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ACCELERATION OF COMETARY PLASMA TAILS

(*Letter to the Editor*)

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Abstract. Cometary plasma tails are accelerated by the solar wind to ≈ half its velocity, corresponding to some 10^2 times the solar-wind momentum density. We corroborate Alfvén's (1957) 'wind-sock' mechanism according to which the momentum transfer is brought about by magnetic rigidity.

1. Introduction

The problem of cometary tail formation has been of key interest to both observers and theorists ever since Biermann's pioneering work in 1951. Whereas Biermann overestimated the solar-wind pressure, Alfvén (1957) noted that the interaction has a range some 10 times larger than its geometrical extent: the required viscosity is brought about by the frozen-in magnetic field which introduces an effective rigidity via its $\mathbf{j} \times \mathbf{B}$ force-density. In this way, a 10^2 times larger solar-wind volume shares its momentum with the plasma in the cometary tail.

Although this explanation has remained the only one which can solve the momentum balance, a number of different explanations has been proposed in the recent literature (see Mendis *et al.*, 1985). Among them are attempts to transfer the momentum locally via shear stresses, enhanced by various instabilities (Krishan, 1980, 1988), and via the 'tooth-paste-tube' mechanism according to which magnetic pressure gradients squeeze the plasma into the cometary tail (Ioffe, 1968). The latter mechanism deals with the same pressure gradients as Alfvén's 'wind-sock' model (which we support), hence arrives at reasonable quantitative estimates, but does not stress the pulling action of the solar-wind plasma.

An exact analytic solution of the MHD equations has been obtained by Parker (1975) for the case of a transverse plasma cylinder inside a magnetised plasma flow. The overtaking flow can wrap a magnetic bandage of $\leq$ equal pressure around the transverse cylinder, via field-line reconnection behind the obstacle (Kundt and Krotscheck, 1980). Parker's solution is 2-dimensional whereas the cometary-tail problem has no continuous symmetries: the tail's pencil shape implies axial symmetry, but the direction of the transverse magnetic field destroys the latter. For this reason, an exact solution is not in sight. Schmidt and Wegmann (1980, 1982) circumvented the lack of symmetry in their

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numerical approach by invoking an axially-symmetric magnetic field, ignoring the non-vanishing divergence along the axis. Their solution has, therefore, not convinced the scientific community even though it arrives at reasonable values for the MHD quantities.

Perhaps the best-studied case of magnetic plasma rigidity is the partially corotating solar wind. Weber and Davis gave it a careful theoretical treatment with (Weber and Davis, 1970) and without (Weber and Davis, 1967) a hydromagnetic viscosity tensor. The viscosity tensor enhances the rigidity but (slightly) reduces the effective coupling of the wind to the solar surface. In any case, the magnetic field achieves an effective lever arm of the order of the Alfvén radius whose value for the Sun lies between 12 and 25 solar radii. Pizzo *et al.* (1983), who favour the smaller of the two values on observational grounds, have not been able to convince us: Indulekha *et al.* (1988). In any case, magnetic rigidity appears to be sufficiently well understood to be applied to the cometary tail problem.

2. Quantitative Estimates

In this section we want to show that all the necessary constraints for Alfvén's wind-sock model are satisfied, thereby removing most of the doubts expressed in the literature (Mendis *et al.*, 1985). Our estimates are based on the geometry drawn qualitatively in Figure 1.

As the solar wind encounters the cometary head, it is confined by the comet's partially-ionised wind at a standoff distance of $r \gtrsim 10^{3.5}$ km (Ip and Axford, 1986, 1987). Dynamically unimportant, frozen-in transverse magnetic fields grow in proportion to v^{-1}. A (supersonic) hydrodynamic flow around a spherical obstacle has an almost vanishing velocity at the upstream stagnation point; here the magnetic field would grow unlimited. As soon as magnetic pressures $B^2/8\pi$ grow comparable with ram pressures $\rho v^2/2$, they influence the flow, trying to avoid dominance. We, therefore, expect maximal magnetic fields B of the order of

$$B \gtrsim (4\pi\rho v^2)^{1/2} = 10^{-3.3}\,\mathrm{G} \tag{1}$$

for $\rho = 10^{-23}$ g cm^{-3} and $v = 400$ km s^{-1}, in agreement with the results of Schmidt and Wegmann (1982) and with independent estimates reported by Mendis *et al.* (1985, p. 262). I.e., magnetic fields will reach mG-values near the standoff shock.

The comet's ion plasma is, therefore, exposed to one-sided pressures of order $B^2/8\pi \gtrsim 10^{-7.5}$ dyn cm^{-2}. For a number density $n_i = 10^2$ cm^{-3}, average ion mass $m_i = 28$ g and tail length $l = 10^{5.7}$ km, the resulting acceleration a is

$$a = p/\rho_i l = 10^{2.5}\,\mathrm{cm\,s^{-2}}\,B_{-3}^{\;2}\,, \tag{2}$$

in agreement with the observed values of $a = 10^{2.5 \pm 0.5}$ cm s^{-2} for $B \approx mG$.

The final momentum-flow rate density $\rho_i v_i^2$ of the plasma tail, at its downstream end where it is lost from sight because of dilution, is some $\xi := 10^2$ times higher than that of the solar wind because of a $10^{2.5}$ times higher mass density and a lower velocity (of

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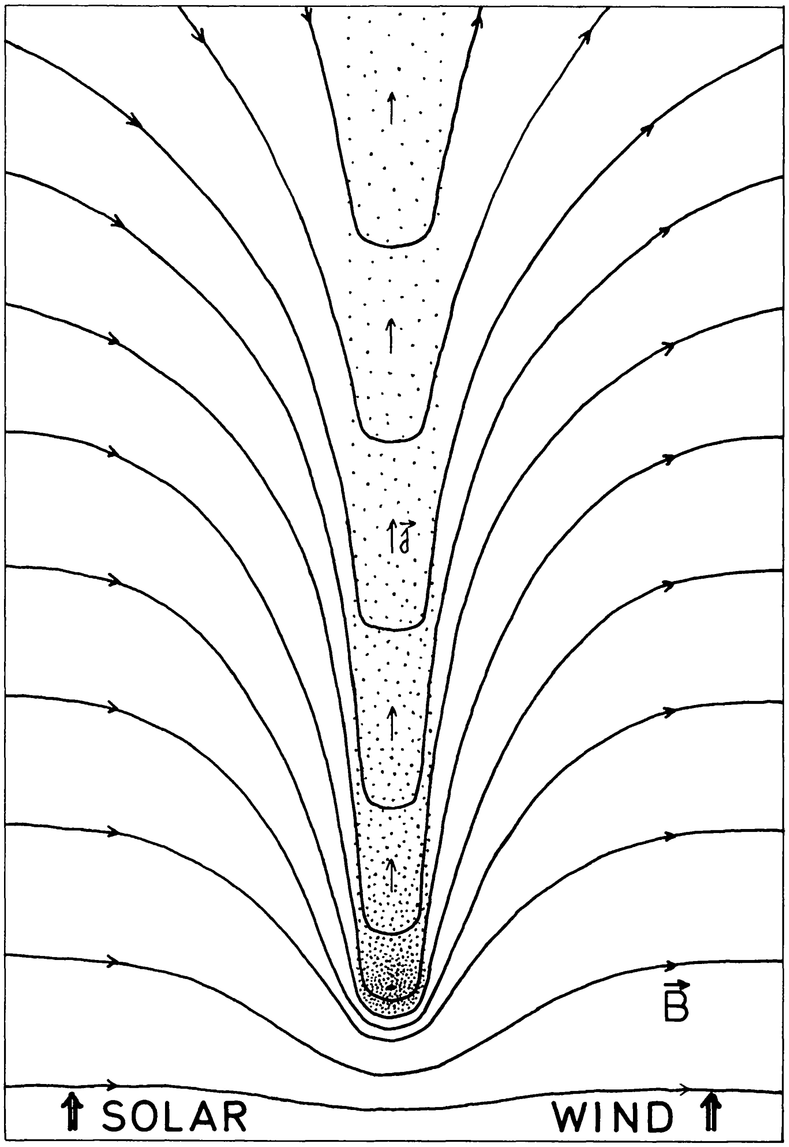

Fig. 1. Predicted cut through the magnetic-field configuration of the solar wind as it is dragged across a comet and its plasma tail. For simplicity, the field **B** is assumed strictly transverse before encounter. In 3 dimensions, the frozen-in field lines curve around the cometary tail; their pressure thus confines it and causes diffusive flux penetration. In this way, not only the tail's surface but also its interior is accelerated. The induced currents **j** cross the tail, approaching the viewer, and close parallel to it, opposite on opposite sides. Tail rays, tail-tail rays and helical field structure are suppressed.

order $0.5v_{sw}$). Momentum conservation implies that the accelerating magnetic field will decelerate the ambient solar wind plasma out to a radial distance at which a sufficient inertia is encountered. This force-balance radius must be some $\sqrt{\xi} = 10$ times the radius of the plasma tail, much larger than any boundary-layer instabilities can reach.

The precise field-line geometry can be coarsely gleaned from pulling a rubber band across a pencil: field lines do not only take approximate V-shape in projection; they also curve around the pencil, exerting an inward radial pressure. This means that the

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field wants to penetrate into the plasma tail. The diffusive flux penetration time-scale t through a distance r into a low-density plasma is approximately given by

$$t = 4\pi\sigma r^2/c^2 \approx 4\pi\omega_e r^2/c^2 = 10^{3.5}\ s\ r_9^2\,, \tag{3}$$

where $\omega_e = (4\pi ne^2/m_e)^{1/2} = 10^{5.5}\ \mathrm{s}^{-1}$ is the conductivity (e.g., Kundt and Krotscheck, 1980) and $r = 10^9$ cm is the tail's radius. During this time t, the cometary plasma moves some $10^{10.7}$ cm downstream, corresponding to the tail's visible length. In other words: the dragging field can just about penetrate into the tail's interior. This estimate guarantees that the tail is accelerated as a whole, not only its surface layers.

3. Details of the Flow

After having judged the overall importance of solar-wind magnetic dragging, we now want to discuss a few important fine-structure effects.

The wind-sock acceleration depends on diffusive penetration of two plasma flows; such an interaction is expected to show clumpy, or knotty structure (as observed), because of irregular injections.

The tail gets disconnected when a magnetic sector boundary is traversed, because the accelerating magnetic pressure passes through zero so that a gap forms.

During switchon, one observes the 'folding umbrella' phenomenon, at a rate of $3°/h$. Such an angular confinement process is expected when the dragging magnetic field gets more tightly strained, thereby narrowing its V-shape.

An important detail are 'helical' structures seen occasionally in the plasma tail. In order to understand them, note that the accelerating force density is proportional to $\mathbf{j} \times \mathbf{B}$. For an acceleration along the tail, the current $\mathbf{j}$ has to cross the tail at right angles to $\mathbf{B}$; it must close along the tail's boundary, preferentially parallel to the tail's axis, oppositely on opposing sides of the 'neutral sheet' (spanned by the axis and the solar-wind's transverse field). The solar wind's frozen-in magnetic field has a component parallel to the comet's tail which we have so far ignored. This parallel component exerts transverse forces on the induced currents $\mathbf{j}$ whose sign is invariant under field reversals because $\mathbf{B}$ and $\mathbf{j}$ change their orientation simultaneously. We consider these transverse forces responsible for the helical appearance.

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