Sublimative Torques as the Origin of Bilobate Comets

by

Taylor K. Safrit

Submitted to the Department of Earth, Atmospheric and Planetary Sciences

in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Earth, Atmospheric and Planetary Sciences

at the Massachusetts Institute of Technology

May 18, 2018 [June 2018]

Copyright 2017 Taylor K. Safrit. All rights reserved.

The author hereby grants to MIT permission to reproduce and to
distribute publicly paper and electronic copies of this thesis
document in whole or in part in any medium now known or
hereafter created.

Signature redacted

Department of Earth, Atmospheric and Planetary Sciences
May 18, 2018

Certified by

Signature redacted

Amanda S. Bosh
Thesis Supervisor

Accepted by

Signature redacted

Richard P. Binzel
Chair, Committee on Undergraduate Program
Sublimative Torques as the Origin of Bilobate Comets

Abstract

About 70 percent of observed cometary nuclei are bilobate (made up of two masses of material connected by a narrow neck)\(^1\)\(^\text{-}^7\). In contrast, only 10–20 percent of similarly-sized asteroids are contact binaries or bilobate\(^8\), suggesting that some process unique to comets is responsible for the formation of bilobate shapes. We examine a new mechanism for creating bilobate nuclei in Jupiter-family comets (JFCs), in which sublimative torques acting on a comet during its migration through the Centaur region spin the nucleus up to disruption, after which it may reform in a bilobate shape. We find that JFCs smaller than approximately 100 kilometers in radius should experience enough torque from carbon monoxide and carbon dioxide sublimation over their dynamical evolution through the Centaur region to be restructured into bilobate shapes. This suggests that the observed bilobate distribution of comet shapes could be the result of cometary evolution, rather than a feature of primordial cometary reservoirs.
**Background**

Comets in the Solar System can be broadly distributed into two groups: long-period and short-period comets. Long-period comets, which have periods longer than about 200 years, typically originate in the Oort cloud, a large roughly spherical shell extending from \( \sim 1,000 \) to \( \sim 100,000 \) AU from the Sun. Oort cloud comets have a uniform inclination distribution, and are therefore also referred to as isotropic comets. Short-period comets, which have periods shorter than 200 years, typically originate in the scattered disk, a flattened, toroidal region of highly elliptical orbits beyond Neptune. Scattered disk objects (SDOs) have a relatively small inclination distribution with orbital inclinations no greater than around 40° from the ecliptic plane; they are also referred to as ecliptic comets. Small dynamical perturbations with Neptune cause SDOs to leak into the giant planet region of the Solar System on timescales typically on the order of 1 billion years. There, they are reclassified as Centaurs, ecliptic comets with semi-major axes between those of Jupiter and Neptune. Through strong gravitational interactions with the giant planets, Centaurs rapidly dynamically evolve until they are either ejected from the Solar System or perturbed into the inner Solar System—inside the orbit of Jupiter—over timescales on the order of 1–10 million years. Once Centaurs have semi-major axes smaller than Jupiter’s, they are reclassified as Jupiter-family comets (JFCs).

In this region, Jupiter is the most important dynamical influence on comets’ further evolution. This influence can be quantified with the Tisserand parameter, a quasi-conserved quantity that measures the relative velocity between a comet and Jupiter during close encounters. The Tisserand parameter of a comet \( T \) is given by the
equation \( v_{rel} = v_{jup} \sqrt{3 - T} \) where \( v_{jup} \) is the velocity of Jupiter around the Sun and \( v_{rel} \) is the relative velocity between the comet and Jupiter. Comets with Tisserand parameters between 2 and 3 are classified as JFCs, as they are mainly on Jupiter-crossing orbits which are dynamically dominated by the presence of the planet.

JFCs are particularly compelling targets for spacecraft missions because they are relatively easy to study in situ. Their low inclinations and short orbital periods (on the order of 6 years) allow spacecraft missions to be planned in advance and launched on relatively modest rockets. The recent ESA Rosetta mission that orbited and landed the Philae probe on comet 67P/Churyumov-Gerasimenko (67P/C-G) is a successful example of such an endeavor. Earlier missions to JFCs include Deep Space 1, which visited comet 19P/Borrelly; Stardust, which visited comets 81P/Wild and 9P/Tempel; and Deep Impact, which visited comets 9P/Tempel and 103P/Hartley.

<table>
<thead>
<tr>
<th>Comet</th>
<th>Bilobate?</th>
<th>Dimensions (km)</th>
<th>a (AU)</th>
<th>P (years)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>67P/C-G</td>
<td>Yes</td>
<td>4.3 x 2.6 x 2.1</td>
<td>3.5</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>103P/Hartley</td>
<td>Yes</td>
<td>0.6 (mean radius)</td>
<td>3.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>8P/Tuttle</td>
<td>Yes</td>
<td>3.1 (mean radius)</td>
<td>5.7</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>19P/Borrelly</td>
<td>Yes</td>
<td>8 x 4 x 4</td>
<td>3.6</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>1P/Halley</td>
<td>Yes</td>
<td>15.3 x 7.2 x 7.2</td>
<td>17.8</td>
<td>75.5</td>
<td>Isotropic comet</td>
</tr>
<tr>
<td>81P/Wild</td>
<td>No</td>
<td>1.7 x 2 x 2.8</td>
<td>3.5</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>9P/Tempel</td>
<td>No</td>
<td>2.8 (mean radius)</td>
<td>3.1</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comets with constrained shapes and their orbital properties.
Comets 8P/Tuttle and 1P/Halley are not classified as JFCs, but rather as Halley-family comets: highly thermally and dynamically evolved isotropic comets. 8P/Tuttle was observed as bilobate by the Arecibo radio telescope; the rest of these nuclei were observed by spacecraft. While detailed three-dimensional shape models do not exist for 19P/Borrelly and 1P/Halley, spacecraft observations suggest that they have bilobate shapes. Comets 81P/Wild and 9P/Tempel are JFCs that are not observed to be bilobate (each has an oblate nucleus that is not considered elongated).
Nearly all comet nuclei with known shapes have been observed to be bilobate; that is, they appear to consist of two distinct masses of material joined by a relatively narrow neck. Of the seven comets we have direct shape data for, five appear bilobate (see Table 1)\(^1\)-\(^7\). In comparison, only 10–20 percent of asteroids are observed to be contact binaries or bilobate\(^8\). This suggests that there must be some mechanism by which Jupiter-family comets become bilobate or are created bilobate that does not affect asteroids even with similar orbits to affected JFCs.

The large fraction of bilobate nuclei raises the question of whether JFC nuclei have bilobate shapes in the scattered disk or evolve this shape over their dynamical migrations. Hirabayashi et al. (2016) showed that once comets become bilobate, they remain bilobate so long as the ratio of volumes of the lobes is greater than 0.2. For systems that meet this condition, subsequent torqueing that spins up and breaks the nucleus into two masses results in a gravitationally bound system that guarantees the two lobes shall eventually reaccrete and reconfigure into a new bilobate shape\(^10\).

However, available resources constrain our ability to make observations in order to determine when comets become bilobate: we cannot generally reach high enough spatial resolution to infer the shapes of most objects currently in the scattered disk. (At 40 AU from the Earth, a 10-kilometer object is around 350 microarcseconds wide, which would require a telescope of diameter 400 meters to overcome the diffraction limit on resolution at visible wavelengths). Therefore, we cannot draw a sample of shapes of primordial comets from any available data. Instead, we turn our attention towards pathways for comets to become bilobate over their dynamical evolutions, under the assumption that they begin life as single-nucleus bodies.
There are several current theories for the process of becoming bilobate. Sierks et al. (2015) suggest that differential sublimation creating preferential erosion around the neck of these comets might erode the bodies into the shapes we see today. However, we do not expect to see preferential sublimation anywhere on a comet: sublimative torques change cometary rotation states over time; thus, sunlight should not remain focused on one location for long enough to create this kind of bilobate shape.

Jutzi and Asphaug (2015) model the mechanism of two single-lobed comets accreting together into a single bilobate object. This is unlikely to be the case for all nuclei as this process is not dynamically favorable: it requires mutual impact velocities of no more than a few meters per second, whereas objects in the scattered disk tend to have mutual impact velocities between 1–2 kilometers per second, exceeding this mechanism’s survival threshold by several orders of magnitude.

In light of this, Schwartz et al. (2018) and Jutzi and Benz (2017) suggest that impacts by small impactors into larger cometary nuclei could form bilobate comets while preserving cometary volatiles. Schwartz et al.’s dynamic simulations show that, in the case of catastrophic impacts, conditions can be favorable for the body reforming with a bilobate shape. These favorable conditions exist for mutual impact velocities from 20 meters per second to one kilometer per second. In the upper limit, mutual impact velocity is comparable to the lower end of typical scattered disk mutual impact velocities, and could plausibly explain bilobate formation for an individual object. However, it is unlikely that the entire population of observed bilobate comets underwent collisions at impact velocities well below the mean for the scattered disk.
Thus, catastrophic or subcatastrophic collisions are not likely to be the driving mechanism behind the bilobate shape distribution observed for evolved comets.

Instead, the prevalence of bilobate shapes among evolved comets suggests that there is some universal underlying formation mechanism. All cometary nuclei are sublimating volatiles, which should create a small net torque so long as the nucleus has an assymetrical shape\(^\text{16}\). Sánchez and Scheeres (2016) show that objects torqued to angular velocities high enough to break apart can reform in bilobate shapes if their tensile strength and internal friction angles are \(1-10\) Pa and \(35^\circ\) respectively\(^{17}\), which match up well with cometary materials\(^{10}\). We postulate that volatile sublimation on Centaurs may be sufficiently active to lead to a spin-up of the body over the evolutionary lifetime of a short-period comet. We investigate whether this could be enough to spin comets up beyond their material or gravitational strengths.

The sublimation of volatiles from the surface of an object creates a sublimative reaction pressure on the object\(^{10,16,18-20}\). This pressure, in turn, can create a sublimative torque if the object has an irregular shape. Steckloff and Jacobson model this process as analogous to the YORP\(^*\) effect, in which thermal photons asymmetrically emitted from planetary surfaces cause a slight torque on their parent bodies\(^{18,21,22}\). Using Steckloff and Jacobson's terminology, we will refer to the sublimative torquing of cometary bodies as the Sublimation-YORP effect (SYORP).

The resulting rotation state changes in a Centaur or comet nucleus can create significant internal stresses. If the rotational angular velocity of its nucleus exceeds

\(^{1}\) Yarkovsky–O'Keefe–Radzievskii–Paddack; coined by Rubincam (2000).
some critical angular velocity at which internal stresses exceed material or gravitational cohesion, a Centaur will break apart. A disrupted Centaur can reform in a bilobate shape: Sanchez and Scheeres (2016; 2018) showed that the disruption and subsequent evolution of an object with the material properties of a typical cometary nucleus (internal friction angle of around 35° and tensile strength of around 1–10 Pa) can result in the formation of a bilobate shape.

We developed a numerical model to determine whether sublimation during the dynamical migration of a typical Centaur could be sufficient to spin up its nucleus beyond this critical angular velocity, allowing the disrupted nucleus to reform in a bilobate shape.
Methods

We modeled Centaur nuclei as spheres of pure ice with albedos low enough to effectively absorb all incoming radiation. Observed JFC nuclei have very low Bond albedos (0.03–0.06), meaning that 94-97% of all incident radiation is absorbed\(^{25,26}\). We approximated these low albedos as 0, which will introduce negligible errors in our results.

We set up our model as a statement of conservation of energy; we assumed that a sublimating gas is in thermal equilibrium with its source ice and that all energy from incident radiation goes towards overcoming the ice’s latent heat of sublimation, as in Steckloff et al. (2015)\(^{21}\). In order to determine the appropriate temperature \( T \) at each distance \( r \), we solved this energy balance between incoming and outgoing intensity. In the following equations, we balanced the sum of \( I_{\text{sub}} \), the fraction of the incoming radiation that contributes to sublimation, and \( I_{\text{rad}} \), the fraction that goes to heating the material, with \( I_{\text{solar}} \) and solved at each radius \( r \):

\[
I_{\text{solar}} = \frac{L_{\text{solar}}}{4\pi r^2}
\]

\[
I_{\text{rad}} = 4\sigma T^4
\]

\[
I_{\text{sub}} = \frac{\lambda}{m_{\text{mol}}} \left( \frac{m_{\text{mol}}}{2\pi RT} \right)^\frac{1}{2} P_{\text{ref}} e^{\frac{\lambda}{P_{\text{ref}}}(T_{\text{ref}} - T)}
\]

\[
I_{\text{lost}} = I_{\text{rad}} + I_{\text{sub}}
\]

where \( r \) is the heliocentric distance of the material, \( \lambda \) is the material’s latent heat of sublimation, \( m_{\text{mol}} \) is the molar mass of the material, and \( L_{\text{solar}} \) and \( R \) are the Sun’s luminosity and the ideal gas constant, respectively. \( P_{\text{ref}} \) is an experimentally
determined reference vapor pressure at reference temperature $T_{ref}$; this will allow us to
calculate the pressure at other temperatures. We chose appropriate values for each
volatile used in our model\textsuperscript{27}, shown in Table 2 below.

<table>
<thead>
<tr>
<th>Volatile</th>
<th>$\lambda$ (J/mol)</th>
<th>$m_{mol}$ (kg/mol)</th>
<th>$P_{ref}$ (Pa)</th>
<th>$T_{ref}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>6720</td>
<td>0.028</td>
<td>$3.45 \cdot 10^6$</td>
<td>132.572</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>27200</td>
<td>0.044</td>
<td>$4.21 \cdot 10^{-2}$</td>
<td>102.5</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>56200</td>
<td>0.018</td>
<td>$1.97 \cdot 10^{-2}$</td>
<td>187.02</td>
</tr>
</tbody>
</table>

Table 2: Volatiles used and their properties.

For our simulation, we used carbon monoxide, carbon dioxide, and water as volatiles
being sublimated from the surface of Centaurs. To first order, a molecule’s volatility is
determined by and inversely related to its latent heat of sublimation $\lambda$. Carbon
monoxide is around 3 times more volatile than carbon dioxide by this metric; carbon
dioxide is twice as volatile as water. These are the most relevant volatiles sublimating
in the Centaur region.

When sublimation is vigorous, the amount of energy overcoming latent heat of
sublimation dominates the amount lost through emission of thermal photons. Thus, we
can approximate the sublimation pressure as a function of heliocentric distance for
each of CO, CO\textsubscript{2}, and H\textsubscript{2}O according to the following equation:

$$P_{sub} = \frac{2}{3} \left(1 - A\right) \frac{L_{solar}}{4\pi r^2 \lambda} \left(\frac{8RT}{\pi m_{mol}}\right)^{\frac{1}{2}} \cos \phi$$

where $A$ is the Bond albedo of the material and $\phi$ is the position of the material relative
to the object’s subsolar point. This result is shown in Figure 1.
Figure 1: Dynamic sublimation pressure as a function of heliocentric distance.

We plot the dynamic sublimation pressure against heliocentric distance for CO, CO$_2$, and H$_2$O. CO-derived sublimation pressure is significantly greater than radiation pressure for any heliocentric distance relevant to our simulation; were this not the case, we would expect YORP effects to dominate over any SYORP effects. CO$_2$ falls off more rapidly but is still relevant over most of the Solar System. H$_2$O is not relevant at these heliocentric distances.
Steckloff and Jacobson give the angular acceleration associated with this sublimation pressure\textsuperscript{18} by:

$$\frac{d\omega}{dt} = \frac{3P_{\text{sub}}C_s}{4\pi\rho r^2}$$

where $\rho$ is the density of the material, $r$ is the radius of the object, and $C_s$ is a shape-dependent coefficient that represents the fraction of spin- and orbit-averaged sublimative momentum flux which contributes to torque as a result of shape asymmetry. We took $C_s$ to be on the order of $10^{-3}$ or $10^{-2}$ for typical asteroid shapes and surface roughnesses\textsuperscript{28,29}, and made the assumption that these shapes, to first-order approximation, are representative of comet nuclei\textsuperscript{19}.

We graphically determined the time spent in bins of 1 AU heliocentric radii by Jupiter-crossing bodies using a plot produced by Ramon Brasser and David Minton (private communication; reproduced below). Data were extracted from this plot manually, introducing a small uncertainty into our calculations associated with the pixel size of the plot.
Figure 2: Mean time spent in 1 AU bins for dynamically evolving objects. We reproduce Brasser and Minton's plot from a simulation of objects evolving through the outer Solar System. This represents the average time spent in each bin by all Jupiter-crossing objects from that simulation; these can be thought of as SDOs moving through the Centaur region before coming under the dynamical influence of Jupiter and being reclassified as JFCs.
To find the final angular velocity of the object, we summed the velocities acquired at each heliocentric distance given by multiplying the time spent at the distance by the angular acceleration at that distance:

$$\omega_{final} = \sum \frac{d\omega}{dt} \cdot dt$$

With this method, we assume that spin state changes are cumulative over the dynamical evolution of a Centaur, and therefore we are interested only in time spent at each heliocentric distance rather than a precise map of a typical Centaur’s orbits.

We compared this angular velocity to critical angular velocities for breakup in both strength- and gravity-dominated regimes. In the strength-dominated regime, the critical angular velocity is given by:

$$\omega_{crit} = \left(\frac{2\sigma_t}{\rho r^2}\right)^{\frac{1}{2}}$$

where $r$ is the radius of the object, $\sigma_t$ is the tensile material strength and $\rho$ is the material density. For cometary nuclei, we assumed a tensile strength on the order of 10 Pa, consistent with a rubble pile bound by Van der Waals forces \textsuperscript{30}.

In the gravity-dominated regime, the critical angular velocity is given by:

$$\omega_{grav} = \left(\frac{4\pi \rho G}{3}\right)^{\frac{1}{2}}$$

where $G$ is the universal gravitational constant. Note that the gravity-dominated critical velocity $\omega_{grav}$ does not depend on the size of the object, while the strength-dominated critical velocity $\omega_{crit}$ does.
All calculations were carried out in Python using the numpy module; plots were created using the pyplot module. We provide the code used to create this model in the appendix.

Our result was produced by comparison of our computed final angular velocities to the critical angular velocity of objects in both the strength- and gravity-dominated regimes as a function of object radius.
Results

We produced the following plot of final angular velocity versus object radius:

![Plot of angular velocity versus object radius](#)

**Figure 3: Accrued angular velocity as a function of object radius.**
We plot the angular velocity accrued over the dynamical lifetime of Centaurs, which depends on the Centaur's radius, for each of CO$_2$ and CO. As we see in Figure 1, CO produces more sublimative pressure, so objects sublimating CO experience larger torques than those sublimating CO$_2$. In reality, Centaurs should be sublimating some combination of multiple volatiles. We find that Centaurs sublimating CO under 125 km in radius should be torqued enough over their evolutions to break apart: for Centaurs sublimating only CO$_2$, this radius is 65 km.
Our calculations revealed a critical point for each volatile where the sublimative-torque angular velocity intersects the critical angular velocity. Carbon monoxide produces greater sublimative torques than carbon dioxide, so the effects of CO sublimation dominates over CO2 in comets where both are active volatiles.

Objects with radii under the critical point should spin up during their dynamical evolution to angular velocities large enough to cause breakup; after breakup, conditions are favorable for such bodies to reform in bilobate shapes.

We expect cometary bodies with radii larger than approximately 100 kilometers to have large enough moments of inertia to prevent SYORP torques from spinning these bodies up beyond their gravitational strengths due to SYORP torques; we would therefore expect a JFC with radius greater than 100 kilometers not to be bilobate. We expect smaller bodies to typically undergo enough sublimative torqueing as to spin up, fragment, and reform in bilobate shapes. Our idealizing assumptions (that cometary nuclei are spheres of pure volatile ice with zero albedo) mean that we have calculated an upper limit on the final angular velocity that can be reached via our sublimative torquing process, so this result should be treated as an upper bound on the radius cutoff point between bilobate and non-bilobate shapes in JFCs.
Discussion

The major implication of our result—that Centaurs with radii smaller than approximately 100 kilometers should become bilobate as they migrate inwards—is testable with future observations of Jupiter-family comets.

While the distribution of observed cometary shapes is skewed towards the bilobate, it is not unimodal; we have observed two evolved comets which are not bilobate. We offer two potential explanations for this discrepancy.

First, SYORP is inherently a stochastic process; a Centaur could be spun up or spun down by SYORP torques depending on its actively sublimating sites. Indeed, small changes in cometary active regions and shape can change the magnitude and direction of sublimative torques. Thus, SYORP could feasibly be alternately spinning some Centaurs up and down, while maintaining rotation rates far below the critical threshold. Accounting for these stochastic processes may allow some nuclei to survive the bilobate formation process, and could reduce the critical threshold, below which comets become bilobate. Nevertheless, our calculated 100-kilometer critical radius is over an order of magnitude larger than any observed JFC, suggesting that this result should be generally robust for these observed sizes.

Additionally, Hirabayashi et al. (2016) calculate a volume ratio lower limit for bilobate objects as 0.2; that is, bilobate objects that form with lobe-lobe volume ratios less than 0.2 will not be gravitationally bound if their nucleus spins apart due to SYORP torques\textsuperscript{10}. Thus, if Centaur spins up and forms a bilobate nucleus with a lobe-lobe volume ratio smaller than 0.2, subsequent rotational disruption will cause the lobes to drift apart, forming two independent comet nuclei. Each individual nucleus could then
begin experiencing independent SYORP torques; as a result of the additional step of splitting, we would expect to see longer timescales for these nuclei becoming bilobate than for comets that do not experience splitting. Bodies that undergo splitting are more likely to remain spherical while they are in the Centaur region.

This could help to potentially explain the existence of a few split comets, such as 3D/Biela, which was observed to split into two distinct objects in 1846 before disappearing (presumed disintegrated). If Biela was a bilobate comet with lobes having a volume ratio of less than 0.2, subsequent torqueing could have split Biela into a gravitationally unbound system, at which point it would have separated into the two visually distinct objects. A few such systems exist; recent observations have revealed another split comet candidate in comets 252P and BA14. More generally, Chen and Jewitt (1994) predict a splitting rate of cometary nuclei of 0.01 per comet per year. Sublimative torqueing could be the mechanism by which this splitting occurs.

It is worthwhile to explore the possibility of observing a joint breakup and bilobate reformation event. Such an observation would provide very strong evidence that the bilobate cometary population is a result of torqueing beyond material strengths. The probability that a given observation of a Centaur coincides with a breakup and reformation event is vanishingly small, however: a typical event takes on order seconds, while comets spend order 1-10 million years in the Centaur region.

In the event that a telescope were to observe such an event, we would expect it to be somewhat challenging to classify as a breakup. A Centaur breaking apart would increase the surface area of the object and likely be accompanied by a strong release
of volatiles, both of which should create a brightening of the object’s light curve not unlike a typical Centaur outburst

Observational data show bilobate shapes in comets, but not generally in asteroids. However, many binary asteroids have been observed, while no binary comets are known to exist. This discrepancy can be potentially attributed to multiple phenomena. It is possible that there is simply a strong observational bias that results from more easily being able to resolve asteroid shapes from ground-based light curves; the nuclei of comets are obscured by their comas while they are near periapse and too far for telescopes to observe well while they are near apoapse, so current technological limits require us to physically visit comets in order to determine their shapes with high precision. If there were indeed a large binary comet population, it is possible that it would simply be currently hidden from our instruments.

On the other hand, if there is no hidden population of binary comets, this discrepancy might be satisfactorily explained by the SYORP torquing that we examine above. Binary asteroids are formed when an asteroid rotates rapidly enough for material to be rotationally shed from the equator before collecting into a small moon. These systems evolve by the interaction of the two bodies, as their dynamical characteristics cause such systems to become tidally locked and damped out over time. A proposed pathway for this evolution is a form of YORP called Binary-YORP (BYORP). In sublimating objects, we expect to see a similar phenomenon; SYORP forces acting between a binary sublimating pair should significantly influence the

---

1 We do not consider split comets to be binary, as they are likely to be the gravitationally unbound result of cometary breakup.
evolution of the system. Since sublimation pressures are generally much stronger than radiation pressures, we expect that a binary SYORP should be much stronger than BYORP. This could account for observations of binary asteroids being much more common than binary comets. Favorable conditions that could produce a stable equilibrium within a binary system would potentially have to fall in a much narrower range for comets than for asteroids; cometary systems would likely either be aggregated together (perhaps into a bilobate comet) or drift apart on short timescales.

It is reasonable to ask whether our observations of bilobate Jupiter-family comets and our calculations of SYORP forces allow us to make a conjecture about SDO shapes. SDOs could have significantly different shapes than JFCs due to SYORP acting on the latter over their dynamical evolutions: if a roughly spherical SDO or Centaur is able to spin up past its material strength and break apart, it is unlikely to reform with a roughly spherical shape. However, when an already-bilobate SDO or Centaur is torqued by SYORP, the “neck” or connection between the two lobes will likely serve as a weak point at which breakup will first occur. This should effectively decouple the spin rates of the two lobes, and reduce the SYORP torque on both; we expect this to result in cometary reformation with a similarly bilobate shape\textsuperscript{10}. We will not therefore attempt to make the immediate conjecture that SDOs are not already bilobate; we can say that SYORP is a pathway to objects either becoming or remaining bilobate, regardless of their initial shapes. Further development of observational technology is still needed to properly constrain SDO shapes. Direct observations of an SDO, such as the New Horizons spacecraft’s 2019 encounter with the potentially
bilobate or binary object 2014 MU69, will be useful in making further conjectures about shape distributions in the scattered disk\textsuperscript{36,37}.

Further work will include performing a more rigorous analysis of SYORP torques on Centaurs using simulations of cometary dynamical evolution run by David Nesvorny (private communication). These simulations will provide us with individual dynamical paths for a large number of Centaurs that migrate into the JFC population (rather than the aggregated data that we are working with currently). With this data, we will be able to perform statistical analyses which could produce some insight into the origin of the observed non-bilobate evolved comets and allow us to make conjectures about the distribution of cometary shapes in the scattered disk and Centaur regions.
Conclusion

Our results show that there is a pathway for Centaurs to become bilobate as they evolve into the inner solar system. Torques caused by the sublimation of volatiles from the surface of a body are large enough to increase the angular velocity of the body beyond a critical angular velocity. This critical velocity is dependent on either the material or gravitational strength of the body; the SYORP torque is dependent on the characteristics of the sublimating volatile and the size of the body. Modeling for Centaurs, we find that Centaurs smaller than about 100 kilometers sublimating carbon monoxide and carbon dioxide should be able to be broken apart by these SYORP torques. As these Centaurs migrate inwards through the outer Solar System before being reclassified as JFCs, they can spin apart and reform in bilobate shapes through SYORP. We propose this mechanism as an explanation of the shape distribution of observed JFCs, which is strongly skewed towards bilobate shapes.
References


doi:10.2458/azu_uapress_9780816532131-ch009


