CONSTRAINTS ON THE PAST SPIN RATE OF COMET 67P/C-G. D.J. Scheeres[1], M. Hirabayashi[2], S.R. Chesley[3], J.W. McMahon[1] and S. Marchi[4] [1]University of Colorado, Department of Aerospace Engineering Sciences, Boulder, Colorado 80309-0429, scheeres@colorado.edu, [2]Purdue University, West Lafayette, Indiana 47907, [3]Jet Propulsion Laboratory / Caltech, Pasadena, California 99190, [4]SwRI-Boulder, Boulder, Colorado 80302.

Introduction: In a recent study [1], the target of the Rosetta mission, Comet 67P/Churyumov-Gerasimenko, was found to have structural features consistent with a past period of fast rotation, which would have formed the large cracks in its neck (Hapi) region. In that paper the existence of this past fast rotation state was justified by noting that the evolved spin state of the 67P nucleus should evolve chaotically, driven by the sub-solar latitude at perihelion being sensitive to distance flybys of Jupiter which alter the orbital angles. In the current computation we test this theory by evaluating the statistics of likely past spin states of the nucleus, and show that many of them have the nucleus spinning rapidly enough to have formed the observed cracks in its neck region within the last 5000 years. The results, which depend on precision numerical integrations of the comet's orbit backward in time, are tested against a purely random evolution of the spin state and are shown to give a statistically significant preference to sufficiently fast spin rates in the last 5000 years.

Theory: Based on detailed tracking of the 67P spin state it was determined that the outgassing torques acting on the comet nucleus are driven by the insolation and orientation of the nucleus surface [2]. In [1] it was noted that this predicts a nucleus torque similar to the YORP effect, yet being most relevant at perihelion. This suggests a simple model for the rotational evolution of the nucleus, with its spin rate being modified at each perihelion passage based on the sub-solar latitude, which influences the strength and sign of the torque (see Fig. 1).

It was also noted that the sub-solar latitude at perihelion is very sensitive to the heliocentric orbit angles of longitude of the ascending node, argument of perihelion, inclination and true anomaly, and that these shift significantly with every flyby of Jupiter, even if this is a distant flyby. As comet orbits vary chaotically, it is also expected that the orbit angles, and hence sub-solar latitude, should also vary chaotically over time. In [1] this was shown using a set of 1000 Monte Carlo backward integrations of the 67P heliocentric orbit for 5000 years, showing that the perihelion radius and sub-solar latitude at perihelion became uniformly distributed for these populations in less than this timescale (Fig. 1).

Computation: In the current contribution we additionally model the evolution of the comet nucleus spin rate, applying our YORP-based approximate model. To do this we track each trajectory and, whenever it passes through perihelion, the sub-solar latitude at perihelion is computed and an impulsive change in the nucleus spin rate is applied, using an equation that scales with heliocentric radius and with our computed relative intensity as a function of sub-solar latitude at perihelion (both scaling parameters are defined in Fig. 1). To get the proper magnitude of the spin rate change, we define a scaling parameter that matches the change in spin rate that occurred over the previous apparition, and use that same factor [4].

The Monte Carlo runs used current ephemeris uncertainties for comet 67P based on the Rosetta mission arrival state, with a second set of runs using 10 times the uncertainties. These uncertainties also accounted for the uncertainties in the outgassing-induced migration of the orbit. The Monte Carlo runs went back in time for 5000 years using a specially prepared ephemeris that has been extensively used for such historical studies. The state was documented at 100-day timesteps with all close approaches to Jupiter handled carefully. Across this sample none of the states brought the orbit close enough to Jupiter to cause significant tidal stresses or changes to the rotation pole. There are several assumptions in this calculation.

1. We assume that the comet nucleus inertial spin pole remains fixed, while in reality it is changed by outgassing torques and by very close Jupiter flybys. However, changing this term will not change the chaotic nature of the evolution.
2. We assume that the nucleus mass and moment of inertia remains constant backwards in time, although they both should ideally increase as mass is lost forwards in time. This makes the computed spin rate changes larger than might be expected, but again does not influence the chaotic evolution.
3. The torque computation is based on an impulsive assumption evaluated at perihelion. A more precise approach will be considered in the future that integrates the spin rate change as a function of true anomaly, which should average the spin rate change and lessen it, but again not affect the chaotic evolution.
4. The number of virtual comets integrated is modest at 884 and 1000. Future studies will explore greater number of samples and convergence tests.

Results: In the computations we tracked the spin rate of 67P, looking for instances when it would cross through a zero-spin rate, reach a spin period of 9 hours at which the crack can start to form, and reach a spin period of 7 hours at which the head and body should separate, indicating a reconfiguration as detailed in [1]. When a nucleus either crossed the zero-spin rate or 7-hour spin period limit, we no longer evolved the nucleus spin rate due to a lack of an acceptable theory for how the nucleus would respond to an extremely slow spin rate or to a fission event.

The results are shown in Table 1. We find a statistically significant number of cases reaching the 9-hour spin period, necessary for the crack to form as hypothesized in [1]. A further fraction of these also have exceeded the fission spin rate, indicating a relatively high probability that the current configuration is recent. We also find that quite few of the runs reach a zero-spin rate, indicating that this was unlikely in the past. The fact that the number of cases crossing the 9 and 7 hour barriers increase as we decrease uncertainties also indicates that the current state has a higher probability of having had such a fast spin rate.

To test the current runs against a truly random variation, we also implemented a "stochastic" version of the code that does not use the numerically integrated trajectories but instead implements random walk variations in the orbit angles and perihelion – based on the statistical variations seen from the numerical integration cases. This test shows very different behavior, with the most likely outcome being passage though the zero spin state, due to the initial conditions being at a sub-solar latitude that leads to a decreasing spin rate backwards in time. This shows that there is a significant time correlation for the dynamically integrated spin rate results over the 5000-year timespan considered.

Next Steps: We plan to rerun these backwards tests using a longer time span, and include forward integrations as well to produce predictions of future spin states. We also plan to modify the nucleus mass and moment of inertia, and to develop a more precise computation of torque that is integrated through an entire perihelion passage. As noted previously, none of these should markedly affect the chaotic evolution of the spin state, but may moderate the change in spin rate, potentially increasing the time between the current state and past fast rotation states. Of special interest will be whether the systematic outcomes found for the current computations remain.

Conclusions: We develop a statistical model for the past spin rate of 67P, implementing the model developed in [1]. Based on this model we find it likely that the nucleus was spinning at rates fast enough to form its characteristic crack within the last 5000 years. These statistics get significantly more likely when the initial uncertainties are decreased, indicating that this outcome is close to the nominal orbit that the comet inhabits, indicating increased probability. Future studies will be performed, enhancing and refining the model and methodology used herein.

References: [1] Hirabayashi et al. *Nature* 534, 352-355 (2016). [2] Keller et al. *A&A* 579, L5 (2015). [3] Marsden et al. *AJ* 78, 211-225 (1973). [4] Jorda et al. *Icarus* 277, 257-278 (2016).

Acknowledgements: This work was supported in part by grants from JPL and from NASA's SSERVI institute.

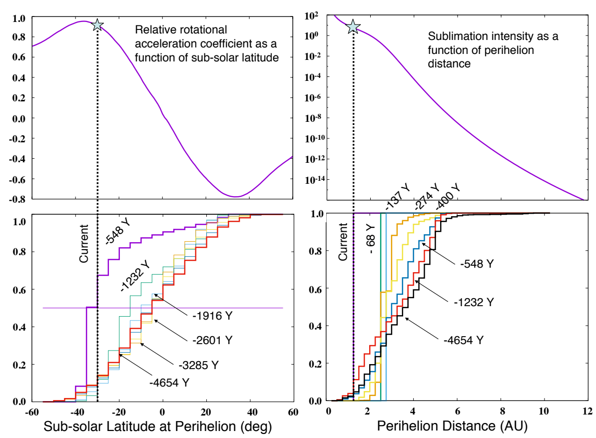

Figure 1: Plot taken from [1] showing: Top left outgassing torque intensity predicted from YORP-based theory as a function of sub-solar latitude at perihelion, and used for computing nucleus torques. Bottom left: Sub-solar latitude distribution for 1000 MC runs as a function of time, showing randomization after less than 5000 years. Top right: Relative intensity of outgassing as a function of heliocentric distance, taken from [3]. Bottom right: Perihelion radius distribution as before.

Case	9 hr	7 hr	0 rate	# Draws
Nominal Uncertainties	45%	35%	3%	884
10 times Uncertainties	35%	25%	4%	1000
Stochastic Simulation	10%	10%	30%	1000

Table 1: Compilation of results of the spin rate evolution for the different cases considered.