DIAMETERS AND ALBEDOS OF THREE SUBKILOMETER NEAR-EARTH OBJECTS DERIVED FROM SPITZER OBSERVATIONS

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ABSTRACT

Near-Earth objects (NEOs) are fragments of remnant primitive bodies that date from the era of solar system formation. At present, the physical properties and origins of NEOs are poorly understood. We have measured thermal emission from three NEOs—(6037) 1988 EG, 1993 GD, and 2005 GL—with Spitzer’s IRAC instrument at 3.6, 4.5, 5.8, and 8.0 μm (the last object was detected only at 5.8 and 8.0 μm). The diameters of these three objects are 400, 180, and 160 m, respectively, with uncertainties of around 20% (including both observational and systematic errors). For all three the geometric albedos are around 0.30, in agreement with previous results that most NEOs are S-class asteroids. For the two objects detected at 3.6 and 4.5 μm, diameters and albedos based only on those data agree with the values based on modeling the data in all four bands. This agreement, and the high sensitivity of IRAC, shows the promise of the Spitzer Warm Mission for determining the physical parameters for a large number of NEOs.

Subject headings: infrared: solar system — minor planets, asteroids

1. INTRODUCTION

Near-Earth objects (NEOs) are bodies whose orbits pass within a few tenths of an AU of the Earth’s orbit. As of this writing, there are around 5000 NEOs known. The Pan-STARRS program is likely to increase the number of known NEOs to ~10,000 or more by 2013. These bodies are of critical interest to both the scientific community and the public. The NEO population is the source of potential Earth-impacting asteroids (hence a Congressional mandate to study these objects), and some may be easily reached by spacecraft, enabling our exploration of the nearby solar system. Because NEOs have only recently been perturbed out of orbits in the main asteroid belt, and so are relatively primitive objects, they contain information that records the origin of our solar system and that may offer insight into both the past (via delivery of organic material) and future (via impact-caused extinctions) of life on Earth. However, the physical characterization of these objects is by far outpaced by discoveries. The NEO size and albedo distributions, crucial inputs for solar system studies as well as the assessment of the NEO Earth-impact hazard, are only poorly constrained, especially at the smallest sizes (e.g., Stuart & Binzel 2004).

The diameter and albedo of asteroids can be determined from thermal-infrared observations together with appropriate thermal modeling (e.g., Lebofsky et al. 1986; Lebofsky & Spencer 1989; Harris & Lagerros 2002), provided the absolute magnitude $H$ (optical magnitude at a standardized observing geometry; see Bowell et al. 1989) is known. A suitable thermal model for NEOs is the Near-Earth Asteroid Thermal model (NEATM; Harris 1998), which allows for simultaneous fits of the asteroid diameter, albedo, and effective surface temperature parameterized through the beam parameter $\eta$ (e.g., Harris 1998; Harris & Lagerros 2002).

We have measured thermal emission from three NEOs with the Spitzer Space Telescope (Werner et al. 2004) and present our data (§ 2) and results (§ 3) here. Using the NEATM, we derive albedos and diameters for all three objects (§ 3). In § 4 we comment on the apparent thermal inertias for these objects and demonstrate that a study of NEOs could profitably be carried out with the Spitzer Warm Mission.

2. OBSERVATIONS AND DATA REDUCTION

We observed three NEOs [(6037) 1988 EG, 1993 GD, and 2005 GL] at 3.6, 4.5, 5.8, and 8.0 μm with Spitzer’s InfraRed Array Camera (IRAC; Fazio et al. 2004) using the moving cluster observing mode, tracking according to the standard NAIF ephemeris. Table 1 gives the observing log and observing geometries. These objects were chosen to be visible by Spitzer on our observing date, have small positional uncertainties, and have a range of absolute magnitudes. IRAC observes simultaneously at [3.6, 5.8] μm and at [4.5, 8.0] μm. Our dithered observations alternated between these two pairs of bandpasses to reduce the relative effects of any light-curve variations within the observing period and to maximize the relative motion of the asteroid to help reject background sources. The high dynamic range mode was used, and the frame times for each object are given in Table 1.

We used the Basic Calibrated Data (ver. 17.2.0) and MOPEX (ver. 16.0) in the moving object mode to construct mosaics of the fields in the reference frame of the asteroid, assuming the offsets given by the NAIF ephemeris. Aperture photometry was performed using an aperture radius of 5 pixels (at 1.22 arcsec pixel$^{-1}$) and an annulus of 5 pixels for background measurement around the source. The aperture and annulus sizes were calibrated using one of the IRAC calibration stars (HD 165459) and the zero point set so that the measurements matched the source magnitudes given in Reach et al. (2005). 6037 and 1993 GD were detected in all four bands; 2005 GL was detected only at 5.8 and 8.0 μm (Table 1). Only 6037 is bright enough to provide good time-series photometry; no significant flux variation was detected in the ~15 minute span of the observations.

Due to the spectral width of the IRAC passbands, measured flux values must be color corrected. The observed asteroid fluxes comprise thermal and reflected-light components, which have different color corrections (although color correction for

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Object & $H$ & $\Delta H$ & $\Delta T$ & $\Delta \eta$ & Diameter (m) \\
\hline
(6037) 1988 EG & 14.7 & 0.3 & 2.7 & 0.1 & 400 \\
1993 GD & 15.2 & 0.5 & 2.9 & 0.2 & 180 \\
2005 GL & 15.8 & 0.7 & 3.2 & 0.3 & 160 \\
\hline
\end{tabular}
\end{table}
the latter is negligible). To derive color-corrected thermal fluxes, we must first remove the reflected flux contribution in each band. The flux component from reflected sunlight was assumed to have the spectral shape of a K blackbody over IRAC’s spectral range. The flux level was determined from the solar flux at 3.6 μm and longward, and the asteroid’s V magnitude as determined from the observing geometry and the known H value. We assumed that asteroid reflectivity at 3.6 μm and longer was 1.4 times the reflectivity in the V band (A. Rivkin 2008, private communication), although using the naive assumption of equal reflectivity makes only a few percent difference in the resulting albedos and diameters. The estimated reflected-light component was subtracted from the measured fluxes to get the (uncorrected) thermal fluxes.

Color-correction factors for the thermal flux were determined using the iterative procedure described in Mueller et al. (2007): color-correction factors were first determined for typical NEATM parameters, the resulting fluxes were fitted using the NEATM, then color-correction factors were rederived using the best-fit NEATM parameters until convergence was reached. Color corrections and color-corrected thermal fluxes for all three targets are given in Table 2.

3. MODEL RESULTS AND UNCERTAINTIES

Thermal fluxes were measured in all four IRAC bands for (6037) 1988 EG and 1993 GD. For each target, the four-band data were fitted using the NEATM by varying diameter D, albedo p, and η until \( \chi^2 \) was minimized. D and p are related through the optical magnitude \( H: p_\alpha = 10^{-0.4(H-D)/2.5} \) (1329 km/D) \(^2\) (Fowler & Chillemi 1992). (In all cases we assume emissivity of 0.9 and standard scattering behavior in the visible, resulting in a phase integral of 0.39.) These best-fit (floating η) values for \( D_p, p_\alpha \), and η are given in Table 2, and the corresponding model spectra are shown in Figure 1.

For these four-band (floating η) fits, we use a Monte Carlo analysis to estimate the statistical uncertainty of our results. A total of 300 random sets of flux values were generated such that their means and standard deviations match the measured fluxes and flux uncertainties, respectively. Each trial was fitted using the NEATM as above. The standard deviations of the resulting diameter and albedo values were taken to be the statistical uncertainties on our four-band results (Table 2). We do the same NEATM/Monte Carlo analysis using just the 5.8 and 8.0 μm data for the brighter two objects (Table 2), allowing us to assess systematic variations in model results. However, because the measurements of 2005 GL have relatively low significance, this Monte Carlo approach does not work, and we require a proxy technique to determine variations among models, as follows.

In this Monte Carlo proxy model, the nominal fit is determined in the usual way (NEATM, as above). We then use the NEATM to fit a “hot” solution, where the short-wavelength
measurement is increased by 0.7σ and the long-wavelength solution is decreased by 0.7σ relative to the nominal flux values (σ is the measurement error). We also fit a “cold” solution, which has the short band decreased and the long band increased by 0.7σ. The uncertainty in derived albedo and diameter then is derived from the range of values produced by the hot and cold solutions. We show in Table 2 that for 6037 this hot/cold proxy approach replicates the full Monte Carlo result quite closely. We present this proxy model here because, in general, this approach is a useful substitute for full Monte Carlo modeling. However, for 2005 GL, the significance of our measurement is so poor that even this technique does not work (producing implausible albedos around 2 and unlikely H-values around 0.38). We must therefore move to yet a simpler technique to assess systematic errors due to model variations.

Delbo et al. (2003, 2007) and Wolters et al. (2008) derived an empirical relationship between the phase angle α at which observations are made and the best-fit H. This “fixed α” technique works here because the number of free parameters is decreased by 1: the surface temperature is specified by the fixed H (compare to the hot/cold models above). Thus, we produce “fixed α (and H) solution for 2005 GL, as well as for 6037 (fitting 5.8 and 8.0 μm data and fitting 3.6 and 4.5 μm data) and for 1993 GD (with the same data subsets) (Table 2). In the interest of assessing variations due to different model solutions, we also derive “fixed H” solutions for 2005 GL using just 5.8 μm data and just 8.0 μm data (Table 2). The formal errors on these fixed H solutions are derived directly from the measurement errors: because any acceptable fit must pass within the measurement error bars, the percent error on diameter is equal to the percent error on the best measurement utilized in the fit, divided by 2 (since flux is proportional to diameter squared). The albedo uncertainty is twice that of the diameter uncertainty or equal to the uncertainty on the best measurement utilized.

We take our final model solutions to be the averages of the solutions from the various techniques (Table 2). This allows us to capture the scatter among the different model solutions in the error bars on our final solutions. The uncertainties on diameter are around 7% for the strongly detected 6037 and around 16% for the less well detected 1993 GD. For 2005 GL, where there are only three models, all of the same type, the uncertainty on diameter is also around 16%. Uncertainties on albedo are twice those on diameter. These final solutions are given in Table 2 and plotted in Figure 1.

Our diameter solutions are hindered by our lack of knowledge about physical target properties such as shape, spin state, thermal inertia, and surface roughness, all of which affect surface temperatures and hence thermal flux; together, these typically imply an uncertainty around 15% (e.g., Wright 2007), comparable to the systematic errors we estimate from our cross-model comparisons above. More realistic thermophysical modeling (e.g., Harris & Lagerros 2002) would require models for shape and spin state as inputs, but those are unlikely to become available for our targets in the near future.

Additional diameter uncertainty derives from the rotational flux variability (light curves) of our targets. The peak-to-peak light-curve amplitude4 of 6037 is around 0.2 mag. Following the arguments presented in the Appendix, we find that the resulting diameter uncertainty due to light-curve effects is negligible: less than 4%. Nothing is known about the light curves of our remaining targets. Given their small size, their light curves are likely to have a rather large amplitude and small period (Pravec et al. 2002). By virtue of our observation design, measured fluxes in all four channels are effectively averaged over ~900 s (1993 GD) and ~2000 s (2005 GL). Assuming a light-curve amplitude of 1 mag and a period of 1 hr for 2005 GL, the corresponding diameter uncertainty due to light-curve effects would be around 2%—negligibly small.

The final diameter uncertainties are therefore the combination of uncertainties from modeling (<20%), uncertainties in physical properties (15%), and light-curve effects (small). The total uncertainties on diameters are likely to be around 20%, including errors from both measurement and systematic uncertainties.

The corresponding albedo uncertainty due to scatter in model results and ignorance of physical properties is therefore around 40%. Uncertainties in H, which leave the best-fit diameter estimate practically unchanged (Harris & Harris 1997), add to the error budget for p. This effect is small for 6037 (where the uncertainty in H is estimated to be 0.15 mag), but H could be in error by 0.3 mag or more for the other two targets, leading to errors in p of 30% or more. Combining these two uncertainties (40% from above and 30% from H uncertainty), we therefore estimate the total uncertainty on our albedo determinations to be around 50%.

4 See the Ondrejov Asteroid Photometry Project at http://www.asu.cas.cz/~pravec/neo.html.

4.
close to 0.3, in agreement that the NEO population is dominated by S-class asteroids (e.g., Binzel et al. 2004). Binzel et al. (2004) also found that the albedos for S-class (and related classes) NEOs rise from their main-belt average value of around 0.22 to greater than 0.3 for objects ≤500 m. Our results appear to confirm this trend (Fig. 1), although with small numbers and not insignificant error bars. It is quite premature to discuss the reality of the potentially interesting downward turn at even smaller sizes.

The best-fit (floating) $\tau$-values found for 6037 and 1993 GD are roughly consistent with empirical expectations (Delbo’ et al. 2003), which were recently used by Delbo’ et al. (2007) to determine the typical thermal inertia of $D \sim 1$ km NEAs. Thermal inertia is indicative of the presence or absence of loose material (regolith) on the surface and is a key parameter for model calculations of the Yarkovsky effect, a nongravitational force that severely influences the orbital dynamics of small asteroids. (Vokrouhlický et al. [2005] even list 6037 as a potential target for direct observations of the Yarkovsky effect.) Our results suggest that our targets have unremarkable thermal inertias and may be similar to the 320 m diameter S-type NEO (25143) Itokawa (Müller et al. 2005; Mueller 2007), the target of the Hayabusa mission. However, more work and a systematic, large survey are needed to determine the typical thermal inertia of sub-km NEAs.

For 6037 and 1993 GD the diameters and albedos we derive using only 3.6 and 4.5 $\mu$m data are in agreement with our other model solutions, particularly for 6037, which is strongly detected (S/N > 10) in both bands. This agreement has important implications for the Spitzer Warm Mission. After Spitzer’s onboard cryogen is exhausted, observations in IRAC bands 1 and 2 (3.6 and 4.5 $\mu$m) can still be made with essentially no loss of sensitivity. Our results show the promise of capitalizing on the superior sensitivity of IRAC to determine the physical properties of a large number of NEOs during the Spitzer Warm Mission.

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Facilities: Spitzer(IRAC)

APPENDIX

THE EFFECT OF UNKNOWN LIGHT-CURVE VARIATIONS ON DIAMETER UNCERTAINTIES

Uncertainties in diameter can arise from the rotational flux variability (light curve) of an observed asteroid. To first order, the projected area $A$ of an asteroid with a double-peak light curve varies as $A(\phi)/A_0 = 1 + (10^{\Delta m/2.5} - 1) \sin 2\phi$, where $\phi$ is rotational phase, $A_0$ is the average area, and $\Delta m$ is the peak-to-peak light-curve amplitude. For an instantaneous area measurement at a random time, the expectation value is $A_0$, and the standard deviation is $\sigma_A = A_0(10^{\Delta m/5} - 1)/\sqrt{3}$. Since area is proportional to diameter squared, the light-curve–induced contribution to the fractional diameter uncertainty is $\sigma_D = (10^{\Delta m/5} - 1)/\sqrt{3}$. Therefore, for objects whose light-curve amplitudes but not periods are known, $\sigma_D$ can be estimated. Only for objects with $\Delta m \geq 1.9$, which is a very large amplitude light curve, is $\sigma_D$ greater than 50%.

Some observations may span a significant portion of an asteroid’s rotation period; our relatively long integrations on 1993 GD and 2005 GL may be examples. The time-averaged light-curve–induced diameter uncertainty is $\sigma_0(t) = \sigma_D \times S$, where $S$ is a smoothing factor and is equal to $|\sin \phi|/\phi$, with $\phi = 2\pi T/P$ (the rotational phase, as above), $T$ giving the duration of the measurement, and $P$ being the rotation period. For all $T \geq 0.4P$, it is the case that $S \leq 0.2$, so $\sigma_0(t)$ will almost always be small for sufficiently long observations. In cases where an asteroid’s light-curve period is known, an observing plan that results in small $\sigma_0$ can be created without requiring that the thermal and reflected-light observations be simultaneous or even phased. Finally, we conclude that for very small asteroids, uncertainties introduced by light-curve effects will almost always be small, as follows. Some very small asteroids have very short rotation periods (just a few minutes), and most generally will require long integration times. Therefore, $T$ is likely to be $\geq 0.4P$, making $\sigma_0(t)$ small.

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