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ON THE FINE STRUCTURE OF COMETARY PLASMA TAILS

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ABSTRACT

It is argued that the small-scale structures observed close to the plasma tail axis of comets may be a consequence of well-known finite-resistivity instabilities in the cometary cross-tail current sheet. While the "tearing" mode instability, which causes a breakup of the layer along the current flow lines, may be responsible for the observed small condensation or "knots" near the axis, the "ripple" mode instability may give rise to the small-scale wavy structures.

Subject headings: comets — plasmas

I. INTRODUCTION

Even during relatively "quiet" times the plasma (type 1) tails of comets exhibit a complicated and time varying fine structure. This includes straight rays and streamers, wavy ("helical") structures, condensations or knots, kinks as well as more irregular features (see Mendis and Ip 1977; Brandt and Mendis 1978, for recent reviews of these phenomena). During more disturbed times—which are, of course, less frequent—a cometary plasma tail may take a highly irregular ("turbulent") form and may sometimes even get totally detached from the cometary head. This latter phenomenon, which seems to be associated with the interaction of the comet with high-speed solar wind streams, has recently been explained in terms of two alternative physical mechanisms (Niedner and Brandt 1978; Ip and Mendis 1978) and will not be discussed further here. The nature and evolution of the tail rays and streamers have also been the subject of several earlier studies (e.g., Alfvén 1957; Marochnik 1964; Ness and Donn 1966; Wallis 1967; Ip and Mendis 1976; Mendis 1978). In this paper, therefore, we will confine our attention to the origin of small condensations and wavy structures observed close to the tail axis (see Fig. 1).

II. THE CURRENT SHEET IN THE COMETARY TAIL

Ip and Mendis (1976) have shown that the folding of the interplanetary field lines into the tail of a comet as the solar wind sweeps past the cometary ionosphere can generate a cross-tail current of the order of 10^7–10^8 A separating the two tail lobes of opposite polarity, at a heliocentric distance ~ 1 AU. From the observed folding rate of the tail rays it is deduced that the magnetic field in the cometary tail (B_t) increases slowly from the solar wind value ($\sim 5\,\gamma$ at 1 AU) to about 100 γ just outside the current-carrying neutral sheet, although its "average" value in the entire plasma sheet would be around 10 γ. Finally, it is shown by these authors that the current-carrying electrons in the neutral sheet can be energized to the Alfvén energy $\approx B_t^2/4\pi n_e \approx$ 1–10 keV, under which circumstances the effective (anomalous) resistivity will increase well above the classical value (see Hamberger and Jancarik 1970; Sagdeev 1974).

Here we will argue that the earlier-mentioned small structures, observed near the plasma tail axis, are a consequence of well-known instabilities in a finite-resistivity current sheet pinch.

III. THE "RIPPLING" AND THE "TEARING" OF THE TAIL CURRENT SHEET

The stability of a plane current layer having finite isotropic resistivity was analyzed in the hydrodynamic approximation by Furth, Killeen, and Rosenbluth 1963, hereafter FKR; (see also Furth 1969). They showed that in an incompressible fluid there can be three basic types of "resistive" instability, namely, a long-wave "tearing" mode corresponding to the breakup of the layer along current flow lines, a shorter-wave "rippling" mode due to the flow of current across resistivity gradients in the layer, and a low-g "gravitational" interchange mode, which would grow despite the finite magnetic shear if there is some curvature of the field lines (see FKR, Fig. 2, for a schematic representation of these instabilities; each of these modes produces changes in magnetic field line topology).

Although pronounced kinks are observed occasionally in the tail streamers when a comet is struck by a fast solar wind stream, the tail streamers are by and large distinguished by their extreme straightness. Since we believe that these straight streamers delineate the undisturbed field morphology in the cometary tail, we will restrict our discussion only to the "rippling" and the "tearing" modes.

FIG. 1.—Comet Kohoutek 1973f (picture taken 1974 Jan 13), showing the small-scale structures in the plasma tail. Note in particular the small elliptical structure ("knot") about a third of the way down the tail axis. (Courtesy Hale Observatories.)

If a is the thickness of the tail current sheet, the resistive diffusion time τ_R of the magnetic field across it is given by

$$\tau_R = \frac{4\pi a^2}{\eta_{\rm eff}} = \frac{4\pi a^2}{\chi \eta_c}, \quad (1)$$

where η_c is the classical resistivity of a fully ionized plasma, and χ ($1 \lesssim \chi \lesssim n_e \lambda_D^3$) is the turbulent enhancement of the resistivity in the neutral sheet due to the large current density (Ip and Mendis 1976). For the range of electron temperatures relevant to our discussion and $n_e = 10\ {\rm cm}^{-3}$,

$$\eta_c \approx \frac{1.3 \times 10^{14}}{T_e^{3/2}}\ {\rm emu} \quad (2)$$

(Spitzer 1962). Also the thickness of the current sheet is given by

$$a = f r_i \approx 1.3 f \times \frac{\mu_i^{1/2} T_i^{1/2}}{B}, \quad (3)$$

where r_i (cm), μ_i, and T_i (K) are, respectively, the Larmor radius, molecular weight, and temperature of the cometary tail ions, B is the magnetic field (in gauss), and f is a number ($\gg 1$).

From formulae (1), (2), and (3) we obtain

$$\tau_R \approx \frac{1.7 \times 10^{-13} f^2 \mu_i T_i T_e^{3/2}}{\chi B^2}. \quad (4)$$

The hydromagnetic transit time τ_H across the sheet is given by

$$\tau_H = \frac{a}{v_{\rm A}} \approx \frac{6.1 \times 10^{-12} f \mu_i T_i^{1/2} n_i^{1/2}}{B^2}, \quad (5)$$

where $v_{\rm A}$ is the Alfvén speed.

Following FKR, we define two dimensionless parameters,

$$S = \frac{\tau_R}{\tau_H} \approx 2.8 \times 10^{-2} \times \frac{f T_i^{1/2} T_e^{3/2}}{\chi n_i^{1/2}} \quad (6)$$

and

$$\alpha = \frac{a}{\lambda} = \frac{1.3 f \mu_i^{1/2} T_i^{1/2}}{\lambda B}, \quad (7)$$

where λ is the wavelength of the disturbance. The following conditions are necessary for FKR's "tearing" mode:[1]

$$\alpha < 1, \quad (8a)$$

$$S^{1/4} \alpha > 1, \quad (8b)$$

and the growth time, $\tau_{\rm TM}$, is given by

$$\tau_{\rm TM} = \tau_R \left(\frac{\alpha}{S}\right)^{2/5}. \quad (9)$$

[1] We note that the zeroth-order equilibrium velocity (or equivalently the $\partial \beta_0 / \partial t$ diffusion term) was neglected in the FKR calculation. Inclusion of this effect (Dobrott, Praeger, and Taylor 1977) does not significantly alter our results.

The observed dominant ion in the cometary plasma tail is CO^+. We therefore take $\mu_i \approx 28$. The numerical values of all the other physical parameters are very uncertain and may vary from comet to comet. However, we may take as representative values $n_i \approx 10\ {\rm cm}^{-3}$, $\langle B \rangle \approx 10\ \gamma$, $T_i \approx 10^5$ K, and $T_e \approx 5 \times 10^5$ K. These temperatures correspond to those typical for the quiet solar wind. It is possible that the cometary tail temperatures are perhaps an order of magnitude smaller (Mendis 1977). We shall consider this point again later. For the moment, working with these values and taking $f \approx 100$, a number which is large enough to warrant the neglect of finite Larmor radius effects but otherwise rather arbitrary, and $\lambda \approx 10^5$ km (a value characteristic of the knot in Fig. 1 and typical for knots observed in other comets), we get $r_i \approx 2.2 \times 10^2$ km, and consequently $\alpha \approx 2.2 \times 10^{-1}$. Clearly, inequality (8a) is satisfied, while inequality (8b) would be satisfied if $\chi \lesssim 2.5 \times 10^8$. Also from equation (9) we obtain

$$\tau_{\rm TM} \approx \frac{3.8 \times 10^9}{\chi^{3/5}}\ {\rm s}. \quad (10)$$

In order for the tearing mode instability to manifest itself in the comet tail,

$$\tau_{\rm TM} < \tau_D, \quad (11)$$

where τ_D is the dynamical time scale over which the cometary parameters change. Whether we take this to be the time scale for orbital change or, more appropriately, the time scale for variability of the solar wind, which is responsible for shaping and maintaining the cometary plasma tail, we get $\tau_D \approx 10^6$ s. Consequently inequality (11) implies that $\chi \gtrsim 9.1 \times 10^5$.

What all this means is that if $9.1 \times 10^5 \lesssim \chi \lesssim 2.5 \times 10^8$, the "tearing" mode instability in the cometary tail current sheet will grow, sufficiently rapidly to manifest itself as an observable effect. Since the maximum value of χ, which corresponds to fully developed turbulence, is approximately $n_e \lambda_D^3$ ($\approx 10^9$, with the assumed numerical values), the range of values obtained for χ are not unreasonable. We therefore suggest that the small condensations or "knots" often observed close to the axis of cometary plasma tails (as, for instance, in the case of comet Kohoutek 1973f [Fig. 1]) are due to the breakup of the cross-tail current sheet along the current flow lines as a result of the sufficiently rapid growth of the "tearing" mode instability there.

Let us next consider the "rippling" mode. The necessary conditions are

$$\alpha < S^{2/3} \quad (12a)$$

and

$$\alpha S^{2/7} > 1. \quad (12b)$$

Condition (12a) is easily met, since it requires only that $\chi \lesssim 9.4 \times 10^{11}$, while (12b) has a more stringent requirement, viz., $\chi \lesssim 5.3 \times 10^8$.

The growth time, $\tau_{\rm RM}$, for the "rippling" mode is then given by

$$\tau_{\rm RM} = \tau_R(\alpha S)^{-2/5} \approx \frac{1.25 \times 10^{10}}{\chi^{3/5}} . \quad (13)$$

As in the case of the "tearing" mode considered earlier, the "rippling" mode will manifest itself in the comet tail if

$$\tau_{\rm RM} < \tau_D . \quad (14)$$

With $\tau_D \approx 10^6$ s, as before, this gives

$$\chi \gtrsim 6.7 \times 10^6 . \quad (15)$$

Therefore the condition for the "rippling" mode instability to grow sufficiently rapidly in order to manifest itself as an observable effect in the cometary plasma tail is that $6.7 \times 10^6 \lesssim \chi \lesssim 5.3 \times 10^8$.

It is seen that for the numerical values of the parameters we have used the "rippling" and "tearing" mode instabilities exist in nearly equivalent ranges. But for a given value of χ the "tearing" mode has a growth rate which is about 3 times larger.

If we decrease both T_i and T_e by one order of magnitude while keeping the other plasma tail parameters fixed, the corresponding range of χ for the "tearing" mode instability is $6.2 \times 10^2 \lesssim \chi \lesssim 2.5 \times 10^4$, while that for the "rippling" mode is $2.1 \times 10^4 \lesssim \chi \lesssim 9.5 \times 10^4$. In this case the range of χ for the "tearing" mode is larger than that of the "rippling" mode, the range of the "rippling" mode being somewhat narrow. However, for a given value of χ the growth rate of the "tearing" mode is nearly an order of magnitude larger.

IV. DISCUSSION

Because of the inherent large uncertainties in almost all the physical parameters in the cometary plasma tail, it is difficult to make definite statements about the growth of the various finite-resistivity instabilities in the central current sheet. However, using reasonable values for these parameters, one sees in a general way that for significant but not too large enhancements of the resistivity, the "tearing" mode instability would develop sufficiently rapidly to break up the cross-tail current sheet along the current flow lines. We suggest that the small condensations or knots seen close to the plasma tail axis in several comets may be caused by this process.

Wallis and Ong (1976) have suggested that these knots may be caused by the so-called recombination instability which has been investigated by D'Angelo (1967). However, it has been pointed out that this requires a number of conditions unlikely to be met in the cometary plasma tail (Mendis 1977).

For larger values of the resistivity, the "rippling" mode can also grow rapidly. While this may cause the small-scale wavy structures observed close to the tail axis, the large wavy structures seen far down the tail (see Fig. 1) may be associated with field aligned currents (Hyder, Brandt, and Roosen 1974; Ip and Mendis 1976).

We stress that the "tearing" mode instability can only produce tearing of the current sheet, thereby producing small structures typically of the thickness of the current sheet ($\sim 10^4$ km). It cannot be responsible for the sudden total detachment of the plasma tails of comets, observed occasionally. The possible causes of the latter phenomenon have been considered elsewhere (Niedner and Brandt 1978; Ip and Mendis 1978).

Finally, we should mention that since the FKR treatment is MHD, possibly important, finite Larmor radius effects have been neglected. Also, the hybrid use of enhanced resistivity and MHD should be viewed with some caution, although the collisionless counterpart of the "tearing" mode has been investigated by Coppi, Laval, and Pellat (1966) in connection with the Earth's magnetotail, and growth rates calculated using their results are in order of magnitude agreement with those herein.

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