

## THE ALBEDO, SIZE, AND DENSITY OF BINARY KUIPER BELT OBJECT (47171) 1999 TC<sub>36</sub>

J. A. STANSBERRY,<sup>1</sup> W. M. GRUNDY,<sup>2</sup> J. L. MARGOT,<sup>3</sup> D. P. CRUIKSHANK,<sup>4</sup> J. P. EMERY,<sup>5</sup> G. H. RIEKE,<sup>1</sup> AND D. E. TRILLING<sup>1</sup>

Received 2005 October 21; accepted 2006 January 25

### ABSTRACT

We measured the system-integrated thermal emission of the binary Kuiper Belt object (47171) 1999 TC<sub>36</sub> at wavelengths near 24 and 70  $\mu\text{m}$  using the *Spitzer Space Telescope*. We fit these data and the visual magnitude using both the standard thermal model and thermophysical models. We find that the effective diameter of the binary is 405 km, with a range of 350–470 km, and the effective visible geometric albedo for the system is 0.079, with a range of 0.055–0.11. The binary orbit, magnitude contrast between the components, and system mass have been determined from *HST* data studied by Margot et al. Our effective diameter, combined with that system mass, indicates an average density for the objects of  $0.5 \text{ g cm}^{-3}$ , with a range 0.3–0.8  $\text{g cm}^{-3}$ . This density is low compared to that of materials expected to be abundant in solid bodies in the trans-Neptunian region, requiring 50%–75% of the interior of (47171) 1999 TC<sub>36</sub> be taken up by void space. This conclusion is not greatly affected if (47171) 1999 TC<sub>36</sub> is “differentiated” (in the sense of having either a rocky or just a nonporous core). If the primary is itself a binary, the average density of that (hypothetical) triple system would be in the range 0.4–1.1  $\text{g cm}^{-3}$ , with a porosity in the range 15%–70%.

*Subject headings:* infrared: solar system — Kuiper Belt — solar system: formation

### 1. INTRODUCTION

The physical properties of Kuiper Belt objects (KBOs) remain poorly known 13 years after the discovery of the first KBO, (15760) 1992 QB<sub>1</sub> (Jewitt & Luu 1993). While they can be discovered, their orbits determined, and their visible-light colors measured (to some extent) using modest telescopes, learning more about KBOs generally requires the largest of ground-based telescopes or space-based instrumentation. The *Hubble Space Telescope* (*HST*) has revealed that the Kuiper Belt hosts a large population of binary systems (e.g., Noll 2003). Currently 21 KBOs are known to be binary (Veillet et al. 2002; Elliot et al. 2001; Noll et al. 2002a, 2002b, 2002c; Millis & Clancy 2003; Stephens & Noll 2004, 2006; Cruikshank et al. 2005a). Very recently, two new moons were discovered in the Pluto-Charon system (Weaver et al. 2006; Buie et al. 2005), making it a quadruple, and the large KBO 2003 EL<sub>61</sub> has been shown to have two moons, making it a triple (Brown et al. 2005).

Stephens & Noll (2006) find that of the 81 KBOs they observed with *HST* NICMOS, 11% are binary (at current detection limits). They also find that objects with very low inclinations and eccentricities (“cold classical” objects) are likely to be binary at a rate of 21%, while other, dynamically hotter classes are binary at a rate of 6%. The high incidence of binarity among KBOs is of considerable intrinsic interest as a probe of the dynamics of the Kuiper Belt (e.g., Stern 2002; Goldreich et al. 2002; Astakhov et al. 2005).

However, binaries are also of particular interest because their masses can be determined from observations of the relative motions of the components. Such measurements would otherwise be impossible without sending a spacecraft. When combined with measurements of sizes, the masses of primitive solar system objects can be used to constrain their density. The densities of KBOs are indicative of their interior structure and can provide clues to

the composition of and conditions in the outermost primitive solar nebula.

*Spitzer* (Werner et al. 2004) offers unique capabilities for measuring the infrared emission from KBOs and other solar system objects, thereby constraining their albedos and sizes (e.g., Stansberry et al. 2004; Cruikshank et al. 2005b; Lisse et al. 2005). The object (47171) 1999 TC<sub>36</sub> and three other KBOs have been detected in the submillimeter (Altenhoff et al. 2004; Margot et al. 2002; Lellouch et al. 2002; Jewitt et al. 2001; see also Grundy et al. 2005). One KBO, Quaoar, has been resolved at optical wavelengths, providing an estimate of its size (Brown & Trujillo 2004). For KBOs, the *Spitzer* Multiband Imaging Photometer (MIPS), with photometry channels near 24, 70, and 160  $\mu\text{m}$ , covers the peak in the typical spectral energy distribution near 80  $\mu\text{m}$ . Measurements at these wavelengths are sensitive to the distribution of temperature across the surface of a KBO and so can reveal something about the thermal properties of near-surface layers, as well as constraining the size and albedo of the target.

#### 1.1. (47171) 1999 TC<sub>36</sub>

Here we report on our *Spitzer* observations of the binary KBO (47171) 1999 TC<sub>36</sub>, the albedo and size that are indicated by those data, and the density we derive by combining our results with the *Hubble Space Telescope* (*HST*) visible-imaging results of Margot et al. (2004, 2005; J. L. Margot 2006, in preparation). The KBO (47171) 1999 TC<sub>36</sub> orbits in the 3 : 2 resonance with Neptune and so likely formed closer to the Sun than its current semimajor axis would suggest (e.g., Malhotra 1993). It is very red, with  $B - V \simeq 1.05$ ,  $V - R \simeq 0.70$  (Dotto et al. 2003; Doressoundiram et al. 2005), and  $V - J \simeq 2.3$  (Dotto et al. 2003; McBride et al. 2003). Lazzarin et al. (2003) and Dotto et al. (2003) give visible to near-IR spectra, and Dotto suggests a combination of tholins, carbon, and water ice as a plausible surface composition. There appears to be some slight confusion as to the absolute magnitude,  $H_V$ , of this object. Both the IAU Minor Planet Center (MPC) and the Solar System Dynamics Division at the Jet Propulsion Laboratory (Horizons)<sup>6</sup> give values of  $H_V < 5$ , presumably

<sup>1</sup> Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; stansber@as.arizona.edu.

<sup>2</sup> Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001.

<sup>3</sup> Department of Astronomy, Cornell University, Ithaca, NY 14853.

<sup>4</sup> NASA Ames Research Center, Moffett Field, CA 94035.

<sup>5</sup> SETI Institute, 515 North Whisman Road, Mountain View, CA 94043.

<sup>6</sup> At <http://cfa-www.harvard.edu/iau/mpc.html> and <http://ssd.jpl.nasa.gov/?horizons>, respectively.

TABLE 1  
 THE 1999 TC<sub>36</sub> BINARY SYSTEM

Parameter	Symbol	Value
Heliocentric orbit:		
Semimajor axis .....	$A^a$	39.23 AU
Eccentricity .....	$e^a$	0.22
Inclination .....	$i^a$	8°4
Binary system:		
Semimajor axis .....	$a^b$	7720 km
System mass.....	$M^b$	$1.44 \times 10^{19}$ kg
Orbit period.....	$P^b$	50.36 days
Contrast.....	$\Delta m^{b,c}$	$2.14 \pm 0.02$
Size ratio .....	$r_1/r_2^d$	2.68

<sup>a</sup> Heliocentric orbit values from the Minor Planet Center.

<sup>b</sup> Values from Margot et al. 2004, 2005; J. L. Margot et al. 2006, in preparation. The uncertainty in the mass is about 15%.

<sup>c</sup> Visual magnitude difference between primary and secondary.

<sup>d</sup> Radius ratio of the components assuming equal albedos.

based on apparent magnitudes from astrometric observations. Photometric studies of (47171) 1999 TC<sub>36</sub> all conclude that  $H_V$  is in the range 5.33–5.55 (Margot et al. 2005; J. L. Margot et al. 2006, in preparation; Romanishin & Tegler 2005; Doressoundiram et al. 2005; McBride et al. 2003, Delsanti et al. 2001; Boehnhardt et al. 2001). Here we adopt the value of Doressoundiram et al. (2005),  $H_V = 5.37 \pm 0.05$ , as representative of the range of  $H_V$ . The  $\leq 5\%$  scatter in the  $H_V$  determinations by different groups is small relative to the photometric errors of our *Spitzer* measurements, so we do not track its quite small contribution to the uncertainties in our results. (We also note a systematic bias between the MPC and Horizons absolute magnitudes and absolute magnitudes found in dedicated photometric surveys, as detailed by Romanishin & Tegler 2005.)

Trujillo & Brown (2002) identified (47171) 1999 TC<sub>36</sub> as a binary, with a separation of about 8000 km. Margot et al. (2005) and J. L. Margot et al. (2006, in preparation) imaged the binary with *HST* over a period of 25 months, determining the system's orbital period, semimajor axis, and total mass to high precision. Table 1 summarizes the heliocentric orbit of (47171) 1999 TC<sub>36</sub> and the binary parameters of the system as determined in that study. In their point-spread function (PSF) and orbital fits for (47171) 1999 TC<sub>36</sub>, Margot et al. found that the residuals were significantly higher than for other binaries in their sample, a finding that can possibly be attributed to the primary being itself a binary, an idea we return to later.

## 2. OBSERVATIONS AND DATA ANALYSIS

We observed (47171) 1999 TC<sub>36</sub> with MIPS on board *Spitzer* (Rieke et al. 2004) in its 24 and 70  $\mu\text{m}$  bands, which have effective wavelengths of 23.68 and 71.42  $\mu\text{m}$ . Data were collected using the photometry observing template, which is tailored for photometry of point sources. The telescope tracked the target during the observations, although the motion was negligible relative to the size of the *Spitzer* PSF at these wavelengths. In photometry mode images of the target are taken at many dithered positions on the arrays to improve the photometric accuracy and the sampling of the PSF. Photometric repeatability on moderately bright sources is better than 2% at 24  $\mu\text{m}$  and is 5% at 70  $\mu\text{m}$ . The uncertainty in the absolute calibration of these bands is 5% and 15%, respectively. For purposes of fitting models to our photometry, we use uncertainties that are the root sum square of the absolute calibration uncertainties and the measurement uncertainties determined from the images themselves. The widths of the filter

bandpasses are about 25%, resulting in modest color corrections. We iteratively applied color corrections to our photometry, which converged to give a color temperature of 64.5 K and color corrections of +1% and +10% at 24 and 70  $\mu\text{m}$ , respectively. The uncertainties on the correction factors are perhaps a few percent of the factors themselves and so are negligible for our study. Color corrections for the MIPS bands are available from the Spitzer Science Center (SSC).<sup>7</sup>

We reduced the raw data and mosaicked them using the MIPS instrument team data analysis tools (Gordon et al. 2005). For the 24  $\mu\text{m}$  data basic processing included slope fitting, flat-fielding, and corrections for droop. All of these steps are currently implemented in the SSC pipeline products. Additional corrections were made to remove readout offset (a jail bar pattern in the images), the effects of scattered light (which introduces a pointing-dependent background gradient and slightly degrades the sensitivity), and the application of a second-order flat, derived from the data itself, to remove latents from previous observations. These additional processing steps will be incorporated into the SSC pipeline data products by about the end of 2006. For the field where we observed (47171) 1999 TC<sub>36</sub>, the additional processing reduced the total noise (including both conventional noise and that due to background sources) in the 24  $\mu\text{m}$  image by 30%. The 70  $\mu\text{m}$  data processing was basically identical to that of the *Spitzer* pipeline (vers. S12). We converted the calibrated instrumental count rates to flux density using factors of 1.042  $\mu\text{Jy arcsec}^{-2}$  and 16.6 mJy  $\text{arcsec}^{-2}$  in the 24 and 70  $\mu\text{m}$  bands, respectively. Figure 1 shows the resulting images.

We measured the flux density of (47171) 1999 TC<sub>36</sub> using apertures 9'96 and 29'6 (about 4 and 3 native pixels) in diameter at 24 and 70  $\mu\text{m}$ ; the PSF FWHM is 6'5 and 20'' in those bands. The apertures were positioned at the center-of-light centroid. These small apertures improve the signal-to-noise ratio of the measurements but require both excellent sampling of the PSF and the application of significant aperture corrections. Mosaics were constructed using 1'245 and 4'925 pixels at 24 and 70  $\mu\text{m}$  (about one-half the native pixel scale of those arrays). Mosaicking at this level of subsampling, in combination with the multiply dithered nature of the observations, results in images with excellent PSF sampling and centroid reproducibility. We computed aperture corrections using smoothed STinyTim model PSFs. We smoothed the model PSFs until they agreed with observed stellar PSFs, giving a noiseless, perfectly normalized, zero-background model PSF. We performed photometry on the result, deriving aperture corrections of 1.91 and 1.85 at 24 and 70  $\mu\text{m}$ , respectively. This method has been verified to result in errors  $\leq 1\%$  in the photometry of calibration stars of moderate brightness. The response of the MIPS detectors is quite linear for signals ranging from the natural sky background to near the saturation limit, so our aperture corrections should apply accurately for photometry of faint sources. Table 2 summarizes the circumstances of our observations and the measured, color-corrected flux densities:  $1.23 \pm 0.06$  and  $25.4 \pm 4.7$  mJy at 24 and 70  $\mu\text{m}$ , respectively.

Because we did not make a second observation of the field where we detected (47171) 1999 TC<sub>36</sub>, it is impossible to rule out the possibility that a background source may have coincided with our target, biasing our photometry. However, the areal density of extragalactic sources bright enough to have influenced our results is quite low, and the probability that one could have serendipitously fallen within our beam is quite low in both bands. The areal density of  $0.1 \pm 0.05$  mJy 24  $\mu\text{m}$  sources is 3  $\text{arcmin}^{-2}$  (Papovich et al. 2004). For our aperture size (0.022  $\text{arcmin}^2$ ) this

<sup>7</sup> At <http://ssc.spitzer.caltech.edu>.

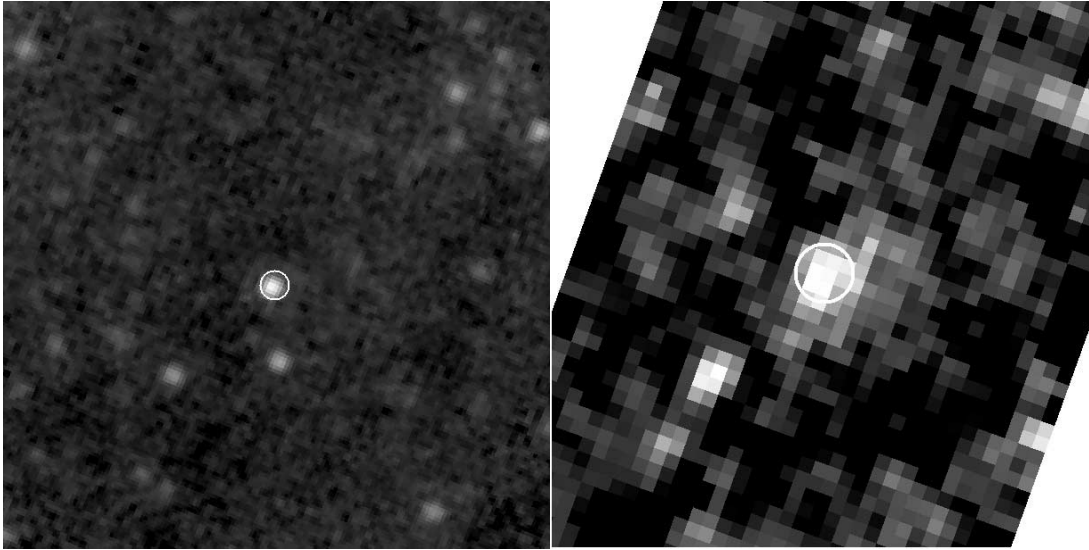


FIG. 1.—Images of (47171) 1999 TC<sub>36</sub> at 24  $\mu\text{m}$  (left) and 70  $\mu\text{m}$  (right). Each image is 190'' square, and the orientation is north to the top, and east to the left. The circles are centered at the ephemeris position of the target. It is just possible to make out the first Airy maximum in the 24  $\mu\text{m}$  image. There is no significant background structure due to cirrus at either wavelength.

translates into a probability of 6.6% that our 24  $\mu\text{m}$  photometry could be contaminated by a 0.1 mJy source. The probability that a fainter source falls in the beam is higher, but such a source would have an insignificant effect on our photometry. We compute the areal density of 70  $\mu\text{m}$  sources based on the results of Dole et al. (2004). At 70  $\mu\text{m}$  the density of  $3 \pm 1$  mJy sources is  $\sim 0.4 \text{ arcmin}^{-2}$ , which translates to an 7.6% probability of a contaminating source in our 0.19  $\text{arcmin}^2$  aperture. Again, fainter sources are more likely than this to fall within the beam, but would have an insignificant effect on the photometry. Thus, not only is the probability of contamination by an extragalactic source small at relevant flux densities, but the effect on our photometry would be small relative to our estimated flux errors. Furthermore, the observed 24 to 70  $\mu\text{m}$  color is redder than would be expected for a typical background source. For (47171) 1999 TC<sub>36</sub> the 70:24 ratio of fluxes is  $\sim 20$ , whereas the results of Papovich et al. (2004) and Dole et al. (2004) indicate that a typical ratio for a background galaxy is  $\sim 10$ . Thus, it is unlikely that our photometry is strongly contaminated by a background galaxy, because such contamination would result in an untenably high color temperature, whereas the color temperature we derive (see below) is very plausible for an object at the distance of (47171) 1999 TC<sub>36</sub>.

Sources within the galaxy can also contaminate far-IR photometry. In particular, thermal emission from extended, uneven clouds of interstellar dust can increase the noise in regions of the sky where such “infrared cirrus” appears in the background. An advantage of *Spitzer* and MIPS over earlier far-IR missions is the relatively small PSF, the fact that the PSF is well-sampled by the

pixels, and the fact that the field of view of the arrays is significantly larger than the PSF. These facts allow for a direct estimation of the contribution of IR cirrus (and extragalactic confusion, for that matter) directly from the images. Inspection of Figure 1 shows that cirrus did not contribute significantly to our photometric errors.

It also seems unlikely that there could be a coma contributing significantly at 24 or 70  $\mu\text{m}$ , because there is no evidence for variability in the visible colors or absolute magnitudes from multiple photometric observations. A possibility that we cannot rule out is that (47171) 1999 TC<sub>36</sub> possesses a coma dominated by relatively large particles that would scatter poorly at visible to near-IR wavelengths, but which could contribute significantly in the thermal. Given the lack of any direct evidence of a coma around (47171) 1999 TC<sub>36</sub> and the requirement that it be both IR bright and *V* invisible to affect our interpretation of the data, we do not pursue this possibility further here.

### 2.1. Thermal Modeling and Results

The standard thermal model (STM; Lebofsky & Spencer 1989) is the most widely used model for interpreting observations of thermal emission from small bodies in the asteroid main belt and the outer solar system (see Tedesco et al. 2002; Fernández et al. 2002; Campins et al. 1994). The model assumes a spherical body whose surface is in instantaneous equilibrium with the insolation, equivalent to assuming either a thermal inertia of zero, a nonrotating body, or a rotating body illuminated and viewed pole-on. In the STM the subsolar point temperature is

$$T_0 = [S_0(1 - p_V q)/(\eta \epsilon \sigma)]^{1/4}, \quad (1)$$

where  $S_0$  is the solar constant at the distance of the body,  $p_V$  is the geometric albedo,  $q$  is the phase integral (assumed here to be 0.39, equivalent to a scattering asymmetry parameter,  $G = 0.15$ ; Lumme & Bowell 1981; Bowell et al. 1989),  $\eta$  is the beaming parameter,  $\epsilon$  is the emissivity (which we set to 0.9), and  $\sigma$  is the Stefan-Boltzmann constant. Given  $T_0$ , the temperature as a function of position on the surface is  $T = T_0 \mu^{1/4}$ , where  $\mu$  is the cosine of the insolation angle. The nightside temperature is taken to be

TABLE 2  
OBSERVATIONAL CIRCUMSTANCES AND FLUX DENSITIES

Wavelength ( $\mu\text{m}$ )	Date <sup>a</sup>	Exposure (s)	$R_{\text{Sun}}$ (AU)	$\Delta_{\text{Spitzer}}$ (AU)	Flux (error) (mJy)
24.....	2004 Jul 12 10:41	1400	31.10	30.94	1.23(0.06) <sup>b</sup>
70.....	2004 Jul 12 11:09	800	...	...	25.4(4.7) <sup>b</sup>

<sup>a</sup> The J2000.0 pointing for the observations was 00:45:29.8,  $-04 \ 16 \ 59$ .

<sup>b</sup> Errors include those from the absolute calibration. The SNR of the detections was  $\simeq 50$  at 24  $\mu\text{m}$  and  $\simeq 10$  at 70  $\mu\text{m}$ .

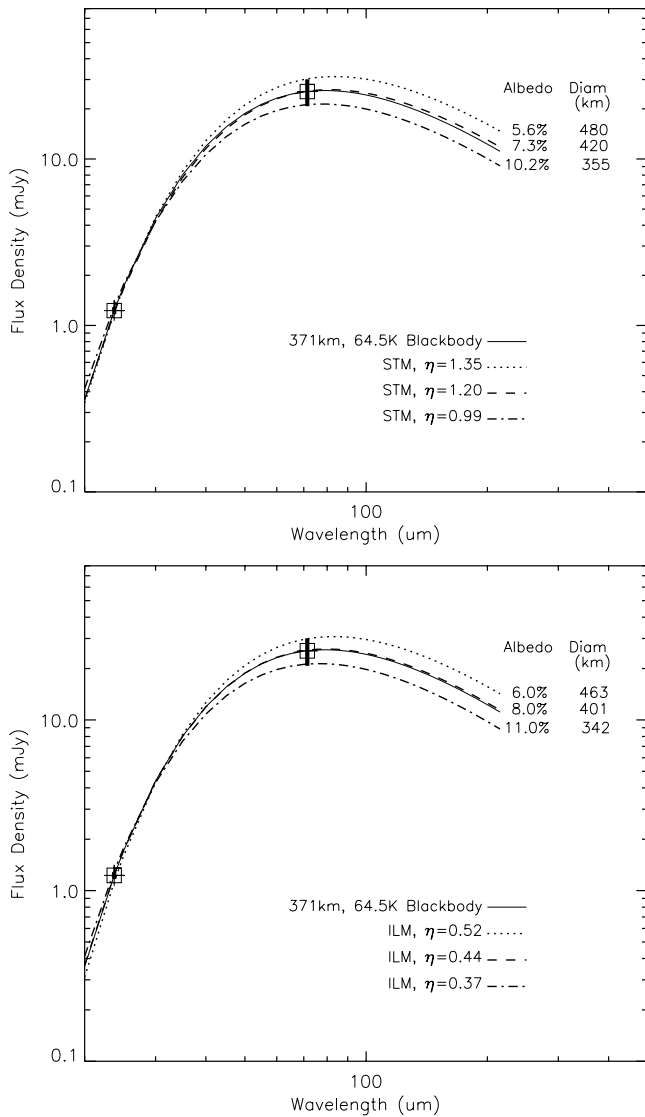


FIG. 2.—Thermal models fitted to our 24 and 70  $\mu\text{m}$  photometry. Results from the STM are given in the top panel, and those from the ILM in the bottom panel. Diameters, which are the effective total diameter for both components of the binary system, and effective geometric albedos corresponding to each model are given at the top right. The beaming parameter  $\eta$  for each model is given in the legend. The temperature of a zero-albedo surface at the distance of (47171) 1999 TC<sub>36</sub> would be 70.6 K.

zero. Surface roughness leads to localized variations in surface temperature and nonisotropic thermal emission (beaming) because individual points on the surface radiate their heat preferentially in the Sunward direction. Thus, when viewed at small phase angles, rough surfaces appear warmer than smooth ones, and the thermal emission tends to be dominated by emission from the warmer depressions and Sunward-facing slopes. This effect is captured by the beaming parameter,  $\eta$ . Lebofsky et al. (1986) found  $\eta = 0.76$  for Ceres and Vesta; the nominal range for  $\eta$  is 0–1, with unity corresponding to a perfectly smooth surface (Lebofsky & Spencer 1989). In modeling the thermal emission from a large sample of Jovian Trojan asteroids, Fernández et al. (2003) found a typical value of  $\eta$  for that population of about 0.94. It is worth noting that  $\eta$  enters the equations for the surface temperature in a manner analogous to the emissivity, so our results could be couched in terms of emissivity rather than beaming parameter.

The thermal emission from a target is calculated by computing a surface integral of the Planck function over the visible portion of the object (because we do this integral, our model is formally a modified version of the STM). The Planck function at a particular point on the surface depends on the calculated temperatures (eq. [1]) and the wavelength of interest. This flux density is then scaled by a dilution factor proportional to  $D^2/\Delta^2$ , where  $D$  is the diameter, and  $\Delta$  is the *Spitzer*-centric distance. The phase angle, which is invariably very small for KBOs, enters into the integral over the visible hemisphere. Here we have set  $\alpha = 0$ , as the effects are negligible for the actual phase of our observations ( $\alpha = 1^\circ 86$ ). The total flux density thus depends on both the target’s unknown diameter,  $D$ , and albedo,  $p_V$ , as well as its distance from the Sun and the observer. Solutions for the size and albedo require a second equation; the object’s visible magnitude typically provides this constraint. We used the absolute visual magnitude of Doressoundiram et al. (2005),  $H_V = 5.37$ , to relate the diameter and albedo via  $D = 10^{-H_V/5} 1329/(p_V)^{1/2}$  (e.g., Harris 1998), where  $D$  is the diameter in kilometers.

The 24 and 70  $\mu\text{m}$  photometry and results from the STM thermal model are shown in Figure 2 (*top*). Using the values of  $q$  and  $\epsilon$  noted above, we allowed  $\eta$  to vary. The best fit to the data in Figure 2 (*top*) has  $D = 420$  km,  $p_V = 0.073$ , and  $\eta = 1.2$ . The range of model parameters that are consistent with the  $1\sigma$  error bars of our data are summarized in Table 3. We note that the model parameters are the *system average, or effective, values of the diameter, albedo, and beaming parameter*, because the system is not resolved at 24 nor 70  $\mu\text{m}$  (nor at  $V$  for the ground-based visible measurements). It is not unusual to allow  $\eta$  to range above unity (Harris 1998; Fernández et al. 2003; Delbo et al. 2003) when fitting thermal data with the STM. As can be seen from equation (1),  $\eta > 1$  will result in overall lower surface temperatures, even though  $\eta$  was traditionally introduced to model elevated localized

TABLE 3

THERMAL MODEL RESULTS

Model	$D$ (km) <sup>a</sup>	$p_V$ (%) <sup>a</sup>	$\eta$ <sup>a</sup>	$\Gamma$ <sup>a,c</sup>
STM .....	420 (355–480)	7.3 (10–5.6)	1.2 (1.0–1.4)	0
ILM .....	401 (342–463)	8.0 (11–6.0)	0.44 (0.37–0.52)	$\infty$
ILM (tilted) <sup>b</sup> .....	420 (364–488)	7.3 (9.7–5.4)	0.80 (0.7–0.95)	$\infty$
Thermophysical (10 hr) <sup>b</sup> .....	434 (362–504)	6.9 (9.9–5.1)	...	3.5 (0.3– $\infty$ )
Thermophysical (40 hr) <sup>b</sup> .....	434 (362–504)	6.9 (9.9–5.1)	...	7.9 (0.7– $\infty$ )
Adopted .....	405 (350–470)	7.9 (11–5.8)	...	...

<sup>a</sup> Model results given as best value and (range).

<sup>b</sup> The tilted ILM and thermophysical models assumed a subsolar and sub-*Spitzer* latitude of  $48^\circ 6$ .

<sup>c</sup> The units of  $\Gamma$  are  $\text{J m}^{-2} \text{K}^{-1} \text{s}^{-1/2}$ .

temperatures caused by roughness. We interpret  $\eta > 1$  to be an indication that the body has a nonzero thermal inertia, a relatively short rotation period, a fairly smooth surface, or some combination of the three. Therefore, the idealized assumptions in the STM do not perfectly apply. This is not entirely surprising given the low temperature of the object, which has the effect of lengthening the radiative cooling timescale, violating the instantaneous thermal equilibrium assumption of the STM.

The isothermal latitude model (ILM) is the opposing end-member model to the STM: the target is assumed to have a surface with infinite thermal inertia, or, equivalently, to rotate instantaneously (also called the “fast-rotator model”; Lebofsky & Spencer 1989). In real terms, the ILM applies to objects with rotation periods much shorter than the timescale for radiative cooling of the surface. It is also typically assumed that the subsolar latitude is zero, although other geometries can be readily computed. In this geometry the surface temperature depends only on the latitude and is constant over longitude (strictly speaking, under the ILM  $\eta = 1$ ).

Figure 2 (*bottom*) compares our photometry with ILM models. We were unable to fit the data under the assumption that  $\eta = 1$ , and so again we allowed it to be a free parameter. The resulting best fit has  $D = 401$  km,  $p_V = 0.080$ , and  $\eta = 0.44$ . The range of model parameters consistent with our data is summarized in Table 3. We interpret  $\eta < 1$  under the ILM as an indication that the thermal inertia could actually be rather low (although the STM results indicate that it is very likely greater than zero).

If the orientation of the rotational axis and the rotational period are known, it is possible to improve the ILM model results by accounting for the actual viewing geometry. Such a tilted ILM is an end-member case of a thermophysical model, incorporating the time-dependence of insolation, conduction, and reradiation. If we assume that the rotational axes of the (47171) 1999 TC<sub>36</sub> binary components are approximately aligned with the orbit normal, the viewing geometry of our observations is specified. Using the position of the normal to the (47171) 1999 TC<sub>36</sub> orbit (J. L. Margot et al. 2006, in preparation), we find that the sub-*Spitzer* and subsolar latitude was  $\simeq 49^\circ$ . Table 3 summarizes the results of the ILM for this geometry.

Using the same assumption for the orientation of the rotation axes, we also fit the data using a smooth-surface thermophysical model, which includes the time-dependent effect of conduction into and out of the subsurface (e.g., Spencer 1990). The results in terms of  $p_V$ ,  $D$ , and thermal inertial,  $\Gamma$ , and for assumed rotational periods of 10 and 40 hr are summarized in Table 3. The spectral energy distributions resulting from these models are nearly indistinguishable from those shown in Figure 2. Also, because we have added a model parameter, somewhat larger ranges of  $p_V$  and  $D$  are found to be consistent with the data.

We also undertook a Monte Carlo approach to see if we could constrain the pole orientation of (47171) 1999 TC<sub>36</sub>. In this case we used the rough-surface thermophysical model of Spencer (1990). Thermal inertias (5–100), emissivities (0.9–1.0), albedos (0.01–0.5), rotational periods (6–32 hr), and spin orientations were all varied randomly (within the ranges just given); the spin orientation was distributed homogeneously in terms of a solid angle with respect to the line of sight. Parameters from thermophysical models with 24 and 70  $\mu\text{m}$  fluxes consistent with our data and the absolute  $V$  magnitude for (47171) 1999 TC<sub>36</sub> (to within  $\pm 1 \sigma$ ) were tabulated. Of the 300,000 models we ran, 539 were consistent with the observations. The results of this modeling are shown in Figure 3. While a significant range of model parameters are consistent with our thermal measurements, the clustering of the

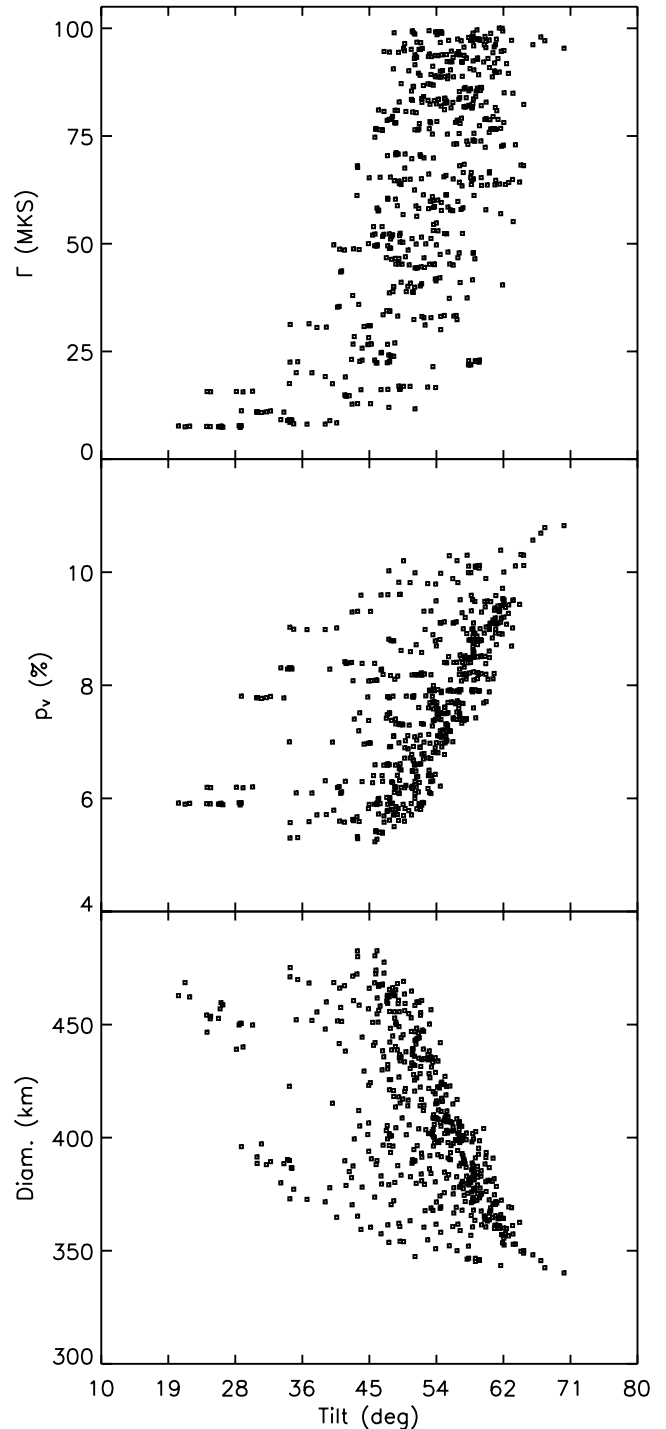


FIG. 3.—Model parameters for rough-surface thermophysical models consistent with our thermal photometry and the absolute  $V$  magnitude of (47171) 1999 TC<sub>36</sub>. A point is plotted for each of the 539 models that fit the data (of 30,000 models run).

points shows that some portions of the parameter space are more likely than others. Acceptable models had geometric albedos between 0.052 and 0.108 and effective diameters between 340 and 483 km, entirely consistent with the ranges of those parameters found earlier and confirming that those ranges encompass uncertainties resulting from model assumptions.

Interestingly, thermophysical models with very high ( $>70^\circ$ ) or with very low ( $<24^\circ$ ) subsolar latitudes could not fit the data. Of the fitting models 80% have subsolar latitudes between  $40^\circ$  and

60°, neatly bracketing the 49° implied by alignment between the spin-axis and the satellite orbit angular momentum vector. Tidal evolution frequently drives satellite spins toward zero obliquity (Peale 1999), but the obliquity of the primary is relatively insensitive to tidal evolution under the influence of the satellite. If the (47171) 1999 TC<sub>36</sub> binary formed in a massive impact (similar to the Pluto-Charon forming impact; Canup 2005) the angular momenta vectors of the orbit and primary rotation should be nearly parallel. Other mechanisms proposed for forming Kuiper Belt binaries do not appear to predict any particular relationship between the orientation of spin and orbital angular momenta (Weidenschilling 2002; Goldreich et al. 2002; Funato et al. 2004). If our prediction that the spin of the (47171) 1999 TC<sub>36</sub> primary is roughly aligned with the orbital angular momentum could be independently verified (or disproved), it would help constrain how the binary formed in the first place.

The rough-surface thermophysical models suggest that  $\Gamma > 30 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  for (47171) 1999 TC<sub>36</sub>. Many of the best-fitting models are clustered at the upper end of the range of  $\Gamma$  we explored (see Fig. 3), so it is possible the thermal inertia is greater than the upper limit of 100 that we imposed. Some models that are consistent with the data also have  $\Gamma$  as low as 7.5, but are associated with improbable combinations of the other model parameters.  $\Gamma$  is around 50 for the Moon and in the range 15–100 in these units for Pluto (Lellouch et al. 2000). Cruikshank et al. (2005b) estimated  $\Gamma$  for 2002 AW<sub>197</sub> to be below 20, for an assumed equatorial viewing geometry. As the geometry moves to higher latitudes the effect of thermal inertia is diluted (in the extreme case, a pole-on ILM is equivalent to the STM, and no constraint can be placed on  $\Gamma$ ). These values of  $\Gamma$  are consistent with a porous or particulate surface, or the presence of a low-conductivity material, such as amorphous water ice or unconsolidated carbonaceous particles in the surface layers.

From all of these model fits to the data, we find that the effective diameter of the (47171) 1999 TC<sub>36</sub> system is in the range  $350 < D < 470 \text{ km}$ , and the visible geometric albedo in the range  $0.055 < p_V < 0.11$ . These adopted values (Table 3) encompass both measurement uncertainties on the fluxes and the uncertainties associated with interpreting the fluxes using the suite of thermal models described above. Because the only common outputs of all the models are albedo and size, we only provide adopted values for those quantities. These parameter ranges exclude some of the most extreme models that fit the data but span most of the reasonable models. It further appears that the surface has a thermal inertia large enough to result in nonzero nightside temperatures but that diurnal temperature variations are also likely to be important. For STM models, this is evidenced by the necessity to set  $\eta$  to values greater than unity, while for ILM models we have to set it to values around 0.5 (see Table 3). The thermophysical models confirm that (47171) 1999 TC<sub>36</sub> has a temperature distribution intermediate between the STM and ILM, with thermal inertia between about 30 and  $100 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ .

## 2.2. Comparison with Submillimeter Results

Altenhoff et al. (2004) used the 30 m IRAM mm telescope to measure the 1.2 mm flux density from (47171) 1999 TC<sub>36</sub> as  $1.1 \pm 0.26 \text{ mJy}$ . They used the ILM with  $\eta = 1$  to interpret their data and derived diameter and albedo values of  $D = 609 \text{ km}$  (562–702 km) and  $p_V = 0.05$  (0.04–0.06). Extrapolating our STM and ILM models to 1.2 mm we predict the flux density there to be  $0.6 \pm 0.16 \text{ mJy}$ , or 55% of their observed flux, although our  $1 \sigma$  upper bound of 0.76 mJy is not far from their  $1 \sigma$  lower bound of 0.84 mJy. A similar discrepancy exists between the *Spitzer* results for (55565) 2002 AW<sub>197</sub> (Cruikshank et al.

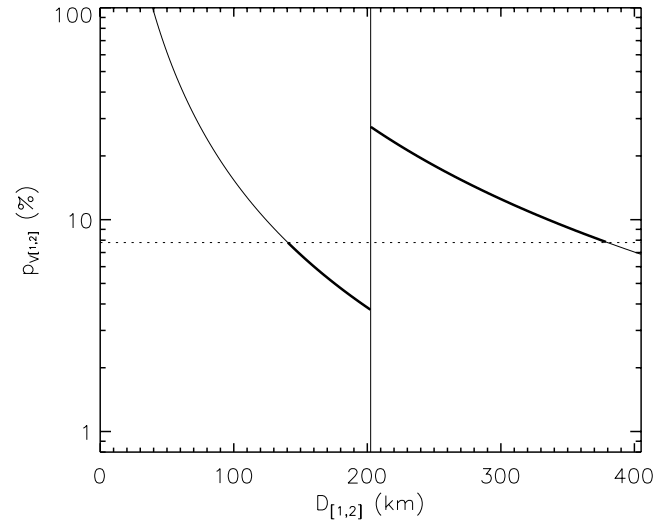


FIG. 4.—Locus of combinations of albedo and diameter for the (47171) 1999 TC<sub>36</sub> primary (to the right of the vertical line) and companion. The solution shown applies for an effective system diameter and albedo of 405 km and 7.9%. The heavy lines show the range of solutions for which the primary has a higher albedo than the secondary; the thin lines show those ranges in which the primary has a lower albedo than the secondary.

2005b) and the submillimeter results reported by Margot et al. (2002), although the disagreement in the case of (47171) 1999 TC<sub>36</sub> is somewhat worse.

The Altenhoff et al. data for (47171) 1999 TC<sub>36</sub> were taken in queue mode in several epochs during the winter months of 2001–2003. Their errors include a 15% absolute calibration uncertainty and an 18% uncertainty based on the measured noise in the data. When data from all epochs are stitched together, the signal integrates upward smoothly, in spite of being obtained in such a distributed way: there is nothing within the data set to suggest that there is an issue (W. J. Altenhoff 2005, private communication). Nevertheless, it seems possible that combining data from so many epochs might contribute to errors higher than nominal, so perhaps the discrepancy with our data can be attributed to somewhat optimistic error estimates for the 1.2 mm data. If irreconcilable differences between submillimeter measurements and *Spitzer* measurements turn up for additional distant solar system objects, a coordinated effort to compare the two calibrations may be called for.

## 2.3. Component Diameters

Given the constraints of the observed magnitude difference of the pair,  $\Delta m$  (from Margot et al. 2004, 2005, and Table 1) and total brightness consistent with our values for the effective diameter and albedo for the system, some limits can be inferred on the sizes of the components of (47171) 1999 TC<sub>36</sub>. Figure 4 shows the combinations that satisfy these constraints for  $D = 405 \text{ km}$  and  $p_V = 0.079$  (these same basic curves are traced out for other values of  $D$  and  $p_V$ ; they simply extend to somewhat larger or smaller values of  $D$ ). Assuming that the components have equal albedos, the ratio of their diameters in terms of their observed magnitude difference is  $(d_1/d_2)^2 = 10^{\Delta m/2.5}$ , where  $d_1$  is the radius of the primary. Given the effective diameter,  $D$ , of the pair from our thermal results, the diameter of the primary is  $d_1 = D/[1 + (d_2/d_1)^2]^{1/2}$ , and  $d_2$  is found from the previous equation. Taking  $D = 405 \text{ km}$ , the sizes of equal-albedo components are 379 and 133 km.

An alternate case is that the two components have diameters equal to  $0.5D$ , and the apparent brightness difference is entirely

TABLE 4  
DENSITY RESULTS

MODEL	DENSITY <sup>a,b</sup> (g cm <sup>-3</sup> )	POROSITY <sup>a,b</sup>		
		$\rho_0 = 1.2$ gcc	$\rho_0 = 1.5$ gcc	$\rho_0 = 1.8$ gcc
Binary:				
Equal $p_V$ .....	0.48 (0.81–0.31)	0.59 (0.39–0.72)	0.67 (0.50–0.77)	0.71 (0.58–0.80)
Equal size ( $D/2$ ).....	0.59 (0.99–0.37)	0.51 (0.26–0.68)	0.60 (0.40–0.73)	0.66 (0.49–0.77)
Maximum difference.....	0.42 (0.73–0.27)	0.64 (0.45–0.75)	0.70 (0.55–0.80)	0.74 (0.62–0.83)
Adopted.....	0.5 (0.9–0.3)	0.53 (0.32–0.72)	0.65 (0.45–0.77)	0.69 (0.54–0.80)
Ternary:				
Equal size <sup>c,d</sup> .....	0.69 (1.10–0.41)	0.43 (0.08–0.66)	0.54 (0.26–0.72)	0.62 (0.39–0.77)

<sup>a</sup> Results given as best value and (range).

<sup>b</sup> The values correspond to our adopted values for  $D$ , with further constraints as noted in the model column.

<sup>c</sup> The ternary model assumes equal albedos for all three components. The primary is assumed to be two equal-sized components ( $d_3 = d_1$ ).

<sup>d</sup> Ternary model values are based on the adopted binary densities and the density enhancement for  $d_3 = d_1$ .

due to an albedo difference. In this case the above expressions can be rewritten to show that the albedos of the primary and companion are 0.28 and 0.039, respectively. The most extreme sizes that are allowed are  $d_1 = D = 405$  km (in which case  $p_{V1} = 0.069$ ), and  $d_2 = 40$  km (in which case  $p_{V2} = 1$ ). An albedo of 1 is probably quite unrealistic for a smallish KBO; a more reasonable upper limit might be  $p_{V2} = 0.4$ , in which case  $d_2 = 66$  km. The data collected by J. L. Margot et al. (2006, in preparation) were unsuitable for making the difficult measurement of the mass ratio, but knowledge of that ratio would provide another useful constraint on the sizes of the components and thereby improve our density determination (as discussed below). In summary, for our best effective diameter,  $D = 405$  km, the component diameters seem likely to lie in the ranges  $202.5 \leq d_1 \leq 405$  and  $202.5 \geq d_2 \geq 66$ .

### 3. DENSITY

Given the mass determined by Margot et al. (2004; 2005) and J. L. Margot et al. (2006, in preparation) and our determination of the effective diameter of the (47171) 1999 TC<sub>36</sub> pair, the system density in terms of the sizes of the primary and companion is

$$\rho = \frac{6M}{\pi D^3} \frac{(1 + \Delta_2)^{3/2}}{1 + \Delta_2^{3/2}},$$

where  $M$  is the system mass,  $\Delta_2 = 10^{-\Delta m/2.5} = d_2^2/d_1^2$ , and other quantities are as defined earlier. Due to the  $D^3$  term, the error in our determination of the size of (47171) 1999 TC<sub>36</sub> strongly dominates the error in the mass in determining the uncertainty in the density. Table 4 summarizes the resulting densities for our adopted range of  $D$  and  $p_V$  and for the range of component diameters discussed above. Considering the densities that result from the entire suite of model parameters, we adopt  $\rho = 0.5$  g cm<sup>-3</sup> as our best estimate of the density, with the true value likely to fall in the range 0.3–0.8 g cm<sup>-3</sup>.

Very low densities have been determined for many primitive solar system objects, in particular small bodies. For example, Asphaug & Benz (1996) estimated the density of the comet Shoemaker-Levy 9 to have been 0.6 g cm<sup>-3</sup> based on observations of its tidal breakup during a close encounter with Jupiter. Three main-belt asteroids with diameters >100 km have densities <1.5 g cm<sup>-3</sup> (15 Eunomia, 45 Eugenia, and perhaps 90 Antiope). Of these, Eunomia is particularly interesting because its density ( $0.96 \pm 0.3$  g cm<sup>-3</sup>) is far below the average density for S class

(stony) asteroids (2.7 g cm<sup>-3</sup>) and because it is the largest asteroid (diameter 255 km) with such a low density (see Britt et al. 2002 and Hilton 2002, and references therein). Anderson et al. (2005) find that the density of Jupiter's moon Amalthea (diameter  $\approx 83$  km) is  $0.86 \pm 0.2$  g cm<sup>-3</sup>. Margot & Brown (2001) discovered that 87 Sylvia was a binary, and using the IRAS diameter, derived a density of  $\approx 1.6$  g cm<sup>-3</sup>. Marchis et al. (2005) subsequently discovered that Sylvia is actually a triple asteroid (the first known, with two satellites orbiting the primary) and estimated the density of the  $\approx 150$  km diameter primary be  $1.2 \pm 0.1$  g cm<sup>-3</sup>. Trilling & Bernstein (2006) applied rotational stability arguments to the 33 KBOs and Centaurs with published light curves and showed that none require densities larger than 0.5–1.5 g cc<sup>-1</sup> (for various models) to remain gravitationally bound, given their observed rotation rates. While this does not mean their densities are in that range (higher densities are not ruled out), it is interesting to note that the low density we find for (47171) 1999 TC<sub>36</sub> is in accord with the lower end of their limits. Because the rotation period of (47171) 1999 TC<sub>36</sub> is unknown, their analysis cannot be directly applied to it (although such an analysis could be very revealing).

It is relatively easy to imagine strength-dominated objects less than around 200 km across having very low densities (and presumably high porosities). Most of the low-density objects just mentioned are known to have irregular shapes (see references given above), indicating that material strength does indeed dominate gravity in their interiors. Such densities could be achieved via catastrophic disruption and reaccumulation (e.g., Richardson et al. 2002). Such configurations are far less intuitively appealing in the case of an object such as (47171) 1999 TC<sub>36</sub>, likely to be more than 300 km in diameter, in which gravitational forces are likely to dominate material strength for some significant portion of the interior.

#### 3.1. Interior Structure

Given an assumption for the density,  $\rho_0$ , of the material making up the solid portions of (47171) 1999 TC<sub>36</sub>, the fractional void space, or porosity,  $f$ , can be calculated from the total mass and the component diameters as  $f = 1 - \rho/\rho_0 = 1 - (6M)/[\pi(d_1^3 + d_2^3)\rho_0]$ . Plausible values for  $\rho_0$  range from around 0.9 g cm<sup>-3</sup> (that of water ice, almost certainly the dominant constituent [e.g., Anders & Grevesse 1989], and other molecular ices likely to be present) to that of Pluto and Triton (2 g cm<sup>-3</sup>; McKinnon et al. 1997), which are composed of roughly equal mass fractions of water ice and “rocky” material. Pluto is a particularly

likely compositional surrogate for (47171) 1999 TC<sub>36</sub>, because both bodies occupy the same orbital resonance with Neptune and so probably formed at a similar heliocentric distance (although (47171) 1999 TC<sub>36</sub> has a lower orbital inclination and so may have formed exterior to Pluto). While Pluto is differentiated, significantly compressed by its own gravity, and probably lost some icy material in a Charon-forming impact (Canup 2005), it is very difficult to imagine how (47171) 1999 TC<sub>36</sub> could have formed with a significantly different rock fraction. That being said, our density for (47171) 1999 TC<sub>36</sub> would be easier to accept if  $\rho_0$  were near or even below  $1 \text{ g cm}^{-3}$ , suggesting a dearth of silicate materials and a corresponding enrichment of water ice and other low-density molecular ices. Candidate ices other than water that might be somewhat abundant are CO ( $\rho = 1.0 \text{ g cm}^{-3}$ ), N<sub>2</sub> ( $\rho = 0.95 \text{ g cm}^{-3}$ ), and CH<sub>4</sub> ( $\rho = 0.5 \text{ g cm}^{-3}$ ) (Scott 1976; Jiang et al. 1975; Manzhelii & Tolkachev 1964). However, appealing to such an extreme composition is ad hoc at best, and it seems highly unlikely that the low density can be explained without significant internal porosity or some other effect.

Figure 5 shows the porosity we derive for (47171) 1999 TC<sub>36</sub> for the plausible range of material densities and for our adopted range of effective diameter for the system. Porosity values for selected values of  $\rho_0$  are given in Table 4. If we assume that the material density is  $1.2 < \rho_0 < 1.8$ , then for an effective diameter of 405 km the range of porosity required is about 62%–74%. If we take  $1.5 \text{ g cm}^{-3}$  as a likely average material density, then our adopted size limits constrain the porosity to be between 48%–80%. Porosities in the range 45%–80% cover most of the allowed values in Figure 5. If we take  $D = 609 \text{ km}$  from Altenhoff et al. (2004) and set  $\rho_0 = 0.8 \text{ g cm}^{-3}$ , the porosity is 83%, and it gets progressively higher for larger material densities. We conclude that our results, if interpreted in terms of void spaces internal to (47171) 1999 TC<sub>36</sub>, require the porosity to be about 65%, with a range of about 45%–80%. It is astonishing to think of such a large body having more than half of its interior volume taken up by voids. Such an object strains the bounds of what might reasonably be called a “rubble pile” (Weissman 1986), being volumetrically more akin to a “void pile,” with some solid matter thrown in.

Our lower porosity limit, 45%, is still well in excess of the 26% expected for closely packed equal-sized spheres and is also in excess of that expected for randomly packed equal-sized spheres (36%; e.g., Torquato et al. 2000). If the component pieces are unequal, porosity decreases because the smaller ones will infill the gaps between the larger ones. An important effect that increases the porosity of a collection of particles is friction, which could be due to roughness and/or angularity of those particles. Thus, a model which might be consistent with the high porosity implied by our density measurement is that the rubble in the interior of (47171) 1999 TC<sub>36</sub> is both very irregular and of comparable size. Another could be that the rubble is itself porous. Such a configuration might result from relatively gentle assembly of grains to make macro particles, which then assemble to form porous “boulders,” and so on, until a large object with significant porosity at all scales results. Similarly, sublimation of volatile components from within a water ice matrix could result in porosity at multiple scales. However, such paradigms ignore the fact that considerable momentum and energy must be dissipated during accretion, because accreted material will be deposited via high-velocity impacts. Such impacts will lead to local compression, melting, and vaporization and in some cases large-scale fracturing (e.g., Asphaug et al. 1996; Richardson et al. 2002). Indeed, impacts would generally tend to compress such a porous structure as that discussed above, casting doubt on whether it could arise

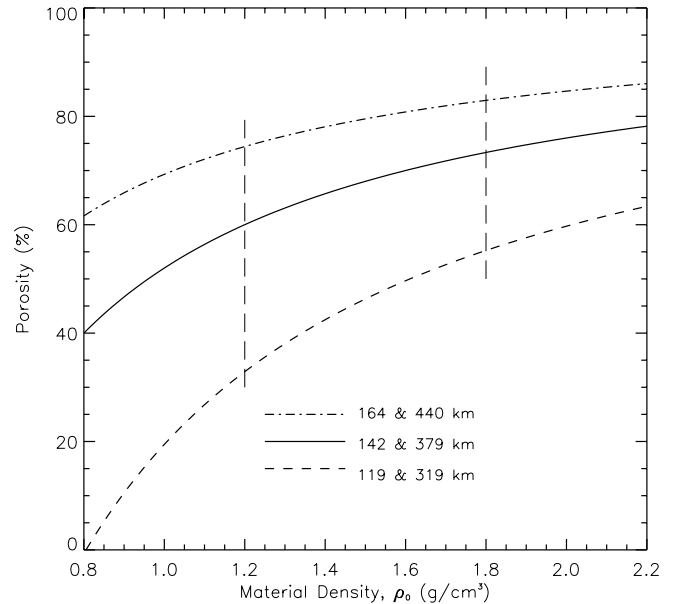


FIG. 5.—Fraction of void space within (47171) 1999 TC<sub>36</sub> resulting from our determination of the effective diameter and the mass determination of J. L. Margot et al. (2006, in preparation). The three lines give the dependence for our adopted value (405 km) and limits (350–470 km) for the effective diameter. The legend gives the corresponding sizes of the components if they have equal albedos. The vertical lines indicate a reasonable range of material density in the outer solar system (see text).

during accretion or be maintained during subsequent billions of years of cratering.

The object (47171) 1999 TC<sub>36</sub> is also large enough that the expected internal stresses should lead to crushing and densification in the interior. The stress at the center of a homogenous sphere is  $P_0 = \pi G \rho^2 D^2 / 6$ . Taking the highest pressure scenario for (47171) 1999 TC<sub>36</sub> we set  $\rho = 1$  (somewhat above the top of our range for density) and  $D = 405 \text{ km}$  and find  $P_0 = 6 \times 10^7 \text{ dyn cm}^{-2}$ . The yield strength of water ice is  $10^7 \text{ dyn cm}^{-2}$  (Beeman 1988) at low confining pressures. In the case of a rubble-pile object, the confining pressure is essentially zero (i.e., the entire weight of overburden is comparable to the deviatoric stress at contact points between the fragments), and the low-pressure strength is the relevant one. So, if the density of (47171) 1999 TC<sub>36</sub> were around  $1 \text{ g cm}^{-3}$  and the primary were as large as our best-fit effective diameter for the system, voids in the deep interior would indeed be closed via the crushing of icy material. However,  $P_0$  depends on the square of both the density and the radius, so modest reductions in either or both lead to significant reduction in interior stress. For a density of  $0.5 \text{ g cm}^{-3}$  and a diameter of 300 km,  $P_0 = 8 \times 10^6 \text{ dyn cm}^{-2}$ . It appears that (47171) 1999 TC<sub>36</sub> may be on the verge of being large and dense enough that it would be compressed, at least near the center, by its own weight. If so, and if the density of larger KBOs can be measured, we predict that the larger objects would indeed have to be denser.

The finding that significant strength-supported void space could exist in the interior of (47171) 1999 TC<sub>36</sub>, is still somewhat puzzling. The lack of a light curve greater than 5%–10% (Peixinho et al. 2002; Ortiz et al. 2003; Margot et al. 2005) is itself evidence that gravity dominates strength in the interior, resulting in the relaxation of mesoscale topography and a near spherical shape. To explore this apparent inconsistency, we examined the possibility that (47171) 1999 TC<sub>36</sub> has a low-density (porous) outer mantle and a denser, nonporous core. Such a configuration might arise in an impact that produced a largest fragment that was a significant

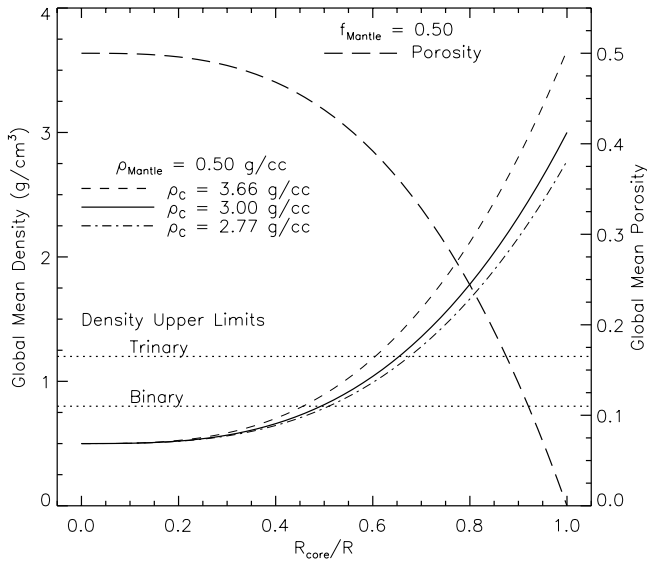


FIG. 6.—Density and porosity of (47171) 1999 TC<sub>36</sub> as a function of the size of a hypothetical core. The density of the mantle (the layer surrounding the core) is taken to be  $0.5 \text{ g cm}^{-3}$ , consistent with a composition dominated by water ice with 50% porosity. The density of the material in the core (assumed to be dominated by silicates) is reflected by the legend labels  $\rho_c$ , with the resulting global mean density indicated by the corresponding line styles. The average porosity of the entire two-layer structure is given by the long-dashed line. Our upper limits on the density of binary and trinary versions of (47171) 1999 TC<sub>36</sub> are shown as horizontal dotted lines. In spite of the high porosities required by our density, large nonporous cores with densities appropriate for rocky material are consistent with our data.

fraction of the size of the original body, as would be expected from a collision with a specific energy at or somewhat above the shattering specific energy,  $Q^*$  (e.g., Holsapple et al. 2002). Figure 6 shows results for the average density and porosity of (47171) 1999 TC<sub>36</sub> as a function of the size of a hypothetical core. The figure assumes that the core is composed of a rocky component, with densities taken from the McKinnon et al. (1997 and references therein) models for the composition of Pluto, and that the density of the mantle is  $0.5 \text{ g cm}^{-3}$  (consistent with a composition dominated by water ice with about 50% porosity). The upper limit on the density of the binary,  $0.8 \text{ g cm}^{-3}$ , places only a weak constraint on the size of a rocky core within (47171) 1999 TC<sub>36</sub>: it could be as large as  $0.45\text{--}0.51$  of the total radius (depending on the core composition) and still satisfy our upper bound on the density of (47171) 1999 TC<sub>36</sub>. If the density is really  $0.5 \text{ g cm}^{-3}$ , there can be no core unless the mantle density is still lower. Setting the mantle density to  $0.3 \text{ g cm}^{-3}$  (i.e., setting its porosity to 70%), we find that a rocky core could exist within (47171) 1999 TC<sub>36</sub> but that its size would be limited to  $0.40\text{--}0.45$  of the total radius. These results offer a compromise wherein (47171) 1999 TC<sub>36</sub> has a relatively dense core overlaid by a very porous, water-ice mantle. The spherical shape of the core would presumably help to moderate the external form, causing the overall shape to tend toward the sphericity suggested by the lack of a measurable light curve.

In summary, while the nominal density and porosity we determined above are not strictly inconsistent with considerations of cosmochemistry, formation, evolution, and strength versus gravity, in each of these areas it seems that our nominal density range ( $0.3\text{--}0.8 \text{ g cm}^{-3}$ ) is extreme. The tolerance of our density for the presence of a high-density core, even if that core is dominated by silicates with densities around  $3 \text{ g cm}^{-3}$ , provides for a plausible scenario in which (47171) 1999 TC<sub>36</sub> can have a low density/high porosity and also have a spherical shape. However, such a low density for such a large object is still extreme.

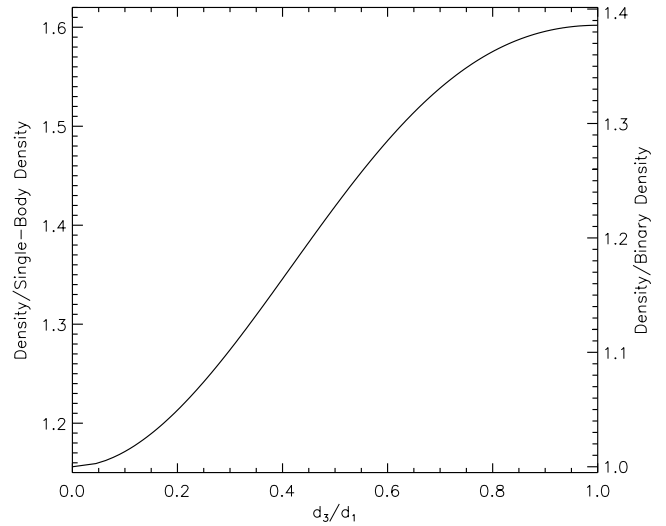


FIG. 7.—Density enhancement relative to the single-component system density [ $6M/(\pi D^3)$ ] for a trinary system. The relationship shown assumes that all three components have the same albedo. For  $d_3/d_1 = 0$  the system is a binary, and for  $d_3/d_1 = 1$  the “primary” is itself a binary with two equal-sized components.

### 3.2. Multiple System?

An alternative to the porous/rubble-pile models above is that one or both components of (47171) 1999 TC<sub>36</sub> are very irregular in external form, essentially incorporating significant void space within their apparent limbs. As just discussed, this seems unlikely because of the lack of a measured light curve. However, an extreme case of such external porosity would be if one or both of the two known components are also binary (or multiple) systems. Three multiple minor planet systems are known: 87 Sylvia is a triple (Marchis et al. 2005), Pluto is a quadruple (Weaver et al. 2006; Buie et al. 2005), and 2003 EL<sub>61</sub> is a triple (Brown et al. 2005). If (47171) 1999 TC<sub>36</sub> is a triple, the lack of a light curve is not particularly telling, as such a subbinary would only possess a light curve when one component eclipses the other (during mutual events), assuming that the intrinsic light curve of each component is negligible. For a multiple system of  $N$  equal-size components, the density is given by  $\rho = 6\sqrt{N}M/(\pi D^3)$ : the density for the multicomponent system is enhanced by a factor of  $\sqrt{N}$  relative to that for a single-component system. In the case of (47171) 1999 TC<sub>36</sub> we postulate that the primary may itself be an unresolved binary with component diameters of  $d_1$  and  $d_3$ ; the diameter of the resolved companion to the primary is  $d_2$ , as before. If we restrict our consideration to the case in which the three components have equal albedos, the density can be written as

$$\rho = \frac{6M}{\pi D^3} \frac{[(1 + \Delta_2)(2 + \Delta_3)]^{3/2}}{1 + \Delta_3^{3/2} + \Delta_2^{3/2}(1 + \Delta_3)^{3/2}},$$

where  $\Delta_2 = d_2^2/(d_1^2 + d_3^2)$  and  $\Delta_3 = d_3^2/d_1^2$ . In addition,  $\Delta_2 = 10^{-\Delta m/2.5} = 0.139$  from the observed magnitude difference between the primary and secondary.

Figure 7 shows the second term of the above expression as a function of the ratio  $d_1/d_3$ . From the figure it is clear that to have a significant effect on the density we derive, the primary must be split into components of comparable size. If the (47171) 1999 TC<sub>36</sub> primary is actually two equal-sized components, this shows that the density of a trinary (47171) 1999 TC<sub>36</sub> is enhanced by a factor of 1.60 relative to the density for a single body and 1.38 relative to the density of a binary system ( $d_3 = 0$ ). The resulting

average density of the triple system is  $0.7 \text{ g cm}^{-3}$ , with a range of  $0.4\text{--}1.1 \text{ g cm}^{-3}$  (compared to  $0.3\text{--}0.8 \text{ g cm}^{-3}$  for the binary system). The porosities derived earlier decrease to about 0.5 with a range of 0.1–0.7. Table 4 summarizes our results for the density of this hypothetical trinary system. These densities and porosities might be achievable given the likely major constituents of (47171) 1999 TC<sub>36</sub> and realizable internal structures. Somewhat larger increases to the density could result if the secondary has a low albedo and is therefore comparable in size to the primary. In this case, and in the unlikely event that the secondary is also double, the density could be enhanced by a factor approaching 2 relative to the single-body density or by a factor approaching 1.7 relative to the equal-albedo binary case.

#### 4. CONCLUSIONS

We detected thermal emission from the binary KBO (47171) 1999 TC<sub>36</sub> at 24 and 70  $\mu\text{m}$  using the *Spitzer Space Telescope*. When interpreted using a range of thermal models, we derive an effective diameter for the system in the range  $350 \leq D \leq 470 \text{ km}$ , with the best value being 405 km. The corresponding range of the visible geometric albedo is  $0.055 \leq p_v \leq 0.11$ , with the best value being 0.079. When combined with the system mass determined from *HST* data by Margot et al. (2004, 2005; J. L. Margot et al. 2006, in preparation), our size determination indicates an average density in the range  $0.3\text{--}0.8 \text{ g cm}^{-3}$ . For likely bulk compositions, dominated by roughly equal mass fractions of rocky material and water ice, the porosity required to explain densities this low is in the range 55%–75%. Such high porosities strain the bounds of what might reasonably be expected for naturally occurring internal structures for such a large object. However, we do find that (47171) 1999 TC<sub>36</sub> is just small enough that it might not be compressed under its own weight, so porosities this high cannot be easily ruled out on those grounds. It is possible that the (47171) 1999 TC<sub>36</sub> primary could have a core with a density around  $3 \text{ g cm}^{-3}$ , so long as that core is smaller than about one-half the radius. The presence of a dense core may help reconcile

the apparent inconsistency between the presence of large amounts of strength-supported void space in the interior and the nearly spherical shape evidenced by the lack of a measured light curve.

If (47171) 1999 TC<sub>36</sub> is actually a triple system, the densities and porosities we derive must be modified accordingly. We derive a general expression for the density of the system as a function of the component sizes and show that the density could actually be as much as 1.38 times greater than for the binary system, if the primary is split into comparably sized components. Such a trinary system would be consistent with the lack of an observed light curve so long as none of the components eclipse one another (if the orbit of the primary binary is inclined  $49^\circ$  to our line of sight, the centers of equal-sized components could be as close as three radii without eclipses occurring). The density of such a system would be in the range  $0.4\text{--}1.1 \text{ g cm}^{-3}$ . At the upper end, these densities are comparable to that of, e.g., Saturn's moons Tethys and Iapetus (e.g., Burns 1986).

These results suggest that in addition to being a binary KBO, (47171) 1999 TC<sub>36</sub> has unexpected internal properties. The large model uncertainties in the density and porosity could be reduced with additional data that provided constraints on the individual sizes of the primary and secondary or that constrained their individual masses. In addition, very high resolution imaging or light curve monitoring could help resolve the question of whether the (47171) 1999 TC<sub>36</sub> primary is itself actually multiple. If (47171) 1999 TC<sub>36</sub> were found to have a short rotation period, that could place a lower bound on the density for which it would be stable against distortion or breakup due to rotation.

This work is based (in part) 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. Support for this work was provided by NASA through an award issued by JPL Caltech.

#### REFERENCES

- Altenhoff, W. J., et al. 2004, *A&A*, 415, 771  
 Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197  
 Anderson, J. D., et al. 2005, *Science*, 308, 1291  
 Asphaug, E., & Benz, W. 1996, *Icarus*, 121, 225  
 Astakhov, S. A., et al. 2005, *MNRAS*, 360, 401  
 Beeman, M. 1988, *J. Geophys. Res.*, 93, 7625  
 Boehnhardt, H., et al. 2001, *A&A*, 378, 653  
 Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peltoniemi, J., & Harris, A. W. 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. Arizona Press)  
 Britt, D. T., Yeomans, E., Housen, K., & Consomagno, G. 2002, in *Asteroids III* (Tucson: Univ. Arizona Press)  
 Brown, M. E., & Trujillo, C. A. 2004, *AJ*, 127, 2413  
 Brown, M. E., et al. 2005, *ApJ*, 635, 97  
 Buie, M. W., et al. 2005, *AJ*, submitted (astro-ph/0512491)  
 Burns, J. A. 1986, in *Satellites*, ed. J. A. Burns & M. S. Matthews (Tucson: Univ. Arizona Press)  
 Campins, H., et al. 1994, *AJ*, 108, 2318  
 Canup, R. 2005, *Science*, 307, 546  
 Cruikshank, D. P., et al. 2005a, *Protostars and Planets V*, ed. V. Mannings, B. Reipurth, D. Jewitt, & K. Klaus (Houston: Lunar Planet. Inst.), in press  
 ———. 2005b, *ApJ*, 624, L53  
 Delbo, M., Harris, A. W., Binzel, R. P., Pravec, P., & Davies, J. K. 2003, *Icarus*, 166, 116  
 Delsanti, A. C., et al. 2001, *A&A*, 380, 347  
 Dole, H., et al. 2004, *ApJS*, 154, 87  
 Doressoundiram, A., et al. 2005, *Icarus*, 174, 90  
 Dotto, E., et al. 2003, *Icarus*, 162, 408  
 Elliot, J. L., Kern, S. D., Osip, D. J., & Burles, S. M. 2001, *IAU Circ.* 7733  
 Fernández, Y. J., et al. 2002, *AJ*, 123, 1050  
 ———. 2003, *AJ*, 126, 1563  
 Funato, Y., Makino, J., Hut, P., Kokubo, E., & Kinoshita, D. 2004, *Nature*, 427, 518  
 Goldreich, P., et al. 2002, *Nature*, 420, 643  
 Gordon, K. D., et al. 2005, *PASP*, 117, 503  
 Grundy, W. M., et al. 2005, *Icarus*, 176, 184  
 Harris, A. W. 1998, *Icarus*, 131, 291  
 Hilton, J. L. 2002, in *Asteroids III*, ed. W. F. Bottke, Jr., A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson: Univ. Arizona Press), 103  
 Holsapple, K., Giblin, I., Housen, K., Nakamura, N., & Ryan, E. 2002, in *Asteroids III*, ed. W. F. Bottke, Jr., A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson: Univ. Arizona Press), 443  
 Jewitt, D. C., Aussel, H., & Evans, A. 2001, *Nature*, 411, 446  
 Jewitt, D. C., & Luu, J. 1993, *Nature*, 362, 730  
 Jiang, G. J. et al. 1975, *J. Chem. Phys.*, 62, 1201  
 Lazzarin, M., et al. 2003, *AJ*, 125, 1554  
 Lebofsky, L. A., & Spencer, J. R. 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. Arizona Press), 128  
 Lebofsky, L. A., et al. 1986, *Icarus*, 68, 239  
 Lellouch, E. R., Laureijs, B., Schmitt, E., Quirico, C., de Bergh, J., Crovisier, A., & Coustenis, A. 2000, *Icarus*, 147, 220  
 Lellouch, E., Moreno, R., Ortiz, J. L., Paubert, G., Doressoundiram, A., & Peixinho, N. 2002, *A&A*, 391, 1133  
 Lisse, C., et al. 2005, *ApJ*, 625, L139  
 Lumme, K., & Bowell, E. 1981, *AJ*, 86, 1694  
 Malhotra, R. 1993, *Nature*, 365, 819  
 Manzhelii, V. G., & Tolkachev, A. M. 1964, *Soviet Phys. Solid State*, 5, 2506  
 Marchis, F., et al. 2005, *Nature*, 436, 822  
 Margot, J. L., & Brown, M. E. 2004, *BAAS*, 33, 1133  
 Margot, J. L., Brown, M. E., Trujillo, C. A., & Sari, R. 2004, *BAAS*, 36, 803 (abstract)  
 Margot, J. L., Brown, M. E., Trujillo, C. A., Sari, R., & Stansberry, J. A. 2005, *BAAS*, 37, 5204

- Margot, J. L., Trujillo, C., Brown, M. E., & Bertoldi, F. 2002, *BAAS*, 34, 871
- McBride, N., et al. 2003, *Icarus*, 161, 501
- McKinnon, W., Simonelli, D. P., & Schubert, G. 1997, in *Pluto and Charon* (Tucson: Univ. Arizona Press)
- Millis, R. L., & Clancy, K. B. 2003, *IAU Circ.* 8251
- Noll, K. S., et al. 2002a, *IAU Circ.* 7824
- . 2002b, *IAU Circ.* 7857
- . 2002c, *IAU Circ.* 8034
- . 2003, *Earth Moon Planets*, 92, 395
- Ortiz, J. L., Gutierrez, P. J., Casanova, V., & Sota, A. 2003, *A&A*, 407, 1149
- Papovich, C., et al. 2004, *ApJS*, 154, 70
- Peale, S. J. 1999, *ARA&A*, 37, 533
- Peixinho, N., Doressoundiram, A., & Romon-Martin, J. 2002, *NewA*, 7, 359
- Richardson, D. C., Leinhardt, Z. M., Melosh, H. J., Bottke, W. F., & Asphaug, E. 2002, in *Asteroids III*, ed. W. F. Bottke Jr., A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson: Univ. Arizona Press)
- Rieke, G. H., et al. 2004, *ApJS*, 154, 25
- Romanishin, W., & Tegler, S. J. 2005, *Icarus*, 179, 523
- Scott, T. A. 1976, *Phys. Rep.*, 27, 89
- Spencer, J. R. 1990, *Icarus*, 83, 27
- Stansberry, J. A., et al. 2004, *ApJS*, 154, 463
- Stephens, D. C., & Noll, K. S. 2006, *AJ*, 131, 1142
- . 2004, *BAAS*, 36, 1706
- Stern, S. A. 2002, *AJ*, 124, 2300
- Tedesco, E. F., Noah, P. V., Noah, M., & Price, S. D. 2002, *AJ*, 123, 1056
- Torquato, S., et al. 2000, *Phys. Rev. Lett.* 84, 2064
- Trilling, D. E., & Bernstein, G. 2006, *AJ*, 131, 1149
- Trujillo, C. A., & Brown, M. E. 2002, *IAU Circ.* 7787
- Veillet, C., et al. 2002, *Nature*, 416, 711
- Weaver, H. A., et al. 2006, *Nature*, 439, 943
- Weidenschilling, S. J. 2002, *Icarus*, 160, 212
- Weissman, P. R. 1986, *Nature*, 320, 242
- Werner, M., et al. 2004, *ApJS*, 154, 1