Complex Planetary Systems
Proceedings IAU Symposium No. 310, 2014
Z. Knežević & A. Lemaitre, eds.

doi:10.1017/S1743921314008060

Trajectory and physical properties of near-Earth asteroid 2009 BD

D. Farnocchia[1], M. Mommert[2], J. L. Hora[3], S. R. Chesley[1], D. Vokrouhlický[4], D. E. Trilling[2], M. Mueller[5], A. W. Harris[6], H. A. Smith[3], and G. G. Fazio[3]

[1]Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
email: Davide.Farnocchia@jpl.nasa.gov

[2]Department of Physics and Astronomy, Northern Arizona University
Flagstaff, AZ 86011, USA

[3]Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138, USA

[4]Institute of Astronomy, Charles University
CZ-18000, Prague 8, Czech Republic

[5]SRON Netherlands Institute for Space Research
9700-AV Groningen, The Netherlands

[6]DLR Institute of Planetary Research
D-12489 Berlin, Germany

Abstract. We analyze the trajectory of near-Earth asteroid 2009 BD, which is a candidate target of the NASA Asteroid Redirect Mission. The small size of 2009 BD and its Earth-like orbit pose challenges to understanding the dynamical properties of 2009 BD. In particular, nongravitational perturbations, such as solar radiation pressure and the Yarkovsky effect, are essential to match observational data and provide reliable predictions. By using Spitzer Space Telescope IRAC observations and our model for the thermophysical properties and the nongravitational forces acting on 2009 BD we obtain probabilistic derivations of the physical properties of this object. We find two physically possible solutions. The first solution shows 2009 BD as a 2.9 ± 0.3 m diameter rocky body with an extremely high albedo that is covered with regolith-like material, causing it to exhibit a low thermal inertia. The second solution suggests 2009 BD to be a 4 ± 1 m diameter asteroid with albedo 0.45 ± 0.35 that consists of a collection of individual bare rock slabs. We are unable to rule out either solution based on physical reasoning. 2009 BD is the smallest asteroid for which physical properties have been constrained, providing unique information on the physical properties of objects in the size range smaller than 10 m.

Keywords. Radiation mechanisms: general, celestial mechanics, methods: analytical, techniques: image processing, astrometry, ephemerides, minor planets, asteroids, infrared: solar system

1. Introduction

Near-Earth asteroid 2009 BD was discovered on 2009 January 16, at a geocentric distance of 10 million kilometers (Buzzi *et al.* 2009), and it is on an Earth-like orbit.

The orbital geometry makes 2009 BD one of the asteroids with the lowest relative velocity with respect to Earth and it is thus considered a potential target for the Asteroid Redirect Mission (ARM, Mazanek *et al.* 2103). The current design of ARM requires that the target asteroid has a diameter between 7 m and 10 m, and a mass of about 500 t.

Little is known about the physical properties of 2009 BD. The absolute magnitude $H = 28.43 \pm 0.12$ (Micheli *et al.* 2012) suggests that 2009 BD is a small object, with a diameter around 10 m or less. However, the lack of albedo information prevents a more accurate estimate. Tholen *et al.* (2013) found that 2009 BD has a rotation period somewhat larger than 3 hours.

Due to its small size, indirect information on 2009 BD physical properties comes from the action of nongravitational perturbations, namely the Yarkovsky effect (Vokrouhlický *et al.* 2000) and solar radiation pressure (Vokrouhlický & Milani 2000). In this paper we combine the constraints coming from nongravitational perturbations and observations from the Spitzer Space Telescope (Werner *et al.* 2004) to estimate the physical properties of 2009 BD. For more details see Mommert *et al.* (2014).

2. The orbit of 2009 BD

The osculating orbit of 2009 BD at epoch 2010 January 4 is very close to that of the Earth. The semimajor axis is 1.01 au, the eccentricity 4%, and the inclination 0.4°. Because of its orbital configuration 2009 BD stayed in the Earth's neighborhood from 2009 to 2011 thus allowing astronomers to collect astrometric observations. Then, the Earth encounter of June 2011 changed the semimajor axis to 1.06 au and 2009 BD started drifting away from Earth to get closer again only around 2022.

Though the observed arc is quite short, nongravitational perturbations are needed in order to fit the observational data (Micheli *et al.* 2012; Farnocchia *et al.* 2013) as the small size of 2009 BD amplifies the magnitude of nongravitational perturbations, which are inversely proportional to the diameter D.

Similarly to Marsden *et al.* (1973), we modeled nongravitational perturbations as

$$\mathbf{a}_{NG} = \left(A_1 \hat{\mathbf{r}} + A_2 \hat{\mathbf{t}}\right) (1 \text{ au}/r)^2 \tag{2.1}$$

where $\hat{\mathbf{r}}$ and $\hat{\mathbf{t}}$ are the radial and transverse directions, respectively, and r is the heliocentric distance. A_2 is related to the transverse component of the Yarkovsky effect while A_1 accounts for solar radiation pressure and the radial component of the Yarkovsky effect.

We included A_1 and A_2 in the list of parameters estimated from the orbital fit and obtained $A_1 = (57 \pm 8) \times 10^{-12}$ au/d^2 and $A_2 = (-113 \pm 8) \times 10^{-14}$ au/d^2. The values of A_1 and A_2 along with their uncertainties affect the ephemeris predictions of 2009 BD and provide constraints on its physical properties. In particular, since A_2 is proportional to $\cos\gamma$, where γ is the obliquity (Farnocchia *et al.* 2013), the negative value of A_2 implies that 2009 BD is a retrograde rotator.

3. Spitzer observations

To obtain additional information on its physical properties, we observed 2009 BD starting on 2013 October 13 for a total of 25 hours with IRAC (Fazio *et al.* 2004) on the Spitzer Space Telescope. We selected the observation window according to Spitzer observability, the predicted flux density of the asteroid, and we chose the IRAC channel 2 to maximize our chances of detecting 2009 BD (Mommert *et al.* 2014).

To make sure that 2009 BD was in the field of view, we computed plane-of-sky position along with the corresponding 3σ uncertainty for different settings of the dynamical model: 1) gravitational-only solution, 2) accounting for solar radiation pressure, and 3) including both solar radiation pressure and the Yarkovsky effect. Moreover, we tested different statistical treatments of the astrometry by selecting different outlier rejection thresholds

https://doi.org/10.1017/S1743921314008060 Published online by Cambridge University Press

(Carpino *et al.* 2003). All these different predictions fell within 20" in right ascension and 2" in declination, well inside the Spitzer field of view, i.e., 312" × 312".

Though we did not detect 2009 BD in the Spitzer field of view, we derived a 0.78 μJy 3σ upper bound to the flux density. The resulting constraints on the physical properties of 2009 BD are discussed below.

4. Nongravitational perturbations and thermophysical modeling

The lack of a clear detection of 2009 BD in our observations precludes a direct determination of its physical properties. To indirectly constrain the physical properties of 2009 BD, we take a probabilistic approach that combines a thermophysical model with a model of the nongravitational effects on the asteroid's orbit.

For solar radiation pressure we adopt the model by Vokrouhlický & Milani (2000) whereas for the Yarkovsky effect we use the model approach described by Vokrouhlický *et al.* (2000). The asteroid is assumed to be spherical and the heat transfer is solved analytically using the linearized heat transfer equation. Using the dependence of solar radiation pressure and the Yarkovsky effect on the physical properties of 2009 BD, the model derives bulk density ρ and thermal inertia Γ as a function of γ, and D as a result of the fit to the available astrometric data.

The thermophysical model approximates the surface temperature distribution to determine the thermal-infrared emission from the surface as a function of the physical properties of 2009 BD, e.g., rotation state, thermal inertia, and surface roughness. We assume a spherical shape of 2009 BD, i.e., the derived diameter is the one of a sphere with the same cross-sectional area as the real shape of 2009 BD. The model numerically solves the heat transfer equation and computes the IRAC channel 2 in-band flux density. The contribution from reflected solar light is added to the calculated flux density as described by Mueller *et al.* (2011), assuming an infrared/optical reflectance ratio of 1.4.

In both the orbital and the thermophysical models we adopt an absolute magnitude $H = 28.43 \pm 0.12$ (Micheli *et al.* 2012), a photometric slope parameter $G = 0.18 \pm 0.13$ (derived as the average from all G measurements of asteroids in the JPL Small-Body Database), and a rotation period $P = 2^{(2\pm0.5)}$ hr.

5. Results

The mutual dependence among physical properties used by the orbital and the thermophysical model require an iterative solution of the problem. We first sampled the obliquity γ from 90° to 180°. We tested the possible diameters using the thermophysical model, based on an upper-limit flux density measurement (0.78 Jy), and obtained that the diameter of 2009 BD is smaller than 8 m.

For each $D < 8$ m and $90° < \gamma < 180°$ we find two solutions for (Γ, ρ) from the orbital fit to the astrometry. The first solution displays a low Γ of about 10 J m^{-2} s$^{-0.5}$ K^{-1} with a higher bulk density, whereas the second solution stands out with $\Gamma \sim 1000$ J m^{-2} s$^{-0.5}$ K^{-1} and a lower bulk density. Based on the orbital fit χ^2, we can also further constrain the obliquity (see Table 1) and confidently rule out that 2009 BD is smaller than 2.6 m.

We use our intermediate results to derive diameter distributions for both solutions according to the thermal inertia constraints and the Spitzer upper-limit flux density measurement. We generate a sample of synthetic objects with pairs (D, Γ) and we sample the parameters (H, G, P, γ). For the surface roughness we randomly pick one of four different roughness models (see Mueller 2007). We model each synthetic sample object and derive its IRAC in-band flux density combined with contributions from reflected

Table 1. Physical properties of 2009 BD.

	Low thermal inertia	**High thermal inertia**
Diameter [m]	2.9 ± 0.3	4 ± 1
Albedo	$0.85^{+0.20}_{-0.10}$	$0.45^{+0.35}_{-0.15}$
Obliquity [°]	170^{+10}_{-15}	180^{+0}_{-5}
Density [g cm^{-3}]	2.9 ± 0.5	$1.7^{+0.7}_{-0.4}$
Mass [t]	36^{+10}_{-8}	55^{+30}_{-25}
Thermal inertia [J m^{-2} s$^{-0.5}$ K^{-1}]	30^{+20}_{-10}	2000 ± 1000

solar light, which we then compare with the upper-limit flux density as derived from our observations. The final solutions for the diameter are shown in Table 1.

Based on the solution-specific diameter ranges, we finally constrain the other physical properties of 2009 BD using the nongravitational perturbation model and the orbital fit to the astrometry. Table 1 shows the derived physical properties of 2009 BD for both the low and high thermal inertia solutions. The first solution shows 2009 BD as a massive rock body covered with regolith-like material, causing it to exhibit a low thermal inertia. The second solution suggests 2009 BD to be a rubble-pile asteroid that consists of individual bare rock slabs. We are unable to rule out either solution at this stage.

Acknowledgements

The authors thank Tom Soifer, Director of the Spitzer Space Telescope, for the time allocation to observe 2009 BD. The work of D. Farnocchia and S. R. Chesley was conducted at the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. D. Vokrouhlický was partially supported by the Grant Agency of the Czech Republic (grant P209-13-01308S). J. L. Hora and H. A. Smith acknowledge partial support from Jet Propulsion Laboratory RSA No. 1367413. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

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https://doi.org/10.1017/S1743921314008060 Published online by Cambridge University Press