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DISTURBANCE STRUCTURES AND ITS MAGNETIC FIELD FEATURES IN PLASMA COMET TAIL *

Li Zhongyuan **

International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

The solar wind disturbances result in the emergence of condensation structures in plamsa comet tail. Most of them are correlated with plasma vortex flow. In this paper, we analyze the features of condensations basing on the theories of MHD and force–free field. Specifically, we discuss the construction and the distribution of magnetic field and its energy in condensations. We also analyze in detail the coupling process between an unsteady plasma motion and a magnetic field. The coupling effect will let the energy in comet tail change into the force–free field in condensations, so that the magnetic field energy in the condensations increases constantly. Many phenomena observed in comet tail can be explained with the model.

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** Permanent address: Department of Earth and Space Science, University of Science and Technology of China, Hefei, People's Republic of China.

1. Type-1 comet tail and its disturbances

Type-1 comet tail is a long, straight and narrow plasma tail. It virtually differences from the dust tail which is short, bend and wide. Interactions between the magnetic field frozen in the solar wind and the cometary plasma result in the formation of type-1 comet tail. The view seems to be sure to date. Some physicists all discussed the coupling process from the different points, such as 'magnetic field line getting "hung up"' (Alfven),[1,2] 'the two stream instability theory' (Hoyle and Harwit),[3] 'toothpaste out of a tube due to lateral pressure' (Ioffe),[4] 'ion sound instability' (Chernikov),[5] and 'complete MHD model' (Schmidt and Wegmann)[6] and so on. In particularly, the detection of the space crafts Gitto and Vega obtained many new results about magnetic field pattern and plasma structures in comets.[7] It's true that the detection provides good conditions for studying the various features in comet further. Observations have told us, there are many 'rays' and 'streams' emanating from the head to the tail. These 'rays' and 'streams' are the cometary plasma track and correspond to magnetic field lines. We can often observe some condensations in type-1 comet tail. Most of them are helical structures or 'kinks' formed by 'rays'. This shows that the magnetic field lines twist heavily in some areas in comet tail. These condensations often move backward with general ions in comet tail. Alfven had pointed out that they were small rotating plasma magnetic clouds.[1,2] At present, Doppler shift is observed to some condensations. As many people pointed out, it is clear that they are ion vortex flow condensed in comet tail.[8-11]

Although there are various theories about the process type-1 comet tail forming, condensations are all considered to be the results from the disturbances acting on comet, such as the magnetic clouds torn away from comet head, the products from plasma instability, or the vertex flow caused by disturbances. Jokers pointed out the phenomena of some 'twines' and 'kinks', correlate with solar wind events.[12] We have made a statistical analysis about 28 type-1 comet tails most of which have condensations and kinks. The statistical results show that "enhancement for solar activity" has a correlation with "increment for the disturbance structures in comet tail".

Particularly, the correlation is stronger when "the solar wind has a sudden change" or "the velocity of the solar wind is very large". So the disturbance which the solar wind acts on comet should be one of the major results which causes the emergence of condensations in comet tail.

When many condensations, specifically, the twines and kinks, emerge in type-1 comet tail, we call that "the cometary events" occurs. Before occurring, many sudden events in comet correlate with "cometary events".[7][9-13] For example, the structures and the flow lines in comet tail are disordered, the comet tail cracks and breaks up, the comet tail is changed into fragments and so on. In this paper, author makes a study further basing on above observations and discusses the features of condensations. Author specifically analyzes the evolution of the magnetic field and the magnetic energy. So we can explain the observations more reasonably.

2. Basic Equations

The results detected by space crafts show that the value of magnetic field is about 20-30γ in comet tail. The morphology of magnetic field in comet tail may similar to in magnesphere tail, or in quiet prominence or in solar atmosphere, sunspot, solar active region. So we can consider the magnetic field to be force-free field. Many people have studied and analyzed in this case.[10][14-16]

The force-free condition is

$$1/c \; (j \times B) = 0 \qquad (2.1)$$

The force-free magnetic field means the Lorentz force does not exist. The ions move only along the magnetic field lines in comet tail, which is correspondent with the observations.

MHD basic equations are:

$$\partial B/\partial t = \nabla \times (v \times B) + \eta \nabla^2 B \qquad (2.2)$$

$$\nabla \bullet B = 0 \qquad (2.3)$$

$$\nabla \times B = \alpha (t, r) B \qquad (2.4)$$

$$\partial \rho/\partial t = - \nabla \bullet (\rho v) \qquad (2.5)$$

$$\rho \, [\partial v/\partial t + (v \bullet \nabla) v] = - \nabla p + 1/4\pi \, (\nabla \times B) \times B \qquad (2.6)$$

Basing on the force-free condition, the second term in the right of equation (2.6) is 0. According to the kinetic momentum conservation, we can obtain the equation:

$$B \cdot [\partial v/\partial t + (v \cdot \nabla)v + 1/\rho \nabla p] = 0 \quad (2.7)$$

$\alpha(t,r)$ is the force-free factor in (2.4). In Equation (2.2), η is the magnetic diffusion coefficient.

The magnetic Reynold number R_m is usually very large ($R_m \gg 1$) in comet tail, so $\eta\nabla^2 B$ is very small. Equation (2.2) will satisfy the frozen condition.

We approximately consider any condensations to be axial-symmetric in comet tail. We can establish a cylindrical-coordinate system (r,θ,z). By using magnetic field (B_r, B_θ, B_z) and velocity field (v_r, v_θ, v_z), we simplify the equations. According to equation (2.3) and introducing the magnetic potential function ψ, we have:

$$\partial\psi/\partial z = rB_r , \qquad \partial\psi/\partial r = -rB_z \quad (2.8)$$

The force-free factor can be written as:

$$\alpha(\psi,t) = -\partial K(\psi,t)/\partial\psi \quad (2.9)$$

and the toroidal magnetic field is

$$B_\theta = K(\psi,t)/r \quad (2.10)$$

In order to know the magnetic field features of condensations in comet tail, it is key to know the distribution of the force-free factor. As $\alpha(t,r)$ is a function of time and position, its change is not very simple. So it is important to consider properly the flow field by using the observations.

Many people have analyzed the relation between the magnetic energy and the twisting effect quantitatively according to the static mechanics.[18,19] But this problem does not belong to the static mechanics even if in the solar atmosphere which has been showed in our paper before.[20,21] In order to discuss the features of condensations in the comet tail, it is necessary to study the coupling process between the three-dimensional velocity field and the force-free field and to analyze the unsteady change.

3. Discussion to the magnetic field and magnetic energy in the condensations in comet tail.

Subatituting Equations (2.8),(2.9) and (2.10) into Equations (2.4) and (2.2), we obtain the following scalar quantity Equations:

$$(\partial^2/\partial r^2 - 1/r\, \partial/\partial r + \partial^2/\partial z^2)\psi = -K(\psi,t)\partial K(\psi,t)/\partial\psi \quad (3.1)$$

$$v_r\, \partial\psi/\partial r + v_z\, \partial\psi/\partial z + \partial\psi/\partial t = 0 \quad (3.2)$$

$$(\partial v_\theta/\partial z)(\partial \psi/\partial r) - (\partial v_\theta/\partial r - v_\theta/r)(\partial \psi/\partial z) =$$
$$-(\partial v_r/\partial r - v_r/r + \partial v_z/\partial z)K(\psi,t) - \partial K(\psi,t)/\partial t \qquad (3.3)$$

Now we discuss the magnetic field in the condensations in comet tail. As there is more or less poloidal flow field, from Equation (3.2), we know that the magnetic potential function should be unsteady, i.e., $\partial\psi/\partial t \neq 0$ (3.4)

Because of influencing ψ, from Equation (2.8), the poloidal flow field should also influence the poloidal magnetic field. So the toroidal plasma flow filed can also amplify the toroidal magnetic field.[21,22] According to the frozen force-free equations is

$$\alpha(t,\psi) = \mp [\alpha_1(t)\psi + 1/2\alpha_2(t)][\alpha_1(t)\psi^2 + \alpha_2(t)\psi]^{-1/2} \qquad (3.5)$$

where $\alpha_1(t)$ and $\alpha_2(t)$ are two factors about α,

$$\text{Hence, } K(\psi,t) = \pm [\alpha_1(t)\psi^2 + \alpha_2(t)\psi] \qquad (3.6)$$
$$K(\psi,t)\ \partial K(\psi,t)/\partial\psi = \alpha_1(t)\psi + 1/2\alpha_2(t) \qquad (3.7)$$

So the force-free Equation (3.1) is changed to

$$\partial\psi^2/\partial r^2 - 1/r\ \partial\psi/\partial r + \partial^2\psi/\partial z^2 = \alpha\ K(\psi,t) = -[\alpha_1(t)\psi + 1/2\alpha_2(t)] \qquad (3.8)$$

Presuming the thickness of the condensations is D and the radius is R, we get the boundary condition

$$\psi(r,0,t) = M(r,t), \qquad \psi(r,D,t) = N(r,t) \qquad (3.9)$$
$$\psi(0,z,t) = 0, \qquad \psi(R,z,t) = 0 \qquad (3.10)$$

R is finite or infinite. In practical problem, it is more proper for R to be infinite. In terms of a Hankel transform

$$A_1(z,t) = \int_0^\infty rA(r,z,t)J_1(\beta,r)\ dr \qquad (3.11)$$

where $J_1(\beta,r)$ is a Bassel function,

$$rA(r,z,t) = \psi(r,z,t) \qquad (3.12)$$

it is not difficult to determine the solutions of Equations (3.8)-(3.10), if we consider some simple cases, for example, $\alpha_2(t)=0$

From (3.11), Equations (3.8)-(3.10) may be reduced to

$$\partial^2 A_1(z,t)/\partial z^2 = -[\alpha^2+\beta^2]A_1(z,t) \qquad (3.13)$$
$$A_1(0,t) = \int_0^\infty M(r,t)J_1(\beta,r)\ dr \qquad (3.14)$$
$$A_1(D,t) = \int_0^\infty N(r,t)J_1(\beta,r)\ dr \qquad (3.15)$$

The solution of the Equations (3.13)-(3.15) is

$$A_1(z,t) = 1/2a_2[A_1(D,t) - A_1(0,t)e^{-a_1 D}]\exp(a_1 z) +$$
$$+\ 1/2a_2[A_1(0,t)e^{a_1 D} - A_1(D,t)]\exp(-a_1 z) \qquad (3.16)$$

where

$$a_1 = (\alpha^2+\beta^2)^{1/2} \qquad (3.17)$$
$$a_2 = \text{sh}\ [(\alpha^2+\beta^2)\ D] \qquad (3.18)$$

An inversion of the Hankel transform leads to

$$A_1(r,z,t) = \int_0^\infty \beta/a_2[a_3A_1(0,t)+a_4A_1(D,t)]J_1(\beta,r)d\beta \qquad (3.19)$$

where

$$a_3 = sh[(\alpha^2+\beta^2)^{1/2}(D-z)] \qquad (3.20)$$

$$a_4 = sh\ [(\alpha^2+\beta^2)^{1/2}z] \qquad (3.21)$$

Substituting (3.19) into (3.12), the solutions of Equations (3.8)-(3.10), i.e., ψ can be obtained.

The poloidal magnetic field is

$$B_r = 1/r\ \partial(rA)/\partial z \quad , \quad B_z = -1/r\ \partial(rA)/\partial r \qquad (3.23)$$

The toroidal magnetic field is

$$B_\theta = 1/r\ K(\psi,t) = \alpha\ A(r,z,t) \qquad (3.24)$$

The toroidal magnetic energy is

$$W_\theta = \alpha^2A^2/8\pi \qquad (3.25)$$

Only substituting the (3.19) into (3.23),(3.24) and (3.25), the above Equations can be obtained.

The toroidal magnetic field is very small in the normal areas in comet tail. But it is obvious from above discussion that the magnetic field may be changed largely as the force-free factor α changes even if in our simple case. And the toroidal magnetic energy can be increased quickly. Clearly in the condensations, the fact that ψ and α are both unsteady is a effect caused by the disturbances of the plasma in comet tail.

In general, the cometary plasma conveys the kinetic energy and magnetic energy from comet head to tail.[9,10,15] The condensations will emerge when the comet tail is disturbed. In this case ,the plasma does not only move along with the tail axis and the magnetic field line is no longer the straight line. Both the flow field and the magnetic field are change unsteadily in some areas. From our conclusion,the coupling between the plasma flow field and the magnetic field will make the force-free factor change quickly with time. The toroidal magnetic energy will also increase constantly. In condensations, obviously, the constant increase of magnetic field is an important factor which results in the comet tail unsteady. The more seriously the conet is disturbed, the more the condensations, twines and kinks are observed. If the coupling process is very strong, the toroidal magnetic energy will be stored more and more with time and become very large. The energy must be released in some condensations when it surpasses the threshold, which will result in the structures confusion in comet tail. So most sudden events observed in comet tail possibly result from the energy releasing abruptly from the condensations.

4. The plasma whirl-flow in disturbances in comet tail

From observations, most condensations accompany with the helical and twisted structures. This means that the plasma whirl flows in comet tail are considerable and sometimes flow quickly in partial areas. In some helical and twisted structures, the toroidal plasma motion is more prominent than the poloidal plasma motion. In this areas, we can only analyze the plasma rotation and neglect the poloidal plasma motion. It is very significant to show the features of the magnetic field and magnetic energy in this case.

In Equation (3.1), the left term is not a function of time t, we have

$$\partial\,[K(\psi,t)\,\partial K(\psi,t)/\partial\psi\,]/\partial t = 0 \tag{4.1}$$

Hence,

$$K^2(\psi,t) = f^2(t)+K_0^2(\psi) \tag{4.2}$$

The potential magnetic field will be twisted into the force-free field. We analyze the evolution of the magnetic field configuration due to the change of angular velocity Ω with time t.

$$\text{Angular velocity} \qquad \Omega = v_\theta/r \tag{4.3}$$

From Equation (3.3), we have

$$\partial K(\psi,t)/\partial t = -\,r[(\partial\Omega/\partial z)\,\partial\psi/\partial r - (\partial\Omega/\partial r)\,\partial\psi/\partial z] \tag{4.4}$$

From (4.2), we have

$$\partial K(\psi,t)/\partial t = [f^2(t)+K_0^2(\psi)]^{-1/2} f(t)\partial f(t)/\partial t$$

Therefore ,the Equation (4.4) virtually shows the relationship between the toroidal magnetic field and the angular velocity Ω. According to Equations (4.2),(2.9) and (2.10),we know the toroidal magnetic field and the force-free factor respectively is

$$rB_\theta(r,z,t) = [f^2(t)+K_0^2(\psi)]^{+1/2} \tag{4.5}$$

$$\alpha(r,z,t) = -[f^2(t)+K_0^2(\psi)]^{-1/2} K_0(\psi)\partial K_0(\psi)/\partial\psi \tag{4.6}$$

Integrating (4.4) with time t, we can discuss the features of the angular velocity.

The characteristic Equations about (4.4) are

$$-r(\partial\psi/\partial r)dr = r(\partial\psi/\partial z)dz \tag{4.7}$$

$$f(t)f'(t)[f^2(t)+K_0^2(\psi)]^{-1/2}dr = r(\partial\psi\partial z)d\Omega \tag{4.8}$$

$$f(t)f'(t)[f^2(t)+K_0^2(\psi)]^{-1/2}dz = -r(\partial\psi/\partial r)d\Omega \tag{4.9}$$

The solution of Equations (4.7)-(4.9) gives the distribution of the v_θ in the form:

$$v_\theta(r,z,t) = r\,\Omega = rH_1(r,z,t)+rH_2(r,z) \quad (4.10)$$

Where, H_1 is the function of r,z,t and H_2 is only the function of r,z. The functions H_1 and H_2 can be determined by the boundary conditions and initial value. H_2 is the term about the steady plasma rotation. H_1 is the term introduced by unsteady plasma rotation as a correctional term. If the relation between v_θ and f(t) is given, we can analyze the relation between the "plasma rotation" and the "magnetic field in condensations".

In simple case, for example, if $K_0(\psi)$ is the liner function of ψ, the Equation of (3.1) can be reduced the linear form.

$$(\partial^2/\partial r^2-1/r\ \partial/\partial r+ \partial^2/\partial z^2)\ \psi = -K_0(\psi)\partial K_0(\psi)/\partial\psi \quad (4.11)$$

the right term is the linear function of ψ. The general solution of the Equation (4.11) is[21,22]

$$\psi(r,z) = r[C_0e^{-\lambda_0 z}J_1(\beta_0 r)+\sum_{n=1}^{\infty}C_n e^{-\lambda_n z}\ J_1(\beta_n r)] \quad (4.12)$$

where $J_1(\beta_n r)$ is the Bessel function, C_n can be determined by the boundary value in the axial direction,

$$\beta_n = \{[\partial K_0(\psi)/\partial\psi]^2+ \lambda_n^2\}^{1/2} \quad (4.13)$$

Because λ_0 is much less than λ_n, the first term in (4.12) is the prominent term.

Substituting Equation (4.12) into (4.10), the toroidal velocity is given:

$$v_\theta(r,z,t) = r[-f(t)f'(t)\ln r\ [f^2(t)+\alpha^2\psi(r,z)]^{-1/2}/\alpha\psi\ ]+ + rH_2(r,z) \quad (4.14)$$

where ψ can be obtained from Equation (4.12). Again, substituting (4.12) into (4.5), we obtain the evolution of toroidal magnetic field.

$$B_\theta = 1/r[f^2(t)+cr^2e^{-2\lambda_0 z}J_1^2(\beta_0 r)+b]^{1/2} \quad (4.15)$$

where c and b are both constant. Toroidal magnetic energy is

$$W_\theta= B_\theta^2/8\pi = 1/8\pi r^2[f^2(t)+cr^2e^{-2\lambda_0 z}J_0^2(\beta_0 r)+b] \quad (4.16)$$

Equations (4.15) and 4.16) are obtained in simple case. $[K_0(\psi)=\alpha_1\psi +b]$. In Equation (4,15), the second term and the third term in the bracket result from steady rotation and the first term results from unsteady rotation. The first term is always a increment and makes the toroidal magnetic field large, so is the toroidal magnetic energy in Equation (4.16). In general cases, from the Equation (4.5), we know that the Equation of B_θ is more complicate than Equation (4.15). But it is same that both B_θ and W_θ are constantly increase with time.

The disturbances acting on comet tail result in the vortex in condensations. The kind of plasma rotation is unsteady. No matter how f(t) change, if vortex exists in condensations, the toroidal magnetic field and energy always increase. Because of the plasma rotation, the magnetic lines of force are twisted and the force-free factor α is increased. So the potential magnetic field is changed into the force-free field, which makes the toroidal field always tend to increase.

The conclusion in this section is a good complement for in section 3. In section 3, we know that the coupling between the unsteady plasma motion and magnetic field can increase the magnetic energy, If the plasma rotation is considerable, or even vary sharply, the force-free factor will be increased quickly, which will enable the toroidal magnetic energy to grow. As was said in section 3, the increment of magnetic energy is the important factor about the instability in type-1 comet tail. Some condensations which energy surpass the threshold will release the energy abruply. So the type-1 comet tail will be confused. These cometary phenomena observed often can be explained logically here.

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