Icarus 312 (2018) 172–180

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The sublimative torques of Jupiter Family Comets and mass wasting events on their nuclei

Jordan K. Steckloff[a,b,c,d,*], Nalin H. Samarasinha[a]

[a] Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, USA
[b] University Texas at Austin, Department of Aerospace Engineering and Engineering Mechanics, W.R. Woolrich Laboratories, C0600, 210 East 24th Street, Austin, TX 78712-1221 USA
[c] Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, Building 54-918, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
[d] Purdue University, Department of Earth, Atmospheric, and Planetary Sciences, 550 Lafayette St., West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 22 January 2018
Revised 23 April 2018
Accepted 26 April 2018
Available online 27 April 2018

Keywords:
Comets
Comets, nucleus
Comets, dynamics

ABSTRACT

Sublimative outgassing of comets produces torques that alter the rotation state of their nuclei. Recently, parameterized sublimative torque models have been developed to study rotation state changes of individual comet nuclei and populations of cometary bodies. However, these models simplify the interactions between the escaping gas and cometary surface into only a few parameters that hide the details of these complex interactions. Here we directly compare the X-parameter model (Samarasinha and Mueller, 2013) with the SYORP model (Steckloff and Jacobson, 2016) to tease out insights into the details of the gas-surface interactions driving sublimative torques. We find that, for both of these models to accurately model sublimative torques, the number of sublimating molecules that contribute to the net torque is largely independent of the detailed shape and activity of the nucleus, but rather depends primarily on the size of the nucleus and the effective heliocentric distance of the comet. We suggest that cometary activity must be largely restricted to regions of steep gravitational surface slopes (above the angle of repose), where mass wasting can refresh activity by shedding mantles of refractory materials and exposing fresh volatiles. We propose a new classification scheme for comets based on the frequency of this mass-wasting process (relative to the timescale of activity fading): quasi-equilibrium, episodic, quasi-dormant, and extinct.

1. Introduction

The sublimation of volatile species is a defining process of cometary bodies (Whipple, 1950, 1951). These sublimating gases can blow off refractory dust, forming dust jets, gas jets, dust comae, gas comae, dust tails (Bessel, 1836), and synchronic dust bands (e.g., Kharchuk and Korsun, 2010). Volatile sublimation can also exert reaction pressures strong enough to fragment nuclei ((Steckloff et al., 2015). Additionally, asymmetric sublimative gas emission can generate net torques on the nucleus that change the rotation state of the nucleus (e.g., Whipple, 1950; Samarasinha and Belton, 1995; Gutiérrez et al., 2003; Neistadt et al., 2003; Samarasinha and Mueller, 2013; Keller et al., 2015; Steckloff and Jacobson, 2016), contribute to stria formation in the dust tail (Steckloff and Jacobson, 2016), induce avalanches and other mass wasting[1] events on the nucleus (Steckloff et al., 2016), or lead to disruption (e.g., Steckloff and Jacobson, 2016; Jewitt et al., 2016) or reconfigurations of the shape of the nucleus (Hirabayashi et al., 2016a). Traditional methods for studying such sublimative torques adopt an approach that integrate the torques caused by sublimation forces over the surface of the nucleus to compute the net torque (e.g., Gutiérrez et al., 2003; Neistadt et al., 2003, Keller et al., 2015), and therefore require detailed information on the shape and activity of the nucleus. However, such sufficiently detailed information, especially the shape of the nucleus, is often only obtainable with high-resolution spacecraft observations of a comet nucleus, limiting the application of these methods to the handful of short-period comets that have been visited by spacecraft.

* Corresponding author at: Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, USA
E-mail address: jordan@psi.edu (J.K. Steckloff).

[1] The term "mass wasting" refers to the downslope movement of geologic materials, which excludes volatile sublimation.

https://doi.org/10.1016/j.icarus.2018.04.031

2. Parameterized sublimative torque models

More recently, parameterized models of sublimative torques have been developed to study changes in the spin states of cometary bodies without high-resolution information. Samarasinha and Mueller (2013) developed a model of sublimative torques to describe the magnitude of a comet nucleus' orbitally averaged angular acceleration[2]:

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

where ω is the angular velocity 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 measures the specific change in rotational angular momentum averaged over the orbital period of a comet. $\overline{|\frac{d\omega}{dt}|}$ and $\overline{Z(r_h)}$ denote the orbitally averaged values during the active phase. Samarasinha and Mueller (2013), and later Mueller and Samarasinha (2018) used this parametric model to study the observed changes in the spin periods of comets 2P/Encke (Mueller et al., 2008), 9P/Tempel 1 (Belton et al., 2011; Chesley et al., 2013), 10P/Tempel 2 (Knight and Schleicher, 2011; Knight et al. 2011; Knight et al., 2012), 19P/Borrelly (Mueller and Samarasinha, 2015), 67P/Churyumov–Gerasimenko (Lowry et al., 2012; Mottola et al., 2014; Accomazzo et al., 2017), and 103P/Hartley 2 (Drahus et al., 2011; Belton et al., 2013; Knight et al., 2015). They discovered that this X parameter is approximately constant amongst the sample of Jupiter family Comets (JFCs) considered in their study, varying by only a factor of a few in spite of active fractions of the comets' surfaces that varied by ~1.5 orders of magnitude (Samarasinha and Mueller, 2013; Mueller and Samarasinha, 2018).

Steckloff and Jacobson (2016) describe another parameterized sublimative torque model analogous to the YORP effect (SYORP), which takes advantage of the similar manner in which photons and rarefied gas molecules are emitted from a porous regolith (e.g., Gombosi, 1994). The SYORP model breaks up the net sublimative momentum flux (ϕ_{sub}) emitted from each area element (dS) of the surface of an icy body into two components with respect to a vector drawn from the body's center of mass to the area element: a radial component directed along this vector (ϕ_{rad}) and a tangential component directed perpendicular to this vector (ϕ_{tan}) (see Fig. 1). Integrating over the surface (S) of the nucleus, the net sublimative momentum flux (Φ_{sub}) and its radial (Φ_{rad}) and tangential (Φ_{tan}) components are

$$\Phi_{rad} = \iint_S \phi_{rad}\ dS \tag{2}$$

$$\Phi_{tan} = \iint_S \phi_{tan}\ dS \tag{3}$$

$$\Phi_{sub} = \iint_S \phi_{sub}\ dS = \iint_S \phi_{rad}\ dS + \iint_S \phi_{tan}\ dS \tag{4}$$

Since the radial components (ϕ_{rad}) [and thus, their integrated sum (Φ_{rad})] exert no torque on the nucleus, the SYORP model only considers the net tangential component of the sublimative momentum flux (ϕ_{tan}) integrated over the surface of the nucleus (Φ_{tan}).

SYORP formalism modifies the YORP treatment presented in Rossi et al. (2009) for sublimative processes, resulting in a description of the average instantaneous magnitude of a comet nucleus's sublimative angular acceleration, normalized by instantaneous sublimative momentum flux at zero solar zenith angle

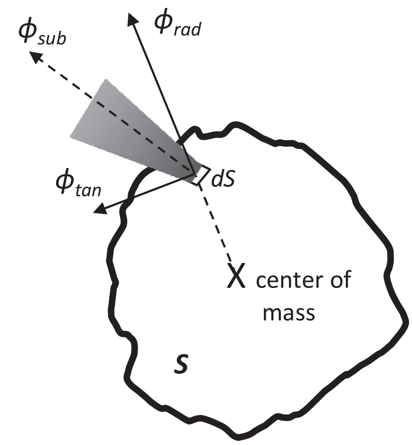

Fig. 1. *SYORP divides sublimative momentum flux into components.* The reaction force of sublimating gas molecules on a cometary surface results due to momentum flux (ϕ_{sub}) from each area element (dS) that is actively sublimating. This momentum flux can be split into radial (ϕ_{rad}) and tangential (ϕ_{tan}) components relative to the center of mass of the nucleus, of which only the tangential component exerts a torque on the body. The reaction forces are in the opposite sense to the momentum fluxes shown.

$$\overline{\left|\frac{d\omega}{dt}\right|} = \frac{3fP_SC_S}{4\pi\rho R_n^2} \tag{5}$$

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 dimensionless SYORP coefficient, which accounts for orbitally averaged asymmetries in the emission of sublimating gas molecules from the nucleus (Steckloff and Jacobson, 2016). The SYORP coefficient is analogous to a body's YORP coefficient (C_Y) (see Rossi et al., 2009) in that it accounts for asymmetries in the shape of a body (Steckloff and Jacobson, 2016). Although one could integrate over the surface of a sublimating object to determine the net torque (the sum of the torques generated by each surface element of the nucleus; e.g., Nieshtadt et al., 2003; Keller et al., 2015; Hirabayashi et al., 2016a), the SYORP model parameterizes these high-resolution details into a single coefficient that accounts for the average magnitude of the net torque acting on a comet nucleus over secular timescales (rather than instantaneous timescales).

The formulation of SYORP presented in Steckloff and Jacobson (2016) assumes that thermally primitive comets (e.g., dynamically new and dynamically young comets) have not built up a significant refractory (e.g., dusty) surface layer, resulting in ices exposed all over the surface ($f = 1$). This assumption does not hold for JFCs, which are thermally evolved comets with both active and inactive (non-sublimating) areas. Nevertheless, the SYORP effect still accounts for inactive regions of the nucleus through its SYORP coefficient.[3] Therefore, the SYORP coefficient (C_S) can be more accurately thought of as the fraction of a nucleus' total sublimative momentum flux that generates a net sublimative torque. Although the SYORP model was developed assuming negligible outgassing from the unilluminated side of the comet, the SYORP coefficient can account for some night-side outgassing, so long as the illuminated hemisphere dominates the comet's overall gas flux. If we define $\langle\phi_{sub}\rangle$ as the average net sublimative momentum flux and $\langle\phi_{tan}\rangle$

[2] Eq. (1) is a rearrangement of the formalism presented in Samarasinha and Mueller (2013).

[3] This has no analogy in the YORP effect because the entire surface can reradiate thermal photons.