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Fine structure of the diamagnetic cavity boundary in comet Halley

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[1] We calculated the electric current density in the diamagnetic cavity boundary layer (DCBL) using magnetic field data obtained during the Giotto mission to comet Halley. This current possesses both the component perpendicular to the local magnetic field and the parallel component. The perpendicular current is responsible for the screening of the diamagnetic cavity boundary from the field in the magnetic barrier. This current is supported by the electric field tangential to the boundary. The behavior of the parallel electric current component resembles the Alfvén wings which arise due to the interaction of the magnetized plasma flow with a conducting obstacle. However, the electric current connecting the two wings does not flow through the whole volume of the obstacle. On the contrary, the wings are connected by the perpendicular current in the DCBL. In the inner portion of the DCBL this current diverges producing the parallel current component whose direction is opposite to that in the outer portion of the DCBL. In order to support such a current system at the diamagnetic cavity boundary, the potential drop across DCBL should be as small as 0.5V. Such a small value of the potential drop agrees with the penetration depth of cometary ions from the cavity to the magnetic barrier: it is equal to the ion gyroradius and therefore is not affected by any significant electric field normal to the diamagnetic cavity boundary. *INDEX TERMS:* 6025 Planetology: Comets and Small Bodies: Interactions with solar wind plasma and fields; 6030 Planetology: Comets and Small Bodies: Magnetic fields and magnetism; 6028 Planetology: Comets and Small Bodies: Ionospheres—structure and dynamics; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; *KEYWORDS:* diamagnetic cavity, comet, electric currents, boundary

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1. Introduction

[2] A conducting obstacle in a magnetized plasma flow short-circuits the Lorentz electric field $-\frac{1}{c}\mathbf{v} \times \mathbf{B}$, thereby representing a load for a unipolar generator. In their pioneering work, *Drell et al.* [1965] have treated the unipolar inductor model in linear approximation. They have shown that the current closure through the plasma flow may be interpreted as Alfvén waves - called 'Alfvén wings'. They are standing waves in the obstacle frame of reference. A non-linear analytical model for Alfvén wings was built by *Neubauer* [1980], who has shown that the currents feeding the plasma obstacle are aligned with Alfvén characteristics and that the Alfvén wings act as an additional external load. *Neubauer* [1980] also has shown that the perpendicular (to the wing axis) currents in the Alfvén wings are closed in loops not generally connected with the obstacle. Combination of currents allowed *Goertz* [1980] to find self-consistent solution for the electric field which decreases approaching the obstacle. However, these models were developed in order to describe the interaction of the corotating Jovian magnetospheric plasma with Io. They allowed the electric current to flow through the whole volume of the obstacle. This is not the case for the inner coma of comet Halley which may also be treated as an obstacle in the magnetized plasma flow.

[3] A magnetic field free cavity with radius of ~4000 km surrounds the nucleus of the comet [*Neubauer et al.*, 1986], and there is a magnetic barrier in front of the cavity. The friction force between almost stagnating plasma and outflowing cometary neutrals generates the electric current which creates the magnetic barrier [*Cravens*, 1986; *Ip and Axford*, 1987]. The electric current induced in the stagnating plasma by the Lorentz electric field $-\frac{1}{c}\mathbf{v} \times \mathbf{B}$ violates a cylindrical symmetry of this current. This current is closed through the solar wind via Alfvén wings [*Neubauer*, 1980; *Goertz*, 1980] and is responsible for the day/night asymmetry in magnetic field line draping about the cometary head, thereby giving rise to the magnetic tail. The electric current is absent inside the diamagnetic cavity. Therefore, the

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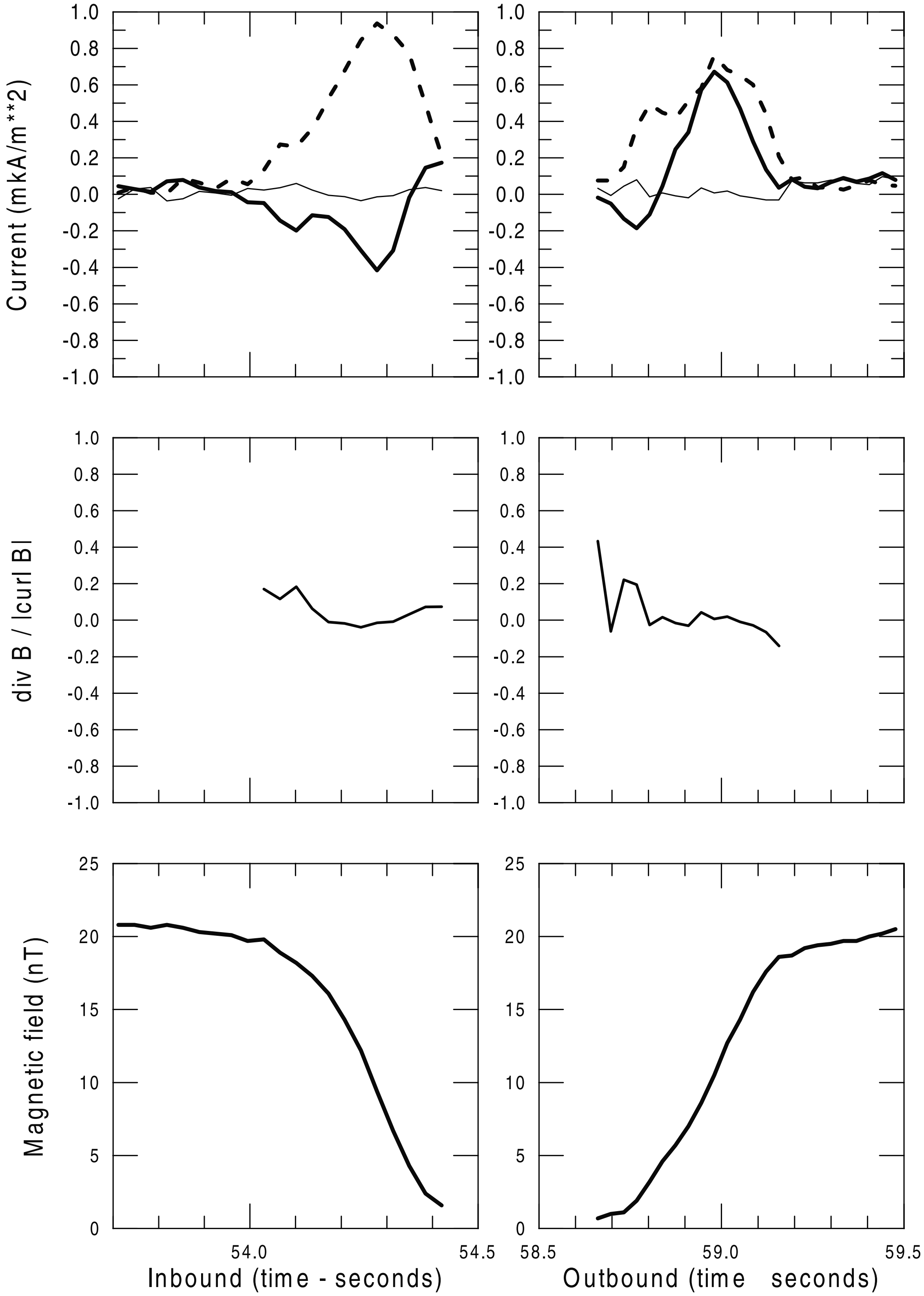

Figure 1. Top: parallel (thick solid line) and perpendicular (dashed) electric current in the DCBL, along with the $\partial B_x/\partial z$ value (thin solid line). Bottom: magnetic field across the DCBL.

electric current flowing in the magnetic barrier drapes about the diamagnetic cavity, the effect known from the Giotto magnetic field measurements [*Israelevich and Ershkovich*, 1994]. The diamagnetic cavity and the magnetic barrier are separated by a rather thin (~20 km) transition region, the diamagnetic cavity boundary layer (DCBL), [*Neubauer*, 1988] where the magnetic field jumps from zero up to ~20 nT. One-dimensional MHD [*Cravens*, 1989] and

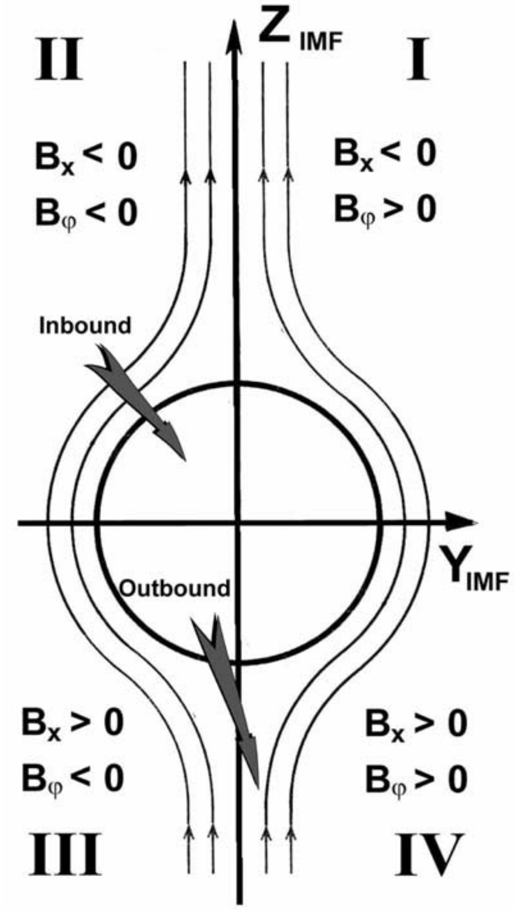

Figure 2. Side magnetic field draping near the diamagnetic cavity. Arrows show schematically the Giotto crossings of the DCBL.

hybrid simulations [*Flammer et al.*, 1991; *Puhl-Quinn and Cravens*, 1995] predict that a narrow layer of enhanced plasma density exists within the DCBL.

[4] The fine structure of the DCBL remains enigmatic. In particular, it is obvious that at least one neutral point should exist at the diamagnetic cavity boundary [*Israelevich and Ershkovich*, 1998]. Unique Giotto traversal through the diamagnetic cavity does not enable us to discriminate unambiguously between possible magnetic field topologies near the DCBL, whereas the numerical simulation favors two *O*-type neutral points configuration [*Israelevich et al.*, 2000]. It is also unclear how the electric current at the DCBL is connected to the currents flowing in the magnetic barrier. In this paper we will try to answer these questions by studying the fine structure of the DCBL electric circuit.

2. Fine Structure of the Electric Current at DCBL

[5] Giotto spacecraft crossed the boundary of the diamagnetic cavity twice, at the inbound and outbound legs of the trajectory, moving approximately along the normal to the DCBL. Figure 1 (bottom panels) shows the strength of the magnetic field as observed during the DCBL crossings. Since the path of the spacecraft within the boundary (~20 km) was much less than the radius of DCBL curvature (~4000 km), it is possible to consider the boundary near each of crossings as a plane. We introduce the coordinate system $X'Y'Z'$ in such a way that the axis Z' is along the normal to the DCBL at the point of crossing (of course, these systems are different for the inbound and outbound DCBL encounters). The assumption about the planarity of DCBL means that only spatial derivatives in the Z' direction are significant. Hence, we calculate the electric current along the DCBL crossings as

$$\begin{aligned} j_{x'} &= \frac{c}{4\pi}\frac{\partial B_{y'}}{\partial z'} \\ j_{y'} &= -\frac{c}{4\pi}\frac{\partial B_{x'}}{\partial z'} \\ j_{z'} &= 0 \end{aligned} \tag{1}$$

[6] The obtained electric current can be easily separated into components parallel and perpendicular to the local magnetic field.

[7] The normal to the DCBL in the vicinity of the crossing was determined by the minimum variance method [*Sonnerup and Cahill*, 1967]. The eigenvalues are: λ_1 = 50.9818, λ_2 = 1.0622, λ_3 = 0.0247 for the inbound crossing, and λ_1 = 51.0540, λ_2 = 3.1603, λ_3 = 0.0155 for the outbound crossings. As in both cases, $\lambda_3 \ll \lambda_2 \ll \lambda_1$, the assumption about DCBL planarity is validated. The eigenvector corresponding to the smallest eigenvalue determines the direction of the normal to the boundary.

[8] The upper panels of Figure 1 show the time profiles of the parallel (thick line) and perpendicular (dashed line) electric current during the Giotto DCBL crossings along with the corresponding profiles of the magnetic field strength (lower panels). The quantity $\partial B_z/\partial z$ is equal to $\nabla \cdot \mathbf{B}$ under our assumptions, and therefore its smallness may be used as another check of the boundary planarity approximation. The ratio of $\nabla \cdot \mathbf{B}$ to $|\nabla \times \mathbf{B}|$ is shown in the middle panels of Figure 1, and, indeed, it happens to be much smaller than 1.

[9] The parallel (to the magnetic field) component of the electric current, $j_{\|}$, is found to be significant, being comparable with the perpendicular component, $j_{\perp}$. The component $j_{\|}$ has opposite signs on the inner and outer sides of the DCBL. For the inbound crossing, $j_{\|}$ is negative on the outer side of the boundary and positive on the inner side. At the outbound, $j_{\|}$ is negative on the inner side and positive at the outer side of the DCBL. The parallel component of the electric current on the inner side of the DCBL is much smaller (by a factor of 5) than the parallel current on the outer side. However, in order to analyze this behavior of the parallel electric current, one should know the geometry of the DCBL crossings.

[10] The induced magnetosphere of a comet rotates around the Sun-comet line following rotation of the interplanetary magnetic field (IMF). Therefore, the coordinate system $X_{IMF}Y_{IMF}Z_{IMF}$, adequate for presentation of the induced magnetospheres, also should follow the IMF vector orientation and is defined in a following way: the X_{IMF} - axis is directed opposite to the solar wind velocity vector, and Z_{IMF} is chosen in such a way that the IMF vector is parallel to the $X_{IMF}Z_{IMF}$ plane. It appeared possible to restore Giotto

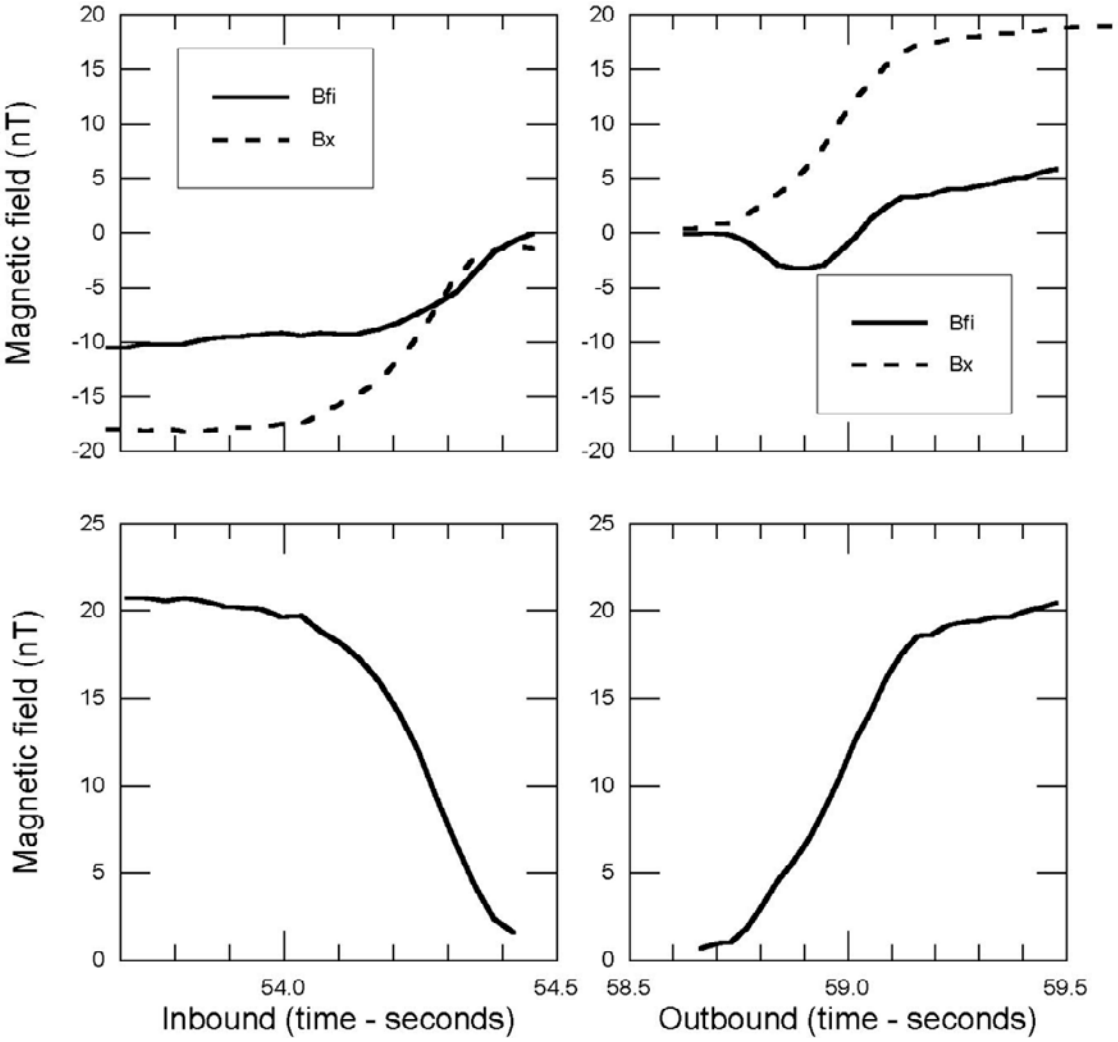

Figure 3. Top: Azimuthal (B_φ) and axial (B_x) components of the magnetic field. Bottom: magnetic field strength across the cavity boundary.

coordinates in the $X_{IMF}Y_{IMF}Z_{IMF}$ system during the spacecraft flight through the magnetic barrier by using the magnetic field measurements [*Israelevich et al.*, 1994]. The position of the spacecraft between two crossings of the DCBL changed from $X_{IMF} = -1000$ km to $X_{IMF} = 2000$ km, therefore the spacecraft trajectory was rather close to the $Y_{IMF}Z_{IMF}$ plane. However, the position of the spacecraft in this plane during DCBL crossings was not determined in [*Israelevich et al.*, 1994] as the time resolution of this method was insufficient. For this reason, here we will determine the positions of crossings using the following considerations.

[11] Figure 2 shows schematically the magnetic field configuration near the DCBL in the $X_{IMF}Y_{IMF}Z_{IMF}$ system. Thin lines show the projections of the magnetic field lines on the $Y_{IMF}Z_{IMF}$ plane. Magnetic field line draping about the cometary head (not seen in this projection) gives rise to the magnetic tail formation [*Alfvén*, 1957] and results in the negative (antisunward) x-component of the magnetic field for $Z_{IMF} > 0$, and positive (sunward) for $Z_{IMF} < 0$. In addition, there is also magnetic field lines draping about the flanks of the obstacle which is shown in Figure 2. This kind of draping was observed in laboratory [*Podgorny et al.*, 1980] and numerical simulations of the induced magnetospheres [*Israelevich et al.*, 1999] and was revealed near comet Halley [*Israelevich et al.*, 1994]. If we consider azimuthal component of the magnetic field vector in a cylindrical coordinate system with axis along the X_{IMF}-direction, then flank draping results in positive azimuthal component of the magnetic field B_φ for positive Y_{IMF}, and in negative B_φ for $Y_{IMF} < 0$. Thus we know that in the first quadrant (see Figure 2) $B_x < 0$, $B_\varphi > 0$; in the second quadrant $B_x < 0$, $B_\varphi < 0$; in the third one - $B_x > 0$, $B_\varphi < 0$; and in the fourth - $B_x > 0$, $B_\varphi > 0$. Components B_x and B_φ appeared to be the same both in the IMF coordinate system and in the usual HSE ecliptic system. Therefore we can easily find in which quadrant of the IMF system was the spacecraft if we determine B_x and B_φ. The profiles of these components for the inbound and outbound crossings are shown in Figure 3. Both components were negative for the inbound crossing, therefore it occurred in the second quadrant. The B_x-component was positive for the whole outbound crossing, and the azimuthal component was negative for the most of the crossing. However, at the end of the crossing,

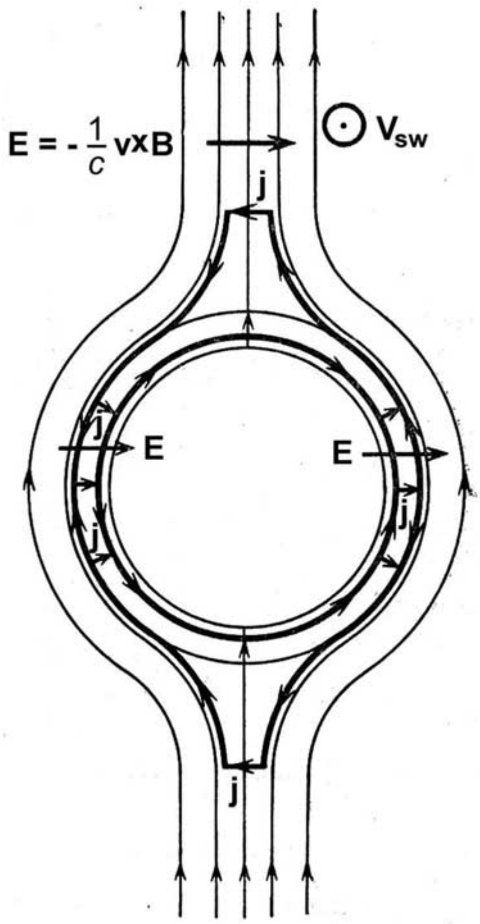

Figure 4. Cartoon of the electric current closure in the DCBL.Thin lines show the projection of the magnetic field lines on the plane, and thick lines show the electric current paths. Large horizontal arrows denote the direction of the electric field $\mathbf{E} = -\frac{1}{c}\mathbf{v}\times\mathbf{B}$.

in the outmost part of the DCBL, the positive B_φ-value was observed. Therefore we arrive at the conclusion that on the outbound leg Giotto entered the DCBL in the third quadrant and remained there for the most of the time, but left the DCBL in the fourth quadrant. Arrows in the Figure 2 show such crossings schematically.

3. Discussion

[12] Figure 4 shows the distribution of electric currents in the $Y_{IMF}Z_{IMF}$ plane. Thin lines show the projection of the magnetic field lines on the plane, and thick lines show the electric current paths. Horizontal arrows denote the direction of the electric field $\mathbf{E} = -\frac{1}{c}\mathbf{v}\times\mathbf{B}$. This distribution corresponds to the observed signatures of the parallel component of the electric current if the DCBL crossings occurred as it is shown in Figure 3. In general, such a scheme is similar to the current system associated with Alfvén wings [*Drell et al.*, 1965; *Neubauer*, 1980; *Goertz*, 1980]. The difference is that in this model the electric currents (generated by the Lorentz electric field) flow in the thin boundary layer (DCBL) rather than through the whole conducting obstacle.

[13] It is interesting to note that similar structure of the electric current is reproduced in the numerical simulation of the solar wind interaction with a comet [*Gombosi et al.*, 1996]. Figure 5 shows the isolines of the parallel component of the electric current in the $Y_{IMF}Z_{IMF}$ plane. Dashed lines correspond to the negative value of $j_{\|}$, and solid isolines are indicative of positive parallel current. One can see the qualitative similarity with Figure 4, namely, the parallel component changes its sign within the inner part of DCBL (DCBL is shown schematically by gray shadowing). Diamagnetic cavity boundary in the numerical simulation possesses two neutral points of *O*-type [*Israelevich et al.*, 2000], hence, the correspondence of the observed current structure to the electric current distribution shown in Figure 5 means that the measurements at least do not contradict the existence of *O*-type neutral points at the DCBL of comet Halley. However, while comparing the distribution in Figure 5 and the real structure of the DCBL in comet Halley, one should keep in mind that the DCBL in the single fluid MHD numerical simulation [*Gombosi et al.*, 1996] arises due to the magnetic field diffusion. On the other hand, the thickness of DCBL in comet Halley is equal to the ion gyroradius, and therefore the two fluids rather than single fluid approach should be used in order to describe the boundary layer fine structure. Simple model of the cometary ionopause [*Ip and Axford*, 1990; *Israelevich and Ershkovich*, 1993] suggests that the cometary ions moving radially outward inside the diamagnetic cavity enter the magnetic barrier and deviate under the action of the Lorentz force. As a result, ions are reflected back into the cavity and the jump of the magnetic field across the DCBL is produced by the drift ion current resulting from this reflection. The thickness of the boundary layer is the depth of penetration of ions into the magnetic field. Ions penetration is deeper than that of electrons, and, therefore, a charge separation might arise in the DCBL resulting in the electric field perpendicular to the layer. This electric field, if exists, should reduce the ions penetration depth. However, the experimental data [*Neubauer*, 1988] show that this depth equals the ion gyroradius as it is expected for the case of zero electric field. This means that the charge separation is effectively reduced, e.g., by means of magnetic field diffusion into the electron component of the plasma.

[14] It is generally believed that the diamagnetic cavity and its thin boundary is a permanent rather than transient structure in a cometary magnetosphere. However, the electric current along the DCBL would inevitably decay because of collisions if there were no electromotive force supporting the current. The model distribution (Figure 4) shows that such an e.m.f. does exist. Magnetic field penetration into the DCBL means that there is an electric field component normal to the layer. It is the Lorentz electric field $-\frac{1}{c}\mathbf{v}\times\mathbf{B}$ projected onto the DCBL from the solar wind along the almost equipotential magnetic field lines.

[15] Let us consider equatorial cross-section (the $X_{IMF}Y_{IMF}$ plane) of the cometary magnetosphere. Figure 6 shows streamlines of the plasma flow around the diamagnetic cavity. Thick arrows show the direction of the perpendicular electric current inside the DCBL. This current system is screening the diamagnetic cavity from the field in the magnetic barrier, and closes the parallel currents flowing along the outer side of the DCBL. The residual part of the

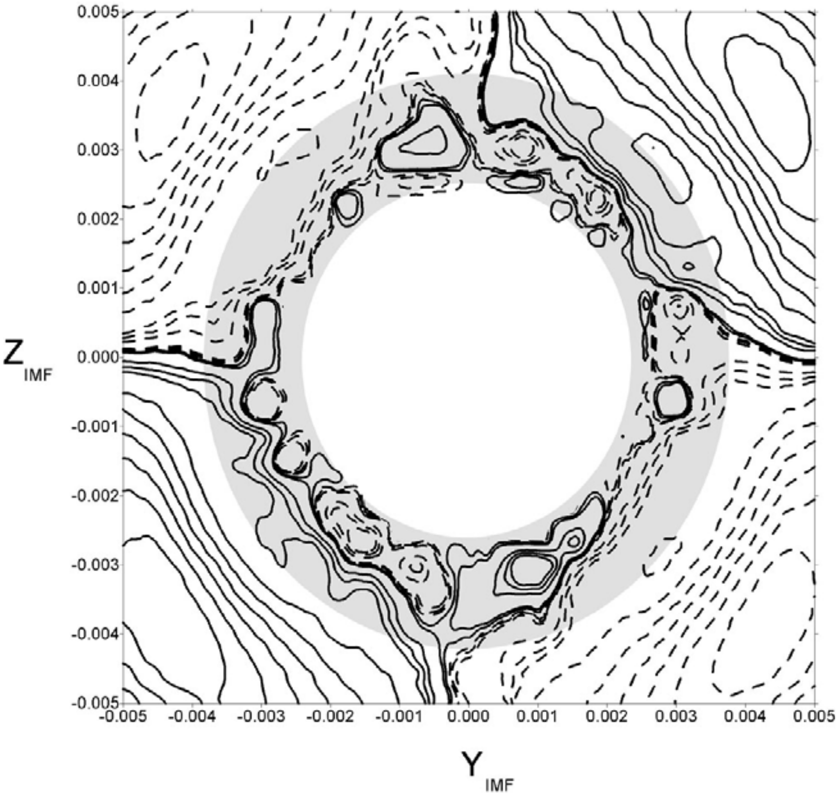

Figure 5. Isolines of the parallel component of the electric current density as obtained in single fluid MHD simulations. Solid and dashed lines correspond to the positive and negative values of the parallel current density, respectively. The gray shadowed area is the DCBL.

perpendicular current is closed by the parallel currents along the inner side of the DCBL. Therefore, the total parallel current on the outer side of the DCBL should be stronger than that on the inner side. This fact accounts for smaller electric current density on the inner side of the DCBL (see Figure 1).

[16] The inner side of the DCBL is equipotential (because it surrounds the field free plasma). The presence of the normal electric field component means that there is a potential difference U_{AB} between dawn and dusk (points A and B) sides of the outer DCBL. Therefore, a tangential component of the electric field exists along the diamagnetic cavity boundary. This electric field supports the current and prevents its decay. The value of this potential difference is

$$U_{AB} = \frac{2}{c} v_{sw} B_{sw} \delta \qquad (2)$$

where v_{sw} is the solar wind velocity, B_{sw} is the interplanetary magnetic field, and the meaning of the characteristic distance δ is clear from Figure 6 - it is the distance of the magnetic field line passing through the point A from the plane of symmetry $X_{IMF}Z_{IMF}$. This distance is unknown, but the potential jump U_{AB} can be estimated using the thickness Δ of the DCBL.

[17] The thickness of the DCBL equals the gyroradius of the outflowing cometary ions, being much larger than the electron gyroradius. Therefore, hybrid models may be used in order to describe the structure of the DCBL. In these models, the electrons are treated as separate fluid. The electron fluid is present inside the boundary layer, otherwise the charge separation would lead to the DCBL thickness much smaller than the ion gyroradius. The mutual penetration of the electron fluid and the magnetic field results from the magnetic diffusion, and can be described by the induction equation in two fluid MHD [*Ershkovich and Israelevich*, 1996]:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v}_e \times \mathbf{B}) + \frac{c^2}{4\pi\sigma_0}\nabla^2 \mathbf{B} \qquad (3)$$

where $\mathbf{v_e}$ is the velocity of the electron component and σ_0 is the plasma conductivity along the magnetic field line. It is the term $\nabla \times (\mathbf{v}_e \times \mathbf{B})$ which balances the magnetic diffusion in the laboratory frame of reference. In the frame of reference moving along the DCBL with the speed $\mathbf{v}_e$, equation (3) becomes

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{c^2}{4\pi\sigma_0}\nabla^2 \mathbf{B} \qquad (4)$$

and the magnetic diffusion is not compensated, so that the width of the DCBL increases with time as the observer moves along the boundary toward the night side. Therefore, the DCBL thickness Δ at the point A can be estimated as

$$\Delta^2 = D\tau \approx \frac{c^2}{4\pi\sigma_0}\frac{R}{v_e} \qquad (5)$$

where $D = \frac{c^2}{4\pi\sigma_0}$ is the magnetic diffusion coefficient and $\tau \sim \frac{R}{v_e}$ is the time of the plasma transfer from the subsolar point to the point A (R is the radius of the diamagnetic

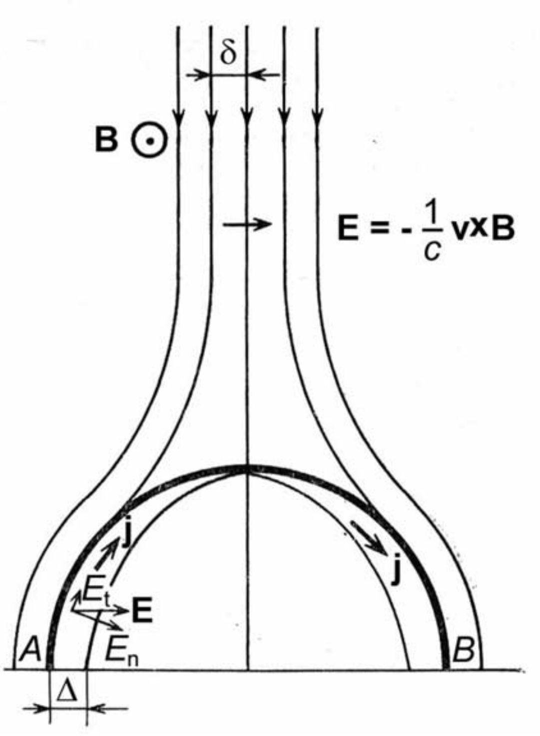

Figure 6. A scheme that shows how the DCBL electric current is supported by the electric field arising due to the magnetic field diffusion. The streamlines of the plasma flow are shown in the plane $X_{IMF}Y_{IMF}$. Thick arrows show the direction of the electric current inside the DCBL, and thin arrows show the electric field $\mathbf{E} = -\frac{1}{c}\mathbf{v} \times \mathbf{B}$ along with its components, perpendicular and tangential to the DCBL.

cavity). The plasma velocity component tangential to the boundary was not measured during the Giotto flyby, but it should be non-zero in order to fulfil the momentum balance at the boundary [*Israelevich et al.*, 1993]. The upper limit of the tangential velocity obtained in [*Israelevich et al.*, 1992] is about 8 km/s. However, the plasma velocity near the DCBL cannot be larger than ≈1 km/s. Otherwise the ion temperature would be higher than was observed due to the ion-neutral collisions [*Cravens*, 1987]. Taking $v_e \approx 1$ km/s we obtain the upper limit for the electric potential jump across the DCBL.

[18] The electric current within the DCBL is supported by the electric field tangential to the boundary:

$$j = \sigma_0 E = \sigma_0 \frac{U_{AB}}{\pi R} \tag{6}$$

[19] The magnitude of the current density can be estimated as

$$j \approx \frac{c}{4\pi}\frac{B_0}{\Delta} \tag{7}$$

where $B_0 \approx 20$ nT is the magnetic field at the outer side of the DCBL. Combining (5), (6) and (7) and eliminating the conductivity σ_0, we obtain

$$U_{AB} = \pi\Delta\frac{B_0 v_e}{c} \approx 1.2V \tag{8}$$

[20] Thus, the electric potential jump across the DCBL is only ∼0.5 V, and the electric field inside the DCBL does not affect the ion penetration depth while being strong enough in order to support the boundary layer electric current.

4. Conclusion

[21] The spatial distribution of the electric current density in the DCBL was calculated by using magnetometer data obtained during Giotto - comet Halley encounter. The DCBL was assumed to be planar (as the boundary thickness is very small as compared to the curvature radius), and the minimum variance method was used in order to find the normal to the boundary. This method allowed us to restore the fine structure of the electric current in the DCBL. The restored electric current was found to possess both the perpendicular (to the local magnetic field) component and the parallel component. The perpendicular current is responsible for the cavity shielding from the magnetic field penetration. This current is supported by the electric field tangential to the DCBL.

[22] The parallel component of the electric current has opposite directions on the inner and outer sides of the DCBL. We determined the positions of the inbound and outbound DCBL crossings in the coordinate system rotating with the IMF by using the information on the magnetic field components signs. This method allowed us to follow the closure of the parallel current and to draw the electric current circuit in the DCBL. It appeared to be similar to the current system associated with the Alfvén wings which arise due to the interaction of the magnetized plasma flow with a conducting obstacle. However, in case of a comet, the electric currents (generated by the Lorentz electric field) flow in the thin DCBL rather than through the whole volume of the obstacle (as in case of Io).

[23] In order to support such a current system, the potential drop of ∼0.5 V across the DCBL happens to be sufficient. Such a small value is compatible with the penetration depth of cometary ions from the cavity to the magnetic barrier. This depth equals the ion gyroradius. Consequently, one may conclude that the charge separation (which may arise due to different penetration depths of ions and electrons) is effectively reduced by means of the magnetic field diffusion into the electron component of the plasma.

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