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Formation of jets in Comet 19P/Borrelly by subsurface geysers

Roger V. Yelle,[a,*] Laurence A. Soderblom,[b] and J. Randy Jokipii[a]

[a] *Department of Planetary Science and Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA*
[b] *United State Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA*

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Abstract

Observations of the inner coma of Comet 19P/Borrelly with the camera on the Deep Space 1 spacecraft revealed several highly collimated dust jets emanating from the nucleus. The observed jets can be produced by acceleration of evolved gas from a subsurface cavity through a narrow orifice to the surface. As long as the cavity is larger than the orifice, the pressure in the cavity will be greater than the ambient pressure in the coma and the flow from the geyser will be supersonic. The gas flow becomes collimated as the sound speed is approached and dust entrainment in the gas flow creates the observed jets. Outside the cavity, the expanding gas loses its collimated character, but the density drops rapidly decoupling the dust and gas, allowing the dust to continue in a collimated beam. The hypothesis proposed here can explain the jets seen in the inner coma of Comet 1P/Halley as well, and may be a primary mechanism for cometary activity.

Keywords: Comets; Comae; Jets

1. Introduction

The visible camera subsystem of the MICAS (Miniature Integrated Camera Spectrometer) instrument observed several jets from the nucleus of Comet 19P/Borrelly (hereafter Borrelly), during the flyby of the Deep Space 1 (DS1) spacecraft in September, 2001. Two distinct styles of jet are easily visible in the image: a diffuse fan symmetrical about the direct sun line and a collimated main jet canted about 30° away from the direct sun line (Soderblom et al., 2002). At the image resolution of 63 m pixel^{-1}, the main jet is seen to be sharp and highly collimated. It remained fixed in orientation (within ±5°, R.A. 218.5° ± 3° and DEC −12.5° ± 3°) for more than one rotation period (∼ 26 h) during the DS1 encounter. Moreover, the main jet is roughly perpendicular to the long axis of the comet, as it would be if the pole were aligned with the principle axis of the nucleus with the largest moment of inertia. These considerations led Soderblom et al. (2002) to conclude that the main jet was roughly coincident with the rotation pole.

At high resolution, Borrelly's main jet is resolved into a series of smaller collimated jets (Fig. 1). Their details are quite distinct; each has a cylindrical core 200–400 m radius that is 4–6 km in length. Spacing between collimated columns is typically ∼ 1 km. Bright hemispheric-shaped isophotes are visible at their bases (Fig. 1), particularly when they are well resolved and their sources are near the limb. Two of the collimated columns are traceable to sources that appear as dark patches in or adjacent to the bright smooth terrain (Soderblom et al., 2002).

Earth-based observations of Borrelly during the recent apparitions, with imaging resolutions of up to 20 km pixel^{-1}, have persistently revealed a strong sunward asymmetry in its coma (Lamy et al., 1998). Although the main jet is visible in the DS1 images only out to a distance of ∼ 100 km, based on its direction, it is the same jet viewed by Earth-based observers during the DS1 flyby (Samarasinha and Mueller, 2002; Farnham and Cochran, 2002; Schleicher et al., 2003). The Borrelly jets appear to be a stable, long term, characteristic of the comet. Collimated structures were also seen in the inner coma of Comet 1P/Halley (Thomas and Keller, 1987; Keller et al., 1987). Thus, both comets exhibit highly collimated structures in their inner comae. There is also evidence of jet-like features in numerous comets in groundbased observations, albeit at much greater spatial scales (Sekinina, 1991).

Another, less obvious manifestation of collimated flow has been seen in the variation of jet brightness with distance from the surface, as measured in the inner coma of Halley.

* Corresponding author.
E-mail address: yelle@lpl.arizona.edu (R.V. Yelle).

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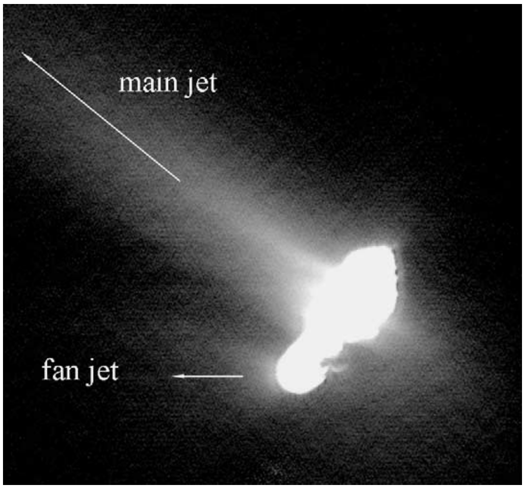

Fig. 1. A MICAS image of the collimated jets in the inner coma of Comet p/Borrelly. This image was taken from a range of 4825 km, at a resolution of 63 m pixel^{-1}, and a phase angle of 62.5°. The Sun is to the left of the image.

The jet brightness decreases away from the surface much more slowly than the inverse of distance from the surface for distances within tens of kilometers of the nucleus. Several investigators have shown this characteristic of the jet can be understood if the jet is produced by a distributed area of activity, rather than a spatially confined source. A best fit to the observed dust distribution is achieved for a distribution of sources with opening angles of $\sim 10°$ from a circular area on the surface with a radius of ~ 1.5 km (Huebner et al., 1988; Reitsema et al., 1989; Thomas et al., 1988). However, these authors offer no explanation for the 10° opening angle of the distributed sources.

Emission from gases, when integrated over the broad bandpass of the MICAS cameras, makes only a negligible contribution to the recorded signal; therefore, the images reveal primarily the distribution of dust in the inner coma. Previous investigators have established that visible/near IR observations of cometary comae are sensitive primarily to particle sizes on the order of 1 µm (Lamy et al., 1987). This occurs because small particles are more numerous than large particles, but scatter sunlight less efficiently and the competition between these two effects produces a peak near ~ 1 µm. Our goal then is to explain why particles of this size appear in collimated jets. Larger particles may be present, but we have no information on their spatial distribution.

The existence of collimated jets from an irregularly shaped object with little atmosphere (pressure ~ 0.03 Pa) and less gravity ($g \sim 10^{-3}$ m s^{-2}) is puzzling. What leads to the extreme preference for one direction over all others? The jets are undoubtedly related to sublimation of water ice from the nucleus, but free-vacuum sublimation should occur into a wide solid angle. Dynamical phenomena adequately described as jets are also seen in volcanic plumes on the Earth and Io and in geysers on Earth and Triton (Kieffer, 1982, 1989; Kirk et al., 1995). Here, we explore an explanation for the collimated Borrelly jets that may share some dynamics in common with these other phenomena, but first we show that jets are not produced by sublimation through a permeable crust.

2. Jets and diffuse sublimation

Most models for the dust distribution in cometary comae assume that the dust is lifted off the surface of the nucleus by gas-drag forces over a large area. For example, Horanyi et al. (1984) model cometary activity as sublimation through a porous regolith, whereas Keller et al. (1994) assume sublimation directly from the surface. Though a permeable crust is possible, and may exist on some areas of the comet, it is difficult to reconcile sublimation through a permeable crust with the collimated dust streams seen in the inner coma of Borrelly. Vapor percolating subsonically through a permeable near-surface layer will have a nearly Maxwell–Boltzmann velocity distribution upon reaching the surface. The departures from an isotropic Maxwell–Boltzmann distribution are of the same order as the ratio of the diffusion velocity to the speed of sound and are therefore small if the diffusion velocity is subsonic. If the gas pressure at the comet's surface is much smaller than in the permeable crust, the random molecular velocities in the gas will cause it to expand laterally, attaining a mean velocity transverse to the surface of order the sound speed as soon as it is free of the confines of the crust. Any collimation acquired from the preferred diffusion direction in the subsurface will be quickly lost because the molecular velocities, which are of order the speed of sound, are larger than the diffusion velocity. Dust lifted off the surface layer would acquire significant transverse velocity from the gas because the gas drag in the transverse direction is of the same order as the gas drag in the radial direction. If the gas pressure at the comet's surface is roughly equal to the pressure in the permeable crust the diffusing gas will simply mix with the ambient gas because the pressure associated with the subsonic diffusion is smaller than the ambient isotropic gas pressure. In this case there will be no jet at all. Supersonic velocities are needed to produce a collimated jet.

Keller et al. (1994) have argued that collimation can be produced by mild topography on the surface of the nucleus, specifically an active area inside a shallow crater surrounded by an inactive area. We re-examine this model, using a statistical mechanical analysis and paying particular attention to the boundary conditions at the surface. For flow from an active region on a flat surface, the situation is cylindrically symmetric so the problem contains two directions. We will label the direction normal to the surface with z and the tangential direction with ρ; the corresponding bulk velocities of the gas are u_z and u_ρ. We let the surface of the comet lie at $z = 0$ and consider an active region of cylindrical radius $\rho_\circ$. Keller et al. set the normal velocity equal to the sound speed, $u_z = c_s$, and the tangential velocity to zero, $u_\rho = 0$. However, this latter condition is inconsistent with the assumption of an area of confined activity. The boundary conditions at the surface follow from the molecular distribution function $f(v_z, v_\rho)$. The bulk velocity of the gas is defined as the average of the molecular velocity over the gas distribution function. The tangential component is given by

$$u_\rho = \int_{-\infty}^{+\infty}\int_{0}^{+\infty} v_\rho f(v_z, v_\rho)\, dv_z\, dv_\rho. \tag{1}$$

At $z = 0$ and $\rho = \rho_\circ$, the distribution function will be zero for $v_\rho < 0$, because of the absence of sublimation for $\rho > \rho_\circ$. The integral is then necessarily positive. The distribution function for sublimation from an icy surface is well approximated by a Maxwellian distribution in the region $v_\rho > 0$ and it follows that $u_\rho = \sqrt{2kT/\pi m}$. The maximum value of the bulk vertical velocity is given by the well-known expression for the number of molecules hitting a surface $u_z = \sqrt{kT/2\pi m}$, which is about one third the sound speed and twice the tangential velocity. Thus, flow from an isolated active area should diverge with an angle greater than $\tan^{-1}(2) = (63)°$. This is much larger than the divergence angles observed for the Borrelly jets. The shallow craters considered by Keller et al. (1994) do little to change the situation. Averaging over the distribution function as above, but restricting the angles to account for shadowing by the walls of the craters implies only a $\sim 30\%$ decrease in bulk transverse velocity for the craters with a 2 : 1 width-to-depth ratio (the shape considered by Keller et al. (1994)). For the 10° collimation seen in the Borrelly jets, $u_\rho < \tan(10°)u_z$, which would imply a deep collimating structure, with a width-to-depth ratio $> \cot(10°) = 5.76$, counter to that assumed by Keller et al. (1994).

3. Comet geysers

The low albedo, the lack of spectral features due to H_2O, surface temperatures much higher than the free-vacuum sublimation temperature of H_2O ice, and the spatially confined regions of enhanced activity all imply an absence of H_2O ice on the surface of Borrelly (Soderblom et al., 2002). The surface is covered with a refractory crust. If the crust is poorly permeable to vapor then activity occurs principally at the location of cracks or holes in the crust. The importance of sublimation from the subsurface through cracks and vents in a non-volatile surface layer has been recognized by previous investigators (Keller, 1989; Komle and Dettleff, 1991; Skorov et al., 1999), but the idea has not been applied previously to the creation of jets. Figure 2 shows our model for vapor evolved from a subsurface cavity and forced through a narrow orifice or vent to the surface. The flow from the geyser will be supersonic if the pressure in the cavity of the geyser is greater than that in the ambient cometary atmosphere (Anderson, 1982). We propose that supersonic flow from these geysers are responsible for the Borrelly jets.

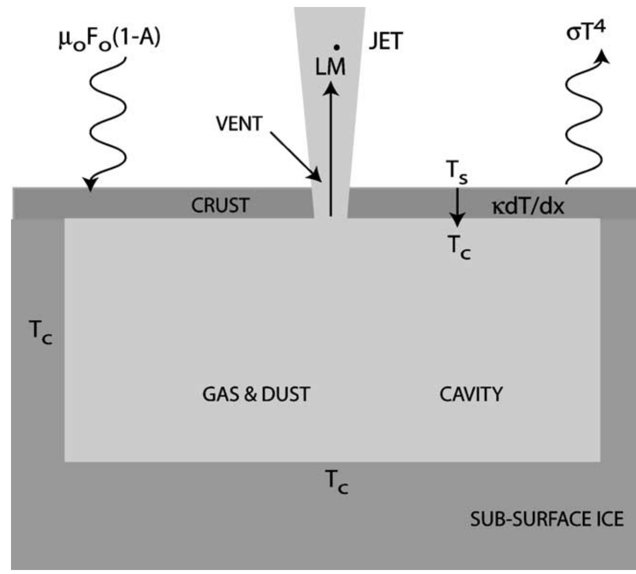

Fig. 2. A diagram of a subsurface geyser showing the important energy fluxes. Solar energy absorbed by the surface is partitioned between re-radiation and conduction to the subsurface. The energy conducted to the subsurface raises the ice temperature and consequently the gas pressure in the cavity. The flux of energy conducted to the subsurface is balanced by the flux of latent heat in the jet.

The shape of the geyser (Fig. 2) is a consequence of its evolution. Once a crack is created in the crust, the ice below will quickly sublimate creating a cavity (Sekinina, 1991). We can make a rough estimate of likely depths from the sublimation rate at the subsolar based on solar insolation. The maximum sublimation rate can be estimated from $\dot{M}_{\max} = \mu_\circ F_\circ/L$, where $\dot{M}_{\max}$ is the sublimation rate per unit area, $F_\circ$ is the solar flux, $\mu_\circ$ is the solar zenith angle at the location of the jets, and L is the latent heat of sublimation. At Borrelly's heliocentric distance of 1.36 AU, $F_\circ = 735\ \mathrm{W\,m^{-2}}$, while $\mu_\circ = 0.87$ for the main jet at the time of encounter, and $L = 2.8 \times 10^6\ \mathrm{J\,kg^{-1}}$. Combining these numbers gives $\dot{M}_{\max} = 2.3 \times 10^{-4}\ \mathrm{kg\,m^{-2}\,s^{-1}}$. However, only a fraction of the absorbed energy is available to power sublimation because some energy is radiated away. Assuming an equal division between sublimation and radiation we estimate a sublimation rate of $7\ \mathrm{m\,year^{-1}}$ for a density of $500\ \mathrm{kg\,m^{-3}}$. Thus, a geyser that has been active for two months should have a depth of order ~ 1 meter.

To investigate our hypothesis further, we have constructed a 1D model for the energetics and gas flow dynamics of the geyser. The 1D assumption is valid if the geyser cavity is wide enough for the primary thermal contact to be with the surface of the comet, i.e., if the cavity is significantly wider than it is deep. The solar energy absorbed on the surface of the comet is partitioned between thermal re-radiation from the surface and loss of latent heat through the geyser,

$$\mu_\circ F_\circ(1 - A) = \epsilon\sigma T_s^4 + \alpha L\dot{M}, \tag{2}$$

where T_s is the temperature at the surface of Borrelly, $\dot{M}$ is the mass flux from the geyser, and L the latent heat of H_2O

and α is the ratio of the minimum cross sectional area in the nozzle to the cross sectional area of the cavity. $\dot{M}$ is given by the product of the gas velocity and density, $\dot{M} = u\rho$. The velocity is calculated by solving the 1D gas dynamical equations assuming that the gas is isothermal (Anderson, 1982).

$$u\frac{du}{dz} = \left(\frac{c^2}{A}\frac{dA}{dz}\right)\frac{u^2}{u^2 - c^2}, \tag{3}$$

where z is the direction along the length of the nozzle, A is the cross sectional area perpendicular to z, u is the velocity along z and c is the speed of sound. Equation (2) is solved subject to the boundary condition that the gas pressure vanish as $z \to +\infty$. This condition also implies that the gas velocity passes through the sonic point at the location where the nozzle area is a minimum. We set the gas density at $z = 0$ equal to the vapor pressure value at the temperature of the cavity walls, T_c. The gas density at other locations follows from mass continuity $\rho u A =$ constant. We assume that the vapor is composed of pure H_2O.

We relate T_c and T_s by solving the thermal conduction equation and equating the energy carried to the cavity by thermal conduction with the latent heat flux from the geyser

$$\alpha L\dot{M} = \kappa\frac{dT}{dz}, \tag{4}$$

where κ is the effective thermal conductivity of the crust. The temperature of the cavity walls is equal to the temperature at the base of the crust and all areas of the walls are at the same temperature. This is a consequence of the rapid energy transfer by latent heat occurs at the speed of sound and the time constant for this process is of order hundreds of seconds, much shorter than the other time constants in the system (Skorov et al., 1999).

Equations (2)–(4) are coupled and must be solved in iterative fashion. To perform the calculations we use a solar zenith angle $\cos^{-1}(\mu_\circ)$ of 30 degrees, an albedo of $A = 0$, and an emissivity of $\epsilon = 1$. We adopt a thermal conductivity for the crust of 10 $\mathrm{W\,m^{-1}\,K^{-1}}$ and a Hertz factor of 0.01 for an effective conductivity of 0.1 $\mathrm{W\,m^{-1}\,K^{-1}}$ (Huebner et al., 1998). We assume that the thickness of the crust is $\Delta z = 0.1$ m.

With our model assumptions, only the ratio of conductivity to crust thickness enters into the calculations. There are no firm observational constraints on either κ or Δz. Our choices are consistent with those made in some recent models of cometary thermal models (Enzian et al., 1999), but other values are possible. These uncertainties strongly affect the details of the flow from the geyser, but not its primary characteristics.

Figure 3 shows calculations of the cavity and surface temperatures as a function of the ratio of α. T_c varies from 202 to 252 K and the pressure inside the geyser from 0.2 and 125 Pa for values of α from 0.1 to 1×10^{-4}. Keeping α fixed at 1.5×10^{-4} and letting $\kappa/\Delta z = 0.1$, 1.0, and 10 $\mathrm{W\,m^{-2}\,K^{-1}}$, we calculate cavity pressures of 1.1×10^1, 8.0×10^1, and 3.4×10^2 Pa. We can calculate a maximum

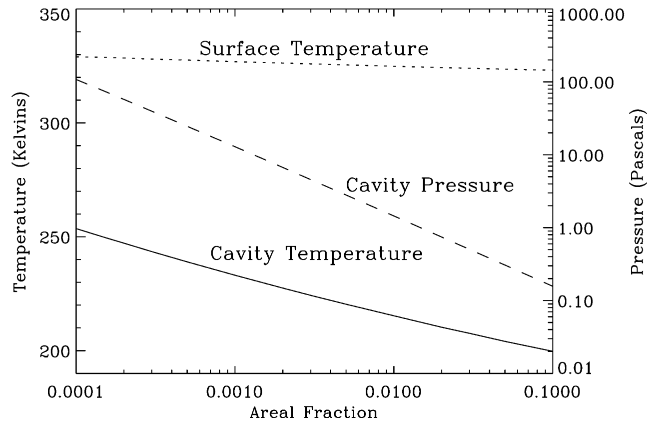

Fig. 3. Calculations of the temperature and gas pressure in a subsurface geyser as a function of the ratio of the area of the vent to the horizontal area of the cavity. Note the relatively constant (and high) surface temperature for the comet at all areal fractions.

pressure for the ambient pressure at the surface of Borrelly by assuming that all of the solar energy goes into powering sublimation. Using the value for the solar flux given previously we calculate a temperature of 190 K and a pressure of 0.03 Pa. Our estimates of gas pressure in the cavity exceed this by a large factor even for $\alpha = 0.1$. Thus, given the uncertainties in the thermophysical properties of the comet, we cannot accurately predict the cavity pressure, but an overpressure strong enough to power a geyser obtains for a wide range of conditions.

The geometry shown in Fig. 2 is that of a de Laval nozzle, a common device for the production of supersonic flows and the study of flow from this nozzle is a standard problem in many gas dynamic texts (Anderson, 1982). The characteristics of the flow from the geyser depend only on the cross section of the nozzle and the gas density down stream from the nozzle. There are two radically different solutions for the flow depending on the down stream boundary conditions. For downstream pressures larger than the pressure in the cavity, the appropriate case for geysers on Earth and Triton, the gas flow through the nozzle will be subsonic and gas velocity decreases as the nozzle opens out. For downstream pressures smaller than the cavity pressure, the appropriate solution for our comet geyser, the downstream boundary condition can only be met with a particular solution that passes through the sonic point at the precise location where the cross sectional area of the nozzle in a minimum. The gas continues to accelerate past the sonic point and is expelled from the nozzle at high velocity and low density. The nature of the flow is not sensitive to the shape of the vent beyond its narrowest point.

Figures 4a–4c shows an example of the solutions to Eq. (2). The length scale for acceleration of the flow depends on the cross section of the nozzle. To be definite we have adopted a cavity depth of 1 m, based on the sublimation rates mentioned above. We also assume sublimation of H_2O ice at a temperature of 250 K, corresponding to $\alpha = 1.4 \times 10^{-4}$. The cavity gas pressure and density are 80 Pa and 7.4×10^{-4} $\mathrm{kg\,m^{-3}}$. The mean free path between

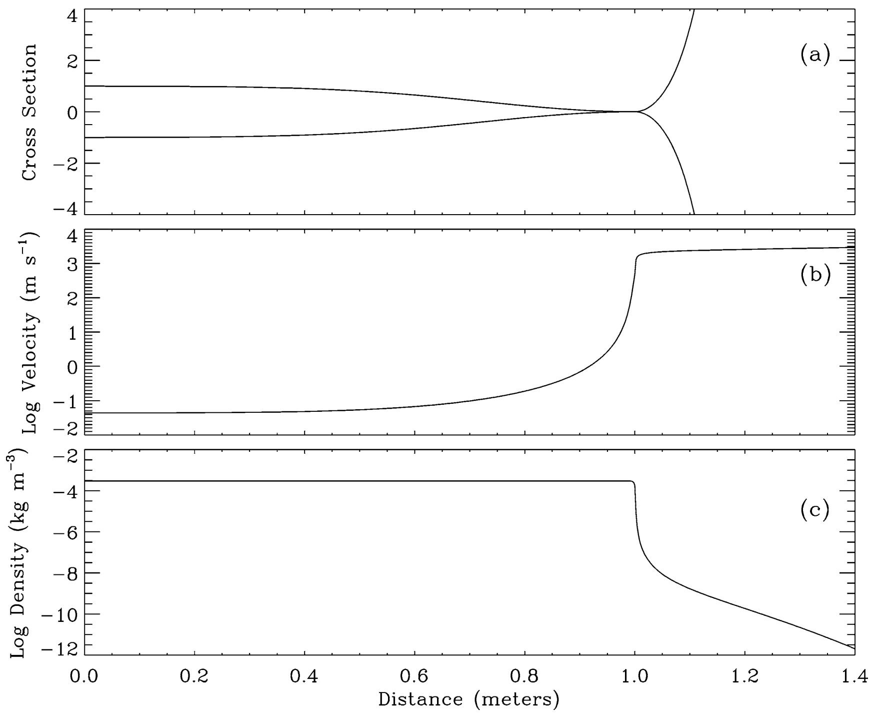

Fig. 4. (a) The geyser cross section in relative units assumed for the gas dynamic calculations; (b) the gas velocity in the geyser; (c) the gas density in the geyser.

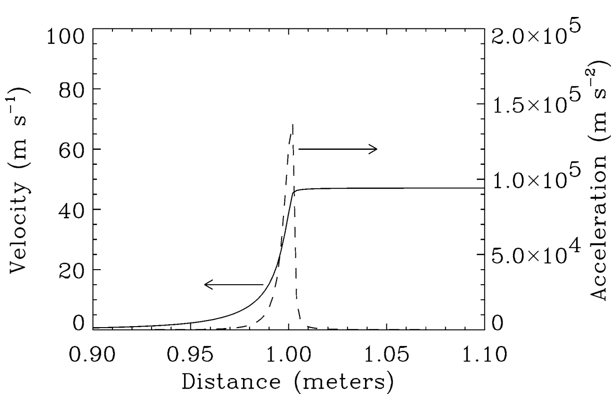

Fig. 5. Velocity and acceleration of 1 µm diameter dust grains entrained in the escaping gas.

molecular collisions is ~ 0.1 mm, which is small enough compared to the size of the vent that the fluid approximation should be valid. The direction of the jet is determined entirely by the geometry of the nozzle and deep collimated mechanical structures are not required to produce a collimated gas jet.

The gas densities and flow velocities shown in Figs. 4b and c are sufficient to accelerate dust particles to substantial velocities. Calculations of the velocity and acceleration of a 1 µm diameter dust particle in the flow field of Fig. 4 are shown in Fig. 5. The dust acquires most of its velocity within several centimeters of the nozzle and reaches an exit velocity of nearly 50 $\mathrm{m\,s^{-1}}$. Both gravity and solar radiation pressure are unimportant for the length scales considered here and the dust acceleration is given by

$$m_d \frac{dV_d}{dt} = \frac{\pi a^2}{2} \rho_v C_D (V_v - V_d)^2, \tag{5}$$

where m_d is the mass of a dust particle, a is its radius, ρ_v is the gas density, V_v and V_d are the velocities of the gas and dust, and C_D is the drag coefficient given by Probstein (1968). The drag forces peak near the sonic point then drop rapidly. This occurs even though the gas velocity is still increasing, because the gas density drops rapidly past the sonic point (Fig. 4c). This is a general result for supersonic flow and a critical factor in our model. A supersonic flow is necessary to produce a highly collimated gas jet but shortly after the gas jet imparts some of its velocity to the dust, the drop in density beyond the sonic transition reduces the drag forces on the dust, which continues unimpeded, even though the gas may expand laterally and lose it collimation. Supersonic nozzles are, therefore, a natural way to produce collimated dust streams.

Although the acceleration drops beyond the geyser throat, the dust is still accelerated at a much smaller rate by the escaping atmosphere of the comet. It is this weaker acceleration acting over distances of hundreds of kilometers that is responsible for the velocity of the dust in the outer coma (Gombosi et al., 1986).

The calculations shown in Figs. 3–5 are unlikely to be correct in the details because we have insufficient information to determine the precise size and shape of the geyser. Rather, we have concentrated on the general characteristics of the flow that should be applicable over a broad range of conditions. We can, however, make some general statements on geysers sizes. First, there could be geysers with a ranges of sizes in operation on an active comet and this should change in a dynamical way on a time scale comparable to the time that the comet spends near perihelion. Geysers will grow with time, because of excavation by sublimation, but there is an upper limit to growth. As the cavity grows it will gather sunlight over a larger area and the fractional area occupied by the vent will decrease. As this happens the temperature and gas pressure in the cavity will increase. Eventually, the gas pressure will exceed the strength of the crust, which will rupture, ending the life of the geyser. The strength of cometary material has been estimated to be 10^3 Pa from the break-up of Comet d/Shoemaker–Levy 9 (Greenberg et al., 1995; Rickman, 1998), which corresponds to an areal fraction of $\sim 10^{-5}$ (Fig. 3). Thus, if the vent were 1 cm in diameter, the cavity would grow to a diameter of $\sim$ 3 meters. However, the strength estimated from Shoemaker–Levy 9 applies to the large scale rupture of the comet and it is possible that small regions of the crust have higher strength and the cavity could therefore grow to larger size. The size of the active regions on Borrelly appears to have been less than a few hundred meters in the aggregate (Soderblom et al., 2002), but the size of individual vents is not well constrained by the observations. The minimum size of a geyser may be determined by the particle size distribution on the surface. The vent must be large enough so that it does not become clogged by escaping dust particles, which are typically of the order 0.1–100 μm (McDonnell et al., 1991; Lisse et al., 1998). In fact, some geysers may be temporarily or permanently blocked by large particles, but others likely survive, especially if the initial vent is large.

4. Discussion

The potential similarity between geysers on Triton and cometary jets has been mentioned by Wallis and Wickramasinghe (1992). These authors do not examine the dynamics of the geysers and suggest that the geyser, rather than being powered by solar insolation, is powered by metabolic activity of cometary life forms. This hypothesis, therefore, has little to do with that advanced here.

Sekinina (1991) has argued that collimated features in the inner coma of Halley may be produced by deep vents in the nucleus. Sekinina (1991) recognized the importance of vents and that, once a vent is created, a deeper cavity will be excavated by sublimation. However, his arguments for the morphology of jets are primarily geometrical in that the collimation is a reflection of the mechanical structure of the vent. In our model the geometry plays a minor role; the primary effects are dynamical. Mechanical collimation does not insure production of collimated dust streams because a jet will expand laterally outside the confines of a vent. The supersonic transition discussed here is necessary to produce and maintain collimation.

Subsequent to submission of this paper a pair of papers on the Halley jets were published by Crifo et al. (2002) and Szegö et al. (2002) and a more complete description of the general aspects of the model upon which the aforementioned papers is based was published by Rodionov et al. (2002). These authors suggest that the jets are a natural consequence of sublimation and dust entrainment from irregularly shaped nucleus even with homogeneous sublimation. Their sophisticated model solves the Navier–Stokes equations with the proper kinetic boundary conditions at the surface of the nucleus. The model has not yet been applied to Comet Borrelly. The MICAS observations of the Borrelly jets are likely to provide a more stringent test of the model because of improved photometry relative to the Halley observations. Moreover, the primary jets observed from Comet Halley that are the subject of the Szegö et al. (2002) paper are characterized by much larger divergence angles than the Borrelly jets. Application of the Crifo et al. models to analysis of the Borrelly images, using the shape model for the Borrelly nucleus (Kirk et al., 2004; Oberst et al., 2004) would answer these questions.

The geyser model presented here could be improved in several ways. Our calculations are for steady state, but time dependent calculations could be used to study the evolution of a geysers, which may provide a better understanding of the geyser morphology. Two-dimensional calculations would have a broader range of applicability and may be more accurate than the 1D calculations employed here. Also, we have considered the gas and dust separately when in fact dust loading should slow the gas acceleration. This effect is considered in the hydrodynamical models of the inner coma models (Kitamura, 1987; Korosmezey and Gombosi, 1990), which still predict a sonic transition, but dust loading can be a sizable effect. However, the primary shortcomings of our analysis are not related to our model directly, but rather to the many uncertainties in the physical properties of cometary surfaces and subsurfaces. Nevertheless, the lack of detailed knowledge of the physical makeup of the cometary nucleus does not obviate the need for a basic physical model of emission from comets that can produce highly collimated dust jets. Because it is impossible to specify the thermal conductivity, density, specific heat, crustal thickness, ice/dust ratio, strength, and geyser geometry with any precision, the calculations presented here are only illustrative. Therefore, the most significant progress on this topic is likely to come from further observations that constrain the physical properties of cometary surfaces and more detailed imaging of cometary activity.

Acknowledgments

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