THE DYNAMICS OF GRAIN SPLITTING IN COMETARY JETS.

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Introduction: Recent high-resolution spacecraft observations of comets have returned a plethora of images showing the diversity of cometary jets, as well as information regarding grains ejected by these jets. During the Stardust-NExT flyby of Comet Tempel 1, it was observed that grains in the cometary coma are grouped together with large voids in between. This implies that that clumps of grains disintegrate as they rise from the surface of the comet [1]. The spacecraft also observed jets on Tempel 1 that originated over the limb of the nucleus (at the time of the fly-by), and which appear to originate from a scarp [2]. These jets appear to rise vertically from the comet, rather than perpendicular to the sloping surface of the scarp.

Here we describe a method for constraining the rate of the disintegration of the clumps of grains in these scarp plumes, performing a numerical integration of the equations of motion of the grains as they are lofted off the surface in a jet. We can then compare model opacities to those observed by the Stardust-NExT mission.

Jet Model: Previous work explains how sloping scarp faces can produce vertically-oriented jets, rather than jets oriented perpendicular to the scarp surface [3]. In our model, a two-layered surface is eroded by a retreating scarp face. A lower, volatile-rich layer is overlain by an upper, volatile-poor layer, which has lost its volatiles over time due to exposure to the sun. As the sun shines on the face of the scarp, the volatile-rich layer forms a relatively weak primary plume, which causes the layer to erode and undermine the volatile-poor layer above. This causes the volatile-poor layer to slump into the plume, where it encounters the edge of the jet, ejecting the slumping material vertically in a bright, tightly-collimated jet (~5° dispersion from its axis).

Numerical Model. We model grain splitting by assuming that spherical clumps divide in half after a set period of time has elapsed. The imposition of a fixed splitting time, rather than allowing splitting to depend on clump size or other possible relevant factors is an arbitrary simplification that is subject to revision as we compare our results to observations. Splitting events reoccur until each clump has reached a fundamental size of ~1 μm. Mass is conserved during each splitting event, which produces two identical spherical daughter clumps. We track a single clump along the centerline of the vertical plume and track the number of daughter clumps produced as the clumps split. The daughter particles are assumed to be non-interacting. The initial clump is placed on the uphill edge of the volatile-rich layer (the edge of the active area of this plume). The clumps, both initial and daughter, are modeled to be spherical, identical in size, and experience two forces: gas drag from the active area, and the force of gravity. The model runs until the clump reaches a predetermined height several kilometers above the surface of the comet.

Forces on the clumps. The drag force on the clumps is due to the gas being emitted from the volatile rich, porous regolith on the face of a long scarp. We model the source region in plane-strain geometry, and assume that the emitted gasses have a Lambertian emission profile. The clumps are assumed to be moving much slower than the gas molecules, and react to the gas via the fluid drag equation. Owing to the tight collimation and vertical orientation of the secondary plume, we track only the vertical position of the clump in this one-dimensional model.

The force of gravity on the clump is due to the mass of the comet. For simplicity, the comet is modeled as a sphere with known size and uniform density. This results in the gravitational force being centrally directed, with a $1/r^2$ dependence on the distance to the center of the comet.

Initial Clump Size. The size of the initial clump is assumed to be near the maximum that the jet can lift off of the surface. This is because, when this clump splits up into grains, its grains will numerically dominate the grains coming off of smaller clumps. The largest clump that the plume can lift is determined by the drag force of the expanding gases from the source and by the force of gravity. By setting these two forces equal to one another, we find that the size of the initial plume depends on many well-constrained physical parameters of the comet, as well as the unknown size of the volatile-rich layer, which is only known to be smaller than the face of the scarp itself. Therefore, our model has two free parameters: the size of the volatile-rich layer, and the time it takes for the clumps to split in two.

Calculating Opacity. The plume is assumed to be optically thin, such that any line of sight through the plume is expected to intersect, at most, one grain or clump of grains. The dispersion of the grains causes the density of the particles to decrease proportionally to the cross-sectional area of the jet. To include this effect, we accept our previous model's 5° dispersion angle, and note that the opacity is inversely proportional to this cross-sectional area. The opacity along the centerline of the plume is thus proportional to the number of clumps or grains produced from the one initial clump, the square of the radius of the clump, inversely proportional to the velocity of the clump, and inversely proportional to the square of the height above the surface and the tangent of the dispersion angle:

$$Opacity_{(y)} = k\frac{N_{clumps}R_{(t)}^2}{v_{(y,t)}y^2\tan^2\theta}$$

where k is a constant that depends on physical constants and physical parameters of the comet, and θ is the angle of dispersion of the jet from the axis.

By observing plots of the log of opacity of the plume versus the log of distance from the comet, we can constrain the splitting time of the clumps. Note that on a log-log plot, the multiplicative constant k in the opacity equation merely shifts the plots up or down, without changing their shapes. Testing a variety of different splitting times, we can see that they produce plots of opacity versus height with different slopes (Figure 1).

To constrain the splitting time, a comparison with the observed plume opacities is required. Complicating this measurement is the lack of knowledge of the location of the base of the plume, or the exact value of the multiplicative constant in the opacity equation. By calculating the log of the opacity of the center of the plume in two or more places, one can determine the slope of the log of opacity versus log of height plot. Matching this with the calculated slopes, one can determine the best fit for the observed opacities of the plume in the context of our splitting model.

Conclusion: This method allows us to confirm the validity of our splitting model with observation, as well as constrain more complicated disintegration models. However, as this method still contains two free parameters, it cannot by itself determine the average splitting time of the clumps in the cometary plume. It does, however, place strong constraints on the splitting behavior of the clumps, the initial size of the dominant clumps, and the size of the active area of the plume (the thickness of the volatile-rich layer). If an independent method can provide an estimate of this size, then the splitting time can be estimated as well.

References: [1] Green S.F. et al (2011) *EPSC-DPS Joint Meeting* Abstract # 1122 [2] Farnham T.L. et al. (2012) *Icarus.* Corr. Proof, in Press [3] Steckloff J.K. and Melosh H.J. (2012) *AGU Fall Meeting XLV* Abstract # P43C-1936

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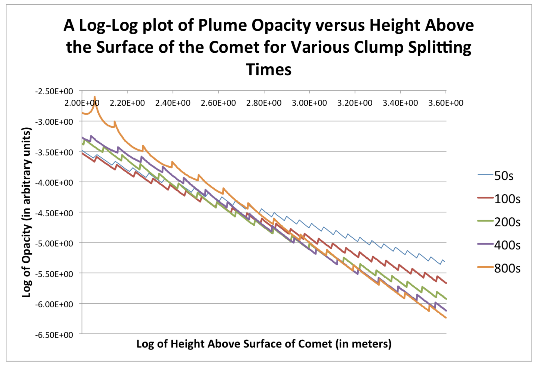

Figure 1: This figure shows a plot of opacity versus height above the cometary surface for a 5 cm initial clump and plume with a radius of 10m. 7 different splitting times are plotted. From 100 m to 4 km above the surface of the comet. The opacity is plotted in relative units, while the height above the surface is measured in meters. Longer splitting times produce steeper opacity gradients in the plume. Note that the prominent zig-zag of the lines is an artifact of our assumption that all clumps split at the same time after ejection from the surface. Only the general trend of the lines is meaningful.