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PHOTOMETRY OF THE TRANS-NEPTUNIAN OBJECT 1993 SC

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ABSTRACT

We obtained broadband photometry of the Trans-Neptunian Object 1993 SC with the Steward Observatory 1.5-m telescope near Mt. Bigelow, Arizona and the Lunar and Planetary Laboratory CCD on 1996 October 8. 1993 SC exhibited a constant brightness (V=22.67) with a 1σ scatter about the average of 0.06 magnitudes during a five hour interval. In addition, we obtained observations of 1993 SC with the Steward Observatory 2.3-m telescope on Kitt Peak, Arizona during 1995 November 24–27. Once again 1993 SC exhibited a constant brightness (V=22.73) with a 1σ scatter about the average of 0.04 magnitude. If 1993 SC has a lightcurve, the amplitude must be at the level of 0.12 magnitude or less. If the obliquity of 1993 SC is near zero degrees, then 1993 SC is spherical with a semi-major to semi-minor axis ratio less than or equal to 1.12. A spherical nature for 1993 SC may be the result of self-gravity exceeding the tensile strength of the material in the interior of 1993 SC. If the obliquity of 1993 SC is large, then 1993 SC could have an irregular shape. The steady intrinsic brightness for 1993 SC suggests that the object has a relatively uniform surface albedo. Our photometry and the assumption of a comet-like albedo (0.04) indicates that the diameter of 1993 SC is ~240 km. © *1997 American Astronomical Society.* [S0004-6256(97)00609-2]

1. INTRODUCTION

Five years ago Jewitt & Luu (1993) made a major breakthrough in planetary astronomy, the discovery of the first member (1992 QB_1) of a new population of outer solar system objects. As of 1997 May the new population consisted of 41 objects on low eccentricity and low inclination orbits between 30 and 50 AU from the Sun (Marsden 1997). Much of the subsequent work by Jewitt & Luu (1995) on Trans-Neptunian Objects (TNOs) has been in the form of surveys to map out their number and size distribution. Jewitt, Luu, and their collaborators have been responsible for the discovery of the majority of the 41 TNOs.

During the last couple of years a few groups have initiated programs to constrain the physical and chemical properties of TNOs (Williams *et al.* 1995; Luu & Jewitt 1996a, 1996b; Davies *et al.* 1997; Tegler & Romanishin 1997; Romanishin *et al.* 1997). These groups have posed questions such as: **(a)** Do TNOs show a similarity or diversity in their surface colors and hence their surface compositions? **(b)** What are the shapes of TNOs? and **(c)** How do TNOs rotate? The answers to these questions will provide important clues for our understanding of the formation and evolution of these distant solar system objects.

Because 1993 SC is one of the brightest TNOs, it is a good object to observe first in a survey aimed at describing the physical and chemical properties of TNOs. Two groups have carried out programs to constrain the shape and rotational properties of 1993 SC. Williams *et al.* (1995) have reported the possible detection of a lightcurve with a 7.7 hour period and an amplitude of 0.5 mag. Their lightcurve is consistent with a major to minor axis ratio of 1.6:1. The lightcurve comes from R band discovery images taken with the 2.5 m Isaac Newton Telescope. However, Williams *et al.*

have mentioned that there is 80% chance that their light curve is pure noise. Davies *et al.* (1997) have reported that 33 R band images, taken with the Isaac Newton Telescope over a five night interval, show that the 1993 SC lightcurve must have an amplitude of less than 0.2 mag.

In this paper, we report on our photometry of 1993 SC with the Steward Observatory 1.5 and 2.3 m telescopes. Our measurements paint a consistent picture of 1993 SC as a spherical (if the rotation axis of 1993 SC is orthogonal to our line of sight) and very red object.

2. OBSERVATIONS

Observations of the TNO 1993 SC were obtained on 1996 October 8 UT, using the Steward Observatory 1.5 m (61 in.) telescope near Mt. Bigelow, Arizona. We used a camera assembly that included reducing optics, a filter that combined the V and R bands, and a TI 800×800 pixel CCD. The $V+R$ filter had a central wavelength of 5900 Å and a full width half maximum of 2150 Å. The reducing optics resulted in each image having a field of view ~ 10 arcmin in diameter and an image scale of 0.93 arcsec per pixel. Besides our observations of 1993 SC, we obtained observations of the standard star field in M67 (Schild 1983). The observations of 1993 SC that we described in detail below were obtained during a five hour interval on 1996 October 8 UT.

We carried out our image processing and photometry with the IRAF software. All images were first bias subtracted. Our flatfield was constructed from 27 bias subtracted images of 1993 SC. Specifically, we systematically moved the telescope between exposures so that a median combination of the 1993 SC images would remove field stars, galaxies, and 1993 SC and thereby result in an excellent flatfield. The flatfield was then divided into the bias subtracted images of 1993 SC.

After bias subtraction and flatfielding, the regions around 1993 SC, the comparison stars, and the standard stars in the images were searched visually for nearby cosmic rays. Cosmic rays on this chip were easy to spot, and usually affected only 3 or 4 pixels. One image contained a cosmic ray coincident with the center of 1993 SC, we discarded this image.

To increase the signal to noise ratio, we averaged groups of individual 600 sec images, taken consecutively. Each group consisted of 3 images. Because of the motion of 1993 SC, two different averages were produced for each group. One average had the individual 600 second images registered on the field stars prior to combination. The other average had the individual 600 second images registered on 1993 SC prior to combination. Typical 1993 SC motion was about 1.5 pixels per half hour. By averaging in this way, the motion of 1993 SC from image to image did not contribute to the smearing of the 1993 SC image. The motion of 1993 SC during each individual image did contribute to smearing, but this motion was small, less than 0.5 pixel.

TNOs are so faint that the uncertainty in their magnitudes is dominated by sky noise. Under such conditions, it is common in stellar photometry to use a small aperture to make the instrumental magnitude measurements, in order to minimize the sky noise. We used this method to get instrumental magnitudes for 1993 SC. For each group of images, we measured the instrumental magnitude of 1993 SC and two comparison stars with an aperture 3.7 arcsec in diameter (4 pixel diameter). The 1993 SC and comparison star instrumental magnitudes were measured from TNO and stellar registered images, respectively. These measurements yielded magnitude differences between 1993 SC and the sum of the two comparison stars which were not affected by seeing variations, tracking errors, or focus problems. Aperture photometry was done with the PHOT task in the IRAF DIGIPHOT package. For all photometry, the sky value was found in an annulus from 5 to 11 pixel radius. The sky value was the peak of a gaussian fit to the histogram of pixel values in the sky annulus. If necessary, the sky annulus was first cleaned of objects which might bias the sky measurement by replacing them with a patch of nearby sky.

As a control, we measured the magnitude difference between a faint, isolated, field star and the two comparison stars. The faint field star was a few tenths of a magnitude brighter than 1993 SC. The magnitude differences for both 1993 SC and the faint field star (relative to the comparison stars) showed random scatter about their averages and standard deviations of 0.06 and 0.07 mag, respectively. Therefore, our photometry suggests that any lightcurve for 1993 SC must have an amplitude $\leqslant 0.12$ mag.

Although our measurements were made through a $V+R$ filter, we were able to convert our instrumental magnitudes from the $V+R$ filter to standard Vmagnitudes on the Kron-Cousins system. We found that the instrumental magnitude of star #108 in the M67 cluster (Schild 1983) is 12.96 magnitudes brighter than the average instrumental magnitude of 1993 SC on 1996 October 8 in the $V+R$ filter, all photometry corrected to zero airmass and for an aperture with a 10 pixel diameter. Since the full width half maximum of the point spread function was ~1.9 arcsec (2.0 pixels), a 10 pixel diameter aperture contained essentially all the light from a point source. Because 1993 SC and star #108 have the same $V-R$ color (see Tegler & Romanishin 1997 and Schild 1983) and star #108 has a V magnitude of 9.71 (Schild 1983), the average V magnitude for 1993 SC on 1996 October 8 was 12.96+9.71 or 22.67.

In Fig. 1 we have plotted our photometry for 1993 SC and the faint field star on the V magnitude scale (1996 October 8 UT). In Fig. 2, we have plotted our V band photometry for 1993 SC from 1995 November 24 to 27 (see Tegler & Romanishin 1997). 1993 SC shows no brightness variation over the nearly five hour interval in Fig. 1 ($V=22.67\pm0.06$) or the four day interval in Fig. 2 ($V=22.73\pm0.04$).

We can compare the photometry from 1995 November and 1996 October and look for a brightness variation if we first correct for changes in heliocentric distance, geocentric distance, and phase angle. We have used the formalism of Bowell *et al.* (1989) to correct our 1995 November photometry to our 1996 October photometry. In the formalism of Bowell *et al.*, the relationship between the apparent magnitude of a bare comet nucleus or asteroid, V, and its absolute magnitude, H, (the magnitude at unit heliocentric and geocentric distance and phase angle of zero degrees) is given by

$$V=H+5\log(r\Delta)+f(\alpha) \qquad (1)$$

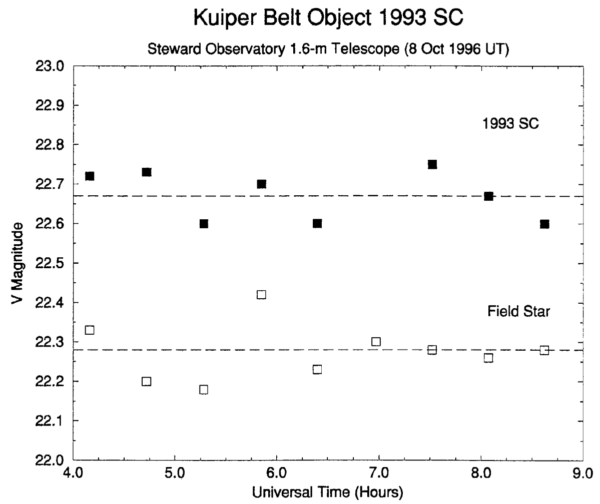

FIG. 1. A V band light curve for the TNO 1993 SC and a field star of brightness similar to 1993 SC. Observations were obtained on 1996 October 8 UT with the Steward Observatory 1.5 m telescope. The 1σ scatter about the average ($V=22.67$) for 1993 SC is 0.06 mag. The amplitude of any light curve must be ≤ 0.12 mag.

and

$$f(\alpha)=-2.5 \log[(1-G)\Phi_1(\alpha)+G\Phi_2(\alpha)], \quad (2)$$

where

$$\Phi_i=\exp[-A_i(\tan\tfrac{1}{2}\alpha)^{B_i}] \quad (3)$$

and $i=1,2$, $A_1=3.33$, $B_1=0.63$, $A_2=1.87$, $B_2=1.22$, r and Δ are the heliocentric and geocentric distances in AU, and α is the phase angle in degrees. These relationships have been adopted by the IAU for asteroid magnitude predictions. We take $G=0.15$ (see Bowell *et al.*). In Table 1 we present r, Δ,

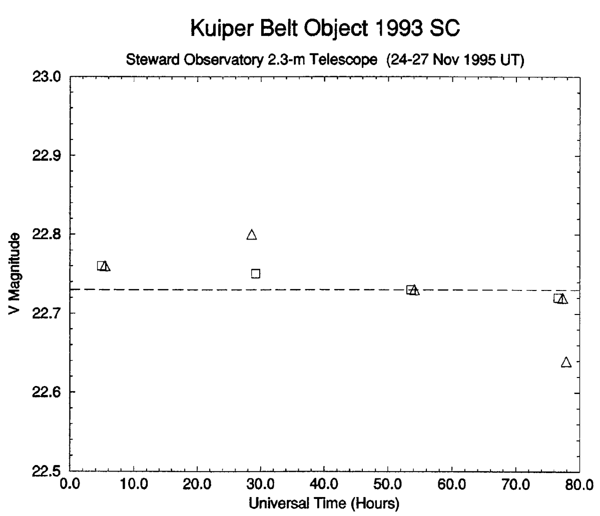

FIG. 2. A V band light curve for the TNO 1993 SC. Observations were obtained over the interval 1995 November 24–27 with the Steward Observatory 2.3 m telescope. The data is adopted from Tegler & Romanishin (1997). The open squares are true V magnitudes. The open triangles are from observations through an R filter and scaled to V magnitudes with a $V-R$ color for 1993 SC of 0.70 (derived in Tegler & Romanishin). The 1σ scatter about the average ($V=22.73$) is 0.04 mag.

TABLE 1. Distances and phase angles for 1993 SC.

Date (UT)	r (AU)	Δ (AU)	α (deg)
1995 Nov 24	34.20	33.69	1.4
1996 Oct 8	34.33	33.35	0.3

and α. From Table 1 and the above expressions, we find that 1993 SC should have been 0.13 mag brighter in 1996 October. Therefore, our 1995 November V magnitude of 22.73 scales to a V magnitude of 22.60 in 1996 October. Such a predicted magnitude for 1996 October is in excellent agreement with our observed V magnitude of 22.67. Hence, any periodic brightness variation of 1993 SC must be equal to or less than 0.12 mag on time scales of hours, days, and nearly a year.

3. ANALYSIS

3.1 Shape

Periodic variation in the brightness of a TNO (a light curve) can have three causes: **(a)** The object has a highly uniform surface albedo, but an elongated shape and hence each rotation results in two minima and two maxima in the light curve. **(b)** The object is spherical, but the surface has albedo variations, perhaps one hemisphere is darker (on average) than the opposite hemisphere, and hence each rotation results in one minimum and one maximum in the light curve. **(c)** Two TNOs are revolving about their common center of mass and occultations and eclipses of the two bodies results in a periodic brightness variation. Perhaps all of these mechanisms operate in the TNO population. In the analysis below, we have assumed that any brightness variation of a TNO is the result of rotation of a triaxial figure.

Although 1993 SC does not show any evidence of periodic brightness variation, we have used our measurements to constrain the shape and orientation of the rotation axis of 1993 SC. Specifically, the amplitude of a light curve, Δm, is related to the long axis, a, and the intermediate axis, b, of a triaxial figure by the equation

$$\Delta m=2.5 \log\frac{a}{b},$$

where we have assumed the axis of rotation is perpendicular to the line of sight and lies along the short axis, c, of the body. Since our measurements have shown that $\Delta m \leq 0.12$ mag, the above expression suggests that $a{:}b\leq 1.12{:}1$, if the axis of rotation is orthogonal to our line of sight. If we viewed the object pole-on, 1993 SC could have an elongated shape.

3.2 Diameter

If we assume a comet like albedo of $p=0.04$, we can estimate the diameter, D (meters), of 1993 SC. From the definition of albedo, we can write the expression

$$p\Phi(\alpha)D^2=9\times 10^{22} r^2\Delta^2 10^{0.4(m_\odot - V)},$$

where $\Phi(\alpha)$ is the phase function of Bowell *et al.* (1989), r is the heliocentric distance (AU), Δ is the geocentric distance (AU), $m_{\odot}$ is the apparent V band solar magnitude (−26.74), and V is the apparent magnitude of 1993 SC (see Jewitt & Luu 1995). From the above expression and the distances and phase angles in Table 1, we find diameters of 240 km and 230 km from our 1995 November, and 1996 October photometry. Our diameters are somewhat lower than the diameter reported by Jewitt & Luu (1995), 319 km. We have no explanation for the difference since Jewitt and Luu used the same albedo and phase function as we did in our analysis.

3.3 Spherical vs Elongated TNOs

The possibility that 1993 SC is spherical in shape suggests some interesting questions for the TNO population: **(a)** Are larger TNOs spherical and smaller TNOs irregular in shape? **(b)** If so, at what diameter does the transition take place between irregular and spherical TNOs? We can estimate the critical diameter for the transition as follows. If we assume a constant density, ρ, throughout an object, then application of the equation of hydrostatic equilibrium gives the pressure, P, at any distance from the center of the object, r,

$$P=\frac{2}{3}\pi G\rho^2(R^2-r^2),$$

where R is the radius of the object and G is the gravitational constant. If in the central region of the object, the tensile strength of the material exceeds the pressure exerted by the overlying material, the object will be strong enough to retain any irregularity in its shape. On the other hand, if the overlying pressure exceeds the tensile strength, then the pressure of the overlying material will crush any irregularities in shape and the object will take on a spherical shape. By setting the tensile strength equal to the pressure at an interior point of the object, we can estimate the diameter at which the transition takes place between irregular shapes and spherical shapes. From the above expression and assuming a density and tensile strength intermediate between comet nuclei and carbonaceous chondrites ($\rho=1.2\times10^3$ kg m^{-3}, $T=3\times10^6$ N m^{-2}, and $r=0.2R$), we obtain $R=120$ km or a diameter of ~240 km for the transition between spherical and elongated objects. 1993 SC is at the critical diameter.

We stress that our results do not rule out an elongated shape for 1993 SC. If we viewed 1993 SC pole-on, it could have an elongated shape. Further observations of TNO light curves are essential to test whether or not a critical diameter exists for TNOs.

4. CONCLUSIONS

We find no evidence that 1993 SC has a light curve with a 7.7 hour period and a 0.5 mag amplitude (Williams *et al.* 1995). Our results are in agreement with those of Davies *et al.* (1997), but set an even lower limit on the amplitude of the light curve than the limit of Davies *et al.* (1997). In addition, 1993 SC shows no variation on time scales of days and after correcting for changes in distances and phase angle, 1993 SC shows no evidence of brightness variation (at the 0.06 mag level or greater) after nearly a year. If the rotation axis of 1993 SC is nearly orthogonal to our line of sight, 1993 SC is spherical in nature (a:$b\leq1.12$:1). If the rotation axis lies in our line of sight 1993 SC can be elongated. Our photometry suggests that the diameter of 1993 SC is ~240 km. Such a diameter may be the smallest diameter a TNO can have and still maintain a spherical shape.

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REFERENCES

Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peltoniemi, J. & Harris, A. W. 1989, in Asteroids II, edited by R. Binzel, T. Gehrels, and M. Matthews (University of Arizona, Tucson), pp. 524–556
Davies, J. K., McBride, N., & Green, S. F. 1997, Icarus, 125, 61
Jewitt, D. C., & Luu, J. X. 1993, Nature, 362, 730
Jewitt, D. C., & Luu, J. X. 1995, AJ, 109, 1867
Luu, J. X., & Jewitt, D. C. 1996a, AJ, 112, 2310
Luu, J. X., & Jewitt, D. C. 1996b, AJ, 111, 499
Marsden, B. G. 1997, http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html
Romanishin, W., Tegler, S. C., Levine, J., & Butler, N. 1997, AJ, 113, 1893
Schild, R. E. 1983, PASP, 95, 1021
Tegler, S. C., & Romanishin, W. 1997, Icarus, 126, 212
Williams, I. P., O'Ceallaigh, D. P., Fitzsimmons, A., & Marsden, B. G. 1995, Icarus, 116, 180