Rev. Mexicana Astron. Astrof., 14, 672-677 (1987)

COLLISIONLESS TEARING INSTABILITY AS THE CAUSE OF AN OBSERVED STRUCTURE IN THE PLASMA TAIL OF COMET HALLEY.

J. Galindo Trejo

Instituto de Astronomía

Universidad Nacional Autónoma de México

RESUMEN. Una estructura ondulada en la cola cercana del cometa Halley fue observada en Tonantzintla el 12 de abril de 1986. Los encuentros recientes de naves espaciales con cometas han confirmado el modelo de cola cometaria con líneas de campo colgadas debido a Alfvén. Tomando en cuenta esto discutimos el origen de la estructura considerando un equilibrio formado por una lámina de corriente neutra con una componente de campo magnético perpendicular a ella. Proponemos aquí que la estructura observada es una consecuencia del inicio de una inestabilidad de desgarre no-colisional del equilibrio de plasma mencionado. Este proceso de reconexión magnética podría ser provocado por una onda de choque interplanetaria.

ABSTRACT. A wavy structure in the near tail of Comet Halley was observed in Tonantzintla on 12 April 1986. Recent spacecraft encounters with comets have confirmed the Alfvén field line draping model of cometary tails. On the basis of this result, we discuss the origin of the structure by considering an equilibrium which consists of a neutral current sheet with a non-vanishing amount of magnetic flux through it. We propose that the observed structure is a consequence of the onset of a collisionless tearing instability in the above mentioned plasma equilibrium. Such a magnetic reconnection process could be triggered by an interplanetary shock.

Key words: COMETS-HALLEY — INSTABILITIES — PLASMAS

I. INTRODUCTION

The qualitative cometary magnetic field model of Alfvén (1957) was recently confronted with the magnetotail observations made by the International Cometary Explorer (ICE) at Comet Giacobini-Zinner (Smith et al., 1986). The magnetic field configuration of the plasma tail is basically characterized by two oppositely-polarized magnetic lobes, which are separated by a neutral current sheet. Above cited in-situ measurements show only little disagreement with such a theoretical description. A small magnetic field component perpendicular to the magnetic lobes was also detected and it indicates clearly the three-dimensional nature of the configuration.

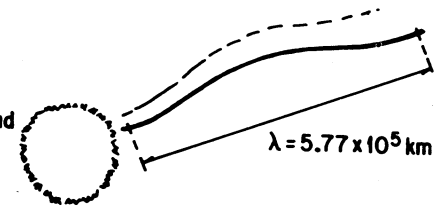
During quiet times, the cometary plasma tail shows a magnetic channeled, nearly uniform, outflow from the cometary ionisphere. However, the tail exhibits occasionally a variety of disturbed structures, i.e. condensations and wavy structures, which can evolve usually in time scales from few minutes to some hours. Considerable work has been devoted to explain these tail features in terms of classical MHD instabilities (see e.g., Hyder et al., 1974; Morrison and Mendis, 1978).

The ICE observations have also revealed an obvious similarity of the earth's magnetosphere with the plasma magnetotail of comets. The plasma in both configurations is collisionless, i.e., binary collisions between particles are negligible because the mean free path is much larger than the characteristic length of the system (thickness of the current sheet). Many theoretical efforts have been performed to describe large-scale dynamic magnetospheric phenomena, which implicate magnetic reconnection; an example of such phenomena is the magnetospheric substorm (Schindler, 1974; Galeev and Zelenyi, 1976).

The purpose of this paper is to show that the collisionless tearing instability, hitherto extensively studied in magnetospheric physics, may explain the existence of wavy structures in the near tail of comets. In order to determine the stability properties of the plasma tail, one considers a generalized equilibrium model of Harris (1962). Schindler (1974) and Galeev and Zelenyi (1976) have found that this equilibrium is unstable against the collisionless ion tearing mode. We use their growth rate and apply it to cometary conditions. As an example, we analyze a wavy structure in the tail of Comet Halley photographed on 12 April, 1986 with the f/2.7 Schmidt camera of the Instituto Nacional de Astrofísica, Optica y Electrónica at Tonantzintla.

II. OBSERVATIONS OF COMETARY PLASMA TAILS.

The forementioned photograph of Comet Halley is shown in Figure 1a. The mid-exposure time was 0920 UT and the exposure elapsed 20 minutes. We have amplified the portion of the original around the head. Figure 1b shows schematically the tail configuration with the wavy feature; we have directly measured a wavelength of approximately 5.77×10^5 km and a thickness about 2×10^4 km at the nearest part to the head. A striking aspect of this feature is that its thickness increases with distance away from the head.



b)

Fig. 1. a) Comet Halley on 12 April, 1986, 0920 UT (mid-exposure) exhibiting a wavy structure in the plasma tail. b) Schematic representation of Figure 1a showing the wavelength of the perturbed tail structure.

Unfortunately, none of the five spacecrafts, which encountered Comet Halley on March 1986, passed through its near tail (see, e.g. Reinhard, 1986). Therefore, in-situ simultaneous data to our observations are not available. However, if we suppose that the parameter data, obtained by the ICE during its crossing of the near tail of the Comet Giacobini-Zinner, are representative ones for cometary tails, we may be able to infer at least the order of magnitude of the involved parameters which lead to an unstable situation in the plasma tail.

Some measured parameters, which are important for the present study, are as follows:

- The ions of the water group (HO^+, H_2O^+, H_3O^+) were the dominant ions in the plasma tail and they are moving with velocities of less than 80 Km s^{-1}, (Ogilvie et al., 1986).

- The magnetotail was 10,800 Km wide and the plasma sheet, 1260 Km. The two magnetic lobes contain oppositely directed fields with strengths up to 60γ ($1\gamma=10^{-5}$G). No classical neutral sheet was observed, since that magnetic components of small strength (compared with 60γ) perpendicular to the lobe component were also detected. The total field magnitude at the sheet's center was 7γ (Smith et al., 1986).

- The density of the plasma sheet was 670 cm^{-3}, the electron temperature of only 13,000°K. These values correspond to the low magnetic field region (Meyer-Vernet et al. 1986). In order to estimate the (unmeasured) thermal velocity of the ions, Siscoe et al. (1986) have considered the transverse pressure balance at the magnetotail:

$$n\kappa T_e + n\kappa T_i + \frac{B^2}{8\pi} = \frac{B_L^2}{8\pi} \quad (1)$$

where B_L is the strength in the absence of any plasma pressure, corresponding to the lobe field strength in the tail. If we take B_L=60γ, B=7γ, $T_e=1.3\times10^4$ °K and n=670 cm^{-3}, we obtain an ion (m_i=18 m_p) thermal velocity $v_{th_i} = \sqrt{2\kappa T_i/m_i}$ = 11.3 Km s^{-1}.

III. THE COLLISIONLESS TEARING INSTABILITY.

Reconnection processes and therefore also annihilation of magnetic field energy with its convertion into particle kinetic energy have long been invoked as the energy source for magnetic substorms in the earth's magnetotail (e.g., Coppi et al., 1966). Due to the collisionless character of the magnetotail plasma, the mathematical treatment of the tearing instability is through the Vlasov theory (i.e., Liouville equations for the one-particle distribution function f together with Maxwell's equations). In such a plasma, the resistivity is anomalous and is due to fluctuating fields acting on the particles.

An isolated current sheet is unstable to filamentation of the current, consequently the current sheet seeks to decrease its energy by bringing parallel current filaments into closer proximity. The redistribution of the currents yields to a change of the magnetic topology; open field lines are now reconnected and close around the joined current filaments. Besides,

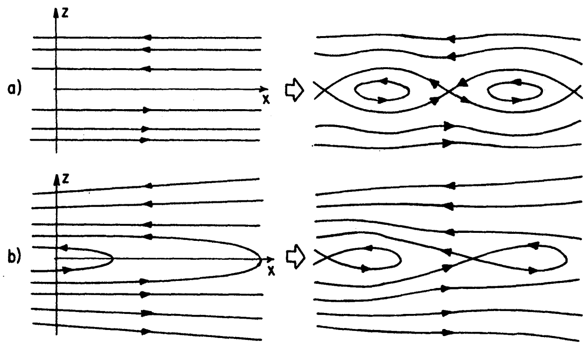


Fig. 2. Magnetic field line reconnection: (a) the tearing instability in a plane neutral plasma sheet. (b) The generalized tearing instability in the case of a weak normal (B_Z) magnetic component (Schindler, 1984).

transport across the magnetic field is enhanced by breaking magnetic surfaces. Large electric fields are induced and accelerate particles efficiently. These complicated processes constitute the so called tearing mode. The tearing mode instability originates in the inverse Landau damping. Therefore, macroscopic energy of the plasma is transferred to particles through microscopic particle-wave resonant processes (Cherenkov interaction). The resonant particles can be both ions and electrons.

Coppi et al. (1966) analyzed a plane neutral current sheet (see Figure 2a) as the simplest plasma equilibrium in the earth's magnetotail. They showed that such an equilibrium is unstable against the electron tearing mode. However, considering the real geometry of the magnetotail (see Figure 2b) Galeev and Zelenyi (1976) have shown that the presence of a weak magnetic field component perpendicular to the sheet (B_Z) suppresses the electron Landau resonance so that the electron tearing mode is stabilized. The applied component B_Z must be strong enough in order to magnetize the electrons in the neutral sheet.

Schindler (1974) and later Galeev and Zelenyi (1976) proposed the occurrence of the ion tearing mode as the cause responsible for the onset of a magnetic substorm. They considered in their stability analysis slightly two-dimensional equilibrium configurations. Galeev and Zelenyi (1976) have explicitly taken into account a generalization of the Harris (1962) configuration (see Figure 2b):

$$\underline{B}_o = \hat{B}_o \tanh (z/L)\ \underline{e}_X + B_n \underline{e}_Z \tag{2}$$

$$n_o = \hat{n}_o\ (X)/\cosh^2\ (z/L) \tag{3}$$

where $\hat{B}_o$, B_n and L are constants. When $B_n \ll \hat{B}_o$ over the whole plasma sheet, then one can neglect dependence of the density n_o on x. We see that 2L gives the sheet thickness. Equations (2) and (3) correspond to an equilibrium distribution function, for each specie j, given by:

$$f_{oj} = \left(\frac{m_j}{2\pi\kappa T_j}\right)^{3/2} \frac{\hat{n}_o}{\cosh^2 (z/L)} \exp\left\{-\frac{m_j}{2\kappa T_j}\left[v_x^{\,2} + (v_y-u_j)^2 + v_z^{\,2}\right]\right\} \tag{4}$$

where U_j is a constant velocity shift along the x-axis. The small perturbation applied to the former equilibrium is assumed to be of the form:

$$\underline{A}_1 = \underline{A}_1 (z) \exp\ [\gamma t + ikx] \tag{5}$$

With $\underline{A}_1$ the perturbed vector potential ($\underline{B}_1 = \nabla x \underline{A}_1$), γ the growth rate of the instability and $2\pi/k$ the wavelength along the x-axis. For long wavelengths (kL<1) the previously described equilibrium becomes unstable to the collisionless ion tearing mode (see Schindler, 1974; Galeev, 1982). The resulting linear growth rate reads:

$$\gamma_i \simeq \frac{v_{thi}}{L} \left(\frac{\rho_i}{L}\right)^{3/2} \left(1 + \frac{T_e}{T_i}\right)(1-k^2L^2) \tag{6}$$

where $\rho_i = m_i v_{thi} c/e\hat{B}_o$ is the Larmor radius of the ions in the magnetic field $\hat{B}_o$. Schindler (1974) has derived a criterion for the onset of the linear ion tearing instability, namely, when by order of magnitude, the gyroperiod $\tau_n = 2\pi m_i c/eB_n$ associated with the normal component B_n becomes equal to the characteristic time of the instability: $\tau_n \simeq \tau_o = 1/\gamma$.

IV. ION TEARING INSTABILITY IN COMETARY PLASMA TAILS.

In order to appreciate the application of the cited theory to cometary conditions, we will use the typical observed parameters quoted in Section II to obtain an order of magnitude estimate for the growth rate γ_i and to establish the stipulations for the onset of the instability in the plasma sheet.

According to the measured wavelength of the perturbed tail structure in Comet Halley (Figure 1), we are dealing with long wavelengths: $kL = \frac{2\pi}{\lambda} L = 6.86 \times 10^{-3} < 1$. Moreover, similarly to the earth's magnetosphere, the ion temperature ($\sim 1.4 \times 10^5$ °K from Eq. (1)) is larger than the electron temperature ($\sim T_e=1.3\times10^4$ °K), so that $T_e/T_i\sim0.1$. This leads to a growth rate $\gamma_i \sim (\rho_i/L)^{3/2}\, v_{th_i}/L$.

With $\hat{B}_o=60\gamma$, $\rho_{i/L}=5.62\times10^{-2}$ we obtain $\gamma_i=2.4\times10^{-4}$ s^{-1} or $\tau_o=4.16\times10^3$ s=1.15 hour.

From the condition for the onset of the tearing mode $\tau_o \approx \tau_n$, one gets the maximal value of $B_n=0.284\gamma$, which assures the development of the instability. The ICE high resolution observations of this component of the magnetic field reveal that the calculated strength is reasonably consistent with the generally weak strength behavior of B_Z around the center of the tail (at approximately 11:02:25 in Figure 3 of Slavin et al. 1986). On the other hand, the growth time τ_o requires to fulfill another condition, namely, it must be smaller than the characteristic time τ_c of the tail parameters change. Then we expect that the tearing instability can manifest itself in the cometary tail. Morrison and Mendis (1978) have assumed $\tau_C \approx 10^6$s as the time scale for variability of the solar wind (main supporter of the cometary plasma tail). Hence, we have indeed $\tau_o<\tau_C$.

V. DISCUSSION AND CONCLUSIONS.

In this paper we have outlined the importance of the collisionless ion tearing instability as a possible cause of the development of perturbed features in the magnetotail of comets. In the case of the wavy structure observed in the tail of Comet Halley on 12 April, 1986, we have considered typical in-situ measured cometary tail parameters (at present, only available for the Comet Giacobini-Zinner) in order to calculate the growth rate γ_i of the instability in such conditions. We found that the instability onset will occur when the magnetic component perpendicular to the current sheet (B_n) is not larger than 0.284γ. The estimated growth time $\tau_o=1/\gamma_i=1.15$ hour seems to be able to explain at least the order of magnitude of the characteristic time of the evolution of similar structures in other comets (see, e.g., Brandt et al., 1980). Figure 3 shows schematically the expected magnetic field topology and the corresponding plasma distribution as result of the tearing instability in a (cometary) magnetosphere (Schindler, 1972). However, the real configuration may be much more irregular, so that specially in the portion near to the cometary coma the plasma tail gets its curved (not necessarily symmetrical) appearance.

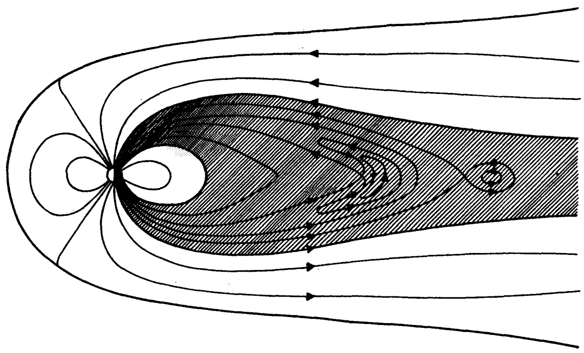


Figure 3. Schematic description of the tearing instability with $B_Z\neq0$ in a magnetosphere. The shaded region represents the plasma sheet (Schindler, 1972).

We believe that the most likely external drivers of perturbations in cometary tails may be interplanetary shock fronts generated during solar flares, 'disparitions brusques' of quiescent prominences and through high-speed solar wind streams.

Finally, we point out that the above applied theory does not take into account the effect of the cometary ionisphere, which is directly connected with the plasma tail through the magnetic field lines. Thus, it seems to be convenient to analyze this more realistic situation.

ACKNOWLEDGMENTS.

The research work reported here was supported in part by the Consejo Estatal de Ciencia y Tecnología de Puebla, México. The author wishes to thank Dr. A. Arellano for comments and for reading the manuscript.

REFERENCES.

Alfvén, H., 1957, Tellus, 9, 92.
Biskamp, D. and K. Schindler, 1971, Plasma Phys., 13, 1013.
Brandt, J.C., J.D. Hawley and M.B. Niedner, 1980, Ap. J., 241, L51.
Coppi, B., G. Laval and R. Pellat, 1966, Phys. Rev. Letters, 16, 1207.
Galeev, A.A., 1982, Magnetospheric Plasma Physics ed. by A. Nishida, p. 143, D. Reidel Hingham, Mass.
Galeev, A.A. and L.M, Zelenyi, 1976, Sov. Phys. JETP, 43, 1133.
Harris, E.G., 1962, Nuovo Cim., 23, 115.
Hyder, Ch.L., J.C. Brandt and R.G. Roosen, 1974, Icarus, 23, 601.
Meyer-Vernet, N., P. Couturier, S. Hoang, C. Perche, J.L. Steinberg, J. Fainberg, and C. Meetre, 1986, Science, 232, 370.
Morrison, P.J. and D.A. Mendis, 1978, Ap. J., 226, 350.
Ogilvie, K.W., M.A. Coplan and B.J. Geiss, 1986, Science, 232, 374.
Reinhard, R., 1986, Nature, 321, 313.
Schindler, K., 1972, Earth's Magnetospheric Processes, ed. by G.M. McCormac, p. 200, D. Reidel Publ. Co.
Schindler, K., 1974, J. Geophys. Res., 79, 2803.
Schindler, K., 1984, Magnetic Reconnection, ed. by E.W. Hones Jr., Geophys. Monograph 30, p. 9.
Siscoe, G.L., J.A. Slavin, E.J. Smith, B.T. Tsurutani, D.E. Jones and D.A. Mendis, 1986, Geophys. Res. Lett. 13, 287.
Slavin, J.A., E.J. Smith, B.T., Tsurutani, G.L., Siscoe, D.E. Jones, and D.A. Mendis, 1986, Geophys. Res. Lett., 13, 283.
Smith, E.J., B.T. Tsurutani, J.A. Slavin, D.E. Jones, G.L. Siscoe and D.A. Mendis, 1986, Science, 232, 382.

J. Galindo Trejo: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., Mexico.