ACCELERATION MECHANISM OF PARTICLES IN THE TYPE-I COMETARY PLASMA

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(Received 13 October, 1991)

Abstract. In the paper, the accelerated effect of ions has been discussed. The transversal magnetic disturbance is able to bring about the magnetic annihilation and merge in some cometary area. The non-steady-state reconnection process can transform the magnetic energy of some cometary area into the kinetic energy of plasma. In addition, the "two stream instability" caused by both solar wind and cometary plasmas exists in Type-I tail, it can also lead the paticles to be accelerated and heated in the plasma tail.

1.

Early, the large accelerations of plasma were already observed in type-I tail. The accelerations can be achieved 300 cm/sec^2. Recently, the direct measurements for comet G-Z showed that the energy of particles reaches 2×10^5 eV. The energy is much higher than the initial energy of comet particles ($\leq 2 \times 10^4$ eV). So there should be an accelerated process in the comet.

The first order Fermi acceleration is the main accelerated mechanism to upper reaches particles in magnetosphere. Amata and Formisano have ever emphasized to point out that it is also a main accelerated mechanism in comet bow shock. We think it is possible that the acceleration exists in comet; but we also think that the Mach number of comet shock is very small ($M \approx 2$), so the accelerated process in comet shock is not as effective as in magnetosphere shock. The reconnection of magnetic field lines also produces high energy particles possibly. But Ip has not agreed with that the reconnection is an effective accelerated mechanism in comet, (and it should also be discussed further, whether or not the steady-state reconnection occurs in any type-I comet). We support Ip's opinion, because some research showed us that the highest energy of comet particles, $E_{\max}$ (by "the reconnection") is only $ZeU_ABL \ll 10^5$ eV. Besides, many people also put forward the concept of stochastic acceleration in coma, the second Fermi acceleration and so on. However, the knottiness of acceleration are still very much, and not solved.

We think the acceleration mechanisms may be varied and not be limited in one or two models. The comet can result in many kinds of plasma instabilities. There are many acceleration sources of particles in the comet, such as the non-steady-

Earth, Moon, and Planets **56**: 243–250, 1992.

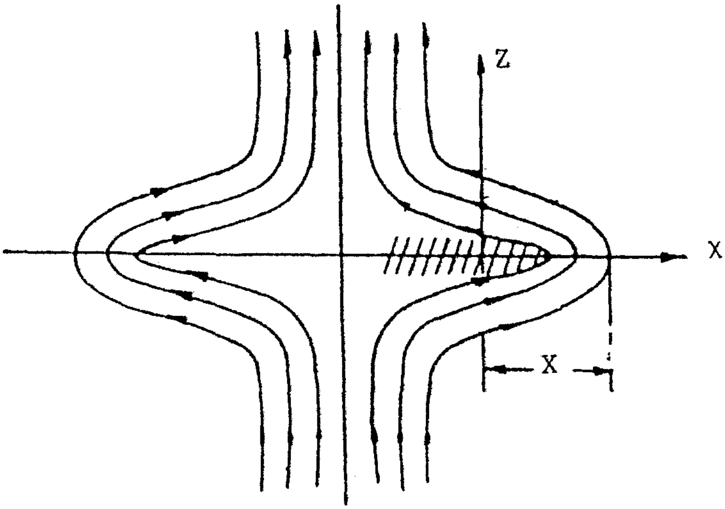

Fig. 1. The magnetic neutral current sheet caused by the transversal turbulence magnetic field.

state reconnection of magnetic field, the couple of waves with particles, a lot of the turbulence forms of magnetic field and so on. They should be a synthetical process and effect. As below, we will also analyze the accelerated mechanisms in type-I comet, and it will be discussed later.

2.

The flow lines in type-I comet are both the ion trace and the magnetic field lines. It is possible that the part plasma turbulences in comet may take transverse disturbed magnetic field to appear in some area. The disturbance perpendicular to magnetic field lines, will be able to hang these lines. Under the pressure of gas around, a magnetic neutral current sheet can be formed there. Figure 1 shows that the boundary clips the reversed polarity region (the magnetic diffusion region and the magnetic reconnection region) and cut the magnetic fields of reversed polarity into two. In the diffusion region, the magnetic lines take to diffuse. The maghnetic fields annihilation occurs. In the reconnection region, the magnetic field lines merge again. The "annihilation" and the "reconnection" nearly occurred in the same twinking. We have already used the mechanism when discussing the type-I tail disruptions.

Both the dissipation and the convection take part in the reversed region. We should adopt the generalized Ohm law in the region,

$$\mathbf{E} + \frac{1}{c} v \times \mathbf{B} = \eta \mathbf{j} + \frac{m_e}{ne^2} \nabla \cdot (\mathbf{jv} + \mathbf{vj}) - \frac{1}{ne} \nabla \mathbf{p} + \frac{1}{nec} \mathbf{j} \times \mathbf{B} . \quad (1)$$

Of course, the magnetic field in comet is till "frozen in" field except the reversed region, we may use equation as

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = 0 . \tag{2}$$

The mass equation of continuity may be written here as

$$v_i \chi = v_x(x) Z(x) , \tag{3}$$

where v_i is the velocity flowing into the reversed region, v_x is the velocity (the component x-direction) in the reversed region, $Z(x)$ is the slow shock delineating the boundary of the reversed region. The component of x-direction of momentum flowing into the reversed region is $[-(\mathrm{d}/\mathrm{d}x')(\rho v_n^2 Z)]$. We suppose the plasma is unable to be compressed. Striding over the slow shock wave, the total pressure (magnetic pressure and plasma gas pressure) is continuous. The total pressure of the external field is well-distributed, therefore, the total pressure acting on the surface of the region is constant, it does not influence upon the momentum. Only the magnetic stress is able to give a contribution of χ-direction of momentum to the surface, and the value is $[-(B_0 B_{on}/4\pi)\,\Delta\chi]$. Here, B_0 is the external field, B_{on} is the component of the normal direction of B_0. Obviously, the magnetic field of the normal direction is continuous from beginning to end, therefore, we have

$$\frac{-B_0 B_{on}}{4\pi}\Delta\chi \simeq -\frac{B_0 B_z}{4\pi}\Delta\chi . \tag{4}$$

Thus, the momentum conservation requires that

$$\frac{\mathrm{d}}{\mathrm{d}x}(\rho v_x^2 Z) = \frac{B_0 B_Z}{4\pi} , \tag{5}$$

where B_Z is the internal field in the reversed region.

The plasmas will be unable as the ideal gas in the magnetic neutral current sheet. We should adopt the equation

$$\mathbf{E} = \mathbf{j}/\sigma - \frac{1}{c}\mathbf{j} \times \mathbf{B} . \tag{6}$$

In the diffusion region, the magnetic fields annihilate and the energy transforms. According to the Ampère law,

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j} , \tag{7}$$

the magnetic field energy flowing into the reversed region in the unit time can be gained easily from

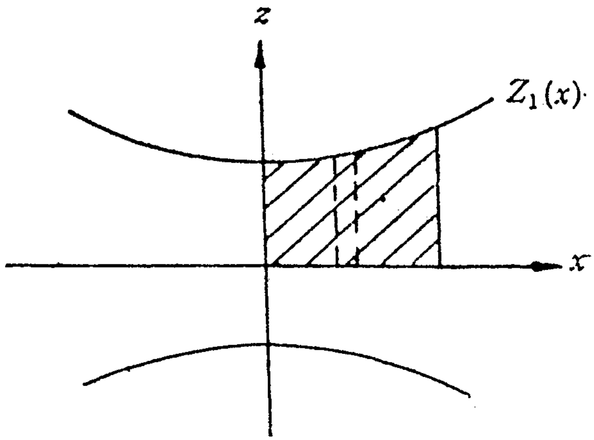

Fig. 2. A schematic diagram of the reversal region of the magnetic field.

$$-\frac{c}{4\pi}\int\int \mathbf{E}\times\mathbf{B}\cdot\mathbf{n}\,\mathrm{d}s = \int\int\int\left(j^2/\sigma + \frac{1}{c}\mathbf{j}\times\mathbf{B}\cdot\mathbf{v}\right)\mathrm{d}\tau$$

$$= \frac{cEB_0X}{4\pi}\left[1 - \frac{8}{\pi}M_AG\right], \tag{8}$$

where

$$G = \left[\frac{1}{2}\ln(1 + L_x^2/X^2) + \frac{L_z}{2}\cot^{-1}\frac{L_z}{2}\right]. \tag{9}$$

The magnetic energy flowing out of the reversed region in the unit time as well, it is

$$\frac{cEB_0X}{4\pi}\frac{8}{\pi}M_A\left[\frac{1}{2}\ln\left(1 + \frac{L_Z^2}{X^2}\right) + \frac{L_Z}{X}\cot^{-1}\frac{L_Z}{X}\right]. \tag{10}$$

Where L_Z is the thickness of the reversed region, X is $\frac{1}{4}$ of the diameter of the reversed region (see Figure 2), M_A is the magnetic field merging rate.

On the basis of Equations (1)–(5), we can get the precise solution as follows (here, the deduced process has been left out),

$$v_x = v_AM_AX/Z(x)\,, \tag{11}$$

$$Z(x) = (M_A^2X^2 + \lambda_e^2)^{1/2}\,, \tag{12}$$

$$B_z = B_0M_A[2M_AX/Z(x) - M_A^3X^3/Z(x)^3]\,. \tag{13}$$

where v_A is Alfvén velocity, λ_e is the electron inertial length,

$$\lambda_e = c(m_e/4\pi ne^2)^{1/2}\,. \tag{14}$$

Equations (8), (9) and (10) show us that a part of the magnetic energy can be changed into Joule heat and dissipated, a part can be changed into the kinetic energy of plasma, and the rest of magnetic energy will flow out of the reversed region.

The non-steady-state reconnection process caused by the transverse magnetic field turbulence is stochastic. Through this process, the cometary particles will be accelerated. In fact, the disturbed waves in the comet are Alfvén disturbances mainly. Given the Alfvén wavelength λ, motion through a distance λ can the Alfvén disturbed waves make the magnetic neutral current sheet restore in terms of MHD principle. So the reconnection occurs in stochastic and restores by itself. Thus, it changes a part of the magnetic energy into the heat and kinetic energy of plasma in comet. Adopting the new data of comet G-Z, we can get the effect of the acceleration mechanism by the equation above. In our calculation, the effect results from the stochastic process is very small in one time. But the total accumulative energy will be effective if the magnetic field turbulence appear repeatedly. The energy of particles may reach 5×10^4 ev and higher. This is nearly correspondence with the results observed in the comets. In general, it is not difficult that the kind of magnetic field turbulence process occurs in the comets.

Of course, the above analysis is only a preliminary study, but it is a new idea to explain the acceleration phenomena in comets. Further work and a large quantity of the numerical simulation calculation has been considered, it will constitute the next step of our research.

3.

Now we discuss the other possible acceleration mechanism basing on plasma dynamics again. When the solar wind encounts the plasmas of the comet, whether the "two stream" instability exists in the comet or not; there are different views about it. Now we discuss the problem here. The Vlasov equation without collisions is

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla f_\alpha + \frac{e_\alpha}{m_\alpha}\left(\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B}\right) \cdot \nabla_v f_\alpha = 0 ; \tag{15}$$

While the Maxwellian equations are as follows:

$$\nabla \cdot \mathbf{E} = 4\pi\rho_E + 4\pi \sum_\alpha e_\alpha \int f_\alpha \, \mathrm{d}v , \tag{16}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\,\partial \mathbf{B}/\partial t , \tag{17}$$

$$\nabla \cdot \mathbf{B} = 0 , \tag{18}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\,\partial \mathbf{E}/\partial t + \frac{4\pi}{c}\,\mathbf{j} + \frac{4\pi}{c}\sum_{\alpha} e_\alpha \int f_\alpha \mathbf{v}\, \mathrm{d}v\,. \tag{19}$$

These Equations ((15)–(19)) are appropriate and complete. Where f_α is particles distribution of component α. It is the $f_{\alpha 0}(v)$ (the distribution in equilibrium state) plus the $f_{\alpha 1}(r, v, t)$ (the disturbance term),

$$f_\alpha(\mathbf{r}, \mathbf{v}, t) = f_{\alpha 0}(\mathbf{v}) + f_{\alpha 1}(r, v, t)\,. \tag{20}$$

The electric field should be the similar form to f_α, we have

$$\mathbf{E}(r, t) = \mathbf{E}_0 + \mathbf{E}_1(\mathbf{r}, t)\,. \tag{21}$$

If we substitute Equations (20) and (21) in (15), Equation (15) can be linearized after the high-order terms are dropped, to leave us with

$$\frac{\partial f_{\alpha 1}}{\partial t} + \mathbf{v}\cdot\nabla f_{\alpha_i} + \frac{e_\alpha}{m_\alpha}\mathbf{E}_0\cdot\nabla_v f_{\alpha 1} = -\frac{e_\alpha}{m_\alpha}\mathbf{E}_1\cdot\nabla_v f_{\alpha 0}\,. \tag{22}$$

Substituting Equations (20) and (21) in (16)–(19), we can similarly linearize these equations; but we omit to write them here.

Now we use the harmonious model and principle value integral. First we expand $f_{\alpha 1}$ to Fourier function in time and space

$$f_{\alpha 1}(\mathbf{r}, \mathbf{v}, t) = \int\int f_{\alpha 1}(\mathbf{k}, \mathbf{v}, \omega)\cdot \exp(i\mathbf{k}\cdot\mathbf{r} - i\omega t)\,\mathrm{d}\mathbf{k}\,\mathrm{d}\omega\,. \tag{23}$$

Transforming $E_1 = -\nabla\phi_1$, however, to a form similar to Equation (23), we have

$$\phi_1(r, t) = \int\int \phi_1(\mathbf{k}, \omega)\cdot \exp(i\mathbf{k}\cdot\mathbf{r} - i\omega t)\,\mathrm{d}\mathbf{k}\,\mathrm{d}\omega\,. \tag{24}$$

Substituting the forms (23) and (24) into the previous equations; and by both calculating and deducing them in detail we can get

$$\frac{1}{k^2}\int_{-\infty}^{+\infty} \frac{F_0'(v_z)\,\mathrm{d}v_z}{v_z - \omega/k} = 1\,, \tag{25}$$

$$F_0(v_z) = \int\int \sum_\alpha \left(\frac{4\pi n_\alpha e_\alpha^2}{m_\alpha}\right) f_{\alpha 0}\,\mathrm{d}v_x\,\mathrm{d}v_y\,. \tag{26}$$

Where Equation (25) is the instability criterion of the plasmas. In order to apply more easily, the criterion (25) can be written the following equivalent equation,

$$U(u) = P\int_{+\infty}^{+\infty} \frac{F_0'(v_z)\,\mathrm{d}v_z}{v_z - u} > 0\,, \tag{27}$$

where $u = \omega/k$, P is the principle value. The plasmas are instability if $U(u) > 0$.

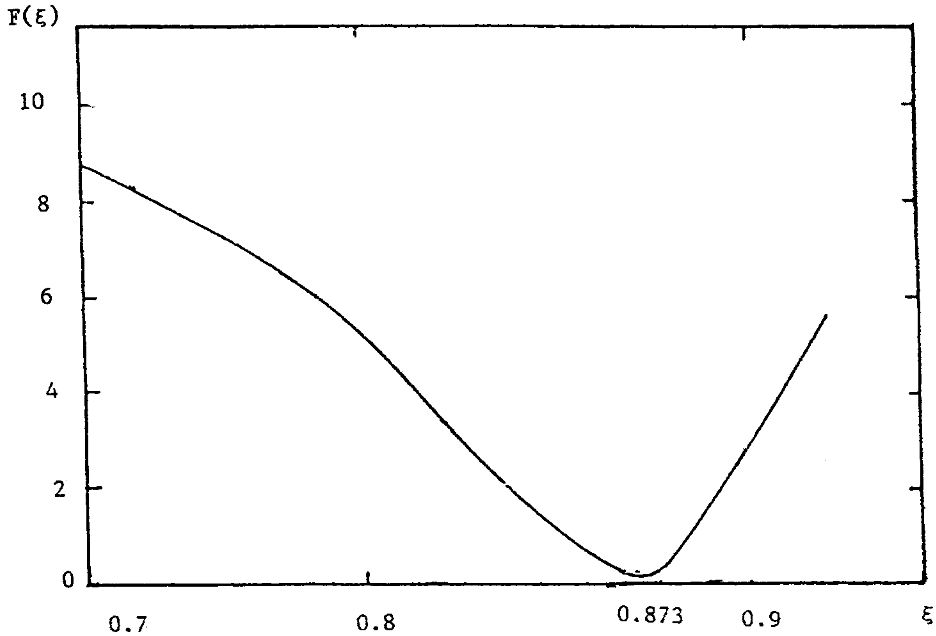

Fig. 3. A correlation curve of the function $F(\xi)$ with ξ.

We adopt Maxwell distribution to positive (or negative) particles in the solar wind and comet. The main components of ions in comet are H_2O^+, O^+, CO^+ and CO_2^+. The ions of solar wind are protons. Given v_0, the velocity of solar wind, and given $\xi = v_z/v_0$; thus we have

$$F_0(v_z) = F_0(v_0\xi) = F(\xi)\,. \tag{28}$$

If $F'(\xi_0) = 0$, $F''(\xi_0) > 0$; the criterion of plasma instability can be expressed as

$$U(\xi_0) = P\int_{-\infty}^{+\infty} \frac{F'}{\xi - \xi_0}\,\mathrm{d}\xi > 0\,. \tag{29}$$

Of course, Equation (29) is not a simple function. Adopting the obtained results of the comet G-Z and other some new data, we have calculated and got the curve of $F(\xi)$ shown in Figure 3. From Figure 3, we know the minimum of $F(\xi)$ is at $\xi_0 = 0.873$. At this point, $U(\xi_0) > 0$. So "two-stream" instability should exist in comet.

Hoyle and Harwit (1962) had shown the "two stream" instability to exist in comets. But they thought it was only a very brief period and a transient effect. Once it has occurred, it will be calmed down swiftly. Some scholars (Cheng *et al.*) thought there was not "two-stream" instability in the comets. In our view, the kind of plasm instability may occur in the inner of comet. We have calculated the data from transition region to tail axis, and discovered the occurs more easily if the distance to axis is closer. So the solar wind can transfer its energy into the ions of the comet and the ions will be able to be accelerated and heated. Especially, the acceleration mechanism is very effective when the solar active strengthen or the velocity of solar wind is speeded up.

Acknowledgments

The authors would like to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.

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