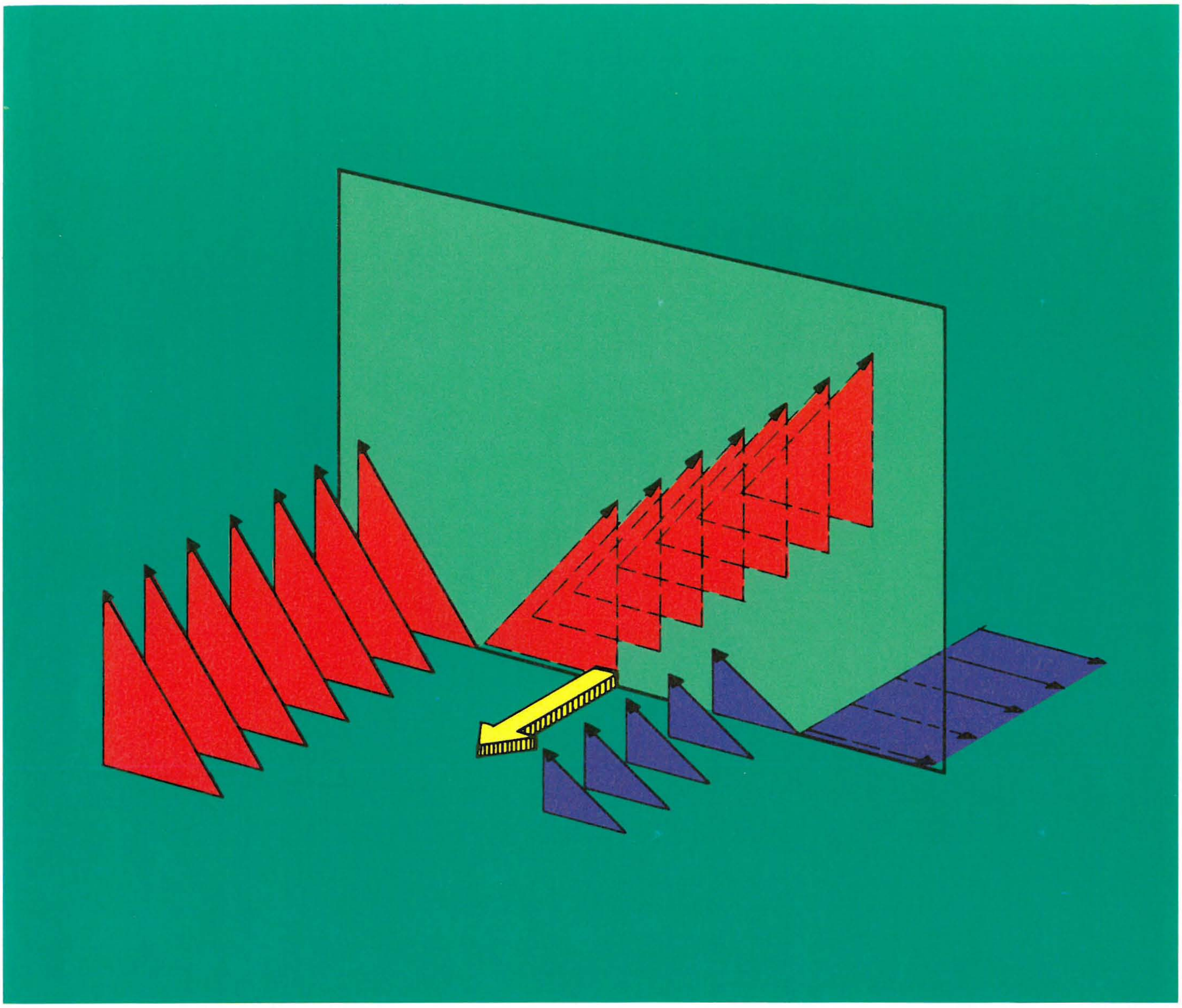
Interdisciplinary Study of Directional Discontinuities in the Solar Wind with ISPM



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Abstract The solar-wind plasma is not the uniform medium that most theoreticians have imagined for the purpose of constructing analytical models. Indeed, it contains large-scale as well as small-scale plasma irregularities or inhomogeneities. These collisionless plasma irregularities can be considered 'plasmoids' according to the definition given by Bostick[1] of 'plasma-field entities'. Two adjacent plasma elements are separated by current layers, which are sometimes as thin as a few ion gyro radii (1000–3000 km). Across directional discontinuities, the magnetic-field direction and intensity change rapidly. Depending on the type of variation shown by the magnetic field and plasma parameters, a directional discontinuity can be either a tangential discontinuity, a shock, a contact discontinuity, or a true rotational discontinuity. Theoretical models of these discontinuities will be developed as part of the ISPM investigation. The magnetic and particle observations obtained by ISPM will be used to check these models, and consequently to identify fundamental plasma-physical processes.

Figure 1 shows the values of the three components of the Interplanetary Magnetic Field (IMF) vector as measured by the GSFC magnetometer on Explorer-43 during a brief time interval on 24 March 1971. The spacecraft penetrated, at 16:33:48 UT, through a current layer into what has been called a 'magnetic hole'[2]. At 16:33:58 the spacecraft emerged from this region of low-magnetic-field intensity, and thereafter the field recovered its IMF background value of 7 nT. This spectacular event has been chosen here to illustrate the observation of a directional discontinuity in the solar wind at 1 AU in the ecliptic plane. Note that only one component (B_y) of the magnetic field changes. This variation is similar to that illustrated in the upper panel of Figure 2. The latter is the result of a model calculation based on a kinetic plasma theory of tangential discontinuities, as developed by Lemaire & Burlaga[3,4]. In addition to the change in magnetic-field intensity (B_y) produced by an electric current (J) flowing parallel to the x-axis, there is also a smooth variation in the plasma density (N), the ion flow speed (V), the kinetic temperature ($T_{\parallel}$ and $T_{\perp}$), and the electric potential (ϕ) when the surface of discontinuity is traversed along the z-axis, normal to the current sheet. The small fractional density of electric charges ($\Delta n/n$) required for $\phi(z)$ to satisfy Poisson's equation is shown in the bottom panel of Figure 2. It can also be seen that the polarisation electric field (E_z) which builds up in the direction normal to the surface of the magnetic hole reaches an intensity of 0.027 mV/m for the case illustrated in Figure 2.

At the surface of a 'plasma-field entity' or plasmoid[1] like that illustrated in Figures 1 and 2, all physical quantities vary significantly over distances of the order of the average proton gyro radius in the solar-wind plasma. Considering that the irregularity of Figure 1 is convected with the solar wind at a speed ~400 km/s, the minimum thickness of the current layer can be estimated from the time required for traversal, which in the present case is almost 4 s; if we assume normal incidence, we obtain a sheet thickness of about 1600 km or 10 proton gyro radii, at most. In the example of Figure 2, the current sheets are even thinner than this.

The time resolution of present-day magnetic-field measurements in space is usually high enough to determine the fine structure of such sharp magnetic-field 'discontinuities', but the best time resolution for direct plasma measurements is generally much lower. A time of at least 10–12 s (equal to the spacecraft spin

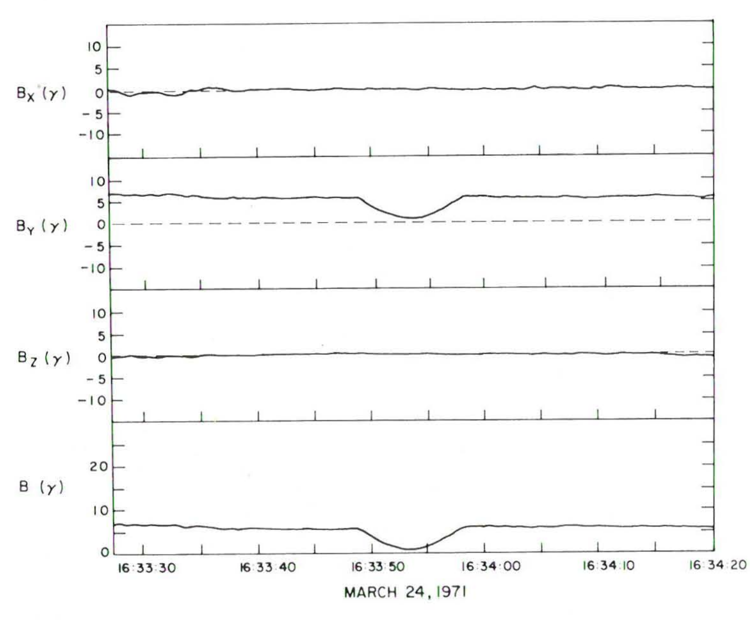


Figure 1. Magnetic hole observed in the solar wind with the GSFC magnetometer on Explorer-43. The magnetic-field components are given in a frame of reference determined by minimum-variance analysis[2]

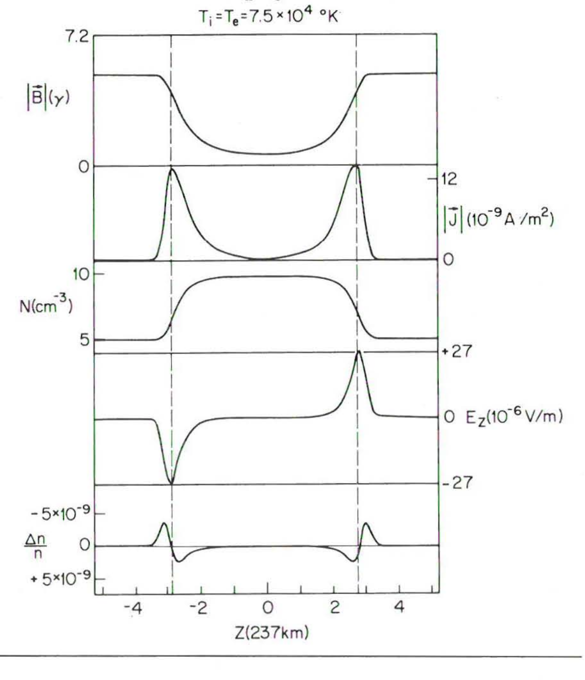


Figure 2. Model calculation for an isothermal magnetic hole in which the magnetic-field intensity decreases to 1 nT without changing direction and then increases symmetrically to its initial value[4]

period) is required to sample particles in all energy ranges and in all velocity directions. Consequently, the highest time resolution for plasma instruments corresponds to just one complete velocity distribution for each spacecraft rotation, i.e. one distribution for every 10 or 12 s. Over such a long period of time, the spacecraft has travelled a distance of 4000 km or more in the frame of the supersonic solar-wind plasma. The despun platform on the cancelled ISPM spacecraft would have given the scientific community a unique opportunity to obtain detailed three-dimensional particle-velocity distributions at time intervals shorter than the traversal time of the sharpest directional discontinuities.

Since the actual time resolution of solar-wind plasma instruments will be much larger than the time ($\sim$1–5 s) required for the interplanetary vehicle to pass through a thin current sheet, interpretation of the observations will be much more difficult than had originally been anticipated. The particle fluxes measured in successive energy channels and successive solid angles must now be compared directly with the corresponding values deduced from theoretical velocity distributions calculated at different depths in the current sheet. This detailed comparison of theoretical calculations with magnetic-field and particle-flux measurements is one of the first objectives of the Interdisciplinary Study of Directional Discontinuities in the Solar Wind.

In Figure 1 the magnetic-field direction inside the magnetic hole is parallel to the external IMF, but this is a rather exceptional event. In general, the direction of the B-field on one side of the current layer makes an angle (θ) with the field direction on the other side of the surface of discontinuity. Depending on this angle, on the field intensities and on the plasma pressures, densities and bulk speeds on both sides, one can assign all one-dimensional directional discontinuities (DDs) to the various categories that have been described by Hudson[5] (see also Landau & Lifschitz[6] for such a classification).

The simplest (but also the rarest) events are those for which the magnetic component normal to the surface of discontinuity is exactly zero. Such a plasma structure is called a 'tangential discontinuity' (TD). The magnetic-field lines then run parallel to the current sheet. To model a tangential discontinuity it is convenient, as a first approximation, to assume that the surface currents are coplanar sheets extending from $-\infty$ to $+\infty$ in directions perpendicular to the z-axis. Figure 3 illustrates how the magnetic-field vector, as calculated by Roth[7] using a kinetic theory, rotates across such a one-dimensional TD. The plasma-and-field boundary conditions assumed on the two sides of this TD correspond to typical values observed on the inner and outer sides of the Earth's magnetopause. The numerical model developed at the Institute of Space Aeronomy in Brussels can be applied directly to tangential discontinuities already observed in the solar wind at low heliographic latitudes as well as those which might be discovered during the ISPM mission out of the ecliptic plane[7,12].

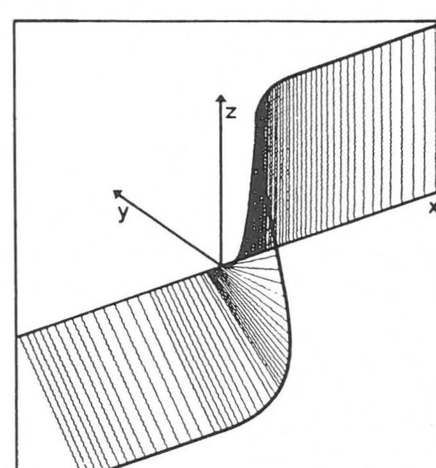
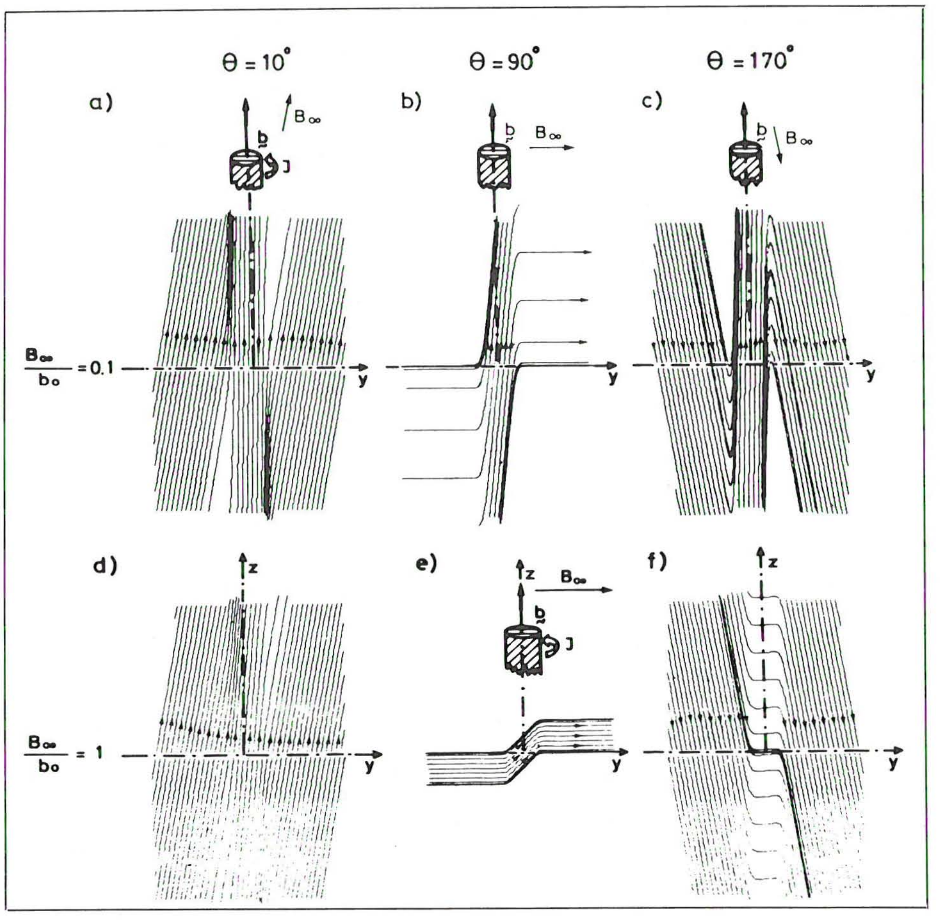


Figure 3. Three-dimensional representation of changes in the direction and length of a magnetic-field vector across a tangential discontinuity perpendicular to the x-axis. The plasma-and-field boundary conditions at $x = \pm\infty$ correspond to typical conditions in the magnetosphere and in the magnetosheath, respectively. The total length of the x-axis is 1075 km. The y- and z-axes are both 45 nT[7,12]

When the magnetic-field intensity has a nonvanishing component normal to the current sheet, the directional discontinuity is then often called a 'rotational discontinuity' (RD)[8]. Note that (in this category) one must distinguish between contact discontinuities, oblique shocks, nonoblique shocks, double layers and true rotational discontinuities[5,6]. A common feature among all of these discontinuities is that magnetic-field lines and flux tubes penetrate through the current sheet: they traverse the magnetic hole, slab, or filament, as is illustrated in Figure 4.

From Figure 4 it can be seen that the configuration of magnetic-field lines depends drastically on the direction θ and on the intensity $\vec{B}_\infty$ of the constant external magnetic field. The magnetic field $\vec{b}$ carried by the plasma element is parallel to the axis of the cylindrical plasmoid; it is produced here by a solenoidal surface-current

Figure 4. Configuration of magnetic-field lines produced by an infinitely long solenoidal current system superposed on a uniform external magnetic field ($\vec{B}_\infty$). The angle θ between the axis of symmetry of the cylindrical currents ($\vec{J}$) and the external field is assumed to be 10°, 90° and 170°, respectively. The intensity of the external field relative to the solenoidal magnetic field ($\vec{b}$) varies from 0.1 (top panels a, b, c) to 1.0 (bottom panels d, e, f). Note the interconnection of magnetic flux inside and outside the filament, except in the ideal cases $\theta = 180°$ (i.e. for special magnetic holes like those of Figs. 1 and 2) and $\theta = 0°$ (i.e. for some special magnetic anti-holes[4])



system J. In contrast to the case of the one-dimensional TD illustrated in Figures 2 and 3, the magnetic flux inside the plasma-field irregularity here is linked to the magnetic flux outside. In all the two-dimensional models of cylindrical plasmoids illustrated in Figure 4, there are only two lines along which B_n, the magnetic-field component normal to the surface layer, is precisely zero; only along these two lines or in their vicinity can the structure of the discontinuity be described as approximately a TD. Everywhere else the discontinuity is an RD, since B_n is not equal to zero.

A completely satisfactory kinetic theory describing the detailed structure of RDs has not yet been published, as far as we know. Thus, it will also be one of the objectives of the present Interdisciplinary Study to develop one-, two- and possibly three-dimensional models of directional discontinuities for which $B_n \neq 0$.

When the angle θ between the magnetic-field directions inside and outside the plasmoid is made equal to 180°, the magnetic lines become parallel to the axis of the infinitely long solenoidal current system. Under these circumstances, there is no longer a magnetic connection between the interior of the solenoid and the magnetic flux outside. This isolation results from the assumption that the solenoid has infinite length. In the real world, however, plasmoids are always of finite extent, and (as for all solenoids of finite length) there is interconnection between the magnetic flux inside and outside. This discussion shows that it is sometimes misleading to use two dimensional models (and *a fortiori* one-dimensional models) to represent the three-dimensional reality[9].

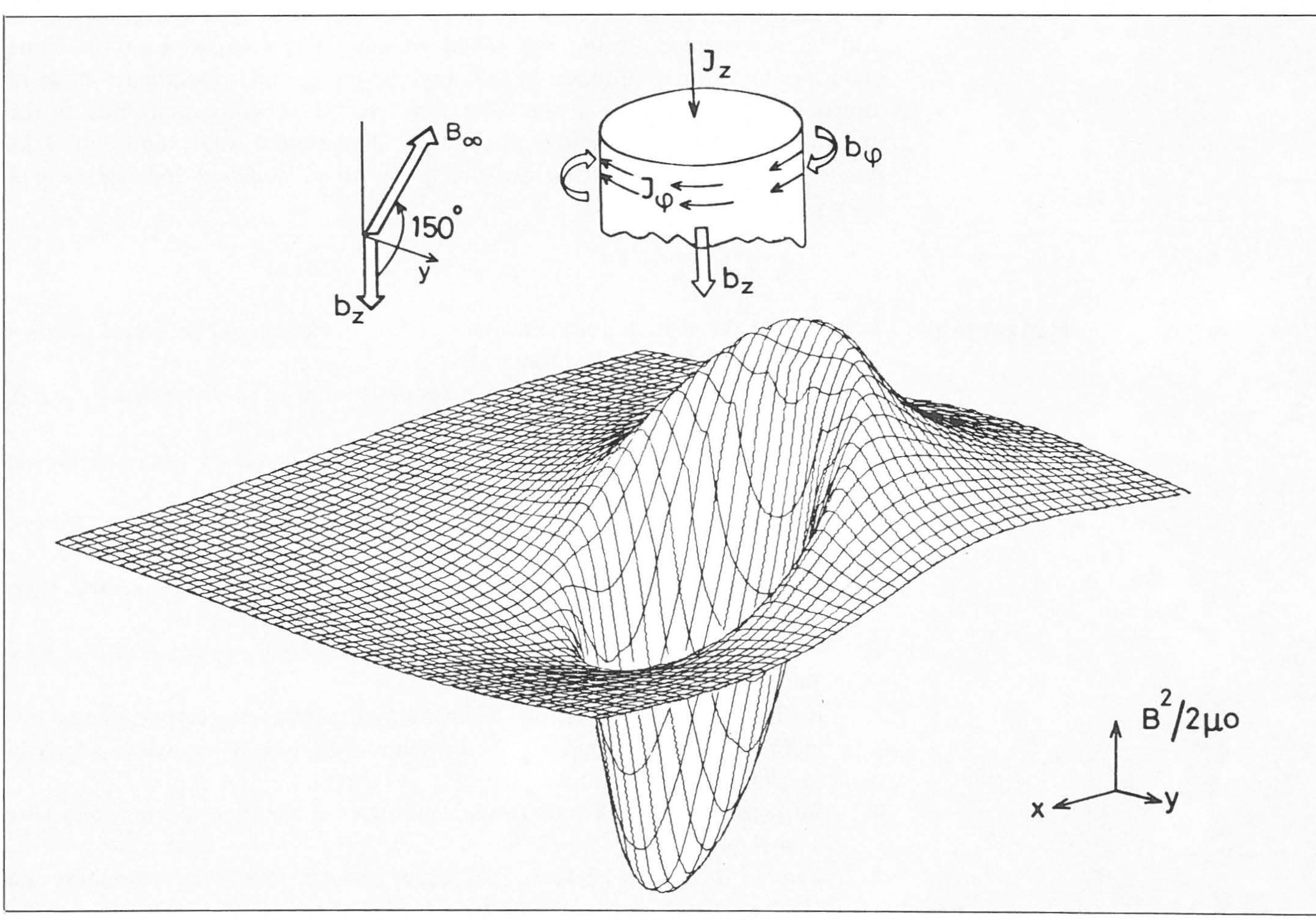
When the angle θ is 180°, the magnetic pressure inside the plasmoid is smaller than that outside, as is illustrated by the magnetic holes shown in Figures 1 and 2. 'Magnetic humps' or 'anti-holes' which are sometimes observed in the solar wind[2] have also been interpreted by Lemaire & Burlaga[3] as magnetised filaments, but in these cases the angle θ is almost equal to zero instead of 180°.

There is no reason to restrict the plasma-current system to be solenoidal only. Figure 5 shows the magnetic-pressure distribution in the xy-plane, which is a cross section of a cylindrical plasmoid for which solenoidal currents have been combined with additional currents flowing parallel to the axis of symmetry of the infinitely long cylinder. In this case both solenoidal and toroidal magnetic fields must be superposed on the external field $\vec{B}_\infty$. Plasma distributions generating such a magnetic-field structure can be imagined and constructed. Such plasmoids are in mechanical equilibrium if the distribution of kinetic pressure satisfies the law of momentum conservation. If the perpendicular plasma pressure is reduced inside this plasma element, then the cross section and volume of the plasma element will shrink until the pressure balance between the inside and outside is eventually achieved, possibly after a few hydromagnetic oscillations.

Not only one-dimensional, but also two-dimensional models of TDs and RDs of infinite extent, in at least one direction, are sometimes poor mathematical representations of real three-dimensional plasmoids, which can assume any shape (as clouds in the gravitational field do)[9]. In addition to having a finite volume, a finite mass, and finite linear and angular momenta, actual solar-wind plasma elements can have finite magnetic dipoles and other multipoles. Moreover, a plasmoid having a finite dipole moment may interact significantly with the magnetic dipole of another magnetised plasmoid, or even with the magnetic dipole of a planetary magnetosphere[10,11].

All these problems of basic plasma physics need to be addressed from various

Figure 5. Distribution of magnetic pressure ($B^2/2\mu_0$) across a two-dimensional solenoidal plasma filament in an external magnetic field $\vec{B}_\infty$ of 2 nT. The solenoidal currents ($\vec{J}_\perp$) produce a magnetic-field perturbation ($\vec{b}_z$) parallel to the axis of symmetry of the filament. The central value of b_z is $-\sqrt{3}$ nT. The thickness of the current layer is 0.25 times the radius of the solenoid. There are also currents (J_z) flowing parallel to the z-axis and producing a toroidal field perturbation ($\vec{b}_\perp$). The inclination of the external field is $\theta = 150°$. Note that the magnetic energy density is depressed in the middle of this magnetic hole or filament. To avoid expansion or implosion of this B-field distribution, the current-carrying plasma must have a kinetic-pressure distribution satisfying the law of momentum conservation



theoretical viewpoints, but only detailed and reliable plasma and field observations will be able to tell us which are the best or most realistic theoretical models among those proposed to describe these microscale plasma structures.

Under certain extreme physical conditions one could expect plasma instabilities to occur at sharp directional discontinuities in regions where the plasma and magnetic field change rapidly. However, from the rather smooth variation of magnetic-field components observed across a variety of directional discontinuities in the solar wind (e.g. in Fig. 1), it can be concluded that within many thin plasma structures perturbations with wavelengths between 1000 and 10 km (i.e. with periods between 3 and 0.04 s) are not significantly unstable, i.e. that the amplitude of such waves does not grow exponentially with a time constant $\leqslant 3$ s. This conclusion does not exclude the possibility that certain categories of directional discontinuity may be dynamically unstable, or that TDs or RDs can be sources or generators of higher-frequency waves.

The spectra of any waves generated will be observed during the ISPM mission. We expect to compare these with theoretical spectra that we plan to calculate as part of the IDS project. How much does the presence of such waves invalidate the collisionless (or zero-order kinetic) approximation used to model these plasma discontinuities? This is a fundamental question that we wish also to address as part of our ISPM investigation. High-resolution AC magnetic and electric-field measurements would have been of great help in sorting out the most realistic models for describing the generation of such waves at sharp DDs.

The distribution of directional discontinuities in the ecliptic plane is already well documented in the literature, but we know nothing about their distribution at higher heliographic latitudes. Their frequency of occurrence, their type, their thickness, and their orientation are important statistical quantities that should also be investigated during the ISPM mission and compared to the same quantities for ecliptic latitudes. In this way, the present interdisciplinary study of directional discontinuities in the solar wind should not only contribute to the improvement of our knowledge of the three-dimensional solar wind and of its micro-scale structure, but it might also help toward an increased understanding of basic plasma physics.

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