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Rotationally resolved spectroscopy of asteroid pairs: No spectral variation suggests fission is followed by settling of dust

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ABSTRACT

The fission of an asteroid due to fast rotation can expose sub-surface material that was never previously exposed to any *space weathering* process. We examine the spectral properties of *asteroid pairs* that were disrupted in the last 2 million years to examine whether the site of the fission can be revealed. We studied the possibility that the sub-surface material, perhaps on one hemisphere, has spectral characteristics differing from the original weathered surface. This was achieved by performing rotationally-resolved spectroscopic observations to look for local variations as the asteroid rotates.

We spectrally observed 11 asteroids in pairs in the near-IR and visible wavelength range. Photometric observations were also conducted to derive the asteroid lightcurves and to determine the rotational phases of the spectral observations. We do not detect any rotational spectral variations within the signal-to-noise of our measurements, which allows us to tightly constrain the extent of any existing surface heterogeneity.

For each observed spectrum of a longitudinal segment of our measured asteroids, we estimate the maximal size of an un-detected "spot" with a spectral signature different than the average. For five asteroids the maximal diameter of such a "spot" is smaller by a factor of two than the diameter of the secondary member of the asteroid. Therefore, the site of the fission is larger than any area with a unique spectral parameters. This means the site of the fission does not have a unique spectrum. In the case of an ordinary chondrite asteroid (S-complex), where the site of fission is expected to present non-weathered spectra, a lack of a fission "spot" (detectable spectroscopically) can be explained if the rotational-fission process is followed by the spread of dust that re-accumulates on the primary asteroid and covers it homogeneously. This is demonstrated for the young Asteroid 6070 that presents an Sq-type spectrum while its inner material, that is presumably revealed on the surface of its secondary member, 54827, has a non-weathered, Q-type spectrum. The spread of dust observed in the disintegration event of the Asteroid P/2013 R3, might be an example of such a process and an indication that P/2013 R3 was indeed formed in a rotational-fission event.

1. Introduction and motivation

The rotational-fission mechanism can result in mass shedding or complete disintegration of a strengthless *rubble-pile* asteroid that fails to remain bound due to an increasing rotation rate. This physical process is backed by multiple independent observations: asteroids were measured to have low density values that reflect high porosity and shattered structure (e.g. (25143) Itokawa; Fujiwara et al., 2006; Carry, 2012); asteroids were measured while spinning-up due to thermal torques from the Sun (the YORP effect; Rubincam, 2000; e.g., (54509) YORP, (1862) Apollo, (1620) Geographos, (3103) Eger; Lowry et al., 2007; Taylor et al., 2007; Kaasalainen et al., 2007; Durech et al., 2008, 2012); and asteroids were observed while **shedding** mass and even **breaking** apart (e.g. P/2010 A2, P/2013 P5, P/2013 R3; Jewitt et al., 2010, 2013, 2014).

Indirect measurements also support our understanding of the rotational-fission mechanism: (1) The lack of asteroids with $D > {\sim}100$ m that rotate faster than 2.2 h per cycle suggests that such asteroids were slowed down by mass shedding or completely disintegrated into smaller $D < {\sim}100$ m fragments (e.g., Richardson et al., 1998; Pravec and Harris, 2000; Warner et al., 2009; Jacobson et al., 2014a). (2) The physical and dynamical parameters

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of binary asteroids and asteroid pairs were shown to match the expected outcome from a rotational-fission event – mainly a correlation between a fast rotation of the primary body to other parameters in the system (e.g., Pravec et al., 2006, 2010; Walsh et al., 2008; Polishook et al., 2011; Fang and Margot, 2012; Jacobson et al., 2014b; Polishook, 2014).

This study was motivated by the idea that the fission event might reveal sub-surface material with a different spectral signature, and these would be detectable by rotationally-resolved observations of asteroid spectra. We focused our study on primary members of *asteroid pairs* that are believed to have formed recently (Vokrouhlický and Nesvorný, 2008) by a fission of a fast rotating asteroid (Pravec et al., 2010). An asteroid pair consists of two unbound objects with almost identical heliocentric orbital elements. Dynamical calculations have shown that the secondary members of each pair were in the Hill sphere of the larger member in the last 2 million years, indicating a single origin. Indeed, spectral measurements show that members of the same pair present the same spectral and color characteristics supporting a single origin of each pair (Moskovitz, 2012; Duddy et al., 2012, 2013; Polishook et al., 2014; Wolters et al., 2014). Finding an area with a unique spectral signature on primary member of an asteroid pair could not only give clues to the way asteroids disrupt but also give us unique opportunity to get a glimpse of the sub-surface material of asteroids.

1.1. Spectral variation on asteroids

The main reason to expect spectral heterogeneity on the young asteroid pairs is the *space weathering* mechanism that modifies the surface of atmosphere-less bodies by different agents such as solar radiation and micrometeorite bombardment (Chapman, 2004). This mechanism is known for maturing the spectral signature of common taxonomical types such as ordinary chondrites by increasing their spectral slope and gradually erasing their 1 μm absorption band (Clark et al., 2002). Laboratory experiments were able to reproduce S-type reflectance spectra by laser irradiation of ordinary chondrite (e.g., Moroz et al., 1996; Sasaki et al., 2001; Brunetto et al., 2006). Space weathering effects on other asteroidal types (such as carbonaceous chondrites/C-complex, achondrite/V-type) are minor as inferred from astronomical (e.g., Pieters et al., 2000; Rivkin et al., 2002) and experimental (e.g., Vernazza et al., 2013; Brunetto et al., 2014) studies. Even though it is not clear how long does it take for the space weathering to mature a spectrum of an ordinary chondrite (studies present a wide range of possible timescales ranging from a 10^5 to 10^8 years; Vernazza et al., 2009; Willman et al., 2010), it seems from dynamic calculations of near-Earth asteroids that 100,000 years is a lower limit for an asteroid to present a non-weathered, “fresh” material (Nesvorný et al., 2010). *Asteroid pairs* are especially relevant in this context since they presumably disrupted in a range of 10^4 to 2×10^6 years, therefore, sub-surface ordinary chondrite revealed by their disruption might did not have the time to mature by space weathering. Furthermore, the fact that most asteroid pairs present “non-fresh” spectral features (Polishook et al., 2014; Wolters et al., 2014) suggests that the possible fresh material on the site of the fission should be more noticeable.

Spectral heterogeneity on asteroid surfaces is known to exist from in situ measurements collected by spacecrafts such as *Galileo* and *NEAR Shoemaker*. These found “colorful” spots (areas with color differing than the average color) on craters located on Asteroid (951) Gaspra (Veverka et al., 1996), and spectral variations on the surface of Asteroid (433) Eros (Murchie and Pieters, 1996). However, measuring spectral variations from the Earth is quite challenging since the parameters of the asteroid spectrum are altered by the Earth’s atmosphere (such as the spectral slope). For example, claims for spectral variability on the young asteroid, (832) Karin (Sasaki et al., 2004) were revoked by Chapman et al. (2007) and Vernazza et al. (2007). Currently, spectral heterogeneity is clearly observed from Earth on (4) Vesta, one of the largest asteroids in the main belt (Bobrovnikoff, 1929; Gaffey, 1997), and this was supported by space-based observations (Reddy et al., 2010, 2012). The large scale heterogeneity on Vesta is probably primordial and due to compositional differences across the crust and excavation of the crust to different depths. Smaller scale heterogeneity is probably due to impacts (Le Corre et al., 2013).

Spectral heterogeneity is not limited to space weathering effects. Spectral heterogeneity was also measured in the near-IR range on near-Earth asteroids such as (101955) Bennu, (162173) 1999 JU3, (175706) 1996 FG3 and (285263) 1998 QE2 that do not present ordinary chondrite spectra. The heterogeneity in all these cases was measured at different epochs and it was suggested to be due to variations in viewing aspect (Moskovitz private communication; Sanchez et al., 2012; Reddy et al., 2012), compositional or grain-size effects (Binzel and DeMeo, 2013), thermal effects (Binzel et al., 2012), or a mere artificial cause, such as bad weather or calibration (Moskovitz et al., 2013). However, the real reason(s) for the spectral variation on these asteroids is not known.

2. Observations and reduction

2.1. Observed asteroids

Eleven asteroids were observed in this study. The candidate pair asteroids were taken from Pravec and Vokrouhlický (2009) and Vokrouhlický (2009). Excluding telescope availability, we limit target selection by a visible limiting magnitude of 18.5 and by a relatively short rotation period of <6 h in order to complete the rotational coverage in a single night. An exception is the Asteroid (54041), with a rotation period of about 18.86 h. The physical information of these asteroids is summarized in Table 1.

Eight of the asteroids were observed in near-IR range, two in the visible range, and one asteroid, (6070) *Rheinland*, was observed in both ranges.

2.2. Infrared spectroscopy

We conducted near-infrared spectroscopy (0.8 to 2.5 μm) using SpeX, an imager and spectrograph mounted on the 3-m telescope of NASA’s InfraRed Telescope Facility (IRTF; Rayner et al., 2003). A long slit with a 0.8 arcsec width was used and the objects were shifted along it in an A–B–B–A sequence to allow the measurement of the background noise. The slit was aligned to the parallactic angle. Exposures of 120 s were taken for each image. Observations were limited to low air mass values to reduce chromatic refraction that can change the spectral slope. Almost all observations (excluding those of Asteroid 4765) were taken at low phase angle of <15° in order to measure maximal area of the asteroids’ surfaces as possible and to avoid any spectral change due to increasing phase angle (*phase reddening*; Sanchez et al., 2012). Solar analog stars were observed during the night to allow the correction of telluric lines and normalization by the Sun’s spectrum. In addition, G2 to G5 stars, that were in close proximity to the asteroids, were also observed during the asteroid rotation to further calibrate each longitudinal segment of the asteroid’s reflectance spectrum separately. Lamps and arcs images were also routinely taken to calibrate the CCD sensitivity map and the dispersion solutions, respectively. The observational details are listed in Table 2. An average reflectance spectrum for each asteroid, made out of these observations were published in a previous paper (Polishook et al., 2014).