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The cool surfaces of binary near-Earth asteroids ☆

Marco Delbo[a,*], Kevin Walsh[a], Michael Mueller[a,b], Alan W. Harris[c], Ellen S. Howell[d]

[a] UNS-CNRS-Observatoire de la Côte d'Azur, Laboratoire Cassiopée, BP 4229, 06304 Nice cedex 04, France
[b] Steward Observatory, University of Arizona, 933 N Cherry Ave., Tucson, AZ 85721, USA
[c] DLR Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany
[d] Arecibo Observatory, HC3 Box 53995, Arecibo, PR 00612, USA

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ABSTRACT

Here we show results from thermal-infrared observations of km-sized binary near-Earth asteroids (NEAs). We combine previously published thermal properties for NEAs with newly derived values for three binary NEAs. The η value derived from the near-Earth asteroid thermal model (NEATM) for each object is then used to estimate an average thermal inertia for the population of binary NEAs and compared against similar estimates for the population of non-binaries. We find that these objects have, in general, surface temperatures cooler than the average values for non-binary NEAs as suggested by elevated η values. We discuss how this may be evidence of higher-than-average surface thermal inertia. This latter physical parameter is a sensitive indicator of the presence or absence of regolith: bodies covered with fine regolith, such as the Earth's moon, have low thermal inertia, whereas a surface with little or no regolith displays high thermal inertia. Our results are suggestive of a binary formation mechanism capable of altering surface properties, possibly removing regolith: an obvious candidate is the YORP effect.

We present also newly determined sizes and geometric visible albedos derived from thermal-infrared observations of three binary NEAs: (5381) Sekhmet, (153591) 2001 SN_{263}, and (164121) 2003 YT_1. The diameters of these asteroids are 1.41 ± 0.21 km, 1.56 ± 0.31 km, and 2.63 ± 0.40 km, respectively. Their albedos are 0.23 ± 0.13, 0.24 ± 0.16, and 0.048 ± 0.015, respectively.

1. Introduction

The population of known binary NEAs has grown steadily to more than 30 objects discovered by photometric lightcurves and radar observations (Pravec and Harris, 2007; Richardson and Walsh, 2006; Noll et al., 2006; Margot et al., 2002). Binary systems are uniquely interesting in that the analysis of their mutual orbits enables a determination of the elusive mass density, which in turn allows conclusions to be drawn on the bulk composition and porosity. Further information on their physical properties may be gained from studies of binary formation.

In this context, it is intriguing that the majority of these systems are found with a rapidly rotating primary, with rotation periods between 2.2 and 3.6 h, which are among the most rapid rotations found for NEAs (Pravec et al., 2006). Among all 325 NEAs with a diameter $D > 200$ m and known lightcurve period, none are observed to have periods shorter than 2.2 h (Pravec et al., 2007). For faster spin rates, surface material could reach orbital speeds.

The satellites in these systems are almost always on close orbits, between 2 and 5 primary radii, R_{pri}, and are typically found with low eccentricity, close to zero. The satellites' spin periods, where known, are typically synchronized with the orbital periods. Discoveries by lightcurve are biased to only discover satellites larger than ~20% the size of the primary body, and also are biased against finding them beyond ~10 R_{pri} (Pravec et al., 2006). Radar observations are not similarly biased, and can discover satellites out to much further distances and to much smaller sizes, but have found only a couple of such systems, namely 1998 ST_{27} and (153591) 2001 SN_{263} (Nolan et al., 2008; Becker et al., 2008; Benner et al., 2001). The general characterization of the NEA binary population presented above, with rapidly rotating primaries and close secondaries applies to ~32 of the 36 known systems.

The similarities in the observed orbital properties of binary NEAs point at a common formation mechanism. It is likely that they formed through spin-up and disruption by the YORP-effect (Yarkovsky O'Keefe Radzievskii Paddack) (Scheeres, 2007; Walsh et al., 2008). The YORP-effect works by the creation of small torques through the reflection and thermal re-emission of solar radiation from an irregularly shaped body (Rubincam, 2000; Rubincam

☆ Observations of (164121) 2003 YT_1 were obtained with the TIMMI2 at the 3.6 m telescope of the European Southern Observatory (PI G.P. Tozzi). Observations of (153591) 2001 SN_{263} and (5381) Sekhmet were obtained at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement No. NCC 5-538 with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.

* Corresponding author.
E-mail address: delbo@oca.eu (M. Delbo).

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et al., 2002). A substantially non-symmetric body can generate substantial torques (clearly represented in the cartoon in Figs. 1 and 2 in Rubincam (2000)), but even small-scale surface features are capable of producing similar torques (Statler and Aug., 2009). This effect has been shown to modify spin rates of NEAs and it has been detected for four NEAs: (54509) YORP (Taylor et al., 2007; Lowry et al., 2007), (1862) Apollo (Kaasalainen et al., 2007; Durech et al., 2008a), (1620) Geographos (Durech et al., 2008b), and (3031) Eger (Durech et al., 2009). The YORP effect can increase or decrease the spin period depending on the spin-pole orientation. The distribution of spin rates among small Main Belt Asteroids (MBAs) and NEAs shows an excess in both fast and slow rotators, which can be produced through the YORP-effect acting widely on the populations (Pravec et al., 2008).

Models of YORP-spin-up of gravitational aggregates, or "rubble piles", have reproduced the fundamental properties of observed NEA binaries: rapid primary rotation, oblate primaries, and basic secondary orbital properties (semi-major axis and eccentricity) (Walsh et al., 2008). This formation mechanism works by slowly pushing bodies towards, and then beyond, their critical spin rates. In the simulations of Walsh et al. (2008), the body takes an oblate shape, which allows ejected mass to accumulate into a satellite in a stable orbit. The simulations show that surface material on the original body is ejected and accumulated into a secondary. In tests where specific surface particles are tracked throughout the simulation (Walsh et al., 2008) found that anywhere from 15% to 30% of the surface on the primary is removed, uncovering originally sub-surface material. Those simulations consist of 1000 similar-sized or nearly similar-sized particles, which means each particle represents the large constituent pieces (boulders) of a rubble pile.

It is unclear how fine-grained surface material (regolith), which is not resolved in the (Walsh et al., 2008) simulations, responds to large-scale surface mobility. We present three plausible scenarious:

(1) The regolith is shed off the surface before any significant mass (large constituent pieces) is lost. If this is the case, then most rapidly rotating NEAs could have altered surface properties compared to other NEAs. With no satellite or large masses in orbit, it is possible that all regolith ejected off the asteroid's surface would escape from the asteroid via radiation effects on timescales faster than satellite accumulation. Theoretically this could be detected in comparisons of surface properties between all rapidly rotating NEAs against all NEAs.

(2) The regolith moves with the large pieces of the rubble pile. The surface properties change only after binary formation has begun, and significant mass has been lofted into orbit. This may also mean that the total surface alteration depends on how far into the binary-formation process the system has progressed. This could be manifested in differing surface properties for binary NEAs as compared to the rest of the NEA population, including the subset of rapidly rotating NEAs.

(3) The regolith does not move, and continues to cover the surface of the asteroid although the large constituent pieces of the body move and escape. This scenario would likely lead to no observable changes in the surface properties of the body, except for possibly uncovering younger, less weathered regolith. Potentially this could be detected via spectroscopic signatures of the new, less weathered, regolith. However, the thermal inertia and albedo of the binary systems would likely remain unchanged in comparison to non-binaries due to similar amounts of regolith covering.

Alteration of regolith on asteroids is in principle observable at the wavelengths of their thermal-infrared emission; a surface depleted of regolith has a less efficient thermal insulation than one covered with fine and thick regolith. Consequently the former has a higher surface thermal inertia than the latter.

Thermal inertia, Γ, is a measure of the resistance of a material to changes in temperature. It is defined as the square root of the product of the thermal conductivity (κ), the heat capacity (c) and the material density (ρ), i.e. $\Gamma = \sqrt{\kappa c \rho}$. Thermal inertia controls the body's diurnal temperature profile and thus affects the intensity and shape of spectral energy distribution of the body's infrared heat emission. For example, in the unrealistic case of zero thermal inertia a body has a prominent temperature peak at the subsolar point and its temperature distribution falls to zero at the terminator.

In the more realistic case of a body with finite thermal inertia and rotating with a spin vector not pointing toward the Sun, the temperature distribution is no longer symmetric with respect to the subsolar point. Each surface element behaves like a capacitor or sink for the solar energy such that the body's diurnal temperature profile becomes more smoothed out in longitude (e.g. Spencer et al., 1989; Delbo' and Harris, 2002; Delbo', 2004; Mueller, 2007). The hottest temperature during the day decreases, whereas those on the night-side do not drop to zero as in the idealistic case of zero thermal inertia, implying non-zero thermal-infrared emission from the dark side of the body. So, information about the thermal inertia of an asteroid can be obtained from the color temperature of the body: high thermal inertia causes the day side color temperature of an object to decrease compared to that of another body with a lower thermal inertia.

In this paper we will present new measurements of thermal-infrared emission for NEA binaries as well as discuss previously published data. Together the sample is significant enough to identify some basic trends that support significant surface alteration in NEA binaries as compared with other rapidly rotating NEAs and NEAs in general. In Section 2 we discuss how the surface thermal inertia of asteroids can be inferred from thermal observations, in Section 3 we present new observations, data reduction and analysis via thermal models, in Section 4 we derive the thermal inertia of the binary NEAs and we compare it with the value derived for the whole population of NEAs, finally in Section 5 we discuss how the observations relate to the YORP model of NEA binary formation.

2. Determination of asteroids' thermal inertia

The thermal inertia of the surface of an asteroid depends on regolith particle size and depth, degree of compaction, and exposure of solid rocks and boulders within the top few centimeters of the sub-surface (see e.g. Mellon et al., 2000). Knowledge of the thermal inertia of asteroids is important because its value can be used to infer the presence or absence of loose material on the surface. Lunar regolith, a layer of fragmentary incoherent rocky debris covering the surface of the Moon, has a low thermal inertia of about $\sim$50 J m^{-2} s$^{-0.5}$ K^{-1} (see e.g. Winter and Krupp, 1971; Spencer et al., 1989 and references therein). Coarse sand has a higher thermal inertia, about 400 J m^{-2} s$^{-0.5}$ K^{-1} (see e.g. Presley and Christensen, 1997b; Mellon et al., 2000; Christensen et al., 2003), whereas that of bare rock is larger than 2500 J m^{-2} s$^{-0.5}$ K^{-1} (Jakosky, 1986), and the thermal inertia of metal rich asteroidal fragments can be larger than 12,000 J m^{-2} s$^{-0.5}$ K^{-1} (Burns et al., 1979 and references therein). The correlation between increasing thermal inertia with increasing regolith grain size is observed in laboratory studies of particulate materials (see e.g. Presley and Christensen (1997a,b) for a review).

Caution must be exercised when comparing thermal-inertia values between different parts of the Solar System, since thermal inertia is temperature dependent. Heat conduction within regolith