JETS ON COMETS' CLIFFS ARE THE DOMINANT CAUSE OF ROTATION STATE CHANGES. J. K. Steckloff[1], [1]Purdue University, Department of Earth, Atmospheric, and Planetery Science, West Lafayette, IN 47907 (jstecklo@purdue.edu).

Introduction: The sublimation of volatile species is a defining process that occurs on cometary bodies [1][2]. These sublimating gases can blow off refractory dust, forming cometary dust jets and the coma and tail [3], and synchronic bands [4]. Volatile sublimation can also exert reaction pressures strong enough to fragment nuclei [5], and generate net body torques that change the rotation state of the nucleus [6][7][8][9]. Traditional methods for studying these sublimative torques require detailed information on the shape and activity of a cometary nucleus to integrate the sublimation pressure over the surface of the nucleus and compute the net torque [6][8]. However, such information can generally only be obtained by high-resolution spacecraft observations of a comet nucleus, which significantly restricts the application of this method to the handful of short-period comets that have been visited by spacecraft.

Parameterized Models of Sublimative Torques: Recently, parameterized models of sublimation torques have been developed to study changes in the spin states of comet nuclei without high-resolution information.

X-parameter model. Samarasinha & Mueller [7] developed a model of sublimative torques in which the angular acceleration of a comet nucleus is

$$\left|\frac{d\omega}{dt}\right| = X\frac{2\pi\, Z(r_h)}{R_n^2} \quad (1)$$

where ω is the angular velocity (rotation rate) of the nucleus, $Z(r_h)$ is the H_2O flux at zero solar zenith angle as a function of heliocentric distance (r_h), R_n is the effective radius of the nucleus, and X is a comet-specific constant that is averaged over the orbital period of a comet. This X parameter is approximately constant amongst the considered Jupiter family Comets (JFCs), varying by no more than a factor of two despite the active fractions of the comets' surfaces varying by ~1.5 orders of magnitude [7].

SYORP model. Steckloff & Jacobson [9] describe another parameterized sublimative torque model based on the YORP effect (SYORP). The angular acceleration of a comet nucleus in this SYORP model is given by

$$\left|\frac{d\omega}{dt}\right| = \frac{3fP_SC_S}{4\pi\rho R_n^2} \quad (2)$$

where f is the fraction of the surface are of the nucleus that is active (active fraction), ρ is the bulk density of the body, P_S is the sublimative momentum flux at zero solar zenith angle, and C_S is the SYORP coefficient, which is the fraction of a nucleus' total sublimative momentum flux that generates a net torque.

Thus, the SYORP approach breaks up the net sublimative momentum flux (ϕ_{sub}) emitted from each area element (dS) of the nucleus into a radial component (ϕ_{rad}) and a tangential component (ϕ_{tan}) with respect the the body's center of mass (see *figure 1*), and integrates over the surface (S) of the nucleus to obtain the net sublimative momentum flux (Φ_{sub}) and its radial (Φ_{rad}) and tangential (Φ_{tan}) components. Becuause the radial component of the sublimative momentum flux does not contribute to a net torque, the SYORP torques are solely due to the net tangential sublimative momentum flux (Φ_{tan}).

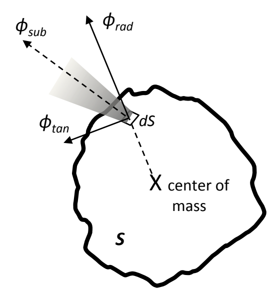

Figure 1: SYORP divides sublimative momentum flux (ϕ_{sub}) from surface element dS into a radial (ϕ_{rad}) and tangential (ϕ_{tan}) components, relative to the nucleus' center of mass. Only the tangential component exerts a torque on the body.

If we define $\langle\phi_{sub}\rangle$ as the average sublimative momentum flux and $\langle\phi_{tan}\rangle$ as its average tangential component, then the SYORP coefficient (C_S) and active fraction (f) can be defined as

$$C_S = \frac{\langle\phi_{tan}\rangle}{\langle\phi_{sub}\rangle} \quad (3)$$

$$f = \frac{\langle\phi_{sub}\rangle}{P_S} \quad (4)$$

Additionally, the average tangential sublimative flux ($\langle\phi_{tan}\rangle$) is a function of heliocentric distance

$$\langle\phi_{tan}\rangle = f_{tan}Z(r_h)m_{water}\langle v_{water}(r_h)\rangle \quad (5)$$

where f_{tan} is the effective fraction of the theoretical maximum volatile flux at zero solar zenith angle ($Z(r_h)$) that is directed tangentially and contributes to a net torque, m_{water} is the mass of a water molecule and $\langle v_{water}(r_h)\rangle$ is the average molecular thermal velocity of the sublimating water molecules in the direction normal to the surface, which is dependent upon heliocentric distance.

Combining sublimation models. If both of these parametric sublimative torque models are to be correct, they must be consistent with one another. we can therefore combine equations (1), (3), (4), and (5)

$$f_{tan} = X \frac{8\pi^2 \rho}{3m_{water}\langle v_{water}(r_h)\rangle} \quad (6)$$

However, both of these parametric models agree that sublimative torques on comet nuclei are only significant in regions of the Solar System where sublimative cooling is the dominant heat-loss mechanism [7][9]. In the region of the JFCs, the average magnitude of the thermal velocity ($\langle v(r_h)\rangle$) of these volatiles where they also sublimate vigorously (where sublimative cooling dominates heat-loss processes) varies by less than ~10% [5]. We can therefore consider $\langle v_{water}(r_h)\rangle$ in equation (6) to be approximately constant. Additionally, the estimated densities of JFCs range cover a narrow range, Varying by a factor of ~1.6 [10][11][12], allowing us to treat the density (ρ) of equation (6) as approximately constant.

Therefore, the entire right-hand side of equation (6) is constant to within a small factor

$$f_{tan} \sim const. \quad (7)$$

This means that the fraction of molecules that contribute to a net torque of the nucleus is a constant fraction of the theoretical maximum production rate $Z(r_h)$. In other words, the number of molecules that contribute to a net torque of the nucleus depends primarily on the size and heliocentric distance of the nucleus, and is largely independent of the detailed shape and active fraction of the nucleus.

Discussion: Such a trend is consistent with the thermally processed nature of the surfaces of Jupiter Family Comets, which require ~10 million years to migrate from the Scattered Disk into the Jupiter Family [13]. Over that period of time, an initially pristine surface should undergo significant evolution of its surface layers. CO_2 and H_2O sublimate vigorously inward of ~8 AU and ~2 AU from the Sun respectively [5][9]. Thus, as a comet's orbit takes it inwards of ~8 and ~2 AU from the Sun, the volatile sublimation fronts from CO_2 and H_2O respectively will recede below the surface of the nucleus. This leaves a volatile poor, dusty surface above the ice, which is an effective thermal insulator due to its low cometary thermal inertia. However, if the slope of the surface exceeds the angle of repose (α_{repose}), then the surface material may avalanche or landslide off, exposing volatile-rich materials to the surface where they can continue to sublimate and drive cometary activity (see *figure 1*) [14].

Thus, areas of active sublimation on Jupiter Family Comets should be largely restricted to steep surfaces on their nuclei, where surface layers landslide away. This is consistent with the observed jets of comet 9P/Tempel 1, which originated from the edge of a scarp [15], and the active lobe of comet 103P/Hartley 2, which recently had a steep, unstable surface [14]. Furthermore, because sublimative torques are due to emission from steep surfaces that resist thermalphysical evolution, sublimative fluxes should be equally strong for both new and evolved comets, allowing existing JFC parameters (e.g. *X* or C_S) to be applied to the study of sublimative fluxes for all comet populations.

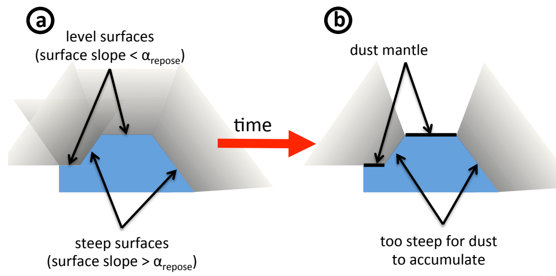

Figure 2: *Evolution of sublimating surfaces over time.* The active surfaces of a comet nucleus are expected to evolve with time. (a) An initial surface lacking in a dust mantle (or other insulating materials) should exhibit sublimative, cometary activity from all of its illuminated surfaces regardless of surface slope angle. (b) Over time, dust will accumulate on the surface of the nucleus. Although dust falls on all surfaces, it is unable to remain on surfaces with slopes steeper than the angle of repose. Cometary dust is an excellent thermal insulator. Thus, horizontal surfaces (surface slope < α_{repose}) will form dust mantles and shut down activity, while steep surfaces (surface slope > α_{repose}) will remain dust free and active.

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