NOTE ON THE SOLAR WIND-INDUCED DRAG ON COMETS

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(Received 3 March, 1969)

Abstract. The solar wind-induced drag on magnetically large comets is estimated as follows. As the comet approaches the sun, solar radiation striking the comet surface generates a surrounding neutral atmosphere which is subsequently ionized. The resulting plasma cloud interacts with the solar wind to produce a comet magnetosphere and associated collision-free shock wave. An approximation to the accompanying drag is obtained using the similarity between the comet magnetosphere and that of the earth, and is shown to be much less than the mechanical mass loss force.

1. Introduction

The existence of non-gravitational forces on comets has been conjectured historically (Bessel, 1836), and recently substantiated through an analysis of the calculated orbital residuals for several different comets (Marsden, 1968); notably, the Comet Encke. An obvious influence to be investigated and estimated is the electromagnetic interaction between the outward-streaming solar atmosphere and the electrically conducting cometary system composed of partially ionized gas coma, nucleus, and tail. In fact, the existence of this solar wind, expanding supersonically into interplanetary space, was predicted by Biermann (1951, 1957) to explain the anti-solar orientation of type I comet tails.

In this paper, the solar wind-induced drag, resulting from the formation of a collisionless plasma shock on the sunward-side of a large magnetic comet (one which generates a magnetic shock), is estimated and shown to be less than both the earth’s gravitational force exerted on the comet (when near the sun), and the mass loss drag.

2. Solar Wind – Comet Interaction

The interaction of the comet with the solar wind follows essentially the mechanism considered by Biermann et al. (1967), and is described below. The solid comet nucleus is supposed small (a sphere with a 1–10 km diam, say), and composed of reasonably well-conducting material (hydrogen bonded chemically to C, O, and N). As the nucleus approaches the sun, an expanding neutral gas atmosphere, spectroscopically observed to contain CN, CH, NH, OH, C₃ and NH² (Brandt, 1968), is evaporated from the solar heated surface. The resulting vapor pressure effects have been considered by Squires and Beard (1961), and Whipple (1950) has investigated the momentum transfer due to mass loss from a rotating nucleus. These mechanisms consequently will not be examined here. Photoionization of the neutral gas by solar uv and soft X-ray radiation generates an initial plasma environment observed to be partially composed of OH⁺ and NH⁺ ions (Wurm, 1961). Charge exchange between


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neutral molecules and solar wind protons also depletes the neutral comet atmosphere slightly. The orbital motions of this tenuous plasma and the solid comet core are coupled together by a magnetic field which permeates the cometary system as first suggested by Alfvén (1957).

As the comet nears the sun, the magnetic lines of force carried by the solar wind are forced into the front surface of the ionized comet atmosphere, and tend to pile up there due to its increased conductivity. Since the solar wind plasma is essentially collision-free (mean-free path of about 1 AU), and transports the magnetic field superalfvénically (faster than the characteristic speed in the collisionless plasma), this magnetic compression cannot propagate upstream into the undisturbed solar wind. Therefore, a collision-free magnetic shock wave is formed in front of the comet similar to that formed by the earth (Ness et al., 1964) and Venus (Bridge et al., 1967). Once a shock wave is formed, the solar wind electrons it accelerates are focused on the comet nucleus, thus increasing the plasma production – particularly the formation of CO$^+$ ions near the nucleus. The solar magnetic field interacting with the plasma atmosphere generates, in effect, a comet magnetosphere (contact discontinuity), and deflects the ions backwards to form a plasma tail. Since the radiation emitted by the OH$^+$ and NH$^+$ ions indicates an equivalent spherical volume of at least $10^4$–$10^5$ km diam (Wurm, 1961), we ascribe to the comet magnetosphere a tear-shaped volume with a circular cross section corresponding to this diameter. The magnetosheath region bounded by the shock wave and magnetosphere contains shock heated solar wind plasma mixed with ionized comet gas due to charge exchange of the neutral gas streaming across the magnetosphere. The solar wind-comet interaction is depicted in Figure 1.

![Solar wind - comet interaction diagram](image)

Fig. 1. Solar wind – comet interaction.
It should be noted that the magnetic field lines may become imbedded in the comet nucleus by the tailward diffusing solar field being either ‘hung up’ on the conducting nucleus itself, or impeded immediately by the coma plasma, and consequently generating ‘ionospheric’ current systems. In addition, plasma instabilities in the tail magnetic field configuration may also implant lines of force from the tail. The magnetic tension exhibited in this field stretching about the comet nucleus constitutes a drag.

3. Drag Calculation

The macroscopic effect of the solar wind on the entire magnetosphere cavity may be represented by the drag force (Landau and Lifshitz, 1959),

$$D_M = C_D \frac{1}{2} \varrho_s (v_s - v_c)(v_s - v_c)^\mathbf{\cdot} \mathbf{A}_M,$$

\hspace{1cm} (1)

where $C_D$ is a drag coefficient, \(\varrho_s\) and \(v_s\) are the solar wind density and velocity, respectively, \(v_c\) is the comet velocity, and \(\mathbf{A}_M\) represents the effective cross-sectional area for the interaction.

The variation of \(\varrho_s\) and \(v_s\) as a function of solar distance \(r\) are fairly well known. A summary of the experimental results is given by Newkirk (1967), and reasonable theoretical comparisons are provided by Parker’s (1958) supersonic expansion solution of the hydrodynamic equations. The solar wind density and velocity in the coronal region \((r > 5 \text{ } R_\odot)\), and near the ecliptic plane we approximate by

$$\varrho_s \approx (2 \times 10^5 \text{ particles/cm}^3)(M + m)(R_\odot/r)^2$$

\hspace{1cm} (2)

and

$$v_s \approx (500 \text{ km/sec})\{1 - [75 \text{ } R_\odot/(105 \text{ } R_\odot + r)]\},$$

\hspace{1cm} (3)

where \(M\) and \(m\) are the respective proton and electron mass, and \(R_\odot\) is the solar radius. However, as indicated above, \(C_D\) and \(\mathbf{A}_M\) generally depend on the interaction structure.

The interaction area \(\mathbf{A}_M\) corresponds to the comet’s magnetospheric cross section, and varies with solar distance and relative comet orientation, nucleus size and construction, and solar activity. Varying the importance of these effects, however, only produces an order of magnitude change in \(\mathbf{A}_M\). Therefore, as a reasonable estimate, we assume a circular area corresponding to a \(10^4\) km diam.

To determine the drag coefficient \(C_D\) requires a detailed solution of the interaction structure. Because the ionized comet atmosphere impedes the solar magnetic field flow and consequently generates a magnetosphere about the comet nucleus, the drag effects on the cometary system should be the same as that for a magnetic body possessing an intrinsic magnetic moment. We accordingly evaluate \(C_D\) by investigating the solar wind – earth interaction using a single fluid hydrodynamic analogue model. In this approach, the solar wind is considered a classical fluid whose properties are maintained by magnetic field perturbations and plasma instabilities acting as effective ‘collisions’. Although the magnetic field dynamics are explicitly excluded, the plasma-magnetic field interaction is implicitly present in the assumed fluid-like
solar wind, and the formation of a contact discontinuity. Therefore, given the solar wind parameters and the contact surface shape, the hydrodynamic equations may be numerically integrated to yield the flow, temperature and pressure profiles in the magnetosheath region. Integrating the resulting pressure distribution over the magnetosphere determines the net drag. Dryer and Faye-Petersen (1966) have performed such a calculation for the earth, obtaining a total drag of $4 \times 10^{11}$ dyn. Using their values of $2 \times 10^5$ km effective magnetic diameter, and respective solar wind velocity and proton density of $400$ km/sec and $6.3$ particles/cm$^3$, one obtains from (1)

$$C_D = 0.148.$$

Therefore, assuming a $10^4$ km cross-sectional diameter, $v_e = 50$ km/sec and anti-parallel to $v_x$, and $C_D$, $\varrho$, and $v_x$ as determined above, one calculates a 1 AU drag estimate of

$$D_M \approx 10^9 \text{ dyn}.\quad (5)$$

The force $D_M$ is exerted on the magnetospheric volume, and thus acts to slow down the nucleus and accelerate the coma plasma tailward. Assuming that the CO$^+$ tail streamers (Wurm, 1962) actually map out the imbedded magnetic field, we approximate the nucleus drag $D_N$ by

$$D_N = \left(\frac{A_T}{A_M}\right) D_M \quad (6)$$

where $A_T$ is the tail cross-sectional area. Consequently, using a tail diameter of $10^2$–$10^3$ km (Beard, 1966), one has

$$D_N \approx 10^7 \text{ dyn}, \quad (7)$$

which is several orders of magnitude less than the vapor pressure forces (Beard, 1968), as well as Whipple’s mass loss effect. However, the presence of a magnetic field may reduce their results.

As an additional comparison, we determine the gravitational force exerted on the comet by the earth at a 1 AU separation, assuming a typical comet mass of $m_c = 10^{15}$ g, yielding

$$F = \gamma \frac{M_\oplus m_c}{r^2} = 1.4 \times 10^9 \text{ dyn}. \quad (8)$$

4. Conclusion

This analysis indicates that the solar wind – comet interaction for large magnetic comets like Halley’s cannot be appreciable. The estimate given in (7) is, however, a little misleading. Since $\varrho$, drops off like $r^{-2}$ and is primarily confined to the ecliptic plane, this force is only experienced when the comet is near the sun, say within 5 AU*.

* Observations on Comet Humason, 1962 VIII, indicate that the solar wind’s influence extends at least to 5 AU.
and has a low orbital inclination. In addition, the drag force on approaching the sun is different from that on leaving. When the comet nears the sun, the counter-streaming solar wind forms a sunward-side shock which tends to slow the comet down. On passing perihelion and leaving the sun, the solar wind pushes on the comet, forming a sunward-side shock (as before), but now it has the effect of accelerating the comet. Because the shock dissipation heats up the solar wind, the initial de-acceleration and final acceleration on rounding the sun do not quite cancel one another for comet orbits with low inclination, and the net drag effect is consequently expected to be even smaller than approximated above. This type of solar wind drag may, however, be important for sun grazing comets; such as Ikai-Seki.

Finally, the interaction of a magnetized comet (a comet which produces a magnetic flux compression in the solar wind) with the magnetic structure of stars and planets, such as the earth's magnetosphere and tail, may generate anomalous comet accelerations.

Acknowledgements

I am grateful to Dr. L. Biermann for his critical reading of the manuscript, and to Joseph L. Brady, Lawrence Radiation Laboratory, Livermore, California, for his comments on comet observations.

References


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