

Size estimates of some optically bright KBOs

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Abstract. Seven recently detected optically “bright” Kuiper-Belt-Objects (KBOs) were observed at 250 GHz using the Max-Planck Millimeter Bolometer (MAMBO) array at the IRAM 30 m telescope. Only the optical binary KBO (47 171) 1999 TC36 was detected, whose components differ optically by $\Delta m \approx 2$ mag. Assuming that the derived mean geometric albedo of $p = 0.05$ is identical for both, the component diameters become 566 and 225 km. For the other six objects upper limits to their sizes and lower limits for their albedos were obtained. The geometric albedo, p , for (28978) Ixion is surprisingly large, ≥ 0.15 . For a consistent comparison all published radio photometric data of KBOs and Centaurs were analyzed again: the average geometric albedo is found to be ≈ 0.08 .

Key words. minor planets – radio continuum: solar system

1. Introduction

The outer regions of the solar system are occupied by three distinct groups of distant minor planets: the Kuiper Belt Objects (KBOs), the Scattered Disk Objects (SDOs), and the Centaurs. The KBOs move in the ecliptic plane in dynamically stable orbits at heliocentric distances larger than 30 AU. Through close encounters KBOs can be forced into less stable highly eccentric orbits within a scattered disk, with typical perihelia of 35 AU, mean heliocentric distances of 85 AU, or into the domain of Centaurs, the “major planet crossers”. If the Centaurs and SDOs, treated also by the Minor Planet Center/CBAT (2003) as one group, are really forced “recently” into their new orbits, their physical constitution should be unchanged since their origin.

The first KBO was detected less than a decade ago. By now (September 2003) 722 KBOs and 132 Centaurs are catalogued (Parker 2003), and many of the brighter ones have been investigated intensively. Their reflection spectra differ from those of the main belt asteroids (MBAs), and they can not be classified in the schema of the MBAs. Tegler & Romanishin (2003) and Peixinho et al. (2003) debate whether the bimodality of the color population is statistically confirmed only for the Centaurs or globally for Centaurs and KBOs. Even the one dimensional continuous color distribution may become a first classification criterion for KBOs. Sheppard & Jewitt (2002) report that 32% of the observed KBOs show (peak to peak) light variations greater 15%, with periods comparable with the average MBA rotation period of 9 hours. They suggest that the light curves are caused by rotationally distorted shapes (the rubble pile model).

Hainaut et al. (2000) and Sheppard & Jewitt (2003) report amplitude variations of the light curves of (19 308) 1996 TO66 and (24 835) 1995 SM55, respectively, which might be explained by cometary activity between the observing sessions. Whether the low brightness variations of the majority of the KBOs is an indication of their sphericity or of their attitude distribution remains to be investigated (Lacerda & Luu 2003).

Nine KBOs were confirmed as binaries (e.g. Noll et al. 2002). The components of these binaries typically have a comparable size and a wide separation, while binary components of the MBAs show a small separations and very different sizes.

Observations of 7 KBOs by Sheppard & Jewitt (2002) show a striking similarity of their phase functions, indicating comparative uniformity of their surface composition, which is very different from that of the Pluto-Charon Binary and also from the MBAs. The different properties of the distant minor planets compared to the MBAs add weight to the claim that they are remnants of the pristine material of the original solar accretion disk.

From all observable parameters of KBOs the size and albedo information is scarce: only one angular size could be measured directly (Brown & Trujillo 2002), and two indirectly by the sensitivity-limited radio photometric method, measuring their thermal emission: the observed flux density is proportional to the cross section of the KBO and to the independently known brightness temperature (Altenhoff et al. 2001).

Here we want to extend the radio photometric size determinations of minor planets (Altenhoff et al. 1994, 1995, 2001) to more distant minor planets and compare the results systematically with other published radio size measurements for an improved set of sizes and albedos.

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Table 1. Distant minor planets observed at 250 GHz.

KBO	alias	epoch	time [h]	S [mJy]	Observing dates
24835	1995 SM55	2001 01 21.0	2.72	<0.83	2000 Dec. 16, 17, 19; 2001 Jan. 21; Feb. 11, 18, 21
19308	1996 TO66	2001 01 21.0	2.56	<0.90	2000 Dec. 15, 16, 19; 2001 Jan. 20, 21; Feb. 11, 18
Chaos	1998 WH24	2001 01 21.0	3.64	<0.80	2000 Dec 15, 17; 2001 Jan. 20, Feb. 12, 13, 16, 17, 21
47171	1999 TC36	2003 01 12.0	4.06	1.11 ± 0.26	2000 Dec. 16, 2001 Jan. 20, 21, 22; Feb. 11, 18; Dec. 5, 9, 20, 27; 2002 Feb. 10, 11; May 19; Dec. 7; 2003 Jan. 11, 12, 15, 16; Mar. 3
Huya	2000 EB173	2001 01 21.0	2.43	<1.04	2000 Dec. 13; 2000 Jan. 12, 14, 21, 22
Ixion	2001 KX76	2002 07 02.0	4.77	<0.92	2001 Dec. 9; 2002 Feb. 1, 9; May 19; Jul. 2; 2003 Jan. 12; Feb. 4, 5, 6, 7; Mar. 4
–	2002 TC302	2003 01 11.0	1.84	<1.47	2002 Dec. 6, 7; 2003 Jan. 11, 12, 13

NOTE – Columns give the object name, provisional designation, epoch of scaled flux densities, integration time, and flux density. Upper limits are 3σ .

2. Observations

The millimeter observations were made with the IRAM 30 m telescope on Pico Veleta, Spain, using the 37- or 117-channel versions of the Max-Planck Millimeter Bolometer (MAMBO), which was built at the Max-Planck-Institut für Radioastronomie (Kreysa et al. 1999). For our observations the performance of both bolometer versions is about identical with respect to angular resolution and sensitivity. MAMBO is a hexagonally close-packed array operating at 0.3 K. It has a half-power spectral bandwidth between 210 and 290 GHz with an effective frequency for steep thermal spectra of 250 GHz. The beam size on the sky is 10.7 arcsec. The sources were observed with a single channel using the standard on-off mode with the telescope secondary chopping in azimuth by 32'' at a rate of 2 Hz; after each integration of 10 s the telescope is moved to the preceding off position. The data were analysed using the MOPSI software created by Zylka (1998), which allows to subtract the mean correlated sky noise observed in the off-source channels from the on-source channel. For absolute flux calibration a number of calibration sources were observed, resulting in an estimated absolute flux uncertainty of 15% (1σ). Considering the number of observing periods for each distant minor planet, listed in Table 1, the statistical error of the absolute calibration becomes negligible compared to the observing accuracy.

For our observations we had selected the optically brightest KBOs known at the time (Table 1). The integrations were deep enough for each object so that it could have been detected if its geometric albedo was near that expected, $p \sim 0.04$. Only one KBO could be detected; it is evident that the typical albedo of the KBOs is therefore higher. Each KBO was observed at many different dates, thus reducing systematic errors like confusion

by background sources, or undersampling of the light curve from a non-spherical, rotating object.

All distant minor planets were observed with ephemerides based on the latest orbital elements provided by CBAT (2003). We expect their quality to have been better than the accuracy of 1 arcsec (i.e. 1/10 of the beam width) required for accurate flux density observations.

3. Interpretation

3.1. Thermal equilibrium

Under the assumption that distant minor planets do not have a significant internal heat source the observed emission is in radiation equilibrium with the insolation. Using Stefan's law and the known solar constant the equilibrium temperature T_{eq} at the sub-solar point of a non-rotating body with low heat conductivity and no atmosphere (see e.g. Kellermann 1966; Weigert & Wendker 1996) is described by:

$$T_{\text{eq}} = T_0 (1 - A)^{1/4} (r/\text{AU})^{-1/2}, \quad (1)$$

where A , r , and $T_0 = 392$ K are the Bond albedo (fraction of reflected light by a spherical body), the heliocentric distance, and the black body equilibrium temperature at 1 AU, respectively. The solar energy absorbed by the surface of the body per unit area is:

$$E = E_0 \cos \Theta, \quad (2)$$

where Θ is the zenith angle of the sun. The temperature distribution on the sun-lit surface becomes

$$T_{\text{eq}} = 392 \cos^{1/4} \Theta \text{ K} \quad (3)$$

and the disk averaged equilibrium temperature becomes

$$T_{\text{eq}} = 392/2^{1/4} \times (1 - A)^{1/4} (r/\text{AU})^{-1/2} \text{ K}, \quad (4)$$

with $T_0 = 329$ the disk averaged temperature of the black body at 1 AU. The emitted energy is described by the Planck law, $B_\nu(T_b)$, T_b is the brightness temperature. The diameter of the KBO, d , is then determined from

$$S_\nu = \frac{\pi d^2}{4\Delta^2} B_\nu(T_b), \quad (5)$$

where Δ is the geocentric distance. It should be noted that at mm-wavelengths the observed flux density is proportional to the product of brightness temperature and the solid angle of the body, thus facilitating the interpretation of radiation equilibrium.

The emission of a KBO can possibly be better described as a grey body with the brightness temperature T_b and emissivity e . The equilibrium, brightness, and physical temperatures of the surface relate as

$$T_{\text{eq}} = T_b = e T_{\text{ph}}. \quad (6)$$

The equality of the equilibrium and brightness temperature was noticed in mm observations by Webster et al. (1988), Johnston et al. (1989), and Altenhoff et al. (1994). The radiation equilibrium was first applied to the interpretation of planetary radio observations by Kellermann (1966).

The Bond albedo is related to the geometric albedo, p , by $A = p q$, where q is the phase integral. For KBOs the phase integral is poorly determined because for distant minor planets the solar phase varies only by about ± 2 deg, it therefore needs extrapolation (e.g. Stumpff 1948).

3.2. Rotation

The black body equivalent temperature T_0 is model dependent: for a non-rotating sphere it assumes a value of 392 K at its subsolar point, and averaged over the illuminated disk it is 329 K. This simplistic thermal model, in which the subsolar and the sub-Earth point coincide, is named (especially in IR-astronomy) the standard thermal model (STM). In case of fast rotation (insolation on a hemisphere, emission from the total sphere) the disk-averaged temperature becomes $T_0 = 329/2^{1/4}$ K = 277 K. This model, in which the Sun and Earth are in the equatorial plane and which assumes an isothermal distribution in longitude, is also called the isothermal latitude model (ILM). Both models are the limiting cases for the equilibrium temperature. In principle an “intermediate latitude model” would be needed, if the Sun and Earth are not in the equatorial plane. But because the spin axis of most distant minor planets are thought to be nearly in the direction of the ecliptic pole (which still needs confirmation), the fast rotation model should approximate the equilibrium temperature at 250 GHz.

For a rotating body the actual rotation model depends not only on the rotation period but on the observing frequency as well, because the emission originates in a surface layer with a depth proportional to the wavelength; the thermal inertia of this layer, and with it the time delay between absorption and re-emission, is wavelength dependent. We used existing measurements of planetary objects with accurately known diameters to derive T_b (Eq. (3)) and scaled them to the heliocentric distance $r = 1$; they are shown as function of the rotation period

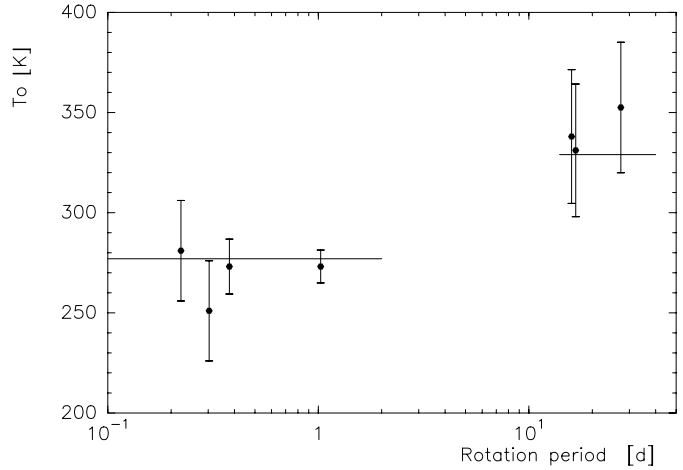


Fig. 1. Observed disk-averaged temperature of MBA and planetary satellites, normalized to a standard distance $r = 1$ AU, as a function of rotation time, t . For fast rotation, $t \leq 2$ days, $T_b = 277$ K; for $t > 12$ days, the observed $T_b \approx 329$ K, corresponding to the slow rotation model. The values of the two rotation models are indicated by thin horizontal lines. References for the 250 GHz data used: Vesta & Hebe (Altenhoff et al. 1994), Ceres (Altenhoff et al. 1996), Mars (prime calibrator), Callisto & Titan (Altenhoff et al. 1988), Moon, scaled to the disk averaged temperature (Krotikov & Pelyushenko 1987).

in Fig. 1. These brightness temperatures are compared with the equilibrium temperature (Eq. (1)) for non-rotation with $T_0 = 329$ K and for fast-rotation with $T_0 = 277$ K. For periods below two days T_b agrees well with T_{eq} for fast rotation, and for periods above 12 days T_b corresponds to the non-rotation model.

For periods smaller than 2 days the fast rotation model is applicable, for periods above 12 days the slow rotation model is valid. All known rotation periods of KBOs and of single MBAs are well below 2 days (see e.g. Shor 2002), thus in the range of applicability of the fast rotation model.

The most precise data in Fig. 1 is that of Mars, the prime calibrator at mm-wavelengths; the agreement of its brightness and equilibrium temperatures is strongly supporting the fast rotation model. An independent argument against the slow motion model for Mars is the missing radio phase. Its disk averaged brightness temperature, T_b , should vary with the phase angle, as we know it from the millimetric phase of the moon. But neither for Mars nor for any MBA such phase effect was observed. Since Mars is the body with the longest rotation period in the sample of the fast rotators, we can safely apply this model to our distant minor planets, which seem to have shorter rotation periods.

Jewitt et al. (2001) used the slow-rotator model and the Rayleigh-Jeans approximation, while Lellouch et al. (2000) used the fast-rotator model but a millimeter emissivity of 0.7, leading to different sizes and albedos.

In Table 2 the derived sizes and albedos for the KBOs we observed are compared with other published radio photometric results, adjusted to our photometry. For all objects the fast rotation model was assumed, and the systematic flux density underestimate due to the microwave background, even though

Table 2. Radio photometric sizes of distant minor planets.

Names	H [mag]	P [hours]	Δ [AU]	r [AU]	d [km]	Δd [km]	p	Δp	Reference	
Centaur and SDOs										
2060, Chiron	6.5	5.92	10.48	10.09	<317	–	–	>0.04	–	Jewitt & Luu (1992)
dto.	6.5	5.92	8.29	8.78	168	–13	+25	0.16	0.04	Altenhoff & Stumpff (1995)
10199, Chariklo	6.4	15.	12.62	13.35	268	–6	+13	0.07	0.01	Altenhoff et al. (2001)
2002TC302	3.7	–	48.45	48.58	<1195	–	–	>0.04	–	this paper
KBOs										
24835, 1995 SM55	4.8	4.0	39.41	39.38	<701	–	–	>0.04	–	this paper
19308, 1996 TO66	4.5	6.25	46.54	46.07	<897	–	–	>0.04	–	this paper
19521, Chaos	4.9	–	41.85	42.31	<742	–	–	>0.04	–	this paper
47171, 1999 TC36	4.9	6.21	31.64	31.27	609	–47	+93	0.05	0.01	this paper
38628, Huya	4.7	–	29.62	29.80	<540	–	–	>0.08	–	this paper
20000, Varuna	3.7	3.18	42.06	43.05	1016	–101	+202	0.06	0.02	Jewitt et al. (2001)
dto.	3.7	3.18	42.35	43.10	914	–104	+208	0.07	0.03	Lellouch et al. (2002)
28978, Ixion	3.2	–	42.24	43.09	<804	–	–	>0.15	–	this paper
55565, 2002 AW197	3.3	–	46.42	47.38	977	–87	+175	0.09	0.02	Margot et al. (2002)
50000, Quaoar	2.6	–	42.57	43.43	1260	–190	+190	0.10	0.03	Brown & Trujillo (2002)

NOTE – H , P , r , Δ , d , and p are, respectively, the optical magnitude, rotation period, heliocentric distance, distance from Earth, diameter, and geometric albedo. Size and geometric albedo of Quaoar are optically derived.

at 250 GHz only about 3% of the observed signal, was corrected. For the phase integral we assume $q = 0.28$. The absolute optical magnitudes, H , were taken from information provided by the Central Bureau for Astronomical Telegrams (CBAT) (2003).

3.3. Note on individual objects

The Pluto-Charon Binary, often considered the prototype of KBOs, we exclude from consideration, because it differs in all relevant aspects from the distant minor planets. Because KBOs, Centaurs, and SDOs seem to be of similar constitution (see above), they will be discussed together.

(2060) Chiron. Luu & Jewitt (1990) found an optically thin coma with a mass loss rate of order 1 kg/s around this Centaur. This is much too small to transport big dust particles into the coma, which could contaminate the observed thermal emission of the disk of Chiron. This is confirmed by the agreement of the radio photometric diameter with that derived from an occultation (Bus et al. 1996). Luu (1993) and others have stressed the “true cometary identity” of Chiron. However, Stern (1995) called Chiron a “hybrid object”, in between a planet and a comet. For the analysis of distant minor planets the cometary activity is only a side aspect, so no Centaur should be excluded.

(24835) 1995 SM55. The quoted rotation period is taken from Jewitt & Sheppard (2003); the optical light curve may be variable.

(19308) 1996 TO66. Hainaut et al. (2000) report a change from a double peaked light curve to a single peaked one, connected with an change of amplitude. Their preferred explanation is cometary activity between observing sessions.

(47171) 1999 TC36. This KBO was recognized as a binary by Trujillo & Brown (2002), which was confirmed by Marchis et al. (2002). The brightness difference between the components is about 2 mag, its orbital period is not yet known. The quoted rotation period was observed by Ortiz et al. (2003) with a high confidence level, but it could not be confirmed in a subsequent observation. If real, it might belong to the brighter component.

Assuming the same albedo and a fast rotation model, our flux measurement implies the components’ diameters to be 566 km and 225 km, respectively.

(28978) Ixion. Bertoldi (2002) initially reported an apparently spurious, marginal 250 GHz detection, which was not confirmed by later observations. Hahn et al. (2001) cite observations with “Astrovirtel” that resulted in an object size ≥ 1200 km, based apparently on the observed absolute optical magnitude H (not quoted) and an assumed geometric albedo $p = 0.07$. Lately, Boehnhardt (private communication) reported that the visual absolute magnitude is close to 3.8; this would reduce the geometric red albedo to $p > 0.08$. We were not able to detect Ixion, which, given its optical brightness, yields a very high lower limit to its geometric albedo.

(50000) Quaoar. The size of the KBO Quaoar was measured directly by Brown & Trujillo (2002). The radio photometric observations are not yet fully published.

4. Discussion

The re-evaluation of observations, e.g., by Jewitt et al. (2001), Lellouch et al. (2002), Margot et al. (2002) leads to sizes and geometric albedos, differing by 10 and 20%, respectively, compared with the original publications. For the observations under

discussion these differences are within the observational uncertainties. For measurements with higher intensity resolution, e.g., of MBAs, the selection of the appropriate thermal model is vital.

The re-evaluated geometric albedos for the three groups of distant minor planets in Table 2 vary between 0.06 and 0.16. The mid-infrared observations of Centaurs by Fernandez et al. (2002) show a similar distribution of the geometric albedo; compared with the cometary albedo, $p = 0.04$, the distant minor planets have a significantly higher albedo, $p \approx 0.08$.

For 6 of the 10 KBOs in our sample McBride et al. (2002) provide absolute magnitudes, H , and $(V - J)$ colors. For 4 distant minor planets the absolute magnitudes of CBAT and McBride et al. agree very well, for two objects there is a difference of about 0.5 mag – this should be followed up. This uncertainty of the absolute magnitude hardly affects the radio photometric size determination, but the derived geometric albedo, p , depends linearly on the optical brightness. We find no apparent correlation between the optical color and the geometric albedo for the objects in Table 2 due also to the small number of objects and the large errors on the albedos. Therefore more precise measurements, especially of the KBOs with high upper limits of the albedo, are urgently needed.

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