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Dynamics of Dust Particles Orbiting the Nuclei of Comets

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Introduction

The existence of bound dust particles around cometary nuclei has been argued based on analytical grounds [1, 2], and demonstrated numerically [3, 4, 5]. Dust particles emitted by cometary nuclei could stay in temporary bound orbits around the nuclei for timescales as large as weeks or months or even longer. These particles could act as a reservoir of cometary dust and may explain some of the baffling observations that have so far eluded a self-consistent interpretation.

In the case of comet 1P/Halley, the gas production rates are nearly symmetric pre- and post-perihelion. On the other hand, the dust production rate is consistently higher in the post-perihelion by approximately factor three [6]. For a comet that is in a principal axis rotation, this could be due to seasonal effects. However, for comet 1P/Halley, which is in a non-principal axis spin state [7, 8], it was shown by [9] that the subsolar point traverses the entire nucleus over "diurnal" timescales and no seasonal effects are likely.

We propose a model of dust dynamics in the near-nucleus coma [10], that allows to assess the observable effects due to particles that move in bound orbits, escape the gravity of the nucleus, and fall back on to the nucleus. The dust particles are ejected from a rotating non-spherical nucleus, and move under the combined influence of comet and solar gravity, solar radiation pressure, and gas drag when near the nucleus.

Based on our preliminary work, it is indeed possible to have higher dust-to-gas ratios during the post-perihelion leg due to dust particles in temporary bound orbits. Similarly, this approach could explain the anomalous increase in brightness of comet 2P/Encke observed near aphelion [11, 12], and might help characterize the bound comae in active Centaurs [13].

Model

The temporary bound trajectories of particles primarily lie within the bound coma radius R_{bound} defined as:

$$R_{\text{bound}} = \min\{R_{\text{exo}}, R_{\text{Hill}}\} \quad (1)$$

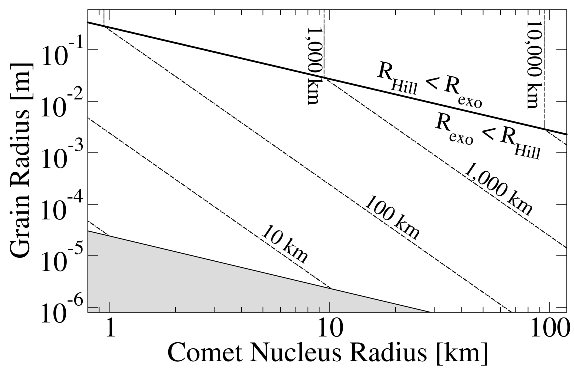

Figure 1: Value of $R_{\text{bound}} = \min\{R_{\text{exo}}, R_{\text{Hill}}\}$ as a function of comet nucleus radius and particle radius, at $r_{\text{h}} = 1$ AU. The bold line marks the boundary between the region where $R_{\text{Hill}} < R_{\text{exo}}$ (above the line) and the region where $R_{\text{exo}} < R_{\text{Hill}}$ (below the line).

$$R_{\text{Hill}} = r_{\text{h}} \left(\frac{M_N}{3M_\odot}\right)^{1/3} \quad (2)$$

$$R_{\text{exo}} = r_{\text{h}} \left(\frac{M_N}{\beta M_\odot}\right)^{1/2} \quad (3)$$

where R_{Hill} is the Hill-sphere radius determined by the stable region for a satellite under the mutual gravity of the comet and the Sun, R_{exo} is the exopause radius defined to be the distance at which the gravitational attraction of the comet equals the radiation pressure force [14], r_{h} is the heliocentric distance, M_N is the mass of the comet nucleus, $M_\odot$ is the solar mass, β is the ratio between the forces due to solar radiation pressure and the gravity of the Sun [15].

In Figure 1 we show R_{bound} as a function of the comet nucleus radius and dust particle radius for a comet at a heliocentric distance of 1 AU. A comet bulk density of 0.5 g cm^{-3} and a particle bulk density of 1.0 g cm^{-3} are assumed. The gray area on the bottom marks where R_{bound} is less than or equal to the radius of the comet nucleus. If a comet has a nucleus radius of $\simeq$ 10 km, for $R_{\text{bound}} = R_{\text{Hill}} \simeq$ 1,000 km, a particle of radius $\geq$ 3 cm can remain bound anywhere within 1,000 km from the nucleus. On the other hand,

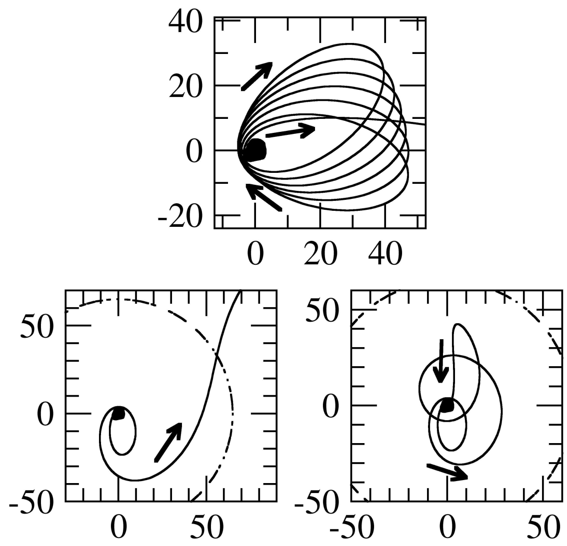

Figure 2: Numerical modeling of the trajectories of dust particles ejected from the nucleus. Top: trajectory of a particle ($\beta = 10^{-5}$, particle radius $r_{\rm g} \simeq 6$ cm) ejected at a velocity $0.97 \times V_{\rm esc}$ when $R_{\rm bound} \simeq 250$ km. Bottom: trajectory of two slightly different particles ($\beta = 1.45 \times 10^{-4}$ in left figure, $\beta = 1.50 \times 10^{-4}$ in right figure, $r_{\rm g} \simeq 4$ mm in both cases) ejected at a velocity $0.95 \times V_{\rm esc}$ when $R_{\rm bound} \simeq 65$ km. The dashed curves mark the value of $R_{\rm bound}$. (Scale: km)

a particle of radius 300 μm must be within 100 km from the nucleus to be bound.

The near-nucleus dynamics is determined by numerical integration of equations of motion, and examples of the resulting trajectories are shown in Figure 2, where three classes of evolution are displayed: a particle escaping after being in a bound orbit (top), a particle escaping shortly after ejection from the nucleus (bottom left), and a particle which falls back onto the comet after being in a bound orbit (bottom right).

To simulate a large number of particles, and obtain measurable quantities out of these preliminary simulations, we follow a statistical approach, where the details of the dynamics of each particle are synthesized to determine the probability to stay in a bound orbit, fall back on to the nucleus surface, or escape the comet. Once all these probabilities corresponding to the relevant parameters have been determined for a given comet, it is possible to model measurable quantities such as the flux (total particle cross section) in continuum bands and compare the model with data.

One example of our modeling is shown in Figure 3 where the flux is plotted for comet 1P/Halley during a perihelion passage. More examples will be presented at the meeting.

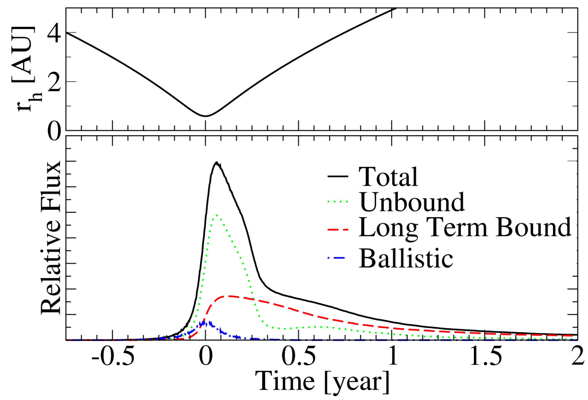

Figure 3: Heliocentric distance $r_{\rm h}$ (top) and modeled flux (bottom) due to dust particles, for comet 1P/Halley. Zero time is at the perihelion. Small tick marks represent months. The total flux (black continuous line) is the sum of the contributes from the cross section of escaping particles (green dotted line), bound particles (red dashed line), and ballistic particles (blue dot-dash line).

Acknowledgments

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