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THERMAL OBSERVATIONS OF CENTAUR 1997 CU26

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ABSTRACT

We combine new measurements of the thermal emission from the Centaur 1997 CU26 with published optical photometry to determine the geometric albedo (0.045 ± 0.010) and effective diameter (302 ± 30 km). While these values are model dependent, they clearly show that 1997 CU26 is the largest of the known Centaurs and that its surface is very dark.

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

1. INTRODUCTION

We define the Centaurs as objects that have both perihelia and semimajor axes located between the orbits of Jupiter (at 5.2 AU) and Neptune (at 30 AU). Currently, nine such objects are known, three of which (P/Oterma, P/Schwassmann-Wachmann 1, and 2060 Chiron) display cometary activity indicative of sublimating surface volatiles, while the remaining six appear stellar. The dynamical properties of Centaurs are largely determined by gravitational perturbations from the nearby gas giant planets. These perturbations limit the dynamical lifetimes to 10^6–10^7 yr (Asher & Steel 1993; Hahn & Bailey 1990; Dones, Levison, & Duncan 1996; Levison & Duncan 1997) and suggest that the Centaur population must be continually replenished if it is to maintain a steady state. The most likely source region is the Kuiper Belt (Jewitt & Luu 1993; Jewitt, Luu, & Trujillo 1998). It is now widely believed that the Centaurs are objects in transition from the Belt to the inner planetary system, where they eventually will appear to Earth-bound observers as short-period comets (Levison & Duncan 1997). In this sense, Centaurs are scientifically interesting as nearby (brighter, more accessible) examples of Kuiper Belt objects.

Centaur 1997 CU26 was discovered with the Spacewatch telescope (Scotti 1997). Both perihelion (13.07 AU) and aphelion (18.35 AU) lie between the orbits of Saturn and Uranus, and the long-term stability of the orbit is presumably affected by both planets. Its physical properties, like those of most other Centaurs, are poorly known. In this Letter, we present observations taken with a thermal imaging camera that were used to determine the size and albedo of this object.

2. OBSERVATIONS

Q-band observations (central wavelength $\lambda = 20.3$ μm, FWHM $\Delta\lambda = 3.5$ μm) were taken at the 3.8 m United Kingdom Infrared Telescope (UKIRT) on UT 1998 January 13. We used the MAX mid-IR camera, which was built at the Max-Planck-Institut für Astronomie in Heidelberg and consists of a 128 × 128 pixel Si:As array cooled to 4.75 K (Robberto et al. 1998). The image scale was 0″.27 pixel^{-1}, giving a field of view 35 arcsec square. Individual integration times were 10.24 ms, with each frame of data consisting of 1000 co-adds, for a total integration time of 10.24 s. The total integration time on 1997 CU26 was 5408 s. Centaur 1997 CU26 was too faint to be seen in the UKIRT guide camera. We tracked the telescope at sidereal rates and took observations of 1997 CU26 interleaved with the infrared standard stars HR 2990 ($Q = -1.21$) and HR 3748 ($Q = -1.49$; Tokunaga 1986) at air masses from 1 to 1.5.

We used a 10″ north-south chop throw and beam switching to eliminate the thermal background. A total of 264 frames of data were obtained for the CU26 field, with pairs of frames corresponding to one telescope beam-switch cycle. The difference of each pair of frames resulted in 132 flat, background-subtracted images in which each source is accompanied by two negative images of itself displaced exactly 10″ to the north and south. Each of these background-subtracted frames was shifted during data reduction to account for the motion of CU26 (at about 8″ hr^{-1} west, 0″.7 hr^{-1} north). The median of the resultant frames is shown in Figure 1.

There are three main reasons to believe that the source in Figure 1 is 1997 CU26. First, since the real time spent on 1997 CU26 exceeded 2.5 hr, stars and galaxies will be trailed by 20″, whereas the object in Figure 1 is untrailed. Second, it is highly unlikely that random clumps of noise or chip defects will appear as a negative source with two positive sources exactly 10″ to the north and south. As a test, we combined the data with no positional shifts and with a positional shift opposite to the expected motion of CU26. No sources were detected. Third, the source appeared within 1″ of the ephemeris position of 1997 CU26, and no other comparably bright sources were present within the field of view.

The azimuthally averaged point-spread function (PSF) of the data computed from standard star HR 2990 is plotted in Figure 2. The 1″.35 ± 0″.1 FWHM of the PSF is indistinguishable from the nominal diffraction-limited resolution of the UKIRT at 20 μm (1″.3 FWHM). The surface brightness profile of CU26 is also pointlike (Fig. 2), with a formally identical FWHM of 1″.13 ± 0″.2. Photometry was obtained using a synthetic aperture 3″.2 in diameter, with residual sky subtraction from a contiguous annulus of 9″.7 outer diameter. The *Q* filter is sufficiently broad that we must consider a possible color term due to the difference in temperature between the standard stars and

[1] Guest Observer at the United Kingdom Infrared Telescope.

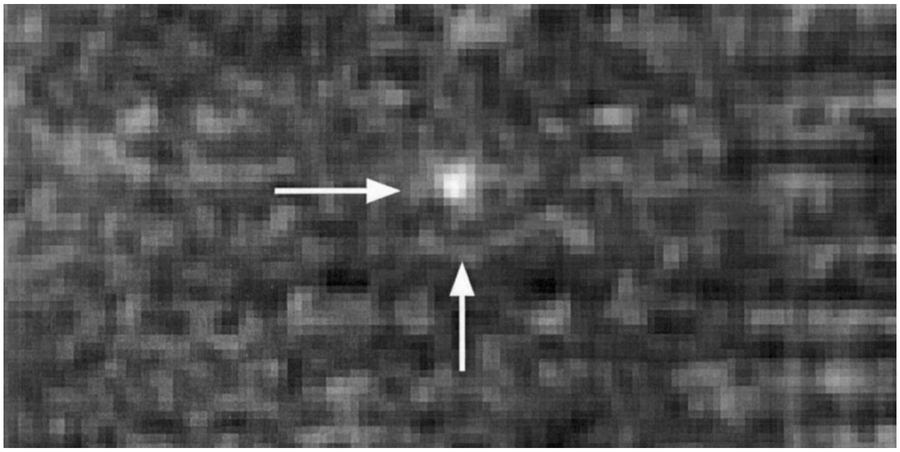

FIG. 1.—A portion of a MAX 20.3 μm image of 1997 CU26 taken on UT 1998 January 13. Separate frames (total integration 5408 s) have been shifted and combined to cancel the proper motion of the object. The image has north to the top, east to the left. The portion shown is 15″ tall.

1997 CU26. We used the filter and atmospheric transmission curves to calculate a monochromatic correction factor of 1.08. This is small compared with the photometric uncertainty, and so we neglect it. The observations are summarized in Table 1.

3. INTERPRETATION

The apparent V magnitude of a body viewed in scattered sunlight is related to its physical properties by (Russell 1916)

$$p_V \phi(\alpha) r^2 = 2.24 \times 10^{22} R^2 \Delta^2 10^{0.4(V_\odot - V)}, \quad (1)$$

where p_V is the V-band geometric albedo, $\phi(\alpha)$ is the phase function at phase angle α (in units of degrees), r is the radius (in units of meters), R and Δ are the heliocentric and geocentric distances (in astronomical units), respectively, and $V_\odot = -26.76$ is the magnitude of the Sun. We take $\phi(\alpha) = 10^{-\beta\alpha}$, with $\beta = 0.04$ mag deg^{-1}, but obtain essentially unchanged results when we use the more complicated HG formalism of Bowell et al. (1989), because α is small. The trajectory defined by equation (1) is plotted in Figure 3.

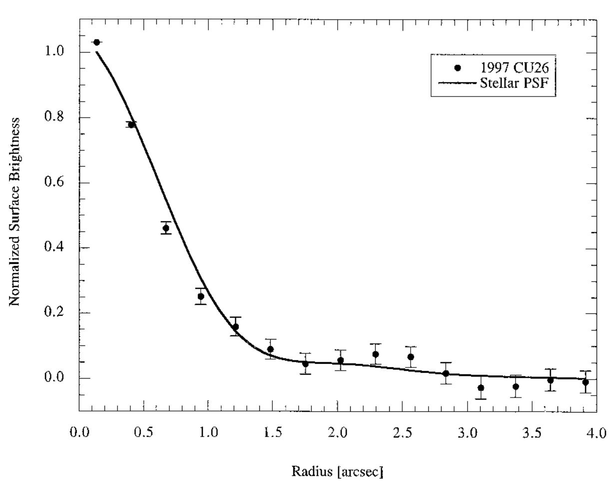

FIG. 2.—Normalized surface brightness profile of 1997 CU26 at 20.3 μm (*circles*) compared with the PSF defined by standard star HR 2990.

The 20 μm flux density is given by

$$S_\nu = \pi \epsilon B_\nu(T) r^2/\Delta^2, \quad (2)$$

where $B_\nu(T)$ is the Planck function for effective surface temperature T (in units of kelvins), ϵ is the emissivity, and Δ is the geocentric distance (in units of meters). The effective temperature is determined by the energy balance at the surface of 1997 CU26. It depends on several unknowns, including the albedo, emissivity, and thermal diffusivity of the surface materials, the spin period, and the orientation of the spin pole with respect to the Sun (Spencer, Lebofsky, & Sykes 1989). Because of these unknowns, it is not possible to solve exactly for the temperature distribution on 1997 CU26. However, to a first level of approximation, we may write the effective tem-

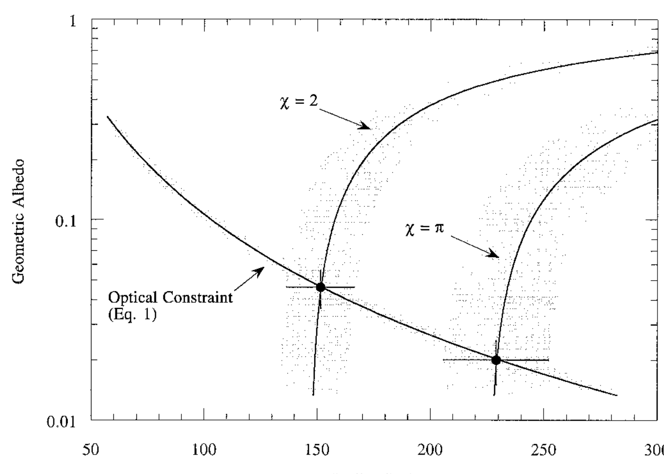

FIG. 3.—Constraints on the albedo and radius of 1997 CU26 from optical (eq. [1]) and thermal infrared (eq. [2]) observations (see text). The two lines marked $\chi = 2$ and $\chi = \pi$ denote different assumed temperature distributions on 1997 CU26, with the former corresponding to subsolar latitude 90° and the latter to subsolar latitude 0°. Shaded regions correspond to uncertainties in the 20 μm flux density and optical flux density of $\pm 20\%$ and $\pm 10\%$, respectively. The best fits to the data are indicated by filled circles. The solution at 151 km, 0.045 is preferred, for reasons given in the text.

TABLE 1
GEOMETRY AND PHOTOMETRY

UT Date (1)	R (AU) (2)	Δ (AU) (3)	α (deg) (4)	Filter (5)	λ (μm) (6)	Magnitude (7)	Reference (8)
1997 May 6	13.857	14.020	4.1	V	0.55	18.47 ± 0.02	1
1998 Jan 13	13.715	12.810	−1.7	Q	20.3	5.6 ± 0.2	2

NOTES.—Col. (1): UT date of the observation. Col. (2): heliocentric distance. Col. (3): geocentric distance. Col. (4): phase angle. Col. (5): filter designation. Col. (6): central wavelength. Col. (7): apparent magnitude.

REFERENCES.—(1) Davies et al. 1998; (2) this work.

perature as

$$T = \left[\frac{F_\odot(1-A)}{\sigma\epsilon\eta\chi R^2}\right]^{1/4}, \tag{3}$$

where $F_\odot = 1360$ W m^{-2} is the solar constant, R is the heliocentric distance (in astronomical units), $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is Stefan's constant, A is the Bond albedo (the scattered fraction of the incident solar flux), ϵ is the emissivity integrated over all frequencies, η is a correction factor (known as the "beaming parameter"; Lebofsky et al. 1986) needed to account for anisotropy of the thermal emission, and $2 \leq \chi \leq \pi$ is a dimensionless parameter that represents the spatial distribution of temperature. The geometric and Bond albedos are related by $A = p_V q$, where the "phase integral," q, is a measure of the angular dependence of the scattered radiation. Based on measurements of other airless planetary bodies (Harris 1961), we adopt $q = 0.75$ and note that this value is likely to be accurate to within about ±30%. A nonrotating body (or a body rotating with its spin axis aligned with the Sun) has $\chi = 2$ (this case is known, in the asteroid community, as the standard thermal model; Lebofsky et al. 1986). At the other extreme, the temperature variation on an equatorially illuminated, fast-rotating body will be constant with respect to longitude but will vary with latitude, θ, as $T(\theta) = T(0)\cos^{1/4}\theta$. In this case, $\chi = \pi$.

We believe that 1997 CU26 is viewed nearly pole-on ($\chi = 2$), since optical observations show no evidence for a rotational light curve at even the few percent level (Davies et al. 1998). Hence, we combine equations (2) and (3) with $\chi = 2$, $\epsilon = 0.9$ (Spencer et al. 1989), and $\eta = 0.756$ (Lebofsky et al. 1986) to obtain the second trajectory in Figure 3. The intersection of the optical and infrared trajectories in Figure 3 gives the best estimate of the radius, $r = 151 \pm 15$ km, and geometric albedo, $p_V = 0.045 \pm 0.010$, of 1997 CU26. However, systematic errors due to uncertainties in the adopted parameters (principally χ, but also η and ϵ) clearly exceed the quoted formal errors. For example, with the extreme $\chi = \pi$, we obtain the third trajectory in Figure 3, with best-fit values $r = 230 \pm 23$ km and $p_V = 0.020 \pm 0.005$. Regardless of the adopted rotation parameter, it seems certain that the nucleus of 1997 CU26 is both large and dark. With no way to resolve the ambiguities in the rotational properties and temperature distribution on the surface, we consider the $\chi = 2$ case as providing a sensible lower limit to the radius and an upper limit to the geometric albedo.

The physical properties of the Centaurs are summarized in Table 2. Optical-infrared observational constraints exist only for 2060 Chiron, 5145 Pholus, and 1997 CU26. Table 2 shows that 1997 CU26 is the largest known Centaur, with an effective radius 50% larger than that of Centaur prototype 2060 Chiron. If displaced to $R = 40$ AU, 1997 CU26 would rival in brightness many of the known Kuiper Belt objects (Jewitt et al. 1998). The geometric albedo of 1997 CU26 is formally identical to that of 5145 Pholus (Table 2). The albedo estimate for 2060 Chiron appears marginally higher than that for Pholus or CU26. However, the possibility of photometric contamination by a near-nucleus coma (2060 Chiron is one of the three cometary Centaurs) suggests that we should regard the listed 14% albedo as an upper limit rather than a measurement. Low albedos are also found on the surfaces of short-period comets (Campins, A'Hearn, & McFadden 1987; Millis, A'Hearn, & Campins 1988; A'Hearn et al. 1989), most of which are presumed to be ex-Centaurs (albeit smaller in size than 1997 CU26 by a factor of 10–30). Low albedo probably indicates a carbonized surface

TABLE 2
PROPERTIES OF THE CENTAURS

Name	a (AU) (1)	e (2)	i (deg) (3)	q (AU) (4)	Q (AU) (5)	Class (6)	r (7)	p_V (%) (8)	Reference (9)
P/SW1	6.00	0.05	9	5.7	6.3	C	20?	?	1
P/Oterma	7.28	0.25	2	5.5	9.1	C	?	?	...
2060 Chiron	13.65	0.38	7	8.5	18.8	C	90 ± 7	14^{+6}_{-3}	2
1997 CU26	15.71	0.17	23	13.1	18.4	A	151 ± 15	4.5 ± 1.0	3
1994 TA	16.84	0.30	5	11.7	22.0	A	11	?	4
1995 GO	18.07	0.62	18	6.9	29.3	A	37	?	4
5145 Pholus	20.22	0.57	25	8.7	31.8	A	95 ± 13	4.4 ± 1.3	5
7066 Nessus	24.59	0.52	16	11.8	37.4	A	39	?	4
1995 DW2	24.92	0.24	4	18.9	31.0	A	35	?	4

NOTES.—Col. (1): semimajor axis. Col. (2): eccentricity. Col. (3): inclination. Col. (4): perihelion distance. Col. (5): aphelion distance. Col. (6): morphological class: C = comet, A = asteroid. Col. (7): radius. Col. (8): geometric albedo.

REFERENCES.—(1) Meech et al. 1993; (2) Campins et al. 1994, Altenhoff et al. 1995, and Bus et al. 1996; (3) this work; (4) radius calculated from optical photometry alone assuming a geometric albedo of 0.04; (5) Davies et al. 1993.

composition, possibly one that has been processed by long-term cosmic-ray bombardment (Moroz et al. 1998). The reddish optical reflection spectrum (Binzel 1997) and near-infrared photometry (Davies et al. 1998) of 1997 CU26 are compatible with this interpretation. Curiously, well-established differences among the optical and near-infrared colors of Chiron, Pholus, and CU26 (Luu, Jewitt, & Cloutis 1994; Luu & Jewitt 1996; Binzel 1997; Davies et al. 1998) do not seem to correspond to a wide range in the albedos. This finding, while clearly preliminary in view of the small available sample size, tends to support published estimates of Kuiper Belt object diameters obtained under the assumption of low (4%) uniform albedo.

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