NEUTRAL POINTS AT THE COMETARY DIAMAGNETIC CAVITY BOUNDARY AS POSSIBLE SOURCE OF COMETARY RAYS

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Abstract. The point source of neutral gas undergoing ionization and expanding into an uniform magnetic field is considered. Friction between the neutral and ionized particles results in the formation of the magnetic field barrier and diamagnetic cavity surrounding the source. At least one neutral point inevitably arises at the boundary of the cavity. When the neutral gas production rate grows, two neutral points may arise at this boundary. In the vicinity of these points magnetic field lines converge, along with the plasma flow which is magnetic field aligned in the steady state. As a result, two plasma jets originate from the neutral points. Possible relation of these jets to cometary rays is discussed.

Keywords: Cometary rays, comets, neutral points

1. Introduction

Diamagnetic cavity surrounding the nucleus of comet Halley was discovered during the Giotto mission (Neubauer et al., 1986). Inside the cavity the magnetic field is absent, and cometary ions move radially outward with the neutral gas velocity. Upstream from the cavity, the magnetic barrier exists. Because of the presence of the magnetic field, the velocities of ions and neutral particles are different (the ion velocity along the Giotto trajectory was almost zero near the cavity boundary). As a result, a friction force between ion and neutral components of the cometary gas arises. This friction force is responsible for generations of electric currents giving rise to the magnetic barrier (Cravens, 1986; Ip and Axford, 1987). The magnetic field profile observed by Giotto in the barrier can be fairly well described by one-dimensional (or spherically symmetric) model of interaction between stagnating ions and the neutral gas flow (Cravens, 1986; Ip and Axford, 1987; Haerendel, 1987). At the boundary between the cavity and the barrier, the magnetic field pressure (on the barrier side) is balanced by the dynamic pressure of the cometary plasma flow from the cavity side (Israelevich and Ershkovich, 1993). The width of the boundary is approximately equal to the ion gyroradius.

Diamagnetic cavity is essentially three dimensional structure. Wu (1987) found the shape of the boundary of the cavity from the pressure balance. Similar tear-drop shaped cavity was obtained in multiscale 3D MHD model by Gombosi et al. (1996). This numerical model reveals more details about the structure of the

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magnetic field and plasma flow in the inner cometary coma. On the nightside, the cavity becomes narrow and a relatively fast and dense cometary plasma beam is ejected into the tail. This beam may result from the convergency of the external plasma flow toward the sun-cometary axis under the action of the pressure gradient perpendicular to the axis of the cometary wake.

The diamagnetic cavity seems to be a rather common feature which may arise from the plasma expansion into the external magnetic field. In particular, very similar structures were observed during lithium and barium releases in AMPTE experiment (Lühr et al., 1986).

Two points concerning the structure of the diamagnetic cavity should be mentioned. First, it can be easily shown, that no steady state solution can exist if the plasma velocity is zero everywhere inside the magnetic barrier. In other words, a friction between ions and neutrals inevitably creates plasma flow along magnetic field lines. Second, the magnetic field violates spherical symmetry, and at least one neutral point ($B = 0$) should exist at the boundary of the diamagnetic cavity. Finite plasma conductivity may affect the formation of the neutral points because of magnetic field diffusion. However, in the vicinity of the diamagnetic cavity boundary the plasma conductivity is high enough, and the magnetic Reynolds number $\mathrm{Re}_m \gg 1$ (Ershkovich and Israelevich, 1996). For this reason, the magnetic field diffusion can be neglected, and neutral points may exist.

Plasma can penetrate through the neutral points from the cavity into the region with the magnetic field surrounding the cavity, giving rise to plasma field aligned beams. Figure 1 shows two possible diamagnetic cavity configurations with one (a) and two (b) neutral points. Configuration with a single neutral point (Figure 1a) is expected to occur when the external plasma flow around the cavity is significant. In particular, this configuration of the magnetic field lines was obtained in the numerical model (Gombosi et al., 1996). Configuration with two neutral points is more plausible for plasma expansion into an almost uniform magnetic field.

In this paper, we will discuss a situation when two neutral points may arise on the cometary ionopause, and analyze the magnetic field and plasma velocity distribution near the diamagnetic cavity in this case. We solve numerically a cylindrically symmetric problem for this configuration of the diamagnetic cavity. It will be shown that two plasma jets of the enhanced density arise in this case. We will also discuss possible relation of these jets with the cometary ray structure.

2. Model

Let us consider a point source of neutral gas radially expanding into initially uniform magnetic held which is parallel to the z-axis. The problem is cylindrically symmetric ($\partial/\partial\varphi = 0$) with respect to the magnetic field direction, and is described by the following system of equations:

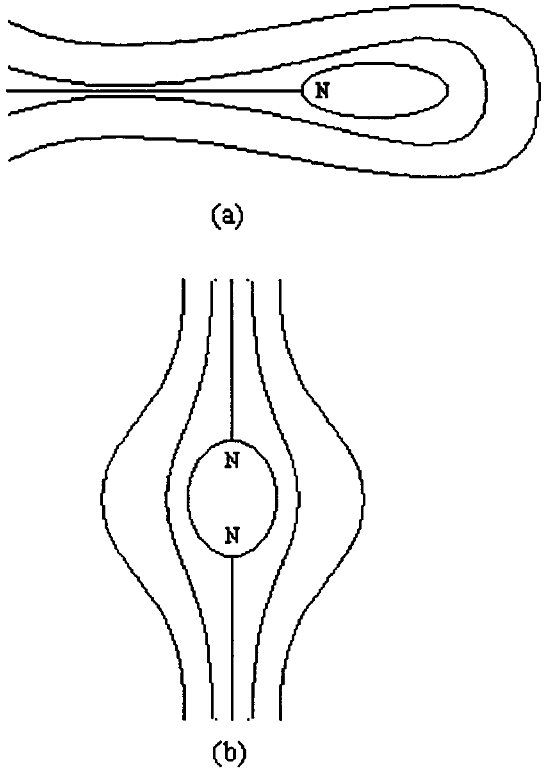

Figure 1. Topology of magnetic field lines in the vicinity of the diamagnetic cavity for cases of one (a) and two (b) neutral points.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = \delta \rho_n - \frac{\alpha \rho^2}{M}.$$

Induction equation for ideal conductivity:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}).$$

Equation of motion:

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\nabla)\mathbf{v} \right] = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \left(\nu + \frac{\delta \rho_n}{M} \right) (\mathbf{v}_n - \mathbf{v}).$$

Here, ρ and ρ_n are the plasma and neutral density, respectively, $\mathbf{v}$ is the plasma velocity, $\mathbf{B}$ is the magnetic field, M is the ion mass, $\mathbf{v}_n$ is the neutral gas velocity, δ is the photoionization rate, α is the recombination rate, and ν is the ion-neutral collision frequency.

In dimensionless form these equations are:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial (r\rho v_r)}{\partial r} + \frac{\partial (\rho v_z)}{\partial z} = \frac{1}{r^2+z^2} - \rho^2,$$

$$\frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}(v_z B_r - v_r B_z),$$

$$\frac{\partial B_z}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r v_z B_r - r v_r B_z),$$

$$\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z} = \frac{1}{\rho}\left(B_z\frac{\partial B_r}{\partial z} - B_z\frac{\partial B_z}{\partial r}\right) + \frac{r/\sqrt{r^2+z^2} - v_r}{r^2+z^2}\left(Es + \frac{1}{\rho}\right),$$

$$\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + v_z\frac{\partial v_z}{\partial z} = \frac{1}{\rho}\left(B_r\frac{\partial B_z}{\partial r} - B_r\frac{\partial B_r}{\partial r}\right) + \frac{z/\sqrt{r^2+z^2} - v_z}{r^2+z^2}\left(Es + \frac{1}{\rho}\right).$$

Here, r and z are dimensionless cylindrical coordinates, ρ, $\mathbf{v}$, and $\mathbf{B}$ are dimensionless plasma density, plasma velocity and magnetic field respectively. The system depends only on a single dimensionless parameter $Es = K_{\text{in}}(\rho_0/\delta M)$, where $K_{\text{in}} = M\nu/\rho_n$ is the ion-neutral momentum exchange rate, and ρ_0 is the characteristic plasma density. This parameter is proportional to the neutral gas production rate, and physical parameters relevant to comet Halley ionopause correspond to the value $Es \sim 5$.

The system was solved in the region $0 \le r \le 10$, $0 \le z \le 10$ with the following boundary conditions:

$$B_z(10, z) = 0.8, \quad B_r(10, z) = 0, \quad v_r(10, z) = 0,$$

$$\frac{\partial v_z(10, z)}{\partial r} = 0, \quad \frac{\partial \rho(10, z)}{\partial r} = 0, \quad \frac{\partial B_z(0, z)}{\partial r} = 0.8, \; B_r(0, z) = 0, \quad v_r(0, z) = 0,$$

$$\frac{\partial v_z(0, z)}{\partial r} = 0, \quad \frac{\partial \rho(0, z)}{\partial r} = 0, \quad \frac{\partial B_z(r, 0)}{\partial z} = 0, \quad B_r(r, 0) = 0, \; v_z(r, 0) = 0,$$

$$\frac{\partial v_r(r, 0)}{\partial z} = 0, \quad \frac{\partial \rho(r, 0)}{\partial z} = 0, \quad \frac{\partial B_z(r, 10)}{\partial z} = 0, \quad \frac{\partial B_r(r, 10)}{\partial z} = 0,$$

$$\frac{\partial v_z(r, 10)}{\partial z} = 0, \quad \frac{\partial v_r(r, 10)}{\partial z} = 0, \quad \frac{\partial \rho(r, 10)}{\partial z} = 0.$$

Steady state solution was found by the relaxation method. It is obvious that for such a choice of boundary conditions, the steady state configuration depends on the initial condition, namely on the amount of the magnetic flux in the box. $B_z = 0$ for $z < 5$, $B_z = 0.8$ for $z \ge 5$, and $B_r = 0$ everywhere are chosen with $t = 0$.

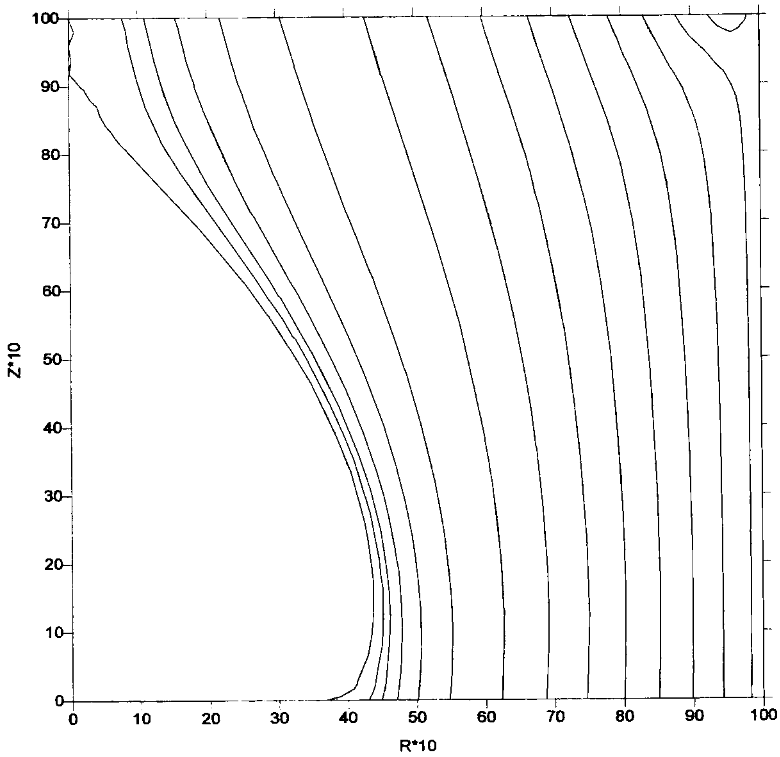

Figure 2. Calculated shape of magnetic field lines.

3. Results

Figure 2 shows the resulting configuration of magnetic field lines when the Lorentz body force is balanced by the friction force for the case of $Es = 10$. As expected, it corresponds to geometry with two neutral points (Figure 1b). The ion density is shown in Figure 3. Two different regions of the enhanced ion density are seen. The ion density increases at the inner side of the diamagnetic cavity boundary. This increase of the density is a result of the plasma velocity decrease as the flow approaches the boundary. It is a common feature of all simulations of the magnetic barrier in front of a comet whereas this increase has not been observed during the Giotto flyby. The most probable explanation for the absence of the density peak in observations is insufficient temporal resolution of the plasma instruments aboard Giotto. Indeed, detailed examination of data (Goldstein et al., 1989) shows some evidence for existence of a very narrow density enhancement.

Another region of the enhanced plasma density is the jet in the polar region. The density of the plasma flowing along magnetic field lines in the vicinity of the neutral point is significantly higher than everywhere else at the same distance from the nucleus. This jet is formed due to convergence of the plasma flow in the vicinity

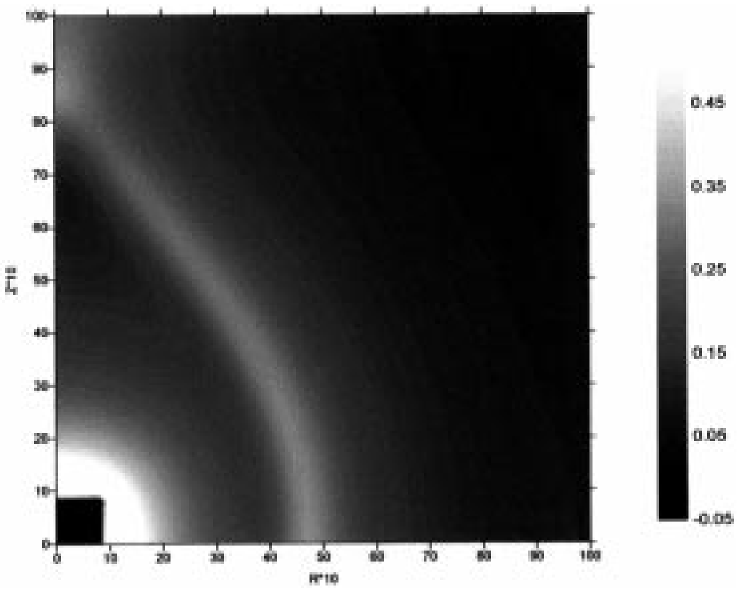

Figure 3. Distribution of the ion density near the diamagnetic cavity.

of the neutral point. In the steady state, the plasma velocity is parallel to the local magnetic field, and converging magnetic field lines in this region (Figure 2) ensure the convergence of the plasma velocity. As the direct consequence of the magnetic field configuration, the same phenomenon is expected to occur also in the vicinity of a single neutral point (Figure 1a).

4. Discussion

Cometary plasma tails exhibit highly time-variable filamentary structures. Cometary rays which usually originate as a pair of short curved jets on the day side of a comet are such prominent features. These jets gradually lengthen and rotate toward the night side. Approaching the tail axis they become almost rectilinear (Figure 4). The dynamics of the tail rays was described in detail by Wurm and Mammano (1972). Spatial geometry of this phenomenon is obscure. In most cases it is impossible to conclude from visual observations whether the rays are linear structures of enhanced density or they are projections of the axisymmetric envelope onto the sky plane. The only evidence for linear structure of the rays is the observation of comet Tebbutt (1861 II) made at the time when the line of sight to the comet was only slightly inclined to the cometary tail axis. One of drawings of this comet (Rahe et al., 1969, p. 14, Figure 2) shows six ray-like structures throughout a full 360°.

However, if the rays are linear structures rather than envelopes, it is difficult to explain why do they fold onto the same axis. In this case, one should assume that all rays occur at the same plane, since otherwise different pairs of rays will fold

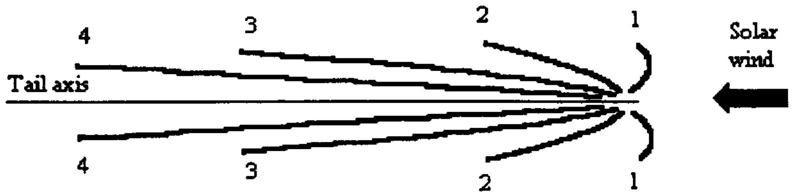

Figure 4. Evolution of rays in the cometary tail.

onto different lines depending on the angle of sight. However, this is not the case (Miller, 1988). The second problem is the mutual orientation of the ray and the local magnetic field. At the last stages of ray evolution, the ray dynamics is reminiscent of that of magnetic field lines in the cometary tail, so that one can assume that the ray is almost parallel to the magnetic field. On the other hand, initially, at the day side, the shape of rays (see Figure 4) differs from that of magnetic field lines, and, hence, the ray plasma motion across the magnetic field should be assumed.

It is tempting to try to associate the plasma jets in the vicinity of neutral points at the diamagnetic cavity boundary (Figure 3) with the cometary rays. In this case, it is possible to resolve above mentioned difficulties in explanation of rays as linear structures. In this case, each pair of rays appears in the plane containing the tail axis and the vector of the interplanetary magnetic field. Figure 5 shows, schematically, the magnetic field configuration when two neutral points at the diamagnetic cavity boundary appear inside the common magnetic field line draping picture. In the distant tail, the plasma jet is moving toward the tail axis under the action of the convection electric field **V**X**B** projected into the tail from the solar wind along magnetic field lines (which are almost equipotential). The convection corresponds to the ray folding. If the orientation of the interplanetary magnetic field changes giving rise to a new pair of jets, this new pair will move toward the same tail axis in the plane defined by the new orientation of the interplanetary magnetic field. Thus, folding of all pairs of rays onto the same line (the tail axis) will occur, being independent on the line of sight.

Plasma jets originating in the vicinity of neutral points are flowing along curved magnetic field lines (see Figure 5). The radius of the field line curvature is the smallest in the cometary head. The centrifugal drift results in charge separation. The resulting polarization electric field causes the plasma drift which is antiparallel to the principal normal to the field line. This effect was studied in a laboratory (Lindberg, 1978; Komori et al., 1977) and requires separate treatment of ions and electrons (two fluid MHD description). For this reason, it is not observed in single fluid MHD simulations. As a result, the jet will be deviated sunward at the initial stage of its evolution, and will not be parallel to the magnetic field line. As the jet lengthens with time, the polarization electric field diminishes, and the jet, finally, becomes almost parallel to the magnetic field line.

According to considerations above, the pair of rays will appear only in the case when two neutral points exist at the diamagnetic cavity boundary. At present, there

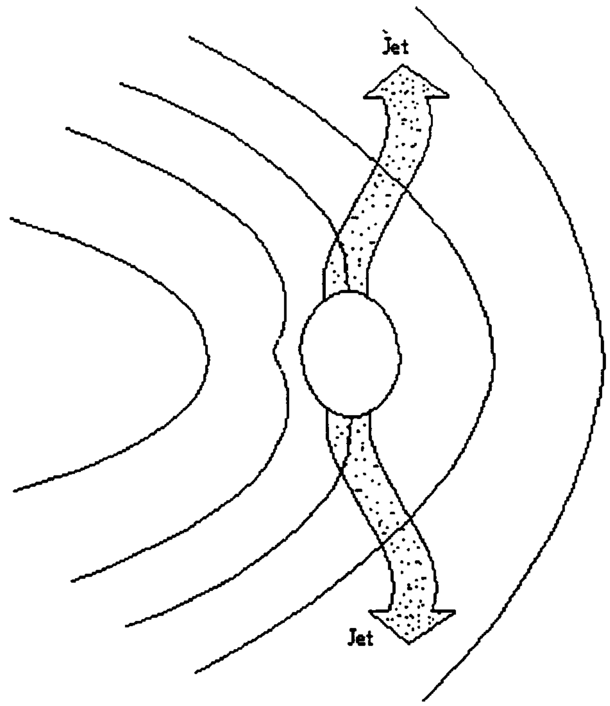

Figure 5. Scheme of the plasma jet motion near the neutral points illustrating initial turning of the ray toward the Sun.

are no *in situ* observations of the neutral points at the diamagnetic cavity boundary, and the steady state of the cometary magnetosphere simulated for comet Halley parameters during Giotto encounter (Gombosi et al., 1996) exhibits a single neutral point. However, two neutral points may arise during sudden increases of the cometary neutral gas production rate.

Indeed let us assume that a single neutral point always exists in a steady state. The magnetic field in the inner coma is a sum of three fields, namely: (a) the external uniform magnetic field of the solar wind, (b) the field of magnetospheric currents (mainly in the magnetic barrier and in the tail), and (c) the field of a surface current at the diamagnetic cavity boundary. All these currents are mutually balanced, according to our assumption, in order to ensure the configuration with a single neutral point. An increase of the neutral gas production rate will violate this balance at least until the next steady state configuration will be reached. The diamagnetic cavity will expand because of an increase of the ion outflow pressure, and, at initial stages of the expansion, the diamagnetic cavity boundary will coincide with the front of the neutral density. This means, that outside the expanding diamagnetic cavity the magnetospheric electric current essentially remains the same since it is determined primarily by the friction between the ions and neutral particles in the magnetic barrier. Thus, first two sources of the inner coma magnetic field remain almost the same, whereas the third term (surface current) changes significantly. This change gives rise to two neutral points at the diamagnetic cavity boundary, and can be illustrated by the following simple 2D model, which allows analytical solution.

Let the uniform magnetic field from the sources at infinity (the solar wind magnetic field) be B_0, and is directed along y-axis. The magnetospheric current in the magnetic barrier surrounding the diamagnetic cavity is simulated by the electric current j flowing in the cylinder of radius b whose axis coincides with the x-axis. Inside this cylinder, there is a cylindrical hole of radius a free of electric current. This hole simulates the diamagnetic cavity, two cylinders being tangential. The condition for diamagnetic current along the surface of the hole is determined by the condition that $B = 0$ inside the hole. Magnetic vector potential will have only z-component in 2D case, and will consist of three parts:

$$A_z = A_z^{\text{ex}} + A_z^{\text{vol}} + A_z^{\text{surf}},$$

where

$$A_z^{\text{ex}} = -B_0 \cdot x$$

is the external potential which corresponds to the uniform solar wind magnetic field; the potential of the volume current in the barrier is

$$A_z^{\text{vol}} = \pi j(a^2 - b^2) - 2\pi j b^2 \ln(r/b) + 2\pi j a^2 \ln(r'/b)$$

if $r^2 = x^2 + y^2 > b^2$;

$$A_z^{\text{vol}} = \pi j[(x + b - a)^2 + y^2] - \pi j(x^2 + y^2)$$

if $r'^2 = (x + b - a)^2 + y^2 < a^2$; and

$$A_z^{\text{vol}} = -\pi j(x^2 + y^2) + \pi j a^2 + 2\pi j a^2 \ln(r'/b)$$

elsewhere; and the potential of the surface current is

$$A_z^{\text{surf}} = [B_0 - 2\pi j(b - a)] \cdot (x + b - a) - B_0(b - a) + \pi j(b - a)^2$$

if $r' < a$, and

$$A_z^{\text{surf}} = a^2[B_0 - 2\pi j(b - a)] \cdot (x + b - a)/[x + b - a)^2 + y^2] - B_0(b - a) + \pi j(b - a)^2$$

if $r' > a$.

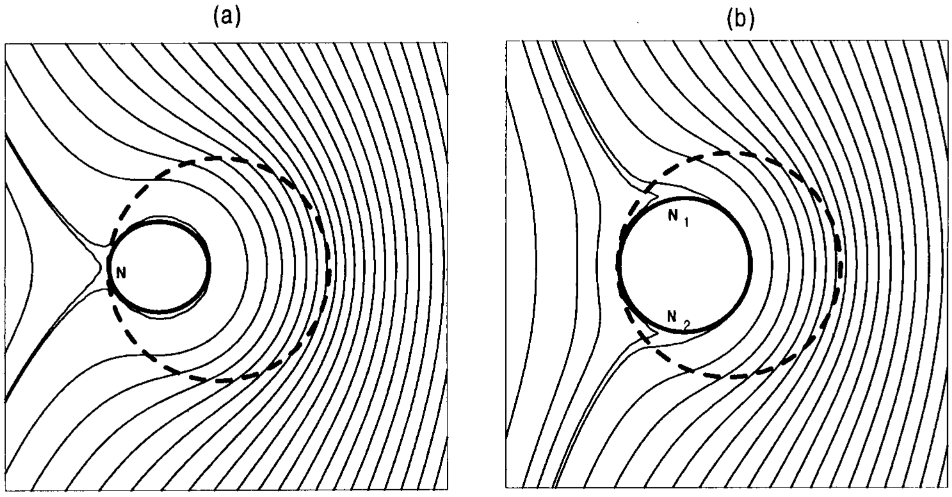

Figure 6. Configurations of the magnetic field lines near the diamagnetic cavity with a single neutral point (a) and with two neutral points (b) in a 2D model.

Figure 6a illustrates the magnetic field line pattern in such a system for the case with a single neutral point N. Solid circle shows the simulated diamagnetic cavity boundary, whereas the dashed circle shows the boundary of the cylindrical current simulating the magnetic barrier. If the diameter of the diamagnetic hole increases by the factor of 1.5 because of an increase of the neutral gas production rate, and the current density in the barrier region remains the same since the neutral gas density has not changed yet in this region, then two neutral points, N_1 and N_2, appear at the cavity boundary, as shown in Figure 6b.

Thus, one can expect that two neutral points should exist at the boundary of the diamagnetic cavity, at least at times when the neutral gas production rate grows. The time interval of the existence of two neutral points during the neutral production rate enhancement can be estimated as $t > L/V_n$, where L is the characteristic size of the magnetic barrier in front of a comet, and V_n is the velocity of the neutral gas expansion. After this time neutral gas with new parameters will fill in the whole magnetic pile up region, and a new steady state, presumably, with a single neutral point, will be established. Taking $L \sim 50{,}000$ km and $V_n \sim 1$ km s^{-1} we get $t \sim 14$ h, which is close to the typical time of the existence of the pair of tail rays (Wurm and Mammano, 1972).

Rays are not always observed in cometary tails. As it follows from ray dynamics (the "folding umbrella" phenomenon), the very appearance of the ray structure means that it is not a steady state phenomenon (otherwise, the ray position with respect both to the nucleus and tail axis would remain the same). In other words, the ray structure may arise only as a consequence of temporal variations of parameters of interaction. We suggest the following scenario for cometary rays generation. In a steady state situation, only one neutral point exists at the diamagnetic cavity boundary (Figures 1a, 6a) as it was obtained via numerical simulations by Gombosi et al. (1996). It was shown above that sudden increase of the neutral gas production rate results in appearance of two neutral points (Figure 6b). The field topology with two neutral points is shown above to be a transient feature lasting 10–20 hours. After this period of time a relaxation of the magnetic held structure of the cometary tail back to the configuration with one neutral point occurs. A pair of rays develops and evolves during this transient period. In case of several subsequent changes of the neutral gas production rate and/or the IMF vector rotations (at time scales shorter than the characteristic transient time) several pairs of rays may arise.

5. Conclusion

Neutral points ($B = 0$) exist at the diamagnetic cavity boundary surrounding the cometary nucleus. Near these points, magnetic field lines converge, and, hence, the plasma flow also converges since the plasma velocity is almost field-aligned. As a result, jets with enhanced plasma density arise near the neutral points. For the diamagnetic boundary configuration with two neutral points, these jets may account for the observed cometary ray structure.

Acknowledgement

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