FRESH SURFACES ON Q-TYPE ASTEROIDS:

Close Planetary Encounters Unlikely to Be the Source

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Mentors

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Abstract

The *S-type Conundrum* refers to a problem in planetary science in which Q-type asteroids, which match the spectra of the most common meteorite found on Earth, the ordinary chondrite (OC), are significantly outnumbered by S-type asteroids, whose color is weathered and reddened by comparison. The accepted solution holds that Q-type and S-type asteroids both have ordinary chondritic composition, but they have experienced a space weathering process that reddened their surfaces. This space weathering process changes the reflectance spectra of OC-composition asteroids from Q-type to S-type over an estimated timescale of about 1 million years. Collisional processes that might resurface asteroids have timescales that are much longer than this space weathering time scale, and therefore all asteroids with ordinary chondrite composition should have experienced extensive space weathering, and only weathered S-type asteroids should be observed at the present time. To explain the currently observed Q-type population, a refreshing mechanism must exist to disturb surface grains and reveal fresh, unweathered material. It has been proposed that tidal forces due to close planetary encounters may be the dominant refreshing mechanism, causing landslides and disturbing the surfaces of asteroids. The hypothesis predicts that most, if not all, Q-type asteroids have recently experienced close planetary encounters within the estimated space weathering timescale. We report that a significant fraction of Mars-crossing Q-type asteroids have not experienced close planetary encounters in the past 1 Myr, implying that other refreshing mechanisms must be active in the Mars-crossing region.

Prymek, M. (2018). Fresh surfaces on Q-type asteroids: Close planetary encounters unlikely to be the source. *Journal of Purdue Undergraduate Research*, 8, 50–56. <https://doi.org/10.5703/1288284316739>

Keywords

asteroids, close Earth encounters, planet-crossing asteroids

INTRODUCTION

Asteroids represent remnants of the early solar system, but we possess only limited means to study their composition and history. Only a few asteroids have been visited by spacecraft, and they must otherwise be studied remotely or through meteorites found on Earth. Telescopic studies of asteroid reflectance spectra measure how much sunlight their surfaces reflect as a function of wavelength and can provide insight into the composition of the surface. Asteroid taxonomy groups asteroids according to similarities in their reflectance spectra, and surveys have revealed many distinct types of asteroids. The most current classification scheme, the Bus-DeMeo taxonomy developed in 2009, defines 24 separate asteroid spectral types (DeMeo, Binzel, Slivan, & Bus, 2009). Considerable work has been invested into inferring the bulk composition and properties of different types of asteroids. However, reflectance spectroscopy only informs us about the nature of the material down to a depth on the order of the wavelength, and additional data is often limited.

While meteorites provide an opportunity to study the properties of planetary bodies in-depth in the laboratory, matching meteorites to their corresponding parent bodies in the solar system has presented significant difficulties. Meteorites have been classified into three broad descriptive categories; stony, iron, and stony-iron, composed of rocky material, metallic material, and a mixture, respectively. The majority of meteorite falls, and by inference the majority of asteroids, are classified chondrites. Composed of primarily the silicate minerals olivine and pyroxene, which also compose most of Earth's upper mantle, and metal grains, chondrites represent undifferentiated samples of the protoplanetary nebula and are some of the oldest solid material in the solar system (Weisberg, McCoy, & Krot, 2006). The study of chondritic meteorites and their parent asteroids provides insight into the early conditions and evolution of the solar system. Chondrites present a wide range of mineralogical differences, with the most common subgroup, ordinary chondrites (OC), composing 80% of meteorite falls (Binzel, Bus, Burbine, & Sunshine, 1996). While ordinary chondrites dominate meteoritic falls, only a relatively small population of asteroids with reflectance spectra that match ordinary chondrites has been observed, classified as Q-type asteroids under the current Bus-DeMeo taxonomy.

Despite the fact that ordinary chondrites are the most common meteorite found on Earth, their spectral analogues, Q-type asteroids, are not the most common near-Earth asteroid (NEA) (Binzel et al., 1996;

DeMeo et al., 2009). Instead, Q-types are substantially outnumbered by S-type asteroids, which have similar spectra but are much redder and have weaker absorption bands by comparison. This apparent mismatch between the most common meteorites and asteroids, referred to as the S-Type Conundrum, has been a problem in planetary science and meteoritics for decades (Chapman, 1996). The accepted solution holds that S-types are mineralogically similar to Q-types, but their surfaces have been altered due to exposure to the space environment. This alteration process, known as space weathering, is thought to be the result of changes in the chemistry of minerals on the surface of asteroids induced by micrometeorite impact and solar wind bombardment. Space weathering in asteroids of OC composition works to increase the spectral slope between 0.35 and 0.9 μm , reddening the surface, and to reduce the deep olivine/pyroxene absorbance bands that result from the high abundance of chondrules, changing their spectra from Q-type to S-type (Binzel et al., 2010; Gaffey, Burbine, & Binzel, 2012; Nesvorný, Jedicke, Whiteley, & Ivezić, 2005; Chapman, 1996; Dukes, Baragiola, & McFadden, 1999).

Evidence for space weathering is substantial. Surveys have revealed that asteroids exhibit a continuum of spectral signatures that fall between Q-types and S-types (Binzel et al., 1996). Additionally, a continuum of spectral signatures has been observed across the surfaces of individual asteroids that have been observed by spacecraft. Observations by the *Galileo* spacecraft during its flybys of S-type asteroids Gaspra and Ida revealed that geologic units with more Q-type-like spectra were correlated with fresher surfaces, such as those recently exposed by an impact or a landslide (Chapman, 1996). Laboratory experiments bombarding olivine with hydrogen and helium ions, replicating the influence of solar wind, have reproduced some changes in spectra consistent with space weathering (Dukes et al., 1999).

If space weathering reddens the surfaces of asteroids with OC composition and changes their spectra from Q-type to S-type, then the currently observed population of unweathered Q-type asteroids requires explanation. There must be some mechanism to refresh the surfaces of S-type asteroids and to reveal unweathered material with Q-type spectra. Hypothetically, any processes that disturb a significant portion of the surface of an asteroid may contribute to the observed population of Q-types. Large impacts with other asteroids are one such mechanism. Alternatively, Nesvorný et al. (2005) proposed that close planetary encounters are the dominant refreshing mechanism. They proposed that close

planetary encounters produce sufficient tidal stress to “reset” an asteroid’s surface, causing landslides, disturbing surface grains, and allowing unweathered surfaces to be exposed (Nesvorný et al., 2005). We refer to this as the *close planetary encounter hypothesis*. Current estimates of the necessary planetary encounter distance to induce resurfacing stand at roughly 5–10 planetary radii, depending on the characteristics of the asteroid, such as spin and internal structure (Carry, Solano, Eggl, & DeMeo, 2016; Nesvorný et al., 2005; Nesvorný, Bottke, Vokrouhlický, Chapman, & Rafkin, 2010). Comparison by Vernazza, Binzel, Rossi, Fulchignoni, and Birlan (2009) of very young asteroid families following catastrophic breakup reveals that space weathering is a rapid process, taking effect within an estimated 1 Myr (Vernazza et al., 2009). This implies that infrequent processes with long timescales, such as asteroid collisions, are unlikely to be the dominant resurfacing mechanism (Binzel et al., 1996; Nesvorný et al., 2005, 2010). The close planetary encounter hypothesis has received significant attention as an alternative mechanism.

Current studies of the orbital histories of asteroids typically employ numerical integration of n-body dynamical models. Sufficiently efficient and fast numerical integration schemes and computer hardware have only been developed in the past few decades, and have been a powerful tool in understanding the long-term behavior of chaotic orbits (Wisdom & Holman, 1991; Levison & Duncan, 1994). Using Newton’s law of gravity, the acceleration from the sum of forces on each planetary body due to the Sun and every other planetary body can be calculated or approximated, and used to “step” their positions and velocities backwards or forwards in time. Alternatively, Kepler’s laws of planetary motion may be used, with regular perturbations added to account for gravitational interactions between planetary bodies.

While many studies have produced work in support of the close planetary encounter hypothesis, we primarily examine the results of Binzel et al. (2010), “Earth Encounters as the Origin of Fresh Surfaces on Near-Earth Asteroids.” Binzel et al. (2010) used the minimum orbital intersection distance (MOID) as a proxy for the distance between two bodies. The MOID measures the closest distance between the paths of two orbits rather than the distance between the bodies themselves. A small MOID is a prerequisite for a similarly close encounter, but does not necessarily imply a close planetary encounter. The close planetary encounter hypothesis would then predict that all observed Q-type asteroids should have

experienced very small MOIDs within the estimated space weathering timescale. Using MOID as a proxy has the advantage that errors in the shape of orbits grow much more slowly than errors in the along-track positions of bodies in their orbits when numerically integrating planetary bodies back in time.

Binzel et al. (2010) numerically integrated the orbits of 95 NEAs and MCs for half a million years back in time, calculated their MOIDs every 50 years with respect to the Earth, and found the lowest MOID that each asteroid had experienced in the past half-million years. They found that, on average, the Q-type asteroids experienced a smaller minimum MOID than the S-type asteroids. In fact, all Q-type asteroids in their sample experienced MOIDs smaller than the Earth-Moon separation distance, whereas only a fraction of the S-type asteroids experienced such small MOIDs. While resurfacing due to tidal forces certainly would not occur near the Earth-Moon separation distance (~ 60 Earth radii), the distance is used as a convenient cut-off when considering “small” MOIDs. Given the low probability that all Q-types in their sample experienced such low MOIDs merely by chance, the correlation between Q-types and recent very low MOIDs is unlikely to be coincidental. The observation supports the close planetary encounter hypothesis, which predicts such a correlation. However, we propose that the observations of Binzel et al. (2010) were limited by a relatively small sample size and are not representative of the Q-type population.

METHODOLOGY

To test the hypothesis that close planetary encounters refreshed the surfaces of S-type asteroids, we sought to replicate the methods and results of the Binzel et al. (2010) study and to extend the methods to a larger sample of S-type and Q-type asteroids. To integrate the asteroid populations back in time, we used the Swifter Regularized Mixed Variable Symplectic (Swifter RMVS) integrator. Swifter RMVS was initially developed by Levison and Duncan (1994) and rewritten by David E. Kaufmann, and is capable of integrating the movements of massive planetary bodies and massless “test particles,” which feel the force of the massive planetary bodies but whose mass is negligible in comparison (Levison & Duncan, 1994). In our integrations, the test particles play the role of asteroids, whose gravitational influence on the planets is unlikely to be significant given their comparatively small total mass and short timescale considered. Symplectic integrators produce a numerical solution to Hamilton’s equations, which calculate

the rate-of-change of the position and momentum of particles in the system,

$$\dot{q} = -\frac{\partial H}{\partial p},$$

$$\dot{p} = \frac{\partial H}{\partial q},$$

where q and p are the position and momentum respectively. H is the Hamiltonian of the system, which is typically the sum of the potential and kinetic energy. In the case of Swifter RMVS, the Hamiltonian is separated into two independent terms, representing the Keplerian motion of each body and the gravitational interactions between planetary bodies respectively,

$$H = H_{\text{Kepler}} + H_{\text{interaction}}.$$

“Mixed variable” refers to the two separate coordinate systems used during integration, Sun-centric and planet-centric. In general, the Keplerian Hamiltonian is integrated, the particles moved along their heliocentric (Sun-centered) orbits, and the interactions due to other planets approximated as small “kicks” to their velocity. But this breaks down during close planetary encounters, when the interaction forces are large compared to the gravitational force of the Sun. During close encounters, planet-planet interaction is emphasized instead, and the time-step is progressively reduced or regularized, concentrating computational power where it is most needed.

For our extended sample, we use a population of 511 NEA and MC asteroids documented in the Sloan Digital Sky Survey (SDSS) and identified and classified by Carry et al. (2016), outlined in Table 1. Following Binzel et al. (2010), we produce six clones for each asteroid to account for the error inherent in numerically integrating chaotic orbits back in time and to increase the robustness of our results. Clones have the same initial position as the original asteroid, but differ in velocity by $\pm 10^{-6}$ AU/year in each Cartesian component. We integrate the asteroid populations back 1 Myr using a 3.65-day timestep, including all eight planets from Mercury to Neptune. We obtained the initial positions and velocities for all planets and asteroids using the ephemerides provided by the JPL Horizons system. We calculated the MOID every 50 years using Fortran code produced by T. Wisniewski and H. Rickman (2013) for each clone of each asteroid. Our data analysis consists of using Fortran to gather the lowest MOID values achieved during numerical integration back in time by all asteroids and their clones, and grouping the results by spectral type.

	Q-type	S-type
NEA	16	78
MC	27	390

Table 1. Breakdown of our sample of the asteroid population identified in Carry et al. (2016).

RESULTS

We first confirm the reliability of our simulation and analysis by demonstrating that we produce a similar orbital history for a given asteroid as Binzel et al. (2010) and by showing that we produce a similar correlation between Q-type asteroids and small, recent MOID. Binzel et al. (2010) plotted the integrated MOID of Q-type asteroid 1566 Icarus with respect to the Earth for the past 200 kyr to demonstrate the frequent forays into very low MOID. We compare this against our own plot of the integrated MOID of the same asteroid in Figure 1. We find the same oscillations in MOID with a period of approximately 12.5 kyr. Given the tendency for highly chaotic orbits in the near-Earth region, the very high degree of similarity between the plots suggests that our initial

Figure 1. The MOID of Q-type asteroid 1566 Icarus with respect to Earth over past 500 thousand years, with MOID calculated every 50 years. Top (a): plot reproduced from Binzel et al. (2010). Bottom (b): plot produced from our own integration. The horizontal dashed or dotted lines in either plot represent the Earth-Moon separation distance for comparison.

Figure 2. Box and whisker plot of the lowest MOID experienced by asteroids in the past 0.5 Myr during our numerical integration of the Binzel et al. (2010) asteroid population. Outliers are given by circles. We observe that the entire Q-type population sampled has experienced recent small MOIDs.

conditions and computational parameters produce adequately accurate results. The oscillating MOID, if typical of Q-types, also provides a very large number of opportunities for actual close encounters and resurfacing within the estimated space weathering timescale of 1 million years.

We summarize our results using the Binzel et al. (2010) asteroid population in Figure 2 where we have plotted the lowest MOIDs with respect to the Earth experienced by all asteroids and their clones in the past half-million years and grouped them according to their spectral type. We find that the Q-type asteroids all experienced MOID values significantly below the Earth-moon separation distance, consistent with the results of Binzel et al. (2010). While a significant fraction of the S-type asteroids also experienced small MOIDs, the mode of their lowest integrated MOIDs is nearly an order of magnitude greater than that of the Q-type asteroids. The similarity of our results to those of Binzel et al. (2010) make us confident in the accuracy of our computer simulation and data analysis, and in our ability to extend the methods to a larger population.

Figure 3 summarizes the results from our simulation using the SDSS NEA and MC asteroid sample classified by Carry et al. (2016). NEA and MC MOIDs are calculated with respect to the orbit of the Earth and Mars respectively. Binzel et al. (2010) had previously used the Earth-Moon distance as a convenient cut-off for considering “small” MOID. For consistency in comparing results, we do so as well. Additionally, because we consider interactions with Mars rather than Earth for the MC population, and because tidal forces approximately scale with planetary radius, we use the corresponding distance of 60 Mars radii for comparison with the MC population. Our results for the NEA population of our sample are consistent with those from Binzel et al. (2010). We continue to observe a clear relationship between recent small MOID and Q-type NEAs for the larger population sampled. All

Figure 3. Box and whisker plot of the lowest MOID experienced by asteroids in the past 0.5 Myr during our numerical integration of the Q-type and S-type subset of the Carry et al. (2016) asteroid sample. Outliers are given by circles.

sampled NEA Q-types have recently experienced very small MOID, in contrast to the much larger range of the lowest MOIDs experienced by the NEA S-types. From comparison of Figure 2 and Figure 3, we observe that the difference between the modes in the lowest MOIDs of the NEA Q-type and S-types is significantly smaller in our extended population than for the results obtained using the Binzel et al. (2010) population. This implies that their dynamical histories may be more similar than previously shown.

However, the correlation between Q-type asteroids and recent small MOIDs does not extend to the Mars-crossing population sampled. A significant fraction of the MC Q-types have not recently experienced small MOIDs, even if we extend our consideration as far back as 1 Myr, as shown in Figure 4. This implies that a significant fraction of the MC Q-types

Figure 4. Box and whisker plot of the lowest MOID experienced by asteroids in the past 1 Myr during our numerical integration of the Q-type and S-type subset of the Carry et al. (2016) asteroid sample. Results are nearly identical to those found using a 0.5 Myr integration.

Figure 5. Plot of the lowest MOID experienced by each asteroid from the Carry et al. (2016) asteroid sample in the past 1 Myr against the perihelion of the asteroid at the time. Q-type asteroids are plotted in blue and S-type asteroids are plotted in red. The horizontal dotted line indicates the Earth-Moon separation distance for comparison.

do not even have the potential to have had a close planetary encounter in the past 1 Myr. Given the estimated space weathering timescale of approximately 1 Myr, the close planetary encounter hypothesis does not account for the observed MC Q-type population. While these results do not exclude close planetary encounters as a resurfacing mechanism, the results imply that other mechanisms must also be active to a significant degree in Mars-crossing space.

The difference in MOID between the Q-types and S-types for the NEA and MC populations may reflect a broader trend. Figure 5 plots the lowest MOID experienced by each asteroid against its perihelion at the time. We observe that virtually all asteroids that experience a perihelion below 1 AU also experience a small MOID. As the sample of asteroids used by Binzel et al. (2010) was largely restricted to this region, this trend in MOID with perihelion may explain their results. For perihelion slightly greater than 1 and 1.5 AU, and so slightly beyond the orbits of Earth and Mars respectively, we observe frequent large MOID values. We also observe multiple Q-type asteroids in these regions with large MOID, which further motivates our conclusion that alternative resurfacing mechanisms must be active.

CONCLUSION

We have numerically integrated a population of near-Earth and Mars-crossing S-type and Q-type asteroids identified and classified by Carry et al. (2016) from

the Sloan Digital Sky Survey 1 Myr back in time. We have verified the correlation previously observed by Binzel et al. (2010) between Q-types and recent small MOIDs for near-Earth asteroids while using a significantly larger population. However, we have also shown that this correlation does not extend to Mars-crossing Q-type asteroids. The close planetary encounter hypothesis of Nesvorný et al. (2005), supported by Binzel et al. (2010), suggests that tidal disturbances due to close planetary encounters are the dominant refreshing mechanism for Q-type asteroids. The hypothesis predicts that the vast majority of Q-type asteroids should experience small minimum orbital encounter distances (MOIDs) within the estimated space weathering timescale of approximately 1 Myr (Vernazza et al., 2009). Our results for near-Earth asteroids support this prediction, but our results for Mars-crossing asteroids do not. Our results for Mars-crossing asteroids imply that close planetary encounters are not sufficient to explain the observed population of Q-type asteroids in the region, and that other refreshing mechanisms must be active to a relatively significant degree. Future modeling work will be necessary to estimate the significance of different possible mechanisms, such as disturbance of the surface due to spin-up from the YORP effect, noncatastrophic meteorite impact, or other possible mechanisms.

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