1998 SM_{165}: A large Kuiper belt object with an irregular shape

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Edited by Robert P. Kirshner, Harvard–Smithsonian Center for Astrophysics, Cambridge, MA, and approved August 9, 2001 (received for review March 26, 2001)

The recent discovery of an ancient reservoir of icy bodies at and beyond the orbit of Neptune—the Kuiper belt—has opened a new frontier in astronomy. Measurements of the physical and chemical nature of Kuiper belt objects (KBOs) can constrain our ideas of the processes of planet formation and evolution. Our 1.8-m Vatican Advanced Technology Telescope and charge-coupled device camera observations of the KBO 1998 SM_{165} indicate its brightness periodically varies by 0.56 magnitudes over a 4-h interval. If we assume a uniform albedo of 0.04, which is typical of values found in the literature for a handful of KBOs, and an "equator-on" aspect, we find 1998 SM_{165} has axes of length 600 × 360 km. If our assumptions are correct, such dimensions put 1998 SM_{165} among the largest elongated objects known in our solar system. Perhaps long ago, two nearly spherical KBOs of comparable size coalesced to form a compound object, or perhaps 1998 SM_{165} is the residual core of a catastrophic fragmentation of a larger precursor.

During the last decade of the twentieth century, planetary astronomers made a major addition to the inventory of our solar system with the discovery of an ancient reservoir of icy bodies at and beyond the orbit of Neptune, the Kuiper belt (1). Over 400 Kuiper belt objects (KBOs) with diameters larger than 100 km are known to exist (see http://cfa-www.harvard.edu/iau/lists/Unusual.html). The present day belt probably contains $\approx 10^5$ objects larger than 100 km in diameter and probably $\approx 10^8$ objects larger than 10 km in diameter (2). The total mass in the belt between 30 and 50 astronomical units (AU) is probably about 0.3 $M_{\oplus}$ (Earth mass; ref. 2). The primitive nature of the material in the belt likely holds important clues about the formation and evolution of our solar system. Unfortunately, even the most fundamental properties of KBOs, such as size and shape, are difficult to discern. A large KBO like 1998 SM_{165}, with a long axis of 600 km and a distance of 35 AU from the Earth, has an angular diameter of only 0.02 arcsec, which is too small for the Hubble Space Telescope to resolve. At present, photometry is the best means to estimate the sizes and shapes of KBOs (3). Here, we report that 1998 SM_{165} is likely among the largest elongated objects known in our solar system.

Observations

Our observations were obtained with Harris B (450 nm), V (550 nm), and R (650 nm) glass filters in front of a 2,048 × 2,048 pixel charge-coupled device (CCD) camera at the f/9 aplanatic Gregorian focus of the 1.8-m Vatican Advanced Technology Telescope (the Alice P. Lennon telescope and Thomas J. Bannan facility) on Mt. Graham, Arizona (see http://clavius.as.arizona.edu/vo/). We binned the CCD 2 × 2, yielding 1,024 × 1,024 pixel images, covering 6.4 arcmin × 6.4 arcmin of the sky at 0.42 arcsec per pixel. The observations were obtained between 1999 November 13 and 15 and 2000 September 28 and October 1 Universal Time (UT) under photometric conditions. The typical seeing (full width at half-maximum of the stellar point-spread function) was $\approx$1.5 arcsec. A short exposure time of 300 s and a sidereal tracking rate combined to smear the images of 1998 SM_{165} by less than a pixel. We obtained bias images at the start and the end of each night and dithered the telescope between exposures during the night to create "dark sky" flat-fields for each filter. Each night, we obtained images of Landolt standard star fields (4). We inspected the aperture and sky annulus around each image of 1998 SM_{165} and a faint star (a control) for contamination by faint background stars or galaxies. If necessary, we cleaned the sky annulus of any faint stars or galaxies that might bias the sky measurements by replacing them with a patch of nearby sky. We discarded any images of KBOs or faint stars contaminated by images of faint background stars or galaxies. We used the PHOT package in the IMAGE REDUCTION AND ANALYSIS FACILITY to measure instrumental magnitudes for 1998 SM_{165}, faint stars, standard stars, and point-spread function stars. To maximize the signal-to-noise ratio of our data, we applied an aperture correction procedure to 1998 SM_{165} and the faint stars (5). We derived extinction coefficients and transformation equations from our observations of the Landolt standard star fields (4) to place the instrumental magnitudes of 1998 SM_{165} and the faint stars on the Kron–Cousins photometric system. The transformation equations derived for the 1999 November and 2000 September/October data differed by only a couple of percent points, indicating a highly stable telescope and detector system.

Results

Our measurements of the size and shape of 1998 SM_{165} come from the photometry data in Fig. 1. In Fig. 1 *a* and *b*, we plotted the 1999 November and 2000 September/October data, respectively. The solid circles and open circles represent 1998 SM_{165} and faint comparison stars (controls), respectively. The points in Fig. 1*a* come from observations made through B, V, and R filters. We used the $B - V = 1.01 \pm 0.10$ and $V - R = 0.75 \pm 0.07$ colors of 1998 SM_{165} (6), which do not exhibit any variation with time, to convert the B and R measurements to V magnitudes. All of the points in Fig. 1*b* come from observations through an R filter. The error bars in both Fig. 1 *a* and *b* are dominated by sky noise. Error bars in Fig. 1*b* are smaller because of better seeing and the extremely red surface color of 1998 SM_{165} (6). The time for each point corresponds to a period midway through an exposure. The zero of time for each panel occurs at 0 h UT on the first night of each run for 1999 November 11 and 2000 September 28. To remove any systematic shifts in time between nights caused by changes in the distance of 1998 SM_{165} from the Earth, we corrected for the time of light travel, i.e., we subtracted Δ/c from each midpoint exposure time, where Δ is the geocentric distance and c is the speed of light. A comparison of the KBO and faint-star points clearly demon-

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This paper was submitted directly (Track II) to the PNAS office.

Abbreviations: KBOs, Kuiper belt objects; UT, Universal Time; AU, astronomical unit.

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www.pnas.org/cgi/doi/10.1073/pnas.211147998

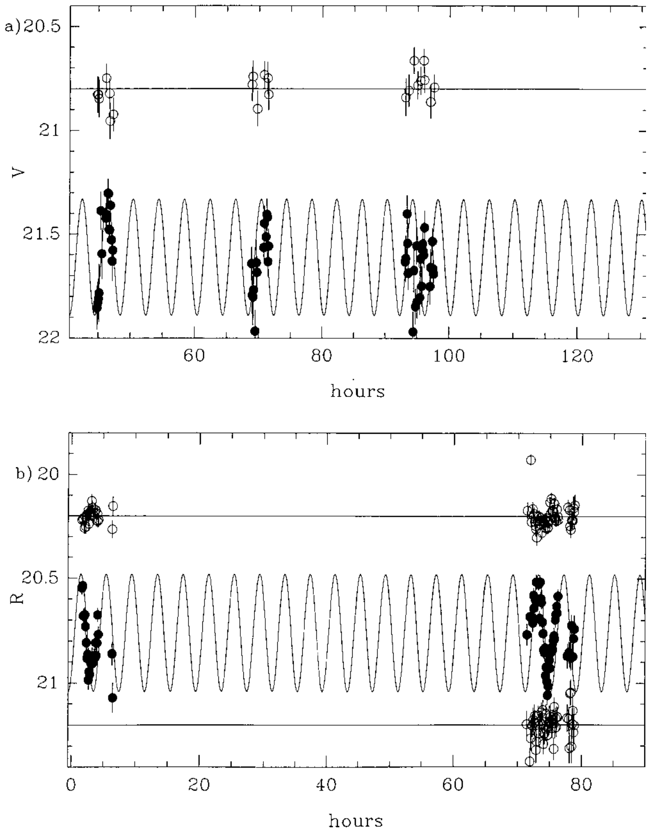

Fig. 1. Vatican 1.8-m telescope brightness measurements of the Kuiper belt object 1998 SM_{165} and a faint field star. (*a*) Observations between 1999 November 13 and 15 UT. ●, 1998 SM_{165}; ○, a faint field star (the control). (*b*) Observations between 2000 September 28 and October 1 UT. The sine curve in both *a* and *b* has a peak-to-trough amplitude of 0.56 magnitudes and a period of 3.983 h. The faint star points (below) nicely bracket the brightness variations of 1998 SM_{165}; i.e., one star has brightness at the peak and the other has brightness at the minimum of 1998 SM_{165}. We have shifted the faint star points upward and downward on the graph by a few tenths of a magnitude for clarity.

strates that 1998 SM_{165} is varying in brightness, i.e., the brightness variation (light curve) of 1998 SM_{165} is not an observational or data-analysis artifact. We analyzed the brightness variations in Fig. 1 by using the techniques of phase dispersion minimization (7) as well as phasing the data with every possible period between 1 and 10 h. We found a single sine curve with a peak-to-trough amplitude of 0.56 magnitudes and a period of 3.983 h best represents the brightness variations in both the 1999 and 2000 data.

If we use the V-R color of 1998 SM_{165} (6) to convert the R magnitudes in Fig. 1*b* into V magnitudes and then scale the brightest V magnitudes of the 1999 November and 2000 September/October data (Table 1) to their values at heliocentric and geocentric distances of 1 AU and a phase angle of 0°, i.e., if we remove the dependence of brightness on distance and phase angle by calculating absolute magnitudes,

$$H_v = V - 5\,\log(r\Delta) + 2.5\,\log[(1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)],$$

where r is the heliocentric distance (in AUs), Δ is the geocentric distance (in AUs), α is the phase angle (in degrees), and Φ is the phase function (8),

$$\Phi(\alpha) = (1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)$$

Table 1. Distances, phase angles, brightest magnitudes, and dimensions of the Kuiper belt object 1998 SM_{165}

Measurements	1999 November	2000 September
r, AU	34.42	34.69
Δ, AU	33.65	33.70
α, °	1.1	0.2
V_{bright}, magnitude	21.33	21.22
H_{bright}, magnitude	5.85	5.83
a × b, km	590 × 350	600 × 360

*The quantity a × b represents the axes, if the KBO has a football-like shape (a = 1.7:b = 1:c = 1). Our analysis assumes an albedo of 0.04 and an "equator-on" aspect.

$$\Phi_i(\alpha) = \exp\{-A_i(\tan\tfrac{1}{2}\alpha)^{B_i}\},$$

where $i = 1{,}2$, A_1=3.33, B_1=0.63, A_2=1.87, B_2=1.22, and G = 0.15, we obtain peak absolute magnitude values of 5.85 and 5.83 for 1999 November and 2000 September/October. Although the brightness of 1998 SM_{165} varies by 0.56 magnitudes on a time scale of hours, the peak absolute magnitude remains remarkably constant over nearly a year.

We can use our observations to constrain the area that 1998 SM_{165} projects on the plane of the sky. The projected area A (in km^2) of a KBO can be derived from the definition of albedo p,

$$p\Phi(\alpha)A = 7x10^{16}r^2\Delta^2 10^{0.4(m\,-\,V)}$$

where m is the apparent solar magnitude in V band (−26.74), and V is the magnitude of the KBO in V band. To determine unambiguously the projected area and albedo, we require simultaneous optical and thermal infrared or submillimeter photometry. Unfortunately, only a handful of KBOs and Centaurs (recent refugees from the Kuiper belt) are bright enough in the thermal infrared or submillimeter for albedo measurements. KBO albedos reported in the literature range from 0.02 to 0.08, i.e., objects as dark as charcoal (9–12). If we use an intermediate value for albedo (e.g., p = 0.04), the heliocentric and geocentric distances and phase angles in Table 1, and the brightest V magnitudes for 1998 SM_{165} in Fig. 1 (see Table 1) we obtain projected areas of 1.6×10^5 km^2 and 1.7×10^5 km^2 for the 1999 November and 2000 September/October data, respectively.

The brightness variation in Fig. 1 could be the result of surface markings. Specifically, 1998 SM_{165} may have a spherical shape with light and dark surface markings (for example, one hemisphere darker on average than the other, as in the case of Iapetus). If this is the case, each rotation of the KBO results in one minimum and one maximum in the light curve and a rotation period of 3.983 h. Such a case probably is not likely. If we calculate the period (P_{crit}) at which a KBO rotates so fast that it will throw material off its equator and hence be unlikely to retain a regolith or even form in the first place by accretion, we obtain

$$P_{crit} = \left(\frac{3\pi}{G\rho}\right)^{\frac{1}{2}}$$

where ρ is the density. If we assume ρ = 1 g/cm^3, we obtain P_{crit} = 3.3 h. Our photometric period of 3.983 h for 1998 SM_{165} is only slightly larger than the critical period. In addition, we find no variation of the B-V and V-R colors with rotational phase. Finally, we point out that albedo variations play only a minor role in the light curves of asteroids (13). It seems unlikely that surface markings give rise to the brightness variation in Fig. 1.

Another possible cause for the brightness variation in Fig. 1 is that 1998 SM_{165} has an elongated shape, and rotation of the object results in a periodic variation of the projected area on the sky. Each rotation of the elongated object results in two minima and two maxima in the light curve as we observe the two different hemispheres. The rotation period of 1998 SM_{165} is then twice the light-curve period, or 7.966 h.

Most asteroid light curves show moderate to extreme deviation from a simple sine curve, because asteroids are not really ellipsoids. After getting the photometric period (3.983 h) for 1998 SM_{165} from a sine curve fit, we created a phased light curve, folded on the rotational period of 1998 SM_{165} (7.966 h). To create this curve, we used the data from the two nights of observation in 2000 and the first two nights of observation in 1999. The data from the third night in 1999 had much larger error bars than the other data sets. To combine properly the 1999 and 2000 data, we need to know which peak in the photometric light curve corresponds to which hemisphere of the body. We do not know the rotation period well enough to know the exact number of rotations between the 1999 and 2000 observations and, hence, are left with an ambiguity: which peak and hemisphere in the 1999 data corresponds to which peak and hemisphere in the 2000 data? To begin, we set the first peak of the first night of the 2000 data (at ≈1.6 h in Fig. 1*b*) to a phase of zero. To determine the phase of the peaks in the 1999 data (Fig. 1*a* at ≈46 and 71 h), we phased the two nights from 2000, and then over-plotted the 1999 data with the 46- and 71-h peaks at a phase of zero and then at a phase of 0.5. We offset the magnitude scale of the 1999 data to match best the 2000 data in the region of overlap between the 1999 and 2000 data on the phase curve. If the two hemispheric light curves were very close in shape, we could not remove the ambiguity. However, the phased-light curve from the 2000 data alone shows a different slope between the two rising portions of the light curve. The over-plotting of the 1999 data shows that the assumption that the first observed peak in the 1999 data corresponds to a phase of 0.5 on the phased light curve gives a better fit than the assumption that the first peak is a phase of zero. The magnitude offset between the 1999 and 2000 data also were calculated by using the known color of the object and distances and solar illumination phases at the two observing epochs. The calculated offset differed from the graphically determined offset described above by a few hundredths of a magnitude, which is well within the uncertainty of the color.

In Fig. 1, the observed magnitudes from 1999 and 2000 have been plotted over the same length of time, with the start time at the same phase of the rotational light curve. This approach makes it easy to see that the first peak observed in 1999 is the opposite hemisphere from the first peak observed in 2000. In Fig. 2, we show the rotationally phased light curve of 1998 SM_{165} using two nights of data from 1999 and two nights of data from 2000, as described above. This light curve was fit by a spline curve, shown by the continuous curved line. The peak to trough amplitude of the spline curve is 0.56 magnitudes.

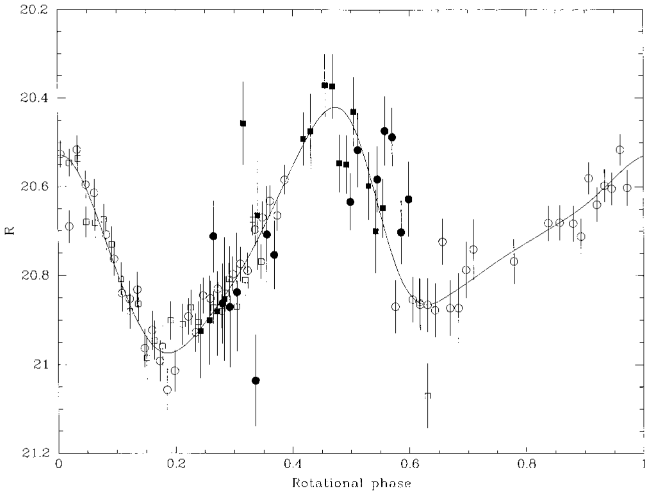

Fig. 2. The light curve from the first two nights in 1999 (Fig. 1*a*) and two nights in 2000 (Fig. 1*b*) phased with the rotational period of the object (7.966 h). The abscissa is the rotational phase, with zero set to the first observed peak in the 2000 data. ■ and ●, data from 1999 November 13 and 14 UT, respectively; □ and ○, data from 2000 September 28 and October 1 UT, respectively. The continuous curved line is a spline function fit to the data.

The amplitude of the light curve, Δm, is related to the major axis, a, and the intermediate axis, b, of a triaxial object by the equation

$$\Delta m = 2.5 \log\left(\frac{a}{b}\right)$$

where we assume that the axis of rotation is perpendicular to the line of sight (an equator-on aspect) and lies along the short axis c of the body. In the case of 1998 SM_{165}, $\Delta m = 0.56$ magnitudes, and so, $a/b = 1.7$. If we could observe the KBO for many decades, we would observe a change in the shape of the light curve as our line of sight changed with respect to the rotation axis. In principle, we could then determine the true axial ratio of 1998 SM_{165}. Because we do not know the orientation of the rotation axis—an axial ratio of $a/b = 1.7$ is a lower limit—1998 SM_{165} could be even more elongated in shape. If we assume a football-like shape, i.e., $a = 1.7$:$b = 1$:$c = 1$, we find 1998 SM_{165} has axes of length 600 × 360 × 360 km.

Conclusions

The large dimensions and irregular shape of 1998 SM_{165} make it an unusual KBO. In fact, the next largest KBO with an irregular shape in our KBO light-curve survey is 1994 VK_8 (3). If we assume an albedo of 0.04 and a football-like shape, we find axes of length 280 × 190 × 190 km for 1994 VK_8, which is significantly smaller than 1998 SM_{165}. We mention that a recent note to the *International Astronomical Union Circulars* reports a brightness variation for a KBO known as Varuna (14). Varuna is known to have a diameter of 900 km and an albedo of 0.07 (11). Further observations of Varuna are necessary to determine whether the light curve is caused by an irregular shape, albedo variations, or a binary.

How does 1998 SM_{165} compare with the largest satellite and asteroid with irregular shapes? An analysis of Voyager 2 images of Hyperion, a satellite of Saturn, found it has axes of 350 × 240 × 200 km (15). The shape and heavily cratered surface of Hyperion suggest that it is a collision fragment of a larger parent body (15). The asteroid 624 Hektor, with axial lengths of 300 km × 150 km and $P = 0.038$ (16), is the largest, highly elongated asteroid known in our solar system. It is difficult to explain Hektor as a collision fragment because the Trojan asteroids that surround Hektor are all smaller and rounder. How could a catastrophic collision produce one very large splinter-shaped fragment and many smaller and rounder fragments? A possible explanation for the origin of Hektor is that two similar-sized and nearly round Trojans gently coalesced to form a dumbbell-shaped object (16).

Hyperion and Hektor point to possible evolutionary paths for 1998 SM_{165}. Perhaps 1998 SM_{165} is the residual core of a catastrophic collision, like Hyperion. The present orbit of 1998 SM_{165} has perihelion and aphelion distances of 30 and 66 AU, respectively, and a large eccentricity of $e = 0.38$. It seems that

1998 SM_{165} is one of only four known KBOs in a stable 1:2 resonance with Neptune. Perhaps the precursor of 1998 SM_{165} was initially on a near-circular orbit and was a member of the classical belt at a distance of ≈45 AU from the Sun. Perhaps the nearly spherical and larger precursor then was caught in the 1:2 resonance as Neptune migrated outward (17). Then, during one of its eccentric orbits about the Sun, the precursor had a catastrophic collision with a classical KBO. Perhaps 1998 SM_{165} is a splinter of such a collision. Another possibility is that before the resonance sweeping of Neptune, two nearly round precursors of similar size coalesced with low relative velocities in the classical belt to form a compound KBO. Perhaps the compound object then became trapped in the 1:2 resonance as Neptune swept outward. In either case, 1998 SM_{165} is an unusual object that likely will shed light on planetary accretion or disruption processes in the outer solar system.

We thank Dr. D. Schleicher for application of his phase dispersion minimization and phasing software to our data. We thank the National Aeronautics and Space Administration Planetary Astronomy Program (NAG5–7757) for financial support. We thank the Steward Observatory and Vatican Observatory Telescope Allocation Committees for consistent allocation of telescope time.

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