FISSION AND RECONFIGURATION OF BILOBATE COMETS REVEALED BY 67P/C-G Daniel J. Scheeres[1], Toshi Hirabayashi[2,*], Steve Chesley[3], Simone Marchi[4], Jay McMahon[1], Jordan Steckloff[2], Stefano Mottola[5], Shantanu P. Naidu[3], Tim Bowling[6], [1]University of Colorado at Boulder, [2]Purdue University, [3]Jet Propulsion Laboratory, California Institute of Technology, [4]Southwest Research Institute, [5]German Aerospace Center (DLR), [6]University of Chicago; *thirabayashi@purdue.edu

Abstract: This paper shows that sublimation torques induced fast rotation of 67P that formed the observed cracks in its neck, and that fast spin periods can fission 67P, but that its separated components would be unable to mutually escape, leading to a new configuration due to another low-velocity merger. Other observed bilobate nuclei have volume ratios between their components consistent with being trapped in a similar cycle. Thus, this rotational fission and reconfiguration process is likely a dominant structural evolution process for short-period comet nuclei.

Introduction: The spin period of 67P was observed to decrease by 0.36 hours across its 2009 perihelion passage, down to 12.4 hours [1], indicating that significant changes in a spin rate can occur over short time periods. On the brittle surface of the nucleus [1, 2], two straight cracks are aligned along the neck, separated by 750 m, and appear to be inactive [1]. El-Maarry et al. [3] hypothesized that they might result from orbital-induced or tidal-line forces although this hypothesis has not been quantitatively tested.

We propose that they were formed during a period of past rapid rotation. To investigate this hypothesis we employed elastic and plastic Finite Element Models (FEMs). An OSIRIS shape model publicly available [4] was used, and the total mass was fixed at 1.0×10^{13} kg [1]. Also, we assume the material to be uniformly distributed and the bulk density to be 535 kg/m3 [5].

Dynamical and structural evolution of the nucleus of 67P: To investigate the structure of the nucleus of 67P, we employed FEMs on ANSYS Academic APDL 15.03. We used the elastic model by Hirabayashi and Scheeres [6] to consider the formation of cracks on the neck. The plastic FEM by Hirabayashi and Scheeres [7] was also performed to obtain the final failure types.

Our elastic analysis confirmed that tensile stress peaks appear at the locations of the observed cracks at shorter spin periods (Figure 1). At a spin period shorter than 9 hours, the locations of the peak stresses are the same as those of the observed cracks. The direction of the maximum principal stress is perpendicular to the crack planes, implying that the cracks are of open-type.

We also identified three failure types of the nucleus (Figure 2). Type I occurs at a spin period longer than $\sim$ 9 hours. Compression may cause failure around the neck surface while the interior does not reach the yield. Type II represents tensional failure appearing on the northern side of the neck at spin periods between $\sim$ 7 and $\sim$ 9 hours. However, since gravity is still predominant, the southern side can support the neck structure. In Type III, since centrifugal force exceeds gravitational force at spin periods shorter than $\sim$ 7 hours, the failure region spreads over the majority of the neck.

Our model shows that a Type I failure does not occur unless the cohesive strength is much smaller than the reported compressive strength, which is on the order of kPa [2]. In Type III, because of the existing cracks on the neck surface, stress concentration at their tips causes propagation of failure across the entire neck.

Based on these considerations, we conclude that a Type II failure resulted in the formation of the observed cracks. Figure 2 describes the upper and lower bounds cohesive strength for the nucleus to keep the original shape. Because of the existing craters, we also found that the bulk cohesive strength is between $\sim$ 10 and $\sim$ 200 Pa (Figure 2), consistent with earlier studies [8].

Once the spin period reaches the 7-hour limit, the body should fission. Computing the system energy of such a fissioned system, we found that at the 7-hour split limit, the system has a negative total energy and is, therefore, Hill Stable, which prevents the two lobes from escaping one another [9]. This would lead them to enter a period of orbiting and re-impacting at speeds less than escape speed ($\sim$ 1 m/s), which would preserve the nature of the lobes [10].

The above discussion raises a question of how the spin period could have exceeded 9 hours in the past without transitioning beyond the 7-hour limit during its current configuration. To analyze this problem, we used the recent observation that shows the nucleus spin acceleration to be correlated to normal emission from its surface, appropriately scaled by the incident sunlight [11]. This allows the application of computational techniques from the YORP effect [12] to a prediction of the spin acceleration of the nucleus as a function of the subsolar latitude at perihelion.

Since sublimation pressure strongly varies with heliocentric distance, the spin acceleration of the 67P nucleus primarily occurs near perihelion [11]. To assess past evolution of the spin period, we integrated 1000 clones for 5000-years by using uncertainties proportional to current orbital uncertainties. This adopted time scale is compatible with the activity lifetime of typical JFCs, $\sim 10^3$ years, which is much shorter than their $\sim 4 \times 10^5$ year dynamical lifetime [13].

Our model showed that the sub-solar latitude at perihelion is uniformly distributed between -40 and $+40$ degrees at heliocentric distances between 2 and 5 AU over a 1000-year activity lifetime (Figure 3). Therefore, this randomization allows the nucleus to pass into and out of the interval between 7 and 9 hours, forestalling spin fission. For a longer timespan, this randomization also allows the nucleus to have experienced previous cycles of the nucleus reconfiguration. Since the orbit of 67P is typical among short-period comets, it is reasonable for them to experience a similar evolution cycle.

Volume ratios of observed bilobate nuclei: We consider a volume ratio of the small lobe to the large lobe of observed bilobate nuclei. For a volume ratio higher than ~ 0.2, the total energy of these systems will be negative after fission, leading them to be subject to a period of bound evolution similar to rubble pile asteroids [14], during which additional sublimation effects could further erode or spin up the individual lobes prior to re-impact. We computed the volume ratios of bilobate cometary nuclei 1P/Halley, 8P/Tuttle, 19P/Borrelly, 67P and 100P/Hartley 2 and found that all of these nuclei had a volume ratio higher than 0.2. Observed nuclei with a single component structure may either be primordial or may have been part of a multi-component nucleus, from which smaller components are more easily shed.

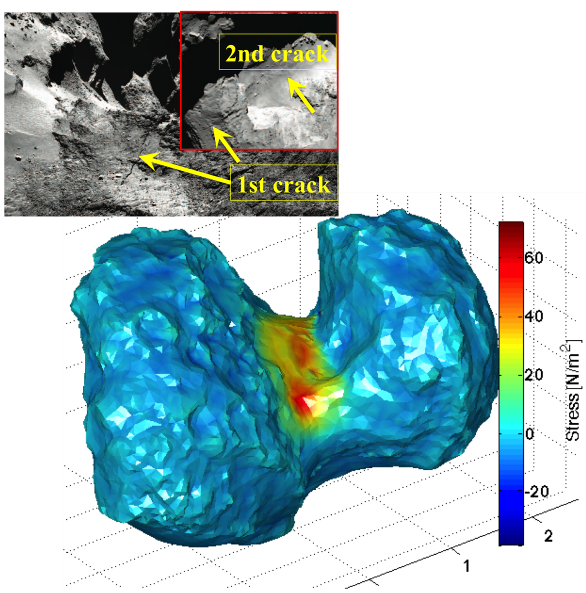

Figure 1: Elastic stress solution at a spin period of 9 hours. The plot shows the maximum component of the principal stress. The locations of the stress peaks are the same as those of the observed cracks. The images on the top are from Sierks et al. [1].

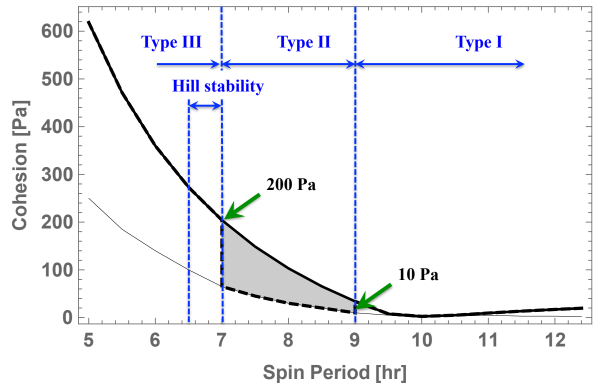

Figure 2: Failure types and conditions at different spin periods.The thicker and normal lines indicate the upper and lower bounds of the cohesive strength. The gray region is a possible region of the cohesive strength.

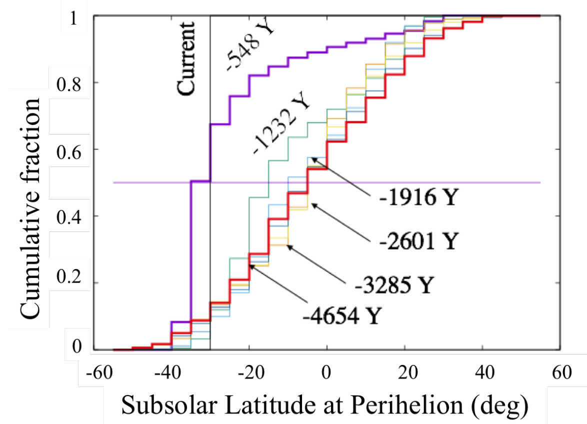

Figure 3: Cumulative fraction of the subsolar latitude of the 67P nucleus.

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Table 1: Volume ratios of bilobate cometary nucleus

Comet	Volume ratio q	Ref.
1P/Halley	0.30	[15]
8P/Tuttle	0.47	[16]
19P/Borrelly	0.22	[17]
67P/Churyumov-Gerasimenko	0.58	[1]
103P/Hartley 2	0.32	[18]