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Magnetic field structure at the diamagnetic cavity boundary (numerical simulations)

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Abstract. A three-dimensional adaptive grid MHD simulation of the solar wind interaction with comet Halley shows that the boundary of the diamagnetic cavity is a closed, well defined surface. On this surface magnetic field neutral points should exist, and indeed, two O-type neutral points were found at the cavity boundary. In addition, the transition from closed magnetic field lines around the diamagnetic cavity to open field lines in the comet tail requires the formation of at least one X-type neutral point. Such a neutral point was also found in the simulated cometary ionosphere downstream from the cavity. The results of numerical simulations show that the plasma density near the neutral points increases significantly. This increase seems to be indicative of plasma escape from the diamagnetic cavity in the neighborhood of the neutral points, resulting in plasma jets.

1. Introduction

The innermost region of comet Halley's coma appears to be magnetic field free up to a distance of ~ 4000 km from the cometary nucleus [*Neubauer et al.*, 1987]. The magnetic field is swept out from this region by the nearly radially expanding ionized gas flow. A sharp jump in the magnetic field strength (approximately 20 nT per 10 km) forms the diamagnetic cavity boundary (hereafter DCB). The thickness of the DCB is of the order of an ion gyroradius [*Neubauer*, 1988]. *Cravens* [1986] was the first to explain this narrow boundary layer and to correctly include the density peak which co-exists with the current layer. *Goldstein et al.* [1989], using Giotto plasma data, were the first to observe fine structure of the DCB. At the DCB the outside magnetic pressure is balanced by the plasma dynamic pressure inside the cavity [*Israelevich and Ershkovich*, 1993]. Upstream from the DCB, there is a magnetic barrier which is maintained by the friction between the almost stagnating plasma in the barrier and the neutral gas outflowing from the nucleus [*Cravens*, 1986; *Ip and Axford*, 1987].

The three-dimensional structure of the diamagnetic cavity cannot be deduced directly from Giotto magnetic field measurements. In particular, it is not clear whether the boundary is well-defined everywhere around the nucleus, or becomes more and more diffuse with increasing distance from the subsolar point (as it happens with the ionopause of Venus [*Russell et al.*, 1979a,b]). The fact that Giotto observed a sharp DCB both on the inbound and outbound parts of its trajectory (both crossings took place at approximately 90° solar zenith angle (SZA)) leads us to expect the boundary is well-defined on the night side (for SZA > 90°) as well. In this case, the DCB is expected to be a closed surface surrounding the nucleus. Since the DCB encircles a region with zero magnetic field, the magnetic field lines at the outer side of the cavity are parallel to the boundary surface. Obviously, it is impossible to cover the closed surface by non-intersecting lines without singularities. In other words, at least one neutral point ($\mathbf{B} = 0$) should exist at the DCB, if it is a closed surface surrounding the nucleus.

Typical configurations with neutral points are sketched in Figure 1. Figure 1a shows a situation with two neutral points which is topologically equivalent to the magnetic field configuration near a superconducting sphere placed into a uniform external magnetic field. This configuration and its possible effect on the plasma flow in the inner coma was considered by *Israelevich and Ershkovich* [1998]. The opposite configuration is shown in Figure 1b. In this case two O-type neutral points can be found on the surface and all magnetic field lines are closed loops near the boundary. If such a situation occurs at a comet, an additional X-type neutral point should also exist somewhere in the tail in order to ensure the transition from closed magnetic field lines to open ones (which are typical for the cometary magnetotail). Finally, Figure 1c corresponds to a geometry with a single neutral point at the boundary. This geometry can be considered as a degenerated transition between the configurations shown in Figures 1a and 1b.

The single encounter of Giotto with comet Halley with two DCB crossings did not provide enough information to decide among the possible magnetic configurations. However, three dimensional numerical simulations constrained by available data can help us to understand the magnetic topology. The purpose of this paper is to analyze the results of 3D MHD simulations of comet Halley's interaction with the solar wind [*Gombosi et al.*, 1996, *Israelevich et al.*, 1999] from the point of view of the diamagnetic cavity structure. The simulation and its main results have been described in [*Gombosi et al.*, 1994, 1996; *Powell et al.*, 1999], and they will not be addressed here.

2. Results

In this discussion we will use the following coordinate system. The X axis is parallel to the upstream solar wind velocity vector, the Z-axis is parallel to the component of the interplanetary magnetic field (IMF) which is ortogonal to the solar wind velocity vector, and the Y-axis completes

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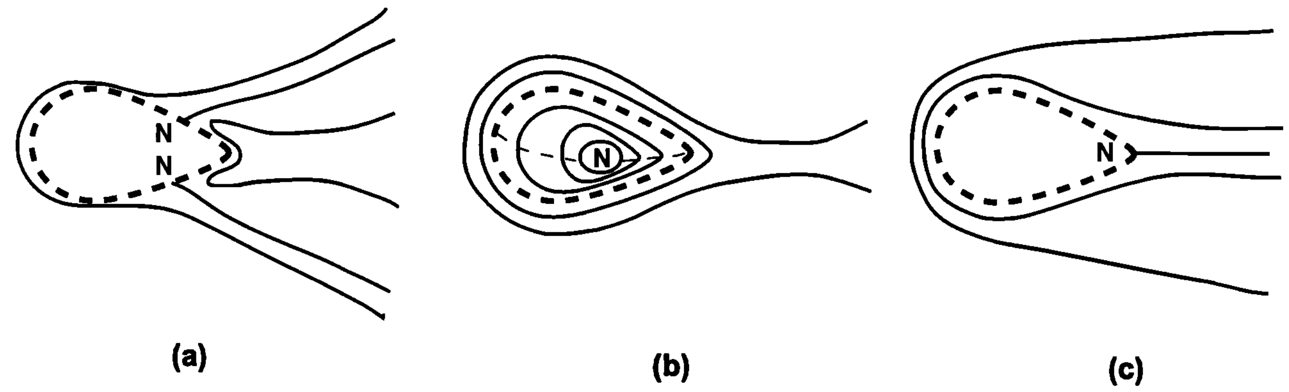

Figure 1. Topology of magnetic field lines in the vicinity of the diamagnetic cavity: (a) two cusp-like neutral points, (b) two O-type neutral points, and (c) single neutral point corresponding to a transition from state (a) to state (b).

the right hand coordinate system. Figure 2 shows the distribution of isolines for the magnetic field strength in the XZ plane (top panel), the directions of the magnetic field vectors along with several field lines in the same plane (middle panel), and the dependence of the B_z-component on x along the Sun-comet line (bottom panel). The axis on the figures are given in 10^6 km, and the magnetic field strength is given in dimensionless units which correspond to 6 nT. The distribution of the magnetic field magnitude shows that the diamagnetic cavity is well defined even on the night side, and the cavity boundary is sharp (rather than diffuse) everywhere. However, the direction of the magnetic field (defined by the B_z-component) at the night side boundary is opposite to that of at the dayside (and that of the IMF). This suggests that the magnetic field configuration is similar to the one depicted in Figure 1b. It can be seen in lower panel

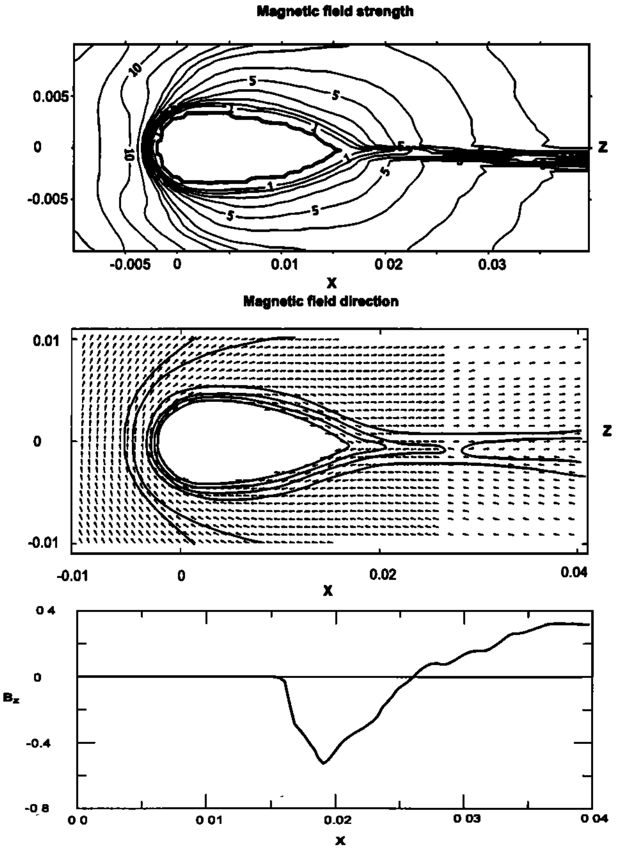

Figure 2. From top to bottom: isolines of the magnetic field strength in the XZ plane, magnetic field directions and field lines in the XZ plane, and B_z-component profile along the X axis on the night side of the diamagnetic cavity.

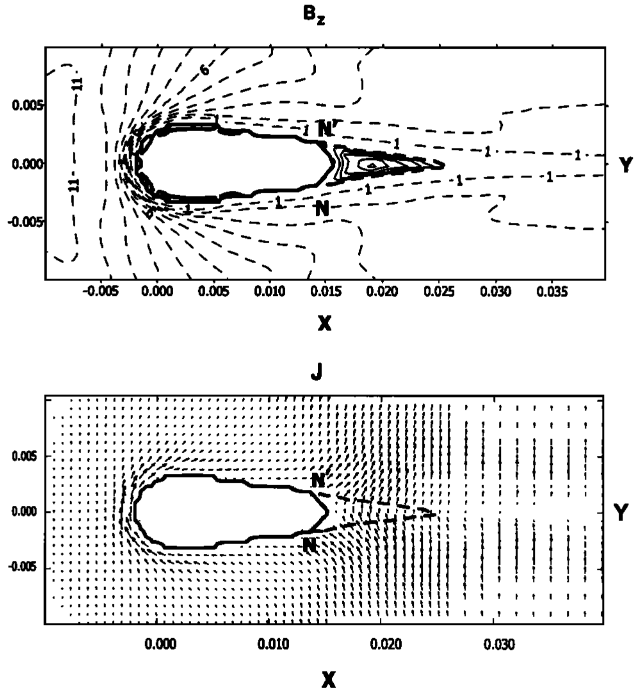

Figure 3. (Top) isolines of B_z-component in the XY plane. Dashed lines correspond to positive B_z, solid lines correspond to negative Bz, and thick solid line shows the DCB, and thick dashed line corresponds to the neutral line. (bottom) distribution of the electric current density vectors in the XY plane. Solid line corresponds to the DCB, dashed line shows the neutral line.

of Figure 2 that at the tailward end of the diamagnetic cavity the perpendicular magnetic field component (B_z) changes become positive and point in the direction of the IMF. For symmetry reasons the B_y and B_x components are zero along the Sun-comet line. Hence, the point at $x = 0.025$, where $B_z = 0$ is an X-type neutral point. Neutral points of O-type lie on the DCB near the XY plane. Since in this plane $B_x = B_y = 0$, therefore $B = |B_z|$.

The top panel of Figure 3 shows the isolines of B_z in the XY plane. The thick solid line shows the DCB. Dashed lines correspond to negative values of B_z, whereas solid lines correspond to positive ones. The line $B_z = 0$ (thick dashed line) is, in fact, the neutral line. It ends at the DCB indicating the positions of two neutral points N and N'. An O-type neutral point on the DCB surface represent a singularity of the electric current. The bottom panel of Figure 3 shows the distribution of the electric current density vectors in the XY plane. Inspection of Figure 3 shows that electric current lines drape around the diamagnetic cavity (this effect was observed by Giotto [*Israelevich and Ershkovich*, 1994, Figure 9]). At the neutral points, the electric current density vector is normal to the boundary surface, and the current diverges in the vicinity of these points along the surface.

Figure 4 shows the distribution of the magnetic field directions at the cavity boundary as viewed from the tail in the sunward direction. Two O-type neutral points are seen in this projection. The Figure is a view of DCB from the tail showing projections (to the YZ plane) of grid points which are closest to the DCB. For this reason, there are several vectors emerging from the same point - several grid points are projected at the same point on the YZ plane.

The radially expanding neutral gas is continuously ionized by the solar UV radiation. Inside the diamagnetic cavity the ionized particles continue to move with the same velocity as their neutral parents exhibiting a radial outward plasma flow. This outflow of the ionized gas is stopped at the DCB where its dynamic pressure is balanced by the outside magnetic field. Neutral particles can freely leave the cavity and continue to be exposed to ionizing radiation. However, beyond the diamagnetic cavity, the newly produced ions do not continue to move with the neutrals but instead gyrate around the moving magnetic field lines. Outside the cavity the friction force resulting from relative motion of the neutral and ionized particles supports the magnetic barrier. If, however, a neutral point is formed at the DCB, there is no "lid" to keep the radially expanding ionized particle flow (generated inside the cavity) inside the cavity and ionospheric plasma can leave the cavity in the vicinity of the neutral point in the form of plasma jets. This effect can be seen in Figure 5 which shows the distribution of the plasma density in the XY plane. The thick white line represents the position of the DCB, whereas the dashed white line corresponds to the neutral line. The plasma density increases significantly near the neutral line, mainly because of plasma escape from the cavity near the neutral points N and N'. At these points plasma jets are formed.

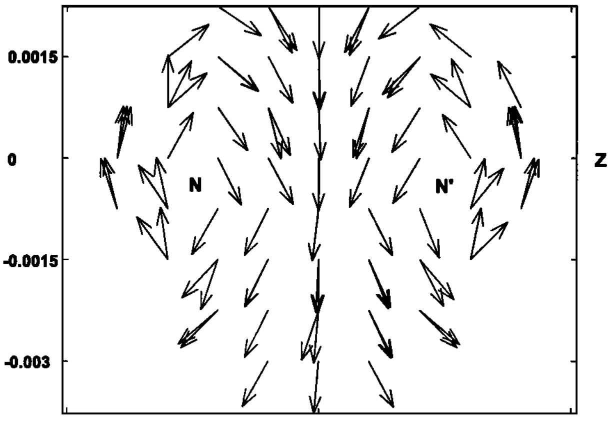

Figure 4. Projections of magnetic field vectors which belong to the closest vicinity of the diamagnetic cavity boundary on the YZ-plane.

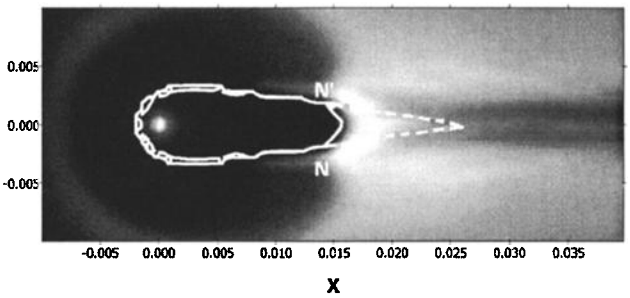

Figure 5. Distribution of the plasma density in the XY-plane. White line corresponds to the DCB, white dashed line shows the neutral line.

3. Conclusions

A three-dimensional adaptive grid simulation of the solar wind interaction with comet Halley show that two O-type neutral points are formed at the DCB. These two points are connected by a neutral line in the XY plane. The point where this line crosses the XZ plane is an X-type neutral point. All magnetic field lines in the immediate vicinity of the DCB are closed and they intersect the XY plane in the region between the cavity boundary and the neutral line. Near the neutral points, the ionized gas outflow from the nucleus leaves the cavity giving rise to plasma jets.

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