THE FORMATION OF Q-TYPE ASTEROIDS FROM YORP SPIN-UP AND FISSION

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Introduction Q-type asteroids are the best spectral match to many ordinary chondrites and have very similar spectra to S-type asteroids. The difference between the S-type and Q-type spectra is that S-types have a darker, redder spectra with shallower absorption bands. These differences are believed to be formed by space weathering, in which solar wind and micrometeorites interact with the asteroid's surface [1]. Since any space weathering would only affect the surface grains, any near global overturn or removal of the surface material of an S-type asteroid would turn it into a Q-type. Additionally, space weathering will work to steadily change any Q-types back to S-types over a certain timescale. Thus, there must be some "resetting" mechanism acting in the NEA region that competes against space weathering to create the approximate 4:1 ratio of S-types to Q-types.

There have been a number of Q-type formation mechanisms proposed [2–5]. It has been shown that impacts between asteroids are not frequent enough to explain the number of Q-types observed, except for small asteroids in closely packed asteroid clusters and families in the main belt [6]. YORP induced spin-up and fission has been suggested as a formation mechanism for few Q-type asteroids that have been found in newly formed asteroid pairs in the main belt [7]. The favored formation mechanism for the large number of Q-types found in the NEA region is that tides raised during close encounters with the terrestrial planets cause landslides that can overturn the surface of the asteroid [4, 8].

Recently, DeMeo et al. [8] conducted a large number of observations and discovered many new Q-type asteroids in the NEA region, shown in Figure 1. They concluded that the tidal mechanism could still explain all Q-types in the NEA region if close encounters with Mars were considered. We used these new data, but instead used a different method, very similar to Nesvorný et al. [4], to analyze the past histories of these asteroids. We found that there were $\sim$15 Q-type asteroids that have a very low probability of ever having had a close encounter with any planet in the last million years.

In addition, we note that there are at least 7 identified binary Q-type asteroids in the NEA region, suggesting that they have had a fissioning event prior to the last close planetary encounter. Thus, there are some asteroids in the NEA region that were most likely formed by YORP spin-up and fission. We built a Monte Carlo simulation to test if most or all Q-type NEAs could be created by YORP spin-up and fission.

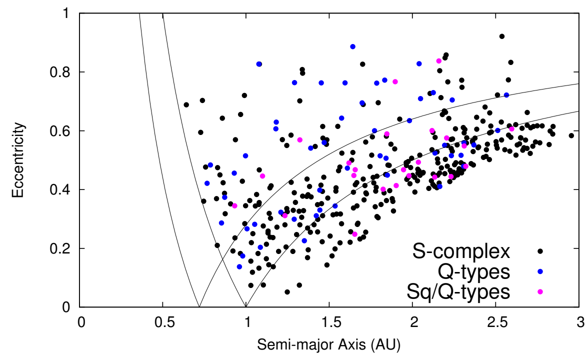

Figure 1: The orbits of all identified S-complex asteroids in the NEA region. Q-types and those with spectra on the boundary between Q-types and Sq-types, called Sq/Q-types, are highlighted.

Orbital Histories We investigated the past orbital positions of these objects using the SWIFTER rmvs integrator [9], and recorded any encounters with a terrestrial planet within 50 planetary radii. We created 100 clones of each asteroid by spreading out their orbital elements in a normal distribution with the covariances taken from the matrices on the JPL Small Body Database [10], and integrated every clone backwards in time for 1 Myr.

In Figure 2, we show examples of 4 Q-type asteroids who have a very low percentage of clones having an encounter with any planet in the last million years. Most of these Q-types with low encounter probabilities are from newer observations, and were classified as those that could only have encounters with Mars [8]. While it could be argued that the limitations of the backwards integrations could account for a few of these asteroids, the larger number are at odds with the explanation that they were created by close encounters with planets.

Binary Populations Using the JPL Small Body Database and the database, "Binary NEAs Detected by Radar" [11], maintained by Lance Benner, we find that 7 out of 23 (30%) S-complex binary asteroids are positively identified as Q-types. While still affected by small number statistics, it is clear that Q-types are present in the binary population with a fraction that is at least similar, if not greater, than the 20% of Q-types in overall NEA S-complex population [8]. Since any close encounter with a planet would much more readily disrupt the binary than reset the surface of either asteroid, we can conclude that the last major event that occurred to

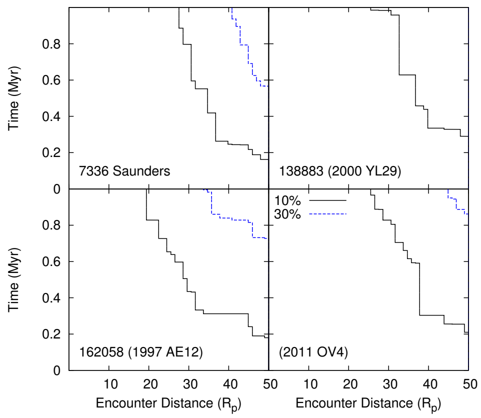

Figure 2: Four of the Q-type asteroids with low encounter probabilities with any planet throughout the last million years. Each point on the line represents the percent of clones that have had an encounter within that distance by that time.

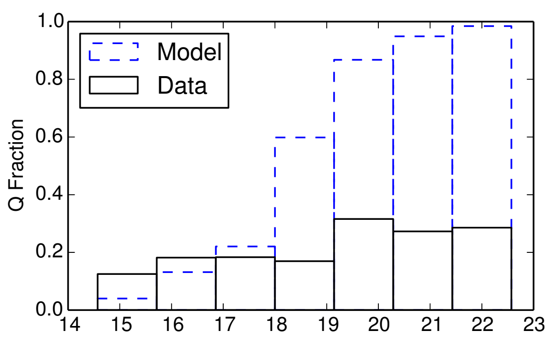

Figure 3: Histograms of the fraction of Q-types of S-complex asteroids in the NEA population and derived from our model.

the surface of these bodies was related to binary formation or evolution.

YORP fission is believed to be the formation mechanism for binary asteroids and pairs [12]. Also, Polishook et al. [7] showed that pair formation can form Q-types, the most reasonable mechanism to create these binary Q-types asteroids is YORP fission.

YORP Fission Model Using a Monte Carlo model, we explored the hypothesis that all Q-types, not just binaries, could be formed from YORP spin-up and fission. We began with a population of 10^4 asteroids with a Maxwellian spin distribution centered on 4.82 rev/day, and with a size frequency distribution matching that of the NEA population [13, 14]. We selected a non-dimensional YORP coefficient from a flat distribution of reasonable values [15], and fixed a 15 Myr, replacing removed asteroids with new ones. We also chose a timescale (T_{SW}) at 1 AU for the space weathering to take a fresh Q-type and make it *no longer* a Q-type. There are a range of values for this timescale calculated both from observations and experiments (e.g. [16]), but we settled on 30 kyr as a best estimate. This is shorter compared to many other estimates because T_{SW} is often chosen to be the timescale to take a fresh Q-type and weather it completely, rather than simply move out of the Q-type class.

In each step of our model, we accelerate the spin rate by YORP [13, 15], and weather each asteroid. Both processes scale with the amount of solar irradiance the asteroids experience at their current orbit [5]. Thus, we should not expect an orbital dependence in our data. Finally, if the asteroid is at or above the spin barrier, we reverse the YORP acceleration and reset the weathering.

With these assumptions, this model predicts that the majority of the asteroids in the NEA population should be Q-types. Figure 3 shows the fraction of Q-types in the population vs the Absolute Magnitude. The model matches well at lower magnitudes, but grossly overpredicts the number of Q-types at high magnitudes. This over-prediction may be due to the lack of "Stochastic YORP" in our model, in which the spin rates of bodies are not uniformly changed, but can vary stochastically due to the large effect of small topography changes on the YORP parameter [17]. Stochastic YORP can potentially have a size dependence because of the difference in the relative size of the asteroid and the boulders that could move around and change the YORP parameter, meaning that small asteroids would take longer to spin-up to disruption than you would otherwise predict.

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