END OF LIFE SCENARIOS FOR SMALL RUBBLE PILE ASTEROIDS. D.J. Scheeres, *U. Colorado, Boulder (scheeres@colorado.edu)*.

Recent theory and observations have shown that rubble pile asteroids may have a small but significant level of cohesion holding their components together, on the order of 100 Pa. One significant implication of this, among others, is that rubble pile bodies less than a certain size subject to the YORP effect will have finite lifetimes in the solar system before they become disaggregated into their individual components due to repeated fission. This occurs for bodies small enough such that their fission spin rate exceeds the escape spin rate, meaning that they undergo abrupt escape after fission. We provide explicit predictions of the possible lifetime of small rubble pile asteroids as a function of their cohesive strength and will discuss the possible implications of this at the conference.

Introduction The physical lifetime of asteroids pose a complex, difficult and diverse set of questions that vary as a function of the size of these bodies. Classical theory has identified collisions and gravitational interactions with planets as the main driver of asteroids, and this remains true for larger bodies. However, as the size of the asteroids considered becomes smaller, non-gravitational effects come into play. In addition to effects that change orbits, it is also now realized that there are effects that control and shape the physical evolution of asteroids. Most significant among these is the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect that causes smaller asteroid to spin-up over time, potentially bringing their spin rates to extremes that can cause a rubble pile asteroid to fission and enter a multiple-component stage of its evolution. It has been shown that YORP spin-up and fission can directly compete with and dominate over collisions as a transformative physical evolution in the main belt at sizes of a few kilometers [1]. This leads to a markedly different type of physical transformation as compared with collisional impacts.

For larger asteroids subject to YORP, rotational fission leads to the creation of unstable multiple-component asteroid systems which undergo a chaotic dynamical evolution. There are a number of different outcomes that can emerge from such interactions, some of which are summarized in Jacobson and Scheeres [2]. The lifetimes of objects that emerge from rotational fission are complex, and can go through a number of iterations before landing into a stable state such as the BYORP-Tide equilibria for binary objects [3,4]. Over time, however the size of a rubble pile may decrease through repetition of evolutionary cycles, collisions, or planetary flybys. As this occurs, the recent theory and observations that have shown that rubble pile bodies can have a weak level of cohesion begins to become important [5,6,7,8]. As the size of a weakly cohesive rubble pile decreases, the spin rate at which this body will fission increases. At some point the spin rate can become so great that the components of the fissioned body may immediately escape, without undergoing further interactions. Once this size limit is reached, the physical evolution of a rubble pile can enter a new phase where it undergoes such fissions with abrupt escapes at increasing rates, rendering a rubble pile body into its component pieces in a finite time. This abstract presents the physics of this final phase of a rubble pile's life and provides a range of estimates for its duration.

An overview of the effect follows. For a rubble pile body with a given level of cohesion, its maximum spin rate is inversely proportional to the body diameter. Thus, every time a rubble pile body is split into smaller components, the resulting bodies can spin proportionally faster before it can shed or fission again. In contrast, the YORP effect's spin acceleration is inversely proportional to the body diameter squared. Thus, the time it takes for the components of a fissioned body to spin up to its new fission limit is proportional to the body diameter squared and takes proportionally less time to achieve their next fission. If a body fissions into N components, the new effective diameters of the components will equal $N^{-1/3}$ times their initial diameter. Thus, if we assume that a fissioned component is immediately accelerated to its next fission rate, the total time for a rubble pile to completely fission is a convergent power series, and can be shown to be equal to the initial YORP time scale of the starting, initial rubble pile. This total time can be extended by an order of magnitude if a fissioned body is initially rotationally decelerated. It may also be extended if its post-fission tumbling state slows its YORP rotational acceleration.

This abstract outlines recent research and predictions for the likely lifetimes of small rubble pile asteroids. Direct comparisons are made between the competing effects of YORP acceleration, dissipation of a complex rotation state back to uniform rotation, and the number of components that a body may split into. We find that, based on recent constraints placed on the μQ values of rubble pile bodies, the relaxation time back to uniform rotation should be short compared to the time to be accelerated to its next fission spin rate. Ultimately, we find that the lifetime of a rubble pile once less than ∼500 meters in diameter at 1AU can be as low as 0.4 MY, but not faster than this in general. At the extreme other end of the spectrum, if a rubble pile is always subject to a deceleration its lifetime can be extended by an order of magnitude.

Spin Limits for Abrupt Escape For a rubble pile with a given level of cohesion, σ, the nominal failure rate of the body is a combination of overcoming gravitational attraction and cohesion. The general expression for the spin rate at which fission will occur is of the form $\omega_F^2 \sim \omega_\rho^2 + \frac{\sigma}{\rho R^2}$, where ω_ρ is the spin rate at which a cohesionless rubble pile will begin to deform and potentially fission, ρ is the density of the body and R is its radius [5]. Note that $\omega_\rho^2 \sim 4\pi\mathcal{G}\rho/3$, where $\mathcal{G}$ is the gravitational constant and is nominally independent of size (although it does have a shape dependence). Thus, for a small enough rubble pile the spin rate for fission is dominated by the cohesion term and is $\omega_F \sim \sqrt{\frac{\sigma}{\rho}}\frac{1}{R}$, where we note that recent theory and observational constraints indicate that the level of cohesive strength is of the order $\sigma \sim 100$ Pa [A,B,C]. Given this dependence, at a small enough body size the failure spin rate will be great enough such that when the components separate they will immediately escape and not undergo the complex dynamical evolution that occurs at lower spin rates. Figure 1 shows the size at which such an abrupt escape occurs for different strength levels.

Assuming mass conservations across such a fission event, we can develop a rule for relating the size of the new asteroids with the prior asteroid. If the body breaks into N distinct and roughly equal components then on average $NR_{i+1}^3 = R_i^3$. This leads to the size of a body at the $(i+1)$th fission as a function of the initial body size when such abrupt fission started: $R_{i+1} = \left(\frac{1}{N^{1/3}}\right)^{i+1} R_0$. Then the change in angular velocity from one fission event to the next can be characterized as: $\Delta\omega_{i+1,i} = \sqrt{\frac{\sigma}{\rho}}\left[\frac{1}{R_{i+1}} \mp \frac{1}{R_i}\right]$. The $-$ sign occurs if the body undergoes rotational acceleration in the same direction, and the $+$ if it first decelerates and goes through zero.

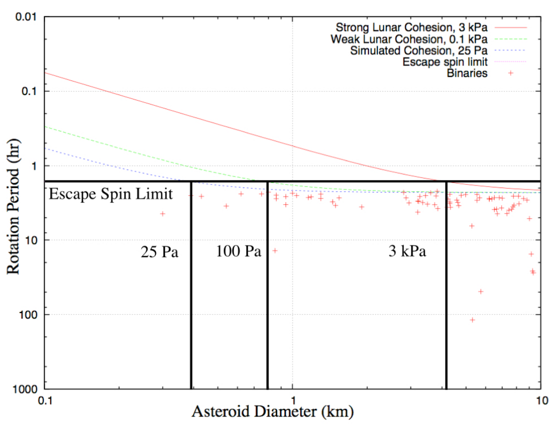

Figure 1: Rubble pile escape spin limit as a function of cohesive strength (from [5]).

YORP Timescales The YORP effect has been extensively studied, especially for uniform rotators. Thus we simply state the general form of the spin rate

$$\dot{\omega} \sim \frac{3\Phi}{4\pi A^2\sqrt{1-E^2}}\frac{\mathcal{C}}{\rho R^2}$$

where $\mathcal{C} \sim 0.001 \rightarrow 0.01$ is a non-dimensional constant that is a function of the shape of an asteroidal body [9]. The parameter Φ is the radiation constant and A is the orbit semi-major axis and E the eccentricity. The timescale of significance here is the the time it takes a body to fission into components of size R_{i+1} at an initial spin rate of $\omega_{F,i}$. This is computed as $\Delta\omega/\dot{\omega}$, and is

$$T_{i+1,i} \sim \frac{4\pi A^2\sqrt{1-E^2}}{3\Phi}\frac{\sqrt{\sigma\rho}}{\mathcal{C}}\left[1 \mp \frac{1}{N^{1/3}}\right] R_{i+1}$$

Relaxation Timescales One prediction of an abrupt escape is that the component bodies will immediately start to tumble, due to the conservation of the body spin vector across a breakup and the immediate mis-alignment of this spin vector from the principle moments of inertia of the body. While extensive study of the YORP effect on a tumbling body has not been made, it is believed that the YORP spin-up effect will be less significant for a tumbling body. Thus, the relaxation time of a body is important to consider. Taking the classical analysis found in Harris [10] and comparing the relaxation timescale to the YORP timescale at 1 AU for the range of possible values outlined above we find that their ratio goes from $\tau_R/\tau_Y \sim 1\times 10^{-5} \rightarrow 0.3$. The lower limit is computed using the newly estimated μQ values for a small, rubble pile binary asteroid made by Scheirich et al. [4], while the upper bound uses the conservative upper constraint found in Margot et al. [11]. Thus we note that the relaxation time appears to be short with respect to the YORP time, meaning that this phase can be ignored in our subsequent computations.

Putting it together: Rubble Pile Lifetimes Given the above model and results we can compute a bound on the total lifetime of a rubble pile body by summing all the times $T_{i+1,i}$, as these will be a convergent power series.

$$\sum_{i=0}^{\infty} T_{i,i+1} \sim \frac{4\pi A^2}{3\Phi}\frac{\sqrt{\sigma\rho}}{\mathcal{C}}\frac{\left[1 \mp \frac{1}{N^{1/3}}\right]}{\left[1 - \frac{1}{N^{1/3}}\right]} R_0$$

We add to this the initial YORP timescale of a body of size R_0 to be accelerated from rest to its failure spin rate, calculated to be $\frac{4\pi A^2}{3\Phi}\frac{\sqrt{\sigma\rho}}{\mathcal{C}} R_0$ which is remarkably equal to the summation chosen with the "-" sign.

Note that if YORP directly accelerates the body to the next fission event, the sum is independent of the parameter N and equals twice the YORP timescale of a body of radius R_0 to achieve its cohesive fission spin rate. If the body is decelerated each time and must pass through a "0" spin rate the total lifetime is lengthened and becomes a function of N.

Taking some nominal / conservative values of $A = 1.5 \times 10^{11}$ m (1 AU), $\Phi = 1 \times 10^{17}$ kg-m/s^2, $\rho = 3000$ kg/m^3, $R_0 \sim 250$ m, $N = 4$, we find the following results. If the body starts at a size of R_0 with no spin and is consistently spun-up to the next fission event without passing through zero, the ultimate time scale ranges from $0.8 \rightarrow 8$ MY for the range of YORP strengths used here. Instead, if the body undergoes a reversal in its spin acceleration the time scale is prolonged, almost by a factor of 5 for $N = 4$, but decreasing as N increases, yielding $3.5 \rightarrow 35$ My. Of ultimate interest is to compare these estimated lifetimes with the measured cosmic-ray exposure ages of meteorites, to better understand the timescale of physical evolution of the parent bodies of meteorites [12].

References: [1]: Marzari et al., Icarus 214: 622-631 (2011). [2]: Jacobson & Scheeres, Icarus 214: 161-178 (2011). [3]: Jacobson and Scheeres, ApJL 736:L19 (2011). [4]: Scheirich et al., Icarus 245: 56-63 (2015). [5]: Sánchez and Scheeres, MAPS 49(5): 788-811 (2014). [6]: Hirabayashi et al., ApJL 789:L12 (2014). [7]: Rozitis et al., Nature 512: 174-176 (2014). [8]: Hirabayashi & Scheeres, ApJL 798:L8 (2015). [9]: Scheeres, Icarus 188: 430-450 (2007). [10]: Harris, Icarus 107: 209-211 (1994). [11]: Margot et al., Science 296: 1445-1448 (2002). [12]: Herzog, in Radioactive Geochronology, Chapter 1 (2011).