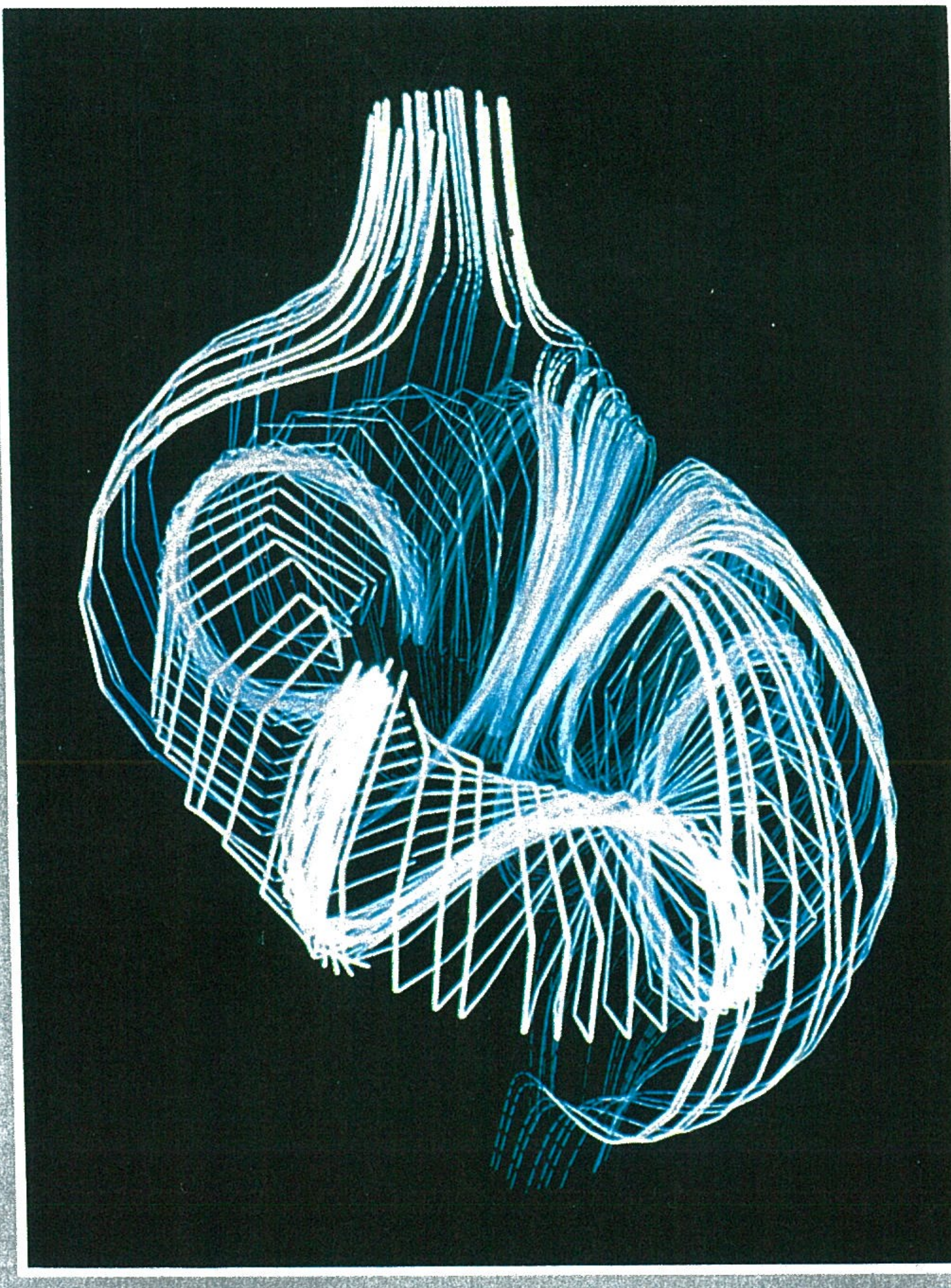
TWENTY YEARS OF PLASMA PHYSICS



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EARTH, JUPITER AND SUN - SIMILARITY OF PLASMA TRANSPORT ACROSS THE CAVITY BOUNDARIES

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ABSTRACT

The question of the structure of the heliopause is discussed from the point of view of the postulated magnetic reconnection processes. It is suggested that the plasma transport (mixing) across the heliopause should be an important phenomenon giving rise to a smearing out of the simple theoretical heliopause surface into a wide boundary layer.

1. INTRODUCTION

The problem of the structure of the heliopause, i.e. of the boundary between the solar wind plasma and the ionized component of LISM (Local Interstellar Medium) recently became a subject of some interest. After the early approach by Parker (1963) who investigated idealized cases of subsonic and supersonic solar wind imbedded in stationary/moving media, several authors recently discussed this problem in more realistic terms, taking into account the relative motion of the Solar System and the LISM as deduced from the scattering of solar UV on neutral gases in the LISM.

Baranov et al. (1979) developed a hydrodynamical nonmagnetic model describing the interaction between the supersonic solar wind and the supersonic LISM. The interaction region is separated from the supersonic solar wind (LISM) plasma by an inner (outer) shock wave. The heliopause separating the two shocked media (ion number density: n_2 for shocked LISM, n_1 for shocked solar wind) is assumed to be a tangential discontinuity with no plasma mixing across it. The typical plasma parameters in the interaction region are shown in Table 1.

In all previous papers, the plasma populations were considered to be kept strictly apart, while the neutrals were allowed to freely cross the heliopause.

An alternative approach was developed by Fahr and Neutsch (1983a,b) and Neutsch and Fahr (1983) in the general context of an astropause. In their hydromagnetic model the energy density of the magnetic field is high enough to insure the LISM flow to be sub-(fast) magnetosonic. The heliopause was also assumed to be a hydromagnetic (tangential) discontinuity surface allowing only for a kind of "diffusive" plasma flow across it driven by electrostatic microinstabilities.

The mixing due to hydromagnetic (combined Rayleigh-Taylor and Kelvin-Helmholtz) instabilities was recently studied by Ratkiewicz-Landowska and Grzędzielski (1984). Besides this hydrodynamical mixing, which could be most effective for weak magnetic fields (say, $B_2 \sim 10^{-7}$ Gs), other processes may also contribute to plasma exchange across the heliopause. The mechanism could be very similar to that operating at the planetary magnetopauses and could be associated with the reconnection of the magnetic field lines. This requires somewhat stronger fields (cf. Table 1).

In the present note we put forward arguments in favour of a substantial plasma mixing at the heliopause based both on hydrodynamical considerations and on an analogy with magnetospheric reconnection processes. We also provide order-of-magnitude estimates of the plasma mixing rate.

2. PLASMA TRANSPORT AT THE PLANETARY MAGNETOPAUSE

The concept of plasma mixing at the terrestrial magnetospheric boundary associated with magnetic field line reconnection is now generally recognized as having a firm experimental basis. As is evident from the in situ data (cf. Fairfield, 1979; Cowley, 1980), "patches" ("windows") of plasma transmission across the magnetopause constitute a quasi-permanent feature of the terrestrial magnetosphere. The degree of "openness" of the magnetopause can be defined as the average ratio α of the inflow velocity V_n to the local Alfénic velocity V_{An} corresponding to the normal (to the boundary) component of the external magnetic field B_n. The typical experimentally determined value of α, averaged over the magnetopause, is of the order of 10^{-1} (Kennel and Coroniti, 1979). Theoretical arguments proposed in the literature give the value of α from 0.1 (Petschek, 1964) to an upper limit of $1+\sqrt{2}$ (Sonnerup, 1970; 1979).

It was also recently suggested by Grzędzielski and Macek (1984) that the relatively high density inside the distant magnetotail of Jupiter can easily be explained by a moderate degree of openness of the Jovian magnetosphere. The resulting inflow of the outer, relatively dense ($\sim 10^{-1}$ cm^{-3}) and cold ($\sim$2 eV) solar wind plasma integrated over the length of the tail fills up the tail cavity (wake) with plasma of the observed density $\sim 3 \times 10^{-2}$ cm^{-3} (Kurth et al., 1982) if the parameter $\alpha \approx 0.3 - 0.4$. In the proposed picture the "patches" or "windows" of reconnection correspond to regions of the magnetopause where there is a magnetic field locally perpendicular to the boundary (rotational discontinuity). The same mechanism (using Grzędzielski and Macek, 1984, formula 2) can also easily explain the average density of $\sim$1 cm^{-3} observed by ISEE-3 in the boundary layers (i.e. wake) of the distant terrestrial magnetotail (220 Earth radii behind the planet, Bame et al., 1983). One obtains in this case again $\alpha \approx 0.3 - 0.4$. It is thought that this degree of openness, with the associated plasma inflow (mixing), can be expected whenever two plasma regimes characterized by values such as those in the discussed context come into contact (cf. Table 1).

3. PLASMA TRANSPORT AT THE HELIOPAUSE

It is appropriate to note that the plausible physical situation expected at the heliopause may resemble the situation at the distant terrestrial or Jovian magnetopause. Table 1 summarizes the most important plasma parameters on the two sides of the boundary for the distant magnetopause of Earth, Jupiter and the hypothetical heliopause. The relative (tangential) velocity of the bulk plasma motion on two sides is also given. It is evident that the contrast in all three cases seems very similar. One should emphasize, however, that while the values for Earth and Jupiter are based on in situ measurements, those for the heliosphere refer to the theoretically predicted schemes only. In particular, the magnetic field strength on the outer side of the heliopause is no more than an order-of-magnitude guess suggested by the astronomical data.

Using the suggested analogy as a basis, we estimate the (averaged over the whole boundary) inflowing plasma flux into the solar wind side of the heliosphere to be equal to $\sim \alpha v_{An} n_2$. Taking $\alpha \approx 0.1 - 0.3$, with the expected value of the interstellar magnetic field (normal component) $B_n \sim 10^{-6}$ Gs, one obtains the inflow velocity $v_n = \alpha v_{An} \approx 0.7 - 2$ km s^{-1}. The resulting transmitted/incident flux ratio is then 0.07 - 0.20.

4. CONCLUSIONS

The main result of our discussion is that one cannot expect the heliopause to be a well-defined surface separating the shocked solar wind from the shocked LISM plasma. Most probably it is a rather wide region with a substantial degree of plasma mixing inside. If the magnetic fields happen to be very weak, the width of the region will probably be determined by the hydrodynamical instabilities of the adjacent flows, with the Kelvin-Helmholtz modes dominant (Ratkiewicz-Landowska and Grzędzielski, 1984). The width of the region could then be of the order of ten or so astronomical units. In the case when the magnetic fields are of the order of at least $\sim 10^{-6}$ Gs (which seems more probable), the structure of the heliopause should be similar to that of the distant planetary magnetopause (interface: solar wind /wake/core). If this analogy is correct, then the transmitting properties of the heliopause should be taken into account in future investigations. Finally, we should like to stress that the structure of this layer should influence the diffusion of galactic cosmic rays into the solar cavity.

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Table 1. The change of the typical plasma-field conditions from the outer solar (interstellar) wind to the inner magnetospheric (heliospheric) side of the interfaces for the cases of: I. Terrestrial magnetosphere, II. Jovian magnetosphere (and III. Solar heliosphere).

	Interface at	density, cm^{-3}		temperature, eV		magnetic field, Gs		tangential velocity difference, km/s
		n_1	n_2	kT_1	kT_2	B_1	B_2	
		inner	outer	inner	outer	inner	outer	
I.	$Earth^+$ (tail) (lobe values)	$4x10^{-2}$	7	$\sim 10^2$	~ 10	$9x10^{-5}$	$6x10^{-5}$	200-300
II.	$Jupiter^‡$ (tail) (core values)	$3x10^{-3}$	$(1-2)x10^{-1}$	$\sim 2x10^2$ $\sim 6x10^2$	~ 2	$(1-2)x10^{-6}$	$5x10^{-6}$	100-200
III.	Sun^* (front heliopause)	10^{-3}	10^{-1}	$\sim 2x10^2$	~ 2	$\sim 10^{-6}$	$(1-3)x10^{-6}$	100-200

Table caption

+Typical plasma parameters measured by the ISEE-3 in the deep geomagnetic tail at $\sim 200\ R_E$ (lobe) are: density $n_1 \simeq 0.04\ \mathrm{cm}^{-3}$, the electron temperature $\sim 8\times10^5$ K (Bame et al., 1983) and the average tailward component of the tail lobe field is fitted to $B_1=9.1$ nT (Slavin et al., 1983). The average solar wind (outer) ion and electron temperatures are $T_i=8\times10^4$ K, $T_e=1.5\times10^5$ K (Slavin et al., 1983).

‡The plasma parameters measured by Voyager 2 in the distant Jovian magnetotail at 3-4 AU behind Jupiter (core) are typically: density $n_1 \sim 3\times10^{-3}\ \mathrm{cm}^{-3}$ and magnetic field $B_1 = 0.1 - 0.2$ nT (Kurth et al., 1982). The average solar wind (outer) magnetic field during the Voyager 2 mission was $B_2 = 4.5$ nT/r, where the heliocentric distance r is given in AU (Burlaga et al., 1982), and plasma density $n_2 \sim (1-2)\times10^{-1}\ \mathrm{cm}^{-3}$ (at ~ 3 AU, Lepping et al., 1982). The average tail temperature was estimated in two ways: from pressure balance with the standard solar wind one obtains $kT_1 \sim 0.2$ keV and from the solar wind kinetic energy dissipation corresponding to the velocity jump across the distant Jovian magnetopause (from 450 to 300 km s^{-1}, Lepping et al., 1982 Figs. 4,10) follows $kT_1 \sim 0.6$ keV.

*As suggested by recent Voyager 1 and 2 measurements (Kurth et al., 1984), the heliopause could be at ~ 50 AU, i.e. it is much closer than the hitherto discussed distances 100-250 AU. In that case either LISM at infinity is much denser or cosmic ray pressure is the dominant factor on the outer side of the heliosphere.

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