so ICME sheaths evolve with distance.

The scales of the interactions vary greatly. Planetary magnetosheaths range from the sheath of Mercury with a scale of $10^{-4}$ AU to that of Jupiter with a scale of 0.1 AU. Plasma residence times are minutes to hours. ICME sheaths increase in size with distance from the Sun and their scale lengths increase from 0.01 AU near the Sun to tens of AU near the termination shock. The shocked solar wind stays in the ICME sheath [1], so the plasma residence time is comparable to the travel time through the heliosphere, about one year. The heliosheath, between the termination shock (TS) and the heliopause (HP), has scales of tens to a hundred AU and plasma residence times of several years.

Despite these different scales, many similar features are observed in or predicted to occur in all three types of sheath. Plasma depletion layers (PDLs) are regions of enhanced magnetic field and depleted plasma density observed in the sheath near the magnetopause. This layer forms when the magnetic field is draped around a planet’s magnetosphere and compressed, driving the plasma along field lines out of this region [2]. PDLs have been observed at Earth, Jupiter, and Saturn and in front of ICMEs [3, 4, 5, 6, 7]. Mirror mode waves are observed in all three sheaths; they are often generated downstream of quasi-perpendicular shocks [7, 8, 9, 10, 11, 12, 13]. We also investigate the thermal proton distribution in these sheaths. At quasi-perpendicular shocks, some thermal ions pass through the shock and are heated. The rest are reflected upstream, then convected back to the shock where they are heated again, forming a hot proton component [14]. These distributions are observed in planetary magnetosheaths.
and we find them in ICME sheaths as well. The last common features we discuss are asymmetries which arise because of the magnetic field in the upstream flow or because of the shape of the obstacle.

**PLASMA DEPLETION LAYERS**

Figure 1 shows a PDL observed upstream of Earth [15], a PDL observed by Voyager 2 at Saturn [5], a PDL observed in an ICME sheath cloud [7], and a model prediction of a PDL near the heliopause [16]. The PDLs comprise about 25% of Earth’s sheath, about 35% at Saturn, about 45% at ICME sheaths, and about 40% in the heliosheath. The density decreases are of order 50% but less in the heliosheath model. All of the PDLs shown here were associated with enhanced magnetic field strength (shown only for Saturn); these regions have low plasma $\beta$, thus PDLs may be stable to mirror mode waves but unstable to electron ion cyclotron waves.
MIRROR MODE WAVES

Mirror mode waves grow in high $\beta$ plasmas when $T_\perp > T_{||}$, so that $T_\perp/T_{||} - 1 > 1/\beta_\perp$ [17], conditions often met in sheaths behind quasi-perpendicular shocks. These waves are characterized by large amplitude magnetic field perturbations which are linearly polarized with maximum variance along $B$ and are anti-correlated with the density fluctuations [18]. Mirror mode waves are not seen in PDLs where $\beta$ is low. Figure 2 shows mirror mode waves observed in the sheaths of Earth, Saturn, an ICME, and the heliosheath. Three types of structures are observed: the sinusoidal structures in the top panel are observed in all the sheaths. Peaks, or increases from a constant baseline, and dips, decreases below a constant baseline, are observed in all the sheaths except that of Earth.

The periods of the waves were 20 s. at Earth [19], 20-120 sec at Jupiter [20], and 2.5 - 7 minutes at Saturn [9]. At Earth, the waves are sinusoidal. In Jupiter’s and Saturn’s magnetosheaths, the plasma residence times are much longer and mirror mode waves have time to evolve. The magnetic field dips occur in low $\beta$ regions near the magnetopause; they may be the remnants of mirror mode structures in plasma which is no longer unstable to the mirror mode. Peaks are observed in higher $\beta$ plasma and occur most often about 24 hours after the bow shock. These peaks may occur in regions where mirror mode waves are saturated [20]. Sinusoidal variations occur throughout the magnetosheath in regions with intermediate plasma $\beta$. Amplitudes of these variations increase with distance from the bow shock for many hours and then sometimes reach a plateau.

The third panel of Figure 2 shows magnetic fluctuations anti-correlated with density in an ICME sheath which were identified as mirror mode waves [7]. Since ICME sheaths are not in steady state but accrete plasma and expand, mirror mode waves evolve over long time scales.

The bottom panel of Figure 2 shows magnetic fluctuations observed in the heliosheath [12] which are probably mirror mode waves [13]. Peaks and dips similar to those observed at Jupiter and Saturn are observed, both with periods of order a few hours. This example was probably observed at least 5 AU from the shock. The correlation of these features with $\beta$ will not be known until Voyager 2 enters the heliosheath.

ION DISTRIBUTIONS

Some of the ions encountering a quasi-perpendicular shock are reflected, then convected back to the shock and again heated, forming a hot proton component [14]. 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 [21]. This prediction seems valid at Earth, but Jupiter, Saturn, and Neptune often have much larger percentages of ions in the hot component, 30-60% [22, 23]. An example of such a distribution in Jupiter’s magnetosheath is shown on the left of Figure 3; two Maxwellians are used to fit the data.

ICME sheaths are often preceded by quasi-perpendicular shocks, although the Mach numbers are less than those at planetary magnetosheaths. We found several shocks in
FIGURE 2. Mirror mode waves, from top to bottom, at Earth, Saturn, an ICME, and in the heliosheath.

the Voyager data with signatures of reflected ions in ICME sheaths. The right panel of Figure 3 shows one such example from 1982 when Voyager 2 was at 13 AU. Log current (in femtoamps) is plotted versus energy channel, which is roughly logarithmic and extends from 10 - 5950 eV. These data follow a shock with a speed jump of about 150 km/s. The solar wind protons could not be fit with a single convected isotropic Maxwellian distribution, so we included a hot proton component in the fit. The hot component comprised about 40% of the solar wind protons and the temperature of the hot component was about nine times that of the thermal protons. In the solar wind upstream of the shock and in the ICME which followed the sheath, this hot component was not present, so it is accelerated at the shock. Similar distributions are observed in other ICME sheaths. The TS is a strong shock, but is modulated by the presence of 15-20% hot pickup ions. V2 will provide an opportunity to look at ion distributions in the heliosheath.
FIGURE 3. Proton distributions in the magnetosheaths of Jupiter and in an ICME sheath. The x axis shows the energy channel of the cup; the channel range in energy from 10 eV to 5950 eV and are roughly logarithmically spaced. Both show a thermal and a hot component. The ratio of the hot/total density is 0.54 for the Jupiter spectrum and 0.4 for the ICME spectrum. The ratios of the hot/cold temperatures are 6 and 9, respectively.

ASYMMETRIES

Sheath asymmetries can be driven either by a non-spherical obstacle or by magnetic fields in the flow. At Earth, densities on the dawn are greater then those on the dusk, an asymmetry possibly resulting from the tilt of the interplanetary magnetic field in the Parker spiral direction [24]. Jupiter’s and Saturn’s bow shocks and sheaths are flattened since the ring currents at these planets cause a larger interior pressure at the equator. The heliosheath is asymmetric [25], with the TS and HP closer to the Sun in the south than in the north and a thinner sheath in the south. These asymmetries result from the tilt of the LIC magnetic field, similar to at Earth. Little is known about asymmetries in ICME sheaths, although they should be present.

SUMMARY

We give a broad overview of sheath regions, including planetary magnetosheaths, ICME sheaths, and the heliosheath. We point out several similarities and differences. PDLs form (or are expected to form) in all these sheaths. Mirror mode waves are observed, with periods increasing with distance in the steady state sheaths and longer periods in ICME sheaths. Both ICME sheaths and magnetosheaths have significant hot proton components behind quasi-perpendicular shocks. Asymmetries are observed or expected to occur due to the influence of the obstacle shape and due to the tilt of the magnetic field in the flow.
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