PECULIARITIES IN THE IONIC TAIL OF COMET IKEYA-SEKI (1965f)

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Abstract. Direct photographs of Comet Ikeya-Seki obtained on four consecutive days from October 29 to November 1, 1965, are used for an analysis of the multiple helical structures in the ionised tail. The formation of these structures is explained on the basis of plasma instabilities excited in the tail containing twisted magnetic fields. The growth rate of the modes excited at the mode rational surface agrees well with the observed results. This model also accounts for the presence of harmonic structures seen in the tail of the comet.

1. Introduction

The properties of the ionic tails of Comets hold forth valuable information not only on the nature of the interplanetary medium, but also on the physics of the interaction between the cometary ionosphere and the solar wind plasma. It is known that the structures such as the kinks, helices etc. noticed in the plasma tails are the results of the interaction of the ionic tail with the interplanetary medium. In the recent years there have been efforts to explain the dynamical properties of these fine structures. Hyder and others (1974) studied the tail structures of Comet Kohoutek and attributed the 'helical' structures moving at a speed of $200\,\mathrm{km\,s^{-1}}$ to a wave excited by the classical kink instability produced by currents flowing along the tail axis. Ershkovich (1976) interpreted the same feature as arising from Kelvin–Helmholtz instability down the tail. Identifying this phase velocity with the Alfvén speed in the cometary plasma the former derived the magnetic fields in the tail to be in the range of 100γ–1000γ corresponding to the range of densities of the CO^+ ions prevailing in the tail.

We have observed a helical pattern in the tail of the comet Ikeya-Seki (1965f) and propose a different mechanism for the possible formation of such structures under the conditions obtaining in the tail. We show that in the presence of twisted magnetic fields in the tail, the plasma acquires the form of the field under certain specific conditions. The existence of magnetic fields in the tail is undoubtedly accepted by all, although there are no observations of these fields so far. In addition to explaining the general helical structure, our model also admits the possibility of the excitation of the harmonics of the helices in the tail.

2. Observations

The direct photographs obtained with an $f/4.5$ Tessar lens ($f = 180\,\mathrm{mm}$) consecutively on four days from October 29 to November 1 when the comet was an early morning

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object show the tail extending to 20° and the helical structures in the latter part of the tail in great detail. Our prismatic spectra in the slitless mode with a camera of $f = 5$ cm follow the tail spectrum upto 12°. In the spectra of October 30.985, the tail bands of CO^+ can be seen although the continuous spectrum is dominant. Also seen is the bright sodium tail extending beyond 2° (Bappu and Sivaraman, 1967). The four helices are best seen on the photograph of October 30.000 (Figure 1).

3. Theory

We carry out the theoretical treatment in cylindrical geometry, which is the appropriate geometry for the comet tail. It has also been recently emphasized by Spicer (1981) that the tearing modes in a planar geometry are very different from the ones in cylindrical geometry, for example the mode $m = 1$ in cylindrical geometry represents a helical displacement of the center of the plasma, whereas no such motions are observed in a slab.

The system under investigation is composed of the following components:

(1) Cometary tail plasma of electron density varying from 10 cm^{-3} to 100 cm^{-3}, which is embedded in a uniformly twisted magnetic field of the form $(O, H_\theta(r), H_z)$, where H_θ and H_z are the azimuthal and axial components of the magnetic field.

(2) The cometary tail plasma is surrounded by the solar wind plasma with its own magnetic field, which in the general treatment, has also been assumed to be twisted in nature. We make use of the ideal magnetohydrodynamic equations to investigate the response of the given magnetoplasma to a specified perturbation. The relevant equations are:

equation of motion

$$4\pi\mu \frac{\partial \mathbf{v}}{\partial t} = -\nabla\psi + (\mathbf{H}\cdot\nabla)\mathbf{h} + (\mathbf{h}\cdot\nabla)\mathbf{H}, \tag{1}$$

equation for perturbed magnetic field

$$\frac{\partial \mathbf{h}}{\partial t} = (\mathbf{H}\cdot\nabla)\mathbf{v} - (\mathbf{v}\cdot\nabla)\mathbf{H}, \tag{2}$$

and the continuity equation

$$\nabla\cdot\mathbf{v} = 0; \tag{3}$$

where **H** is the given magnetic field, **h** is the perturbation in the magnetic field, ψ is the variation in total pressure (kinetic plus magnetic), **v** is the perturbed fluid velocity and μ is the fluid density. The system of Equations (1), (2), and (3) can be solved for a linear perturbation of the form $f(r)\, e^{i(\omega t + qz + m\theta)}$ where (r, θ, z) are the cylindrical coordinates, m is an integer, the harmonic number and ω is the frequency and q is the wave number. One finds the radial dependence of the pressure variation ψ to be: $\psi = \alpha I_m(qr)$, where α is a constant and I_m is the Bessel function. A similar treatment can be carried out

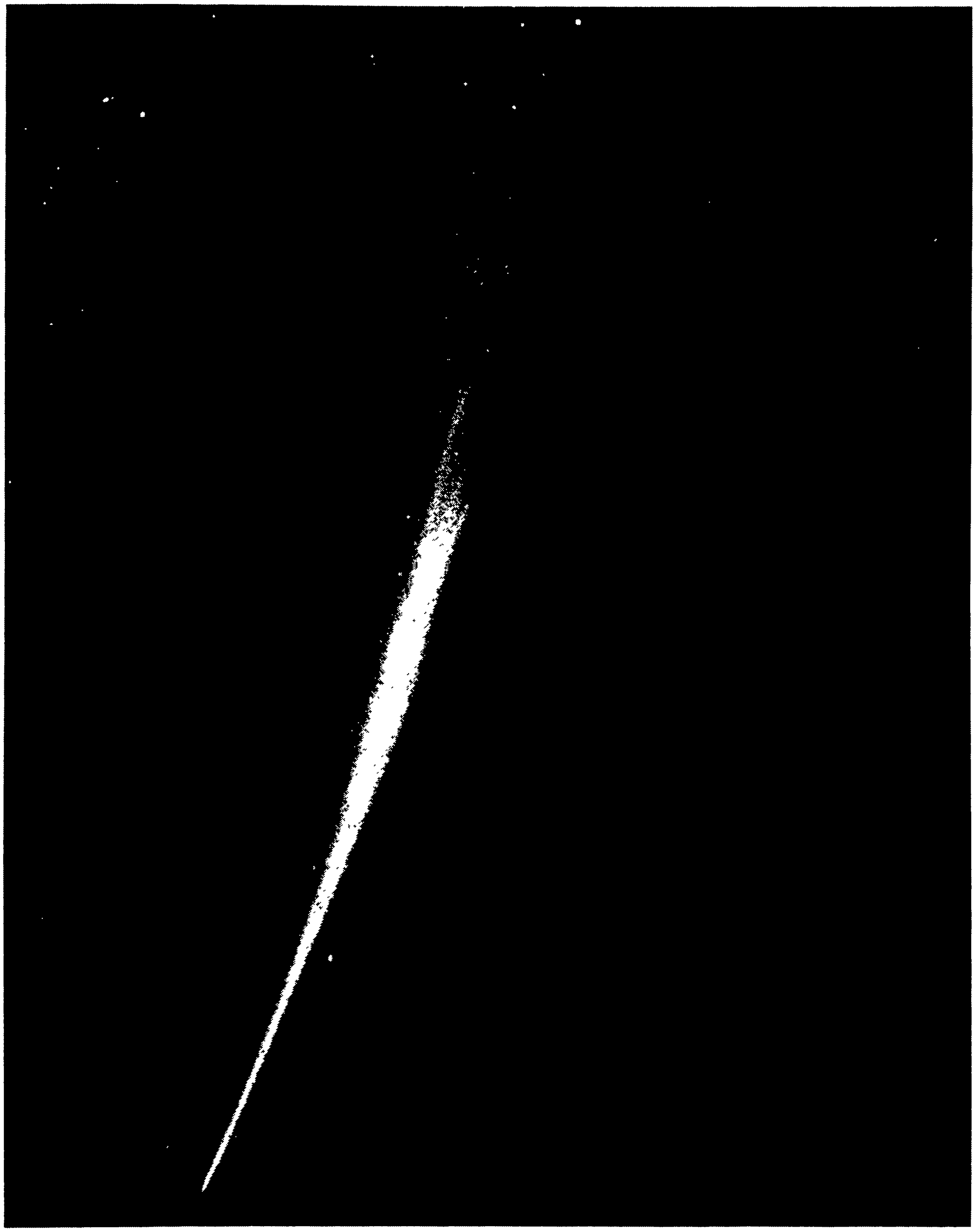

Fig. 1. Comet Ikeya-Seki (1965f) photographed with Tessar lens of 180 mm focal length on October 30.000, 1965. Scale in this reproduction: 2.19° per cm. Notice the helical pattern begin from the brightest part of the tail (about 18° from the coma) and become conspicuous beyond 20°.

for the plasma external to the comet tail. Then the boundary conditions to be satisfied are the continuity of the radial component of the velocity and discontinuity in the pressure across the boundary. The discontinuous change in the pressure across the boundary is given by

$$i(\omega_2\psi_2 - \omega_1\psi_1) = V_r|_{r=R}\,\frac{(H_{1\theta}^2 - H_{2\theta}^2)}{R}, \tag{4}$$

where $\omega_1 = \omega + \mathbf{q}\cdot\mathbf{U}_c$,

$\omega_2 = \omega + \mathbf{q}\cdot\mathbf{U}_s$;

$\mathbf{U}_c$ and $\mathbf{U}_s$ being the cometary plasma flow velocity and the solar wind velocity respectively and R the radius of the tail. The index 1 refers to the cometary plasma parameters and 2 to those of the surrounding solar wind plasma. The expressions for the radial velocity V_r are found to be

$$V_r|_{r<R} = \frac{-i\alpha[2A_1\omega_1K_1mI_m(x_1) - \omega_1x_1(4\pi\mu_1\omega_1^2 - K_1^2)I_m'(x_1)]}{(4\pi\mu_1\omega_1^2 - K_1^2) - 4A_1^2K_1^2}, \tag{5}$$

$$V_r|_{r>R} = \frac{-i\beta[2A_2\omega_2K_2mK_m(x_2) - \omega_2x_2(4\pi\mu_2\omega_2^2 - K_2^2)K_m'(x_2)]}{(4\pi\mu_2\omega_2^2 - K_2^2) - 4A_2^2K_2^2}, \tag{6}$$

where the radial dependence of H_θ has been assumed to be of the form $H_\theta = A\cdot r$, with A as a constant, and $K = qH_z + mA$, I_m and K_m are Bessel functions and I_m' and K_m' are derivatives of I_m and K_m. Furthermore,

$$x_1 = q\left\{1 - \frac{4K_1^2A_1^2}{(4\pi\mu_1\omega_1^2 - K_1^2)^2}\right\}R$$

and

$$x_2 = q\left\{1 - \frac{4K_2^2A_2^2}{(4\pi\mu_2\omega_2^2 - K_2^2)^2}\right\}R;$$

and α and β are constants. Equating $V_r|r<R$ to $V_r|r>R$ at the boundary we determine the ratio β/α. Substituting the value of β/α in Equation (4) gives the general dispersion relation

$$\frac{(4\pi\mu_1\omega_1^2 - K_1^2)\dfrac{I_m'}{I_m}x_1 - 2A_1K_1m}{(4\pi\mu_1\omega_1^2 - K_1^2)^2 - 4A_1^2K_1^2} =$$

$$= \frac{(4\pi\mu_2\omega_2^2 - K_2^2)\dfrac{K_m'}{K_m}x_2 - 2A_2K_2m}{(4\pi\mu_2\omega_2^2 - K_2^2)^2 - 4A_2^2K_2^2 + \dfrac{\left[2A_2K_2m - x_2(4\pi\mu_2\omega_2^2 - K_2^2)\dfrac{K_m'}{K_m}\right]}{[x_2(A_1^2 - A_2^2)]^{-1}}}. \tag{7}$$

We investigate the modes excited through Equation (7) under the condition $k = qp + m = 0$ where p is the pitch of the magnetic field. The behaviour of the plasma system under this condition has been discussed by Dungey and Loughhead (1954). The present treatment, though follows closely that of Dungey and Loughhead does not suffer from their assumptions (e.g., $\omega \to 0$). The invalidity of these assumptions was pointed out by Tayler (1957). Under the specified relationship between the pitch and the wavelength of the perturbation, the whole plasma takes the form of the magnetic field, which we propose to be the cause of the helical structures in the tail plasma. Physically, this condition describes the resonance of the magnetic field lines with the helicity of the given perturbation or the instability. We solve Equation (7) for complex frequencies, such that

$$\omega \simeq qU_c - i\gamma_0,$$

and determine the value of the growth rate γ_0. Since Equation (7) is rather cumbersome, we shall consider a special case for making numerical estimates. We suppose that at the mode rational surface, (the surface at which the helicity of the magnetic field is equal to that of the perturbation) the cometary as well as the surrounding magnetic fields, both satisfy the conditions $K_1 = K_2 = 0$ and $A_1 = A_2$. In this case the expression for the growth rate takes a simple form given by wavelengths of the order of $6R$, $3R$, $2R$ etc. A higher value of the pitch say $p = 2R$ will generate wavelengths of the same order as those obtained from measurements.

4. Discussions

Although our estimates of the growth rates are of the same order as those reported by other investigators (Hyder *et al.*, 1974; Ershkovich, 1976) the mechanism of excitation of the modes envisaged here is different from those considered by them. In the present mechanism the energy is fed resonantly to the modes at the mode rational surface. The source of energy is still the kinetic energy contained in the relative motion between the cometary plasma and the solar wind. Ikeya-Seki appears to be the only comet displaying such multiple helices. The instabilities attributed in the earlier theoretical treatments of other comets cannot explain the existence of such multiple structures, whereas, the harmonic structure of the helices is a natural consequence of the mechanism proposed by us.

Substituting the measured value of the wavelength in the condition for excitation of the mode $K = 0$ for $m = 1$ we find that the pitch of the magnetic field is of the order of the radius of the tail confirming our assumption. This value of the pitch fixes the ratio of the axial to the azimuthal component of the magnetic field close to unity. Therefore,

$$\gamma_0^2 \simeq \frac{\mu_2}{\mu_1} \omega_2^2 \frac{I_m'/I_m}{|K_m'/K_m|}.$$

We assume that the pitch of the magnetic field p is of the order of the radius R. Then the wavelength is found to be $\lambda = (2\pi R)/m$. Adopting $m = 1$, $U_s \sim 540 \text{ km s}^{-1}$, $R \sim 2.5 \times 10^5 \text{ km}$, and $\mu_2/\mu_1 = 1/(20 \times 28)$, and using the relation $\gamma_0 = V_g q_i$ we find $q_i/q_R = 0.3$. Here V_g is the group velocity, q_i is the imaginary part and q_R is the real part of q. This estimate is of the same order as reported by Ershkovich (1980). An important feature of this theory is that it can account for the harmonics of these modes. As the harmonic number m increases, the wavelength decreases. Thus one could expect to observe the helices with wavelengths $\lambda \sim 2\pi R$, πR, $(2\pi/3)R$ etc. Since the growth rate is inversely proportional to the wavelength, large wavelength modes may not be recognisable in the photographs owing to their small growth rates and the finite size of the comet tail. The detection of very small wavelength helices, may on the other hand be limited by spatial resolution of the photographs.

The wavelength of the four helices were obtained by measuring the distance between the consecutive points of opposite phase ($\lambda/2$). It is seen that out of the four helices that could be measured, two of them have wavelengths $10R$ and the other two $8R$ where R is the radius of the tail. Assuming an approximate value of the pitch p to be R, one finds $H_{1\theta}$ will assume values only of the same order of magnitude as H_{1z}. For the case discussed here viz. $H_{1\theta} = H_{2\theta}$ at the surface and $(H_{1z}/H_{1\theta}) = (H_{2z}/H_{2\theta})$, we find H_{1z} is of the same order as H_{2z}.

Thus the magnetic field in the tail of comet Ikeya-Seki turns out to be of the same order as the interplanetary field and so is definitely lower than the fields estimated in other comets like Kohoutek or Arend-Roland. The existence of stronger magnetic fields in these comets is further supported by the streamers that are prominently seen in the photographs. This holds true also for the comets Tago-Sato-Kosaka and Morehouse. The relative geometry of the orbit of the comet with reference to the plane of the ecliptic shows that both the ionic and dust tails would have been in the same line of sight for a terrestrial observer only for a short time of the order of a few hours around September 9, if at all they had existed separately. This together with the CO^+ emission noticed in the spectra leads us to conclude that the dust and ionic tails were mixed in this comet and this is yet another example of the mixed tail according to Belton's classification (1965). The magnetic field in the tail was weak as we have shown earlier and this explains the absence of prominent streamer structures in the tail.

The fast spin associated with the nucleus is responsible for the twisted magnetic field of the tail. The non-gravitational forces tend to speed up the rotation of the nucleus (Sekanina, 1968). We now calculate the period of the spin of the nucleus of the comet in the following way. If θ is the angle which the helical structures make with the tail boundary, V is the velocity in the direction of the tail and U the rotational component of velocity, then T the period of rotation can be computed from the relations

$$U = V \tan\theta \quad \text{and} \quad T = \frac{2\pi R}{V \tan\theta}.$$

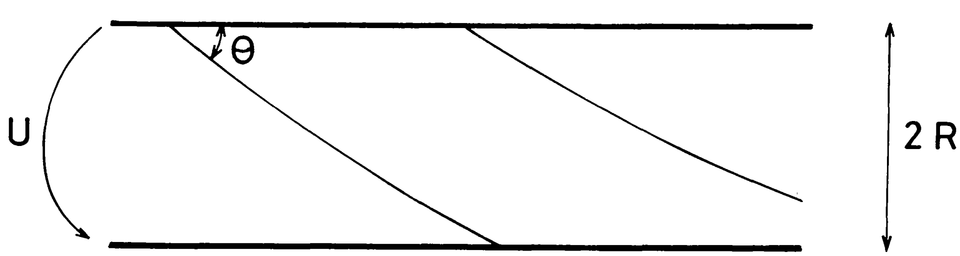

Fig. 2.

Adopting the values $R = 2.5 \times 10^5$ km; $\theta = 15°$ (from our measurements) and $V = 235$ km/sec (Table II of Ershkovich, 1980) we find that $T \sim 7$ hr. Such a fast rotation of the nucleus would in turn stabilise the helical structure of the magnetic field in the tail. Till about 18° from the coma, the dust tail and ionic tail are mixed together and the density is very high for the helices to show up. In some of the best photographs the helices can still be traced in the direction of the coma almost from the brightest portion of the tail (Figure 1). The helices, however, become well defined and conspicuous beyond 20° from the coma when the tail becomes mainly ionic in composition. Comet Bennett (1969i) also had a mixed tail without any streamers indicating possibly a small magnetic field. The mixed tail of this comet did not show any helical structures most presumably due to the slow rotation of the nucleus which was ineffective in maintaining the twists in the magnetic field in the tail. The helical structures crossing the visible ones in the anticlockwise direction which come from the material on the farther side of the tail is not recognisable in the photographs. The density of the ions falls very rapidly along the helices making the visibility of the tips of these helices on the near side marginal. If the same gradient of density continues the helices on the further side would be very weak and would not be seen on the farther side although the tail may be optically thin.

5. Conclusions

The helical structures present in the tail of Ikeya-Seki are interpreted to arise from the instabilities excited through the spatial resonance between the magnetic field lines and the wavelength of the mode. The estimates of the growth rates agree with similar estimates from other mechanisms. In addition the multiple structures of the helices observed in the tail of the comet are also explained by this mechanism. The fast spin of the nucleus is responsible for maintaining the twisted structures of the magnetic field in the tail.

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