COMETARY JET COLLIMATION WITHOUT PHYSICAL CONFINEMENT. J. K. Steckloff[1] and H. J. Melosh[2], [1]Purdue University, Department of Physics, West Lafayette IN 47907 (jstecklo@purdue.edu), [2]Purdue University, Department of Earth and Atmospheric Sciences.

Introduction: Recent high-resolution images of comet nuclei reveal that the gas and dust expelled by the comet is organized into narrow plumes or jets. Contemporary models postulate that these jets are collimated when the expanding gas and dust passes through a physical aperture or nozzle [1]. However, recent high-resolution spacecraft observations fail to detect such apertures on cometary surfaces [2]. Furthermore, these models do not explain why cometary jets appear to be directed normal to the local gravitational potential [2][5][6]. This is especially puzzling because the jet velocity, typically 300 m/sec far from the comet, greatly exceeds the escape velocity of only about 1 m/sec.

Here we describe a simplified computer model of jets emanating from Comet Tempel 1. Our novel mechanism is based on the occurrence of fluidized flow through the surfaces of comets, a process that has recently gained observational support from NASA's Deep Impact and Stardust-NExT flyby missions [3].

Comet Model: We approximate the comet as a smooth, homogenous sphere with two surface terrain types: active and inactive. The active terrain, which accounts for only a small fraction of the area of the comet, is assumed to be responsible for all emissions from the comet. The active terrain is presumed to have a surface like a sieve, with many small pores though which gas escapes. We assume that the escaping gas expands uniformly in all directions from the point of emission. The inactive terrain has no pores emitting gas. These pores (or "jetlets") interact with clumps of dust and ices on the surface of the comet. We assume these clumps are made of the same material as the active regions of the comet and that they themselves emit gases and thus interact with one another. Therefore, the clumps experience three different forces: Drag due to gases venting from the active areas of the comet (hereafter called the vent force), drag due to the interaction of one clump with the emitted gases of the other clumps, and the gravitational attraction of the comet.

Calculating the vent force. The clumps of material on the surface, which are assumed to be spherical for simplicity, feel a drag force from the jetlets. We assume the expanding gas is in free molecular flow, so the jetlets do not interact with one another. Thus, the net force on each clump is the sum of the drag forces from the jetlets:

$$\vec{F}_{jetlets} = \sum_i \frac{\Phi_{active} m_{molar} C_D}{4 N_A v_{gas}} \frac{R_{clump}^2}{r_i^2} v_i'^2 \hat{r}_i$$

where Φ_{active} is the number flux of particles in the active areas, m_{molar} is the molar mass of the emitted gas, C_D is the drag coefficient of the clump, N_A is Avogadro's Number, v_{gas} is the speed of the emitted gas relative to the surface of the comet, R_{clump} is the radius of the clump, $\vec{r}_i$ is the vector pointing from the i^{th} jetlet to the clump, and v_i' is the speed of the emitted gas from the i^{th} jetlet with respect to the clump.

Calculating the interclump force. We assume the clumps contain ices that sublimate and the evolved gas expands uniformly in all directions at the same rate as the active areas of the comet. This gas produces a drag force on all of the other clumps

$$\vec{F}_{clump} = \sum_i \pi \frac{\Phi_{active} m_{molar} C_D}{N_A} R_{s_i}^2 \left(v_{gas} + \Delta v_{cs_i}\right) \left[1 - \cos\left(\arctan\left(\frac{R_{clump}}{r_i}\right)\right)\right] \hat{r}_i$$

where R_{s_i} is the radius of the i^{th} source clump interacting with the clump in question, Δv_{cs_i} is the relative speed between the i^{th} source clump and the clump in question, and $\vec{r}_i$ is the vector pointing from the i^{th} source clump to the clump in question.

We assume the clumps split into two identical daughter clumps after a specified amount of time. The splitting occurs along a random axis, with the two daughter clumps placed next to each other along this axis. A single grain of dust has a higher density than the comet. Therefore, as the clumps divide, the densities of the daughter clumps should increase due to the loss of gas between splitting events. Here we assume that the density of the daughter clumps increases linearly from the density of the comet before the first splitting event to the density of the dust grains after the clump has divided enough times such that the daughter clumps can only be two dust grains. Therefore, while the masses of the daughter clumps equal the mass of their parent clump, the radii of the daughter clumps is given by

$$R_{daughter} = \sqrt[3]{\frac{\rho_0 R_0 - \rho_{dust} R_{dust}}{\rho_0 - \rho_{dust} + \frac{4\pi}{3 m_{daughter}}\left(R_0^3 - R_{dust}^3\right)}}$$

where ρ_0 is the density of the comet, R_0 is the original radius of the clump, ρ_{dust} is the density of a dust grain, and R_{dust} is the radius of a dust grain.

Simulation: We constructed a computer simulation that follows the trajectories of dust/ice clumps as the three forces act upon them. The parameters of the comet in our simulation are derived from Temple 1: comet density of 400 kg/m^3, comet radius of 3 km, dust density of 1000 kg/m^3, dust radius of 1µm, fraction of comet surface that is active of 0.3%, a total gas flux from the comet of 3x10^{27} particles/s, surface temperature of 100° K, and clump temperature of 300° K. We assumed that all of the gas being emitted from the active area of the comet is carbon dioxide, as it is now known to be the predominant driving gas [2], while the gas being emitted from the clumps is assumed to be entirely water vapor.

In our simulation we initiate a specified number of dust/ice clumps on the surface in the active area of the comet both one at a time, and all at once. The simulation runs until the clumps have divided a specified number of times. Although clumps up to a meter in diameter have been observed at Hartley 2 [2], this simulation focuses on smaller initial particles of ~1cm diameter. A particle is placed in or near the active region and divides every 30 seconds for 10 splitting events, for a total simulation time of 300 seconds. We conducted 10,000 such simulations, with the first particle placed in the center of the active region, the last particle placed 2 meters outside of the active region, and the intervening particles at equally spaced intervals between the first and last particle.

We observed that the overwhelming majority of the particles stayed rather close to the central axis of the active area, forming a well-collimated jet that reaches escape velocity. While some particles, particularly those initialized near the edge of the active area, strayed away from the main collimated jet they rarely achieved escape velocity and were numerically overwhelmed by those that remained in the column.

We ran another simulation in which 128 clumps were initially evenly spaced between 1 meter beyond one edge of the active area to one meter beyond the other edge of the active area, and divided every 10 seconds for 7 splitting events (total simulation time of 70 seconds.) Assuming that the multiple clumps approximate the (un-normalized) size and number density distribution of material in the cometary jet, we increased the force between clumps to approximately represent the forces between the more numerous clumps in a real jet that are below the resolution of our computer model.

Although scaling up the force between clumps is expected to drive the clumps apart and decollimate the jet, the jet in our simulation remained well collimated, although it began to diffuse apart as it rose, with the most noticeable diffusion occurring after the clumps had split apart (see Figure 1).

Conclusion: The prevailing view that some form of physical confinement is needed to produce collimated cometary jets appears to be false. Our simulation produced well-collimated jets that reach escape velocity from an active region that was locally flat. Our simulation accounted for interclump drag forces that would tend to decollimate a jet. This mechanism may explain the lack of observed apertures or nozzles on the surfaces of comets.

References: [1] Yelle R.V. (2004) *Icarus* 167, 30-36. [2] A'Hearn M.F. et al. (2011) *Science* 332, 1396-1400. [3] Belton M.J.S. and Melosh H.J. (2009) *Icarus* 200, 280-291. [5] Brownlee D.E. et al. (2004) *Science* 304, 1764-1769. [6] Farnham T.L. et al (2009) *Deep Impact as a World Observatory Event: Synergies in Space, Time, and Wavelength*, 265-270

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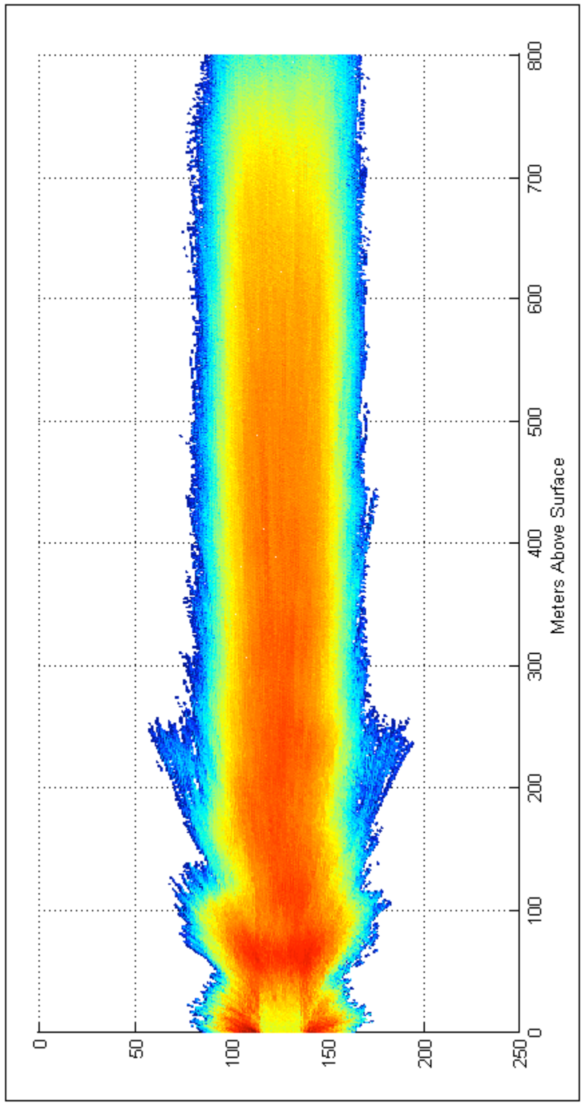

Figure 1: This figure shows a plot of the log of the number density of a simulation with 10 runs of 128 initial clumps placed evenly across the acive area up to 1 meter beyond its edge. The clumps divided every 10 seconds a total of 7 times. Red represents highest number density, while blue shows the lowest.