ON COMETARY DUST AND GAS DYNAMICS

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INTRODUCTION

I select three topics of current interest (and some current confusion) to complement the previous paper of Asoka Mendis. The topics are relevant particularly to the studies developing models and predictions of the comet Halley environment for the forthcoming missions to that comet. The idea that electromagnetic forces are important for the dynamics of submicron dust grains and so should produce fans and structures in the coma indicates that correlations with solar wind conditions should be sought.

DUST EXPULSION BY COMETARY OUTGASSING

The motion of dust grains in a radially-symmetric coma has been described by many authors and was reviewed by Wallis (1982a). For the simple case of constant fluid speed and drag coefficient, analytical solutions can be obtained (see Wallis, 1982a). These bring out two particle size scales, A_{max}, the maximum size that can be lifted against gravity, ~ 1 cm, and , the size that attain speed close to that of the gas, $\sim 1_3$ m. These numbers apply to a comet of radius 3 km, density 1 gm/cm^3, gas flux (H_2O) 10^{29}/S at speed of 0.22 km/S and grain density, 3 g/cm^3.

Limiting forms for small and large grains have been used but a simple analytical expression for the whole range has been obtained (Wallis, 1982a). The current dust coma model (Divine 1981) for the Giotto mission planning uses a more complex analysis, but it behaves erroneously for sizes approaching A_{max}. It uses the large value of expansion velocity (Delsemme and Miller 1971) that is certainly not valid for grains near the nucleus that are barely lifted off. In that situation, it is necessary to look at the dusty gas-dynamic solutions for u(r) as developed by Probstein (1969) and used by Hellmich and Keller (1981), Mendis (1983). These have a subsonic initial Mach number and u(R) some 3 times smaller than u(∞); A_{max} is also that much smaller. On the other hand, the effective u for grains of order Δ is

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closer to u(∞), but that value does depend on heating and cooling mechanisms as included by Mendis (1983).

SUBLIMATING ICE NUCLEUS

A second much-used and oft-maligned equation (Delsemme, 1982) is used for the energy balance at an icy-nucleus surface. Conduction to and from the interior is neglected and optically thin conditions are assumed. It has been customary (Whipple and Huebner 1976, Delsemme 1982) to take some average for cosi, the solar illumination angle, corresponding to a "rapid rotator" with a supposed average temperature. However, calculations by Dobrovolskij and Markovich (1972) including conduction terms, showed the temperature lagged rather little behind the local zenith position, so the comet is really a "slow rotator", with temperature and outgassing varying strongly over the nucleus. This is confirmed in recent computations (Weissman and Kieffer 1981).

For the nucleus a slow rotator, all computations should depend only on the infrared albedo A_{IR}. From the results for constant cosi (e.g. Delsemme 1982) the average vaporization rate $\langle Z \rangle$ over the surface comes out in terms of the exponential integral

$$\langle Z \rangle = r^{-2} E_{7/3}(r^3/r_1{}^3) \quad (1)$$

with $r_1 = 0.65r_o$, r_o being the position where 2 1/2% of the incident flux goes to sublimation (Delsemme 1982). As shown in Fig. 1, this

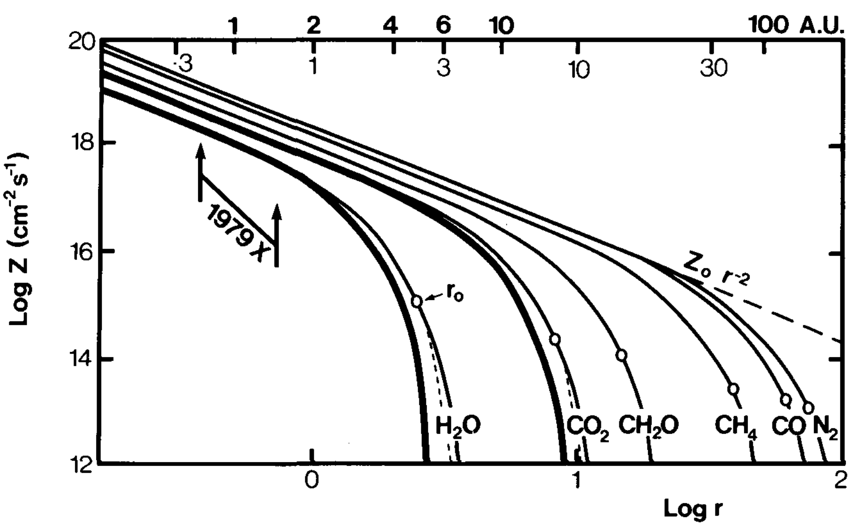

Fig. 1. Sublimation rates of nuclei of frozen gases for A_{IR} = 0.05, A = 0.1 as calculated by Delsemme (1982) on the 'rapid rotator' (uniform temperature) assumption (thin lines), compared with the present 'slow rotator' calculations for H_2O and CO_2 (thick lines and thick r-numbers).

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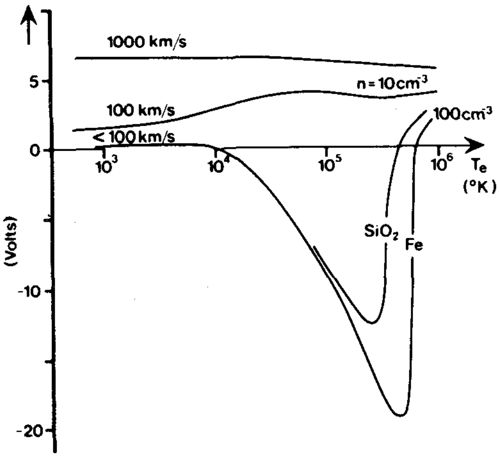

Fig. 2. Dust grain potentials vs. electron temperature, T_e, for speeds and ion densities indicated.

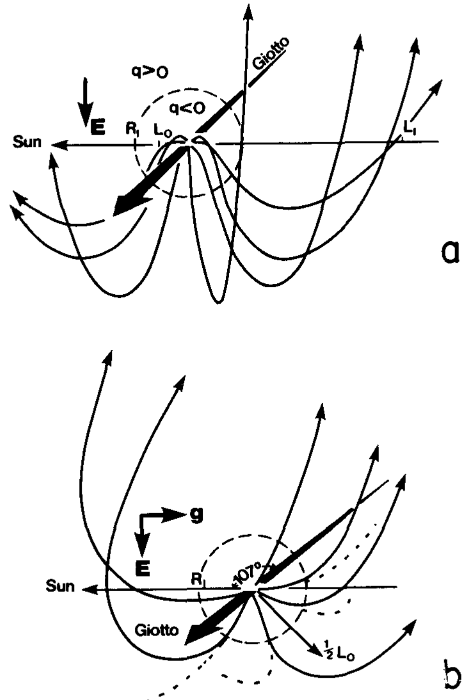

Fig. 3. Dust grain trajectories. Electromagnetic forces are a) dominant, as for 0.01 μm SiO_2 grains, b) comparable to radiation pressure.

primarily doubles the sublimation cut-off scale (because {cosi} = 1/4 was taken) and secondarily, increases the steepness of the cut-off. Weissman and Kieffer's (1981) full calculation agrees qualitatively for the "bare nucleus" case, but their model is not checked nor fully defined. In analysing comet Encke's light curve, the results of Ferrin and Naranjo (1980) for a slow rotator increase their sublimation cut-off scale by $\sqrt{\pi}$. It then follows that comet Encke's sublimating component is less volatile than H_2O-ice. Also Comet Bradfield 1979X, observed regularly with IUE and found to have Z[OH] N $r^{-3.7}$ over 0.7 - 1.5 AU (Weaver et al. 1981, Wallis 1982b), does not fit with H_2O nor with other more volatile compositions often proposed (Fig. 1). This comet had very little dust so complications due to radiation scatter on the dust (Hellmich and Keller 1981, Weismann and Kieffer 1981) should be negligible.

ELECTRODYNAMICS OF SUBMICRON DUST

It has long been recognized that electromagnetic forces are stronger than radiation pressures on small dust grains of order 0.1 μm (Parker 1964, Notni 1964, 1966). The latter author also emphasised that such grains would be positively charged within the solar wind, but negatively charged within the denser cometary plasma. As grain potentials are limited, $\phi < 20V$, sizes above 1 μm feel very little of the solar wind convected field and are simply described by their initial velocity and radiative repulsion (Divine 1981, Wallis and Ip 1982).

Smaller grains have more complex behaviour. Though parameters need to be changed, Notni's formulation still appears accurate and, in particular, the feature that secondary electron emission drives the potential positive, with the hotter cometary plasma that is expected out towards the bow shock. Fig. 2 shows a recalculation of Notni's model for specific secondary emission properties appropriate to SiO_2 and Fe grains. The potential ϕ and therefore charge depends sensitively on electron density and temperature but not on ion type. Depending on the model of the solar plasma flow contaminated by cometary ions through the coma (reviewed by Ip and Axford 1982), particularly the electron heating and cooling mechanisms, one can define a position R_1 where q switches from positive to negative. The transition is quite rapid but its distance R_1 depends on the grain composition.

The total acceleration from radiative and electromagnetic forces $\underline{g} = g_{rad}\,\underline{r} + q\,\underline{E}/m$ defines dynamical scales $L = v^2 / \underline{g}$ if representative values of qE can be taken inside and outside R_1. $\underline{E}$ is near normal to $\underline{r}$ so there are two main non-dimensional ratios defining the problem, g_{rad}:qE/m and R_1:L. Two cases are qualitatively illustrated in Fig. 3: for the smallest dielectric (SiO_2) grains with $L < R_1 \approx 3 \times 10^4$ km, the grain trajectories fill paraboloids inside and outside R_1 (Fig. 3a), and the fan of grains curves anti-sunwards only on a larger scale. Secondly, 0.05 μm dielectric or 0.03 μm Fe grains (Fig. 3b) having $mg_{rad} \approx qE$ and $L > R_1$ so form an inclined but asymmetric fan. If $\underline{E}$ remains in a plane, the fans lie in that plane.

In addition to the dependence on size and composition, such dust fans must switch direction with the reversals of the large scale solar wind field. Evidently electromagnetic forces offer a qualitative explanation of observed fans and asymmetries in the dust coma without the postulate of special sources located on the nucleus.

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