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OBSERVATIONS OF THE DENSITY PROFILE IN THE MAGNETOSHEATH NEAR THE STAGNATION STREAMLINE

P. Song, C. T. Russell

Institute of Geophysics and Planetary Physics, University of California

J. T. Gosling, M. Thomsen, R. C. Elphic

Los Alamos National Laboratory

Abstract. An enhancement in the plasma density occurs in more than half of the ISEE-1 and 2 magnetosheath passes near the stagnation streamline just in front of the magnetopause. On average, this structure is about 0.4 R_e thick and clearly separated from the magnetopause. The average density enhancement is about 44% above the ambient magnetosheath density. The anticorrelation of the magnetic field and density is that expected for the MHD slow mode. Strong fluctuations in the density within the structure are usually accompanied by fluctuations in velocity.

Introduction

In the absence of the interplanetary magnetic field (IMF) the solar wind interaction with the Earth should be well described by the gasdynamic model (e.g. Spreiter et al. 1966). This model predicts a monotonic increase in plasma density from the bow shock to the magnetopause along the stagnation streamline. In the presence of the magnetic field in the flow, Pudovkin and Semenov (1985) predict that the density may increase, may decrease, or may increase then decrease, depending on the shear between the IMF and the magnetospheric field because reconnection affects the flow in the stagnation region. An alternate model of the effect of the IMF called the plasma depletion effect has been proposed by Midgley and Davis (1963), Lees (1964) and Zwan and Wolf (1976). This model predicts a density decrease along the stagnation streamline from the bow shock to the magnetopause.

Observationally, Crooker et al. (1979) found evidence that supports the plasma depletion model in a small data set from IMP 6. All the magnetopause crossings used in their study were more than 35° from the subsolar point, whereas the differences between the gasdynamic model and the plasma depletion model should be most profound near the stagnation region. Observations of the magnetic barrier at Venus (e.g. Russell et al., 1979) have also been considered to result from plasma depletion. Paschmann et al. (1978) and Song et al. (1990) have suggested that the plasma depletion may contribute to the formation of the magnetopause current layer for the northward IMF situation.

In this study, we use data from the ISEE-1 and 2 fast plasma experiment (Bame et al., 1978) to examine the density variations near the stagnation streamline from the bow shock to the magnetopause together with data from the ISEE-1 and 2 magnetometer (Russell, 1978).

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Magnetosheath Density Profile

We select the ISEE-1 and 2 passes with nearly complete measurements from the bow shock to the magnetopause in 1977 and 1978. To insure that the passes are near the stagnation streamline, the magnetopause crossings for these passes are all within 45° solar zenith angle from the subsolar point. We have a total of 26 such passes. Figure 1 shows the location of the magnetopause crossings for these passes.

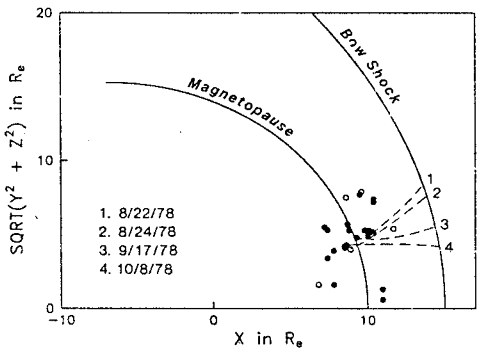

Fig. 1. The locations of the magnetopause crossings for the magnetosheath passes. The solid dots indicate passes with a density maximum in front of the magnetopause. The circles indicate passes without a clear density maximum or with strong fluctuations which make the identification of a density maximum difficult. The solid lines give the average magnetopause and bow shock locations for reference. The four passes presented in this letter are indicated by dashed lines.

Figure 2 shows an inbound pass. The magnetopause crossing is at 1835 UT. In this pass, the density increases essentially monotonically from the bow shock to the magnetopause. This is the only example with this behavior in our data set. We note that the magnetic field was extremely weak for this pass. The magnetosheath β, the ratio of the thermal pressure and magnetic pressure, is about 14. When β is much greater than unity we expect that magnetic field effects can be neglected. In other words the gasdynamics approach should be valid in this situation, and, in fact, the gasdynamic model predicts such a monotonic increase. The value of the density increase is higher than that predicted by gasdynamic model. This may be caused in part by temporal effects.

Figure 3 shows an example in which the density decreases from the bow shock to the magnetopause

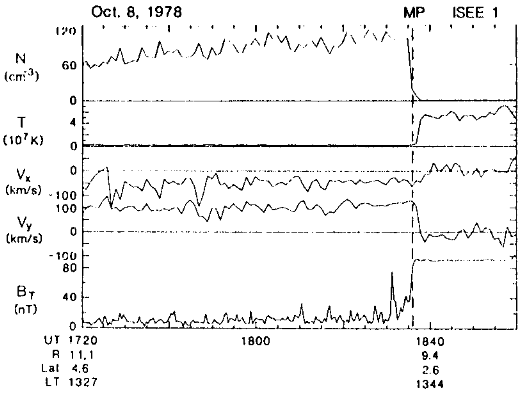

Fig. 2. An inbound magnetosheath pass. The magnetopause crossing is near 1835 UT and indicated by a dashed line. N, T, Vx and Vy are the density, temperature, and x and y components, in GSE coordinates, of the flow velocity measured by the Fast Plasma Experiment. B is the magnetic field strength measured by the magnetometer.

except for a small density enhancement near 1805 UT. We have two examples with this feature in our data set. The magnetosheath β is 3.3 and 1.8 for these two passes.

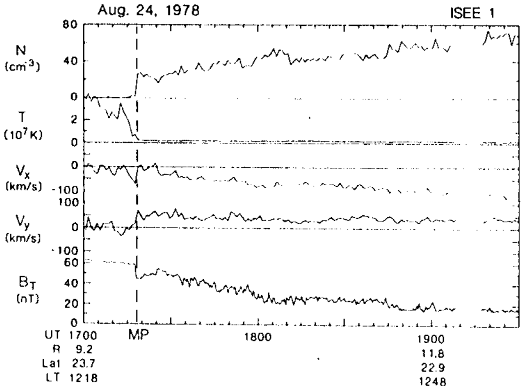

Fig. 3. An outbound magnetosheath pass.

However, for most of the passes, the density remains relatively constant over most of the magnetosheath. In an interval close to the magnetopause, the density increases dramatically and then decreases again in advance of the actual magnetopause crossing. Examples of this behavior are shown in Figures 4 and 5. In 17 out of 26 passes, we see such behavior. Solid dots in Figure 1 indicate the location of the magnetopause on those passes with density maxima in front of the magnetopause. Of the remaining 9 passes, three have a strong density trend as shown in Figures 2 and 3, one shows a density enhancement between two magnetopause crossings, and the rest have density fluctuations through the magnetosheath, are difficult to be identified as a single structure and are usually associated with solar wind density or pressure fluctuations.

Density Maximum in Front of the Magnetopause

Table 1 gives the parameters for the passes with density maxima. The magnetosheath density

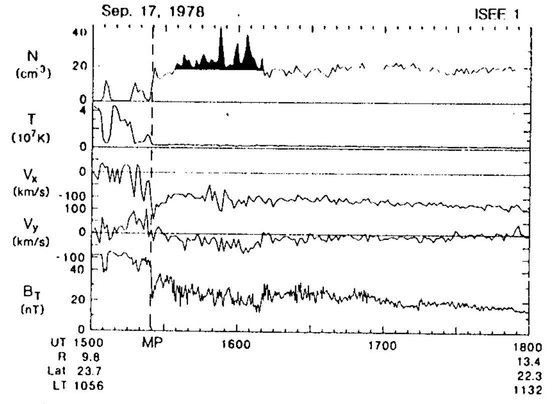

Fig. 4. An inbound magnetosheath pass. The shaded region indicates where the density enhancements were above the average upstream magnetosheath density.

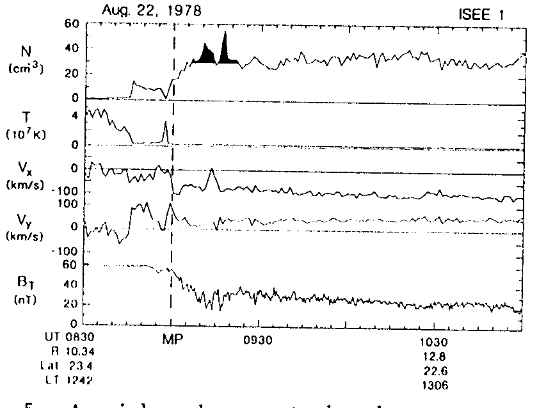

Fig. 5. An inbound magnetosheath pass with a density maximum in front of the magnetopause.

and β are taken from upstream of the density maximum over a time period of half to one hour. The density of the enhancement is averaged over the structure.

On average, the inner edge of the density enhancement is found 12 minutes upstream from the magnetopause currrent layer and lasts about 19 minutes. If we use a spacecraft velocity of 2km/s, we find it is separated from the magnetopause by about 1400 km and is about 0.4 R_e thick assuming the magnetopause remains fixed in space. The outer edge of the density structure is about 0.6 R_e from the magnetopause current layer. There is no clear dependence in its occurrence on the orientation of the IMF and hence on the shear between the IMF and the magnetospheric field. The average density increase over the entire structure is 44% above the ambient magnetosheath density, but as Figures 4 and 5 show the peak increases may be more than double the background value. These density enhancements occur over a wide range of β values. However, as Figure 6 shows, the amplitude of the averaged density enhancement depends inversely on β. The ratios of the x component of the flow velocity and the sound speed are well below unity within the density maximum for most of the passes. We will discuss the implication of this feature in the discussion section. Usually the field strength

Table 1. Observations of the Density Maximum in Front of the Magnetopause

ISEE	Year	Day	Time	Δt	ΔT	L	SZA	N_{sh}	N_{max}	$\Delta N/N_{sh}$(%)	B_z	β_{sh}	M_s
1	77	11/22	1132	29	28	1.1	25	60	75	25	≈0	2.8	.54
1	78	08/17	1208	19	21	.80	24	37	62	70	<0	.7	.32
1	78	09/27	0401	6	39	.90	35	19	29	52	≈0	.8	.96
1	78	11/01	1521	5	4	.93	3	30	48	60	>0	2.1	.10
1	78	11/06	0950	31	7	.76	6	40	51	27	≈0	3.7	.29
1	78	11/20	2010	6	11	.34	11	96	129	35	≈0	2.4	.24
2	77	11/08	0252	1	13	.28	27	17	21	21	≈0	2.3	.10
2	77	11/12	2256	1	11	.24	26	15	31	110	<0	.8	.17
2	77	11/17	1459	20	31	1.0	35	8	14	30	>0	2.7	.47
2	77	12/02	0159	45	21	1.3	37	26	42	63	<0	.7	.49
2	78	08/10	0935	12	10	.44	31	16	19	20	<0	2.5	.35
2	78	08/22	0859	6	15	.42	26	18	23	23	≈0	2.1	.39
2	78	09/08	0038	0	11	.22	26	8	14	74	<0	.3	.95
2	78	09/17	1517	16	36	1.0	27	11	15	32	>0	2.7	.47
2	78	09/21	2252	1	4	.10	37	14	25	76	>0	1.0	.72
2	78	09/22	1032	0	4	.08	28	10	12	20	≈0	1.0	.43
2	78	10/06	1959	0	25	.50	34	8	11	13	<0	4.1	.49

Time: Crossing time of the magnetopause current layer for the pass.
Δt: The interval, in minutes, from the crossing of the magnetopause current layer to the start of the density enhancement.
ΔT: Duration, in minutes, of the density enhancement.
L: Distance, in R_e, from the magnetopause to the outer edge of the density enhancement.
SZA: Solar zenith angle, in degrees.
N_{sh}: Magnetosheath density, in /cm^3, averaged over the region upstream of the density maximum.
N_{max}: The density, in /cm^3, averaged over the density maximum.
$\Delta N/N_{sh}$: $(N_{max} - N_{sh})/N_{sh}$.
B_z: Z component of the field in the magnetosheath.
β_{sh}: Ratio of the thermal pressure and the magnetic pressure taking from the upstream of the density maximum.
M_s: Ratio of the x component of the flow velocity and the sound speed.

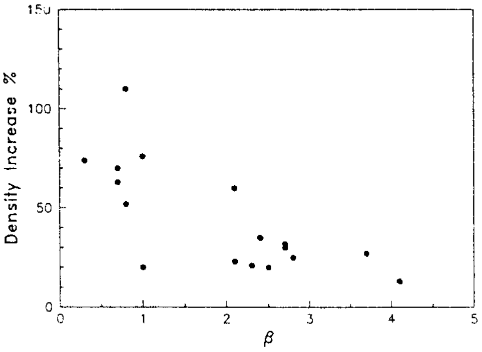

Fig. 6. The fractional density increase relative to the ambient magnetosheath density versus plasma β for the magnetosheath passes with the density maximum.

decreases while the density increases. This is characteristic of the MHD slow mode. The density maximum is, also, usually associated with strong plasma and field fluctuations. Magnetic fluctuations in this region are apparently different from the ambient magnetosheath waves. Usually, the observed frequency within the density structure is lower than the upstream magnetosheath waves. Determination of the wavelength and the direction of the propagation is beyond the scope of this letter and will be reported elsewhere.

An obvious question is whether the density enhancement is temporal rather than spatial in nature. We have checked the simultaneous solar wind data for all passes for which they are available. We find no correlation between the occurrence of the density maxima and solar wind density fluctuations. The relative changes in the solar wind density are usually much smaller than the relative density enhancements in front of the magnetopause. Moreover, the fact that these density enhancements preferentially occur immediate ly in front of the magnetopause and not at random throughout the magnetosheath demonstrates their spatial, as opposed to temporal, nature.

Finally by examining the magnetosheath passes with data from both ISEE-1 and 2 spacecraft, we find that the density structure is standing in front of the magnetopause moving with a very low speed compared with the background flow. A detailed study of this motion is beyond the scope of this letter and will be reported elsewhere.

Discussion

The density enhancement in front of the magnetopause is predicted by neither the gasdynamic model nor the plasma depletion model. We have also checked the dependence of the density structure on the shear between the IMF and the magnetospheric field and we find that it does not have the dependence of the orientations of the IMF as predicted by Pudovkin and Semenov (1985).

It is instructive to look at this phenomenon in terms of MHD waves. In order to divert the solar wind, waves propagate upstream from the magnetopause into the incoming flow. The waves with the fastest speed, appropriately entitled the fast mode, go farthest and eventually form the bow shock. The region downstream from the bow shock is subsonic to the fast mode waves, but can be still supersonic to the intermediate mode and slow mode waves. We expect to see the transitions of the flow to these two modes near the stagnation streamline along which the flow speed finally drops to zero. Thus these two modes could stand in the flow in the stagnation region if such waves are necessary to divert the flow in this region. Since there is only a change in the field direction corresponding to the intermediate mode waves, it is very difficult to identify this transition from the changes in the IMF although there are many sudden field rotations in each of the magnetosheath passes. The observed density maxima could be standing slow mode waves. The location of the structure depends on the local plasma parameters, the field orientation and the role of the wave in the flow diversion. In particular, slow mode waves may be a mechanism to convert the perpendicular flow from the transition to the subsolar magnetopause to the parallel flow needed to flow around the flanks of the magnetosphere in the equatorial regions. Because the slow mode speed is a fraction of sound speed depending on the angle between the field and the wave vector and becuase this angle is very difficult to determine, the exact slow mode speed for each pass is not shown in Table 1. Instead, we show the ratio of the x component of the flow velocity and the sound speed in the density maximum for each pass. If the normal of the density structure is in the x direction, this ratio has the similar meaning as Mach number for the slow mode wave propagating along the field. In most of the passes, this ratio, see Table 1, is well below unity. Therefore, the flow speed normal to the density structure appears to be subsonic to the slow mode speed.

Conclusions

We have examined the plasma density distribution on 26 passes through the magnetosheath near the stagnation streamline. One example is consistent with the prediction of the gasdynamic model. Two cases are supportive of the plasma depletion model. However, in more than half of the passes, we observed a density enhancement in front of the magnetopause not predicted by any present model. This structure is about 0.4 R_e thick and 1400 km away from the magnetopause. The average density increase is about 44% over the ambient magnetosheath density. This increase is inversely dependent on β and independent of clock angle of the IMF. The density enhancement is anticorrelated with field strength as expected for MHD slow mode waves. We interpret this structure to be a slow mode transition in the magnetosheath flow which assists the plasma to flow around the magnetospheric obstacle.

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C. T. Russell and P. Song, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024-1567.

R. C. Elphic, J. T. Gosling, and M. Thomsen, Los Alamos National Laboratory, Los Alamos, NM 87545.

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