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S0019-1035(05)00003-5/FLA AID:7575 Vol.●●●(●●●) yicar7575 [DTD5] P.1 (1-7)
YICAR:m5 v 1.35 Prn:17/02/2005; 12:10 by:JOL p. 1

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The period of rotation, shape, density, and homogeneous surface color of the Centaur 5145 Pholus

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Received 30 September 2004; revised 20 December 2004

Abstract

We present optical photometry of the Centaur 5145 Pholus during 2003 May and 2004 April using the facility CCD camera on the 1.8-m Vatican Advanced Technology Telescope on Mt. Graham, Arizona. We derive a double-peaked lightcurve and a rotation period of 9.980 ± 0.002 h for Pholus, consistent with periods of 9.9825 ± 0.004 and 9.9823 ± 0.0012 h by Buie and Bus (1992, Icarus 100, 288–294) and Farnham (2001, Icarus 152, 238–245). We find a lightcurve peak-to-peak amplitude of 0.60 mag, significantly larger than peak-to-peak amplitude determinations of 0.15 and 0.39 mag by Buie and Bus and Farnham. We use the three observed amplitudes and an amplitude-aspect model to derive four possible rotational pole positions as well as axial ratios of $a/b = 1.9$ and $c/b = 0.9$. If we assume an albedo of 0.04, we find Pholus has dimensions of $310 \times 160 \times 150$ km. If we assume Pholus is a strengthless rubble-pile and its non-spherical shape is due to rotational distortion, our axial ratios and period measurements indicate Pholus has a density of $0.5\ \mathrm{g\,cm^{-3}}$, suggestive of an ice-rich, porous interior. By combining B-band and R-band lightcurves, we find $B - R = 1.94 \pm 0.01$ and any $B - R$ color variation over the surface of Pholus must be smaller than 0.06 mag (i.e., much smaller than the $1.0 < B - R < 2.0$ range seen among the Centaur and Kuiper belt object populations). By combining our $V - R$ measurements with values in the literature, we find no evidence for any color variegation between the northern and southern hemispheres of Pholus. Observations of the Kuiper belt object 2004 DW (90482) over a time interval of seven hours show no color variation Our observations add to the growing body of evidence that individual Centaurs and KBOs exhibit homogeneous surface colors and hence gray impact craters on radiation reddened crusts are probably not responsible for the surprising range of colors seen among the Centaur and Kuiper belt object populations.

Keywords: Centaurs; Kuiper belt objects; Photometry; Trans-neptunian objects

1. Introduction

Early on in their study, Kuiper belt objects (KBOs) were thought to have formed at about the same time and at about the same place in the outer Solar System, and so an early expectation was that essentially all KBOs should exhibit the same surface color. It was quite surprising to find that KBOs and Centaurs (recent escapees from the Kuiper belt on outer planet crossing orbits) exhibit a wide range of surface colors (Luu and Jewitt, 1996; Jewitt and Luu, 1998, 2001; Tegler and Romanishin, 1998, 2000, 2003; Barucci et al., 1999, 2000; Boehnhardt et al., 2001; Delsanti et al., 2001; Doressoundiram et al., 2001, 2002; Hainaut and Delsanti, 2002; Tegler et al., 2003).

In 1996, Luu and Jewitt devised a mechanism consisting of steady radiation reddening and stochastic impact graying to explain the range of colors. In their mechanism, oc-

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0019-1035/$ – see front matter
doi:10.1016/j.icarus.2004.12.011

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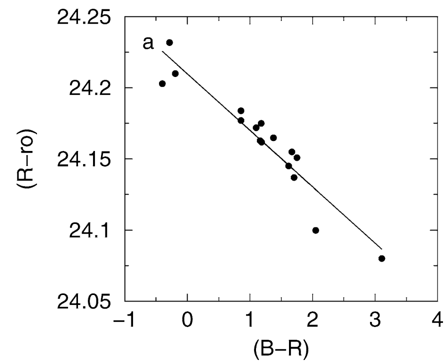
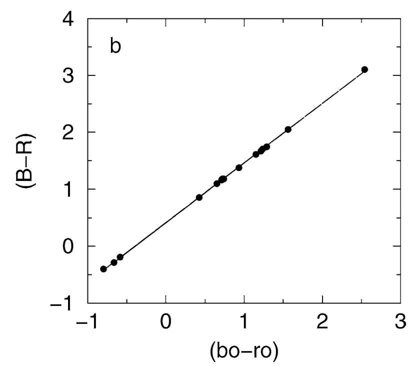
casional impacts by smaller KBOs excavate pristine, gray, icy material from beneath the red crust of a larger KBO. In 2001, Jewitt and Luu discovered a serious blow against their radiation reddening and collisional graying mechanism—repeated measurements of individual KBOs taken at random rotational phases are in general agreement within the uncertainties while color differences among KBOs are many times larger than the measurement uncertainties.

A more robust test of the collisional resurfacing mechanism is to look for color variation on the surface of a KBO or Centaur as a function of rotational phase. Buie and Bus (1992) performed the first such observation on the Centaur 5145 Pholus over one-half of a rotational period. They found the amplitude of any variation in the $V-R$ color must be less than 0.04 mag. Eight years later, Farnham (2001) found tantalizing evidence for an ∼0.1 mag variation in the $V-R$ color of Pholus over an entire rotational period. Farnham attributed the recent color variation to changes in the viewing aspect of Pholus between 1992 and 2000 (i.e., Farnham was seeing color variegation in the northern hemisphere of Pholus whereas the Buie and Bus observations were confined to the southern hemisphere). Farnham's ∼0.1 mag color variation is quite important because it's a significant fraction of the observed $V-R$ color range of KBOs and Centaurs ($0.3 < V-R < 0.8$).

Farnham's tantalizing result encouraged us to make our own measurement of the color of Pholus as a function of rotational phase. Our plan was to measure the $B-R$ color because KBOs and Centaurs exhibit $1.0 < B-R < 2.0$, thereby making it easier for us to see if color variegation on the surface of Pholus is a significant fraction of the color range seen among KBOs and Centaurs.



(a)



(b)

Fig. 1. (a) Johnson–Kron–Cousins $(B-R)$ color vs the difference between Kron–Cousins R magnitude and extinction corrected, instrumental, R-band magnitude, r_o, for our 16 Landolt standard stars. Each point represents a different standard star from our 2003 May observations. The solid line represents a linear regression fit to the points. From the fit, we obtain the transformation between our r_o and Kron–Cousins R. (b) Extinction corrected, instrumental color, $(b_o - r_o)$, vs Johnson–Kron–Cousins $(B-R)$. Each point represents a standard star from our 2003 May observations. The solid line represents a linear regression fit to the points.

2. Observations

Our observations of Pholus were obtained with Harris B (450 nm), V (550 nm), and R (650 nm) glass filters in front of a 2048 × 2048 pixel charge-coupled device (CCD) camera at the f/9 aplanatic Gregorian focus of the 1.8-m Vatican Advanced Technology Telescope (VATT; the Alice P. Lennon telescope and the Thomas J. Bannan facility) on Mt. Graham, Arizona (see http://clavius.as.arizona.edu/vo/). We binned the CCD 2 × 2, yielding 1024 × 1024 pixel images, covering 6.4 × 6.4 arcmin of the sky at 0.375 arcsec per pixel.

Pholus observations were obtained between 2003 May 2 and 2003 May 7 UT and 2004 April 20 and 24 UT. The nights of 2003 May 2, May 3, and May 5 as well as the nights of 2004 April 20 and 24 were photometric. We did not observe on 2003 May 4 due to clouds and high wind. We calibrated observations on non-photometric nights using bright field stars common to the fields of photometric and non-photometric nights. The typical seeing was ∼1.0 arcsec. A short exposure time of 180 s and a sidereal tracking rate combined to smear the images of Pholus by less than one pixel. Each night, we obtained bias and twilight flatfield images. On photometric nights, we obtained images of Landolt fields PG0918 + 029, PG1323 − 086, PG1633 + 099, and SA110 (Landolt, 1992).

We inspected the aperture and sky annulus around each image of Pholus 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 Pholus contaminated by images of faint background stars or galaxies. We used the PHOT package in the IMAGE REDUCTION AND ANALYSIS FACILITY (IRAF) software to measure instrumental magnitudes for Pholus, standard stars, and point-spread function (psf) stars. To maximize the signal-to-noise ratio of our data, we applied an aperture correction procedure to Pholus (Tegler and Romanishin, 1997).

We derived extinction and transformation equations from our observations of Landolt standard star fields so that we could place our instrumental magnitudes and colors of Pholus on the Johnson–Kron–Cousins photometric system. In Fig. 1a, we present a plot of the Johnson–Kron–Cousins $(B-R)$ color vs the difference between Kron–Cousins R

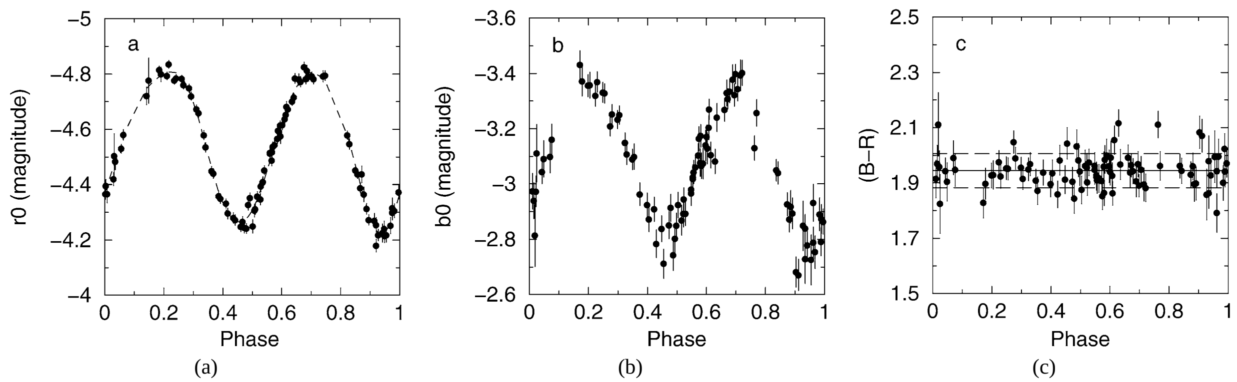


Fig. 2. (a) Double-peaked lightcurve for 5145 Pholus. Extinction corrected, R-band, instrumental magnitude, r_o, vs rotational phase for a period of 9.980 h (solid points). Best cubic spline fit to the points (dashed curve). The lightcurve has a peak-to-peak amplitude of 0.60 mag. The two maxima are of nearly equal brightness while the two minima differ by 0.03 mag in brightness. (b) Extinction corrected, B-band, instrumental magnitude, b_o, vs rotational phase for a period of 9.980 h (solid points). (c) Kron–Cousins $B-R$ color vs rotational phase for a period of 9.980 h. The horizontal line is the average $(B-R)$ of all 94 points, 1.94. The dashed lines are ± 1 standard deviation, $\sigma = 0.06$ mag.

magnitude and extinction corrected, instrumental, R-band magnitude, r_o, for our 16 Landolt standard stars. Each point represents a different standard star from our 2003 May observations. The solid line represents a linear regression fit to the points. From the fit, we obtain the transformation between our r_o and Kron–Cousins R,

$$R = r_o + 24.210 - 0.040(B - R). \quad (1)$$

In Fig. 1b, we present a plot of extinction corrected, instrumental color, $(b_o - r_o)$, vs Johnson–Kron–Cousins $(B - R)$. Again, each point represents a standard star from our 2003 May observations. The solid line represents a linear regression fit to the points,

$$B - R = 1.048(b_o - r_o) + 0.415. \quad (2)$$

When we insert r_o and $B - R$ into Eq. (1) and $b_o - r_o$ into Eq. (2) for the 16 standard stars, and then compare the resulting R and $B - R$ values with the values in Landolt (1992), we find residuals ~0.01 mag.

3. 5145 Pholus analysis

3.1. Period of rotation

We combined all of our 2003 May R-band data to determine the rotational period of Pholus. First, we removed any systematic shifts in time between nights caused by changes in the distance between the Earth and Pholus, i.e., we subtracted Δ/c from each midpoint exposure time, where Δ is the geocentric distance and c is the speed of light. Next, we determined the best period between 3 and 12 h using the technique of phase dispersion minimization (Stellingwerf, 1978). Specifically, we used the PDM task in IRAF to determine a double-peaked lightcurve period of 9.980 ± 0.002 h.

In Fig. 2a, we present a plot of extinction corrected, R-band, instrumental magnitude, r_o, vs rotational phase for the 9.980 h period (solid-circles). The dashed-line is the best cubic spline fit to the data. The lightcurve maxima agree to <0.01 mag; however, the minimum at a phase of ~0.95 is 0.03 mag fainter than the minimum at a phase of ~0.45. The two minima are spaced by half a rotational phase as are the two maxima. We find a maximum lightcurve peak-to-peak amplitude of 0.60 mag.

How does our lightcurve compare with the literature? Our period of 9.980 ± 0.002 h is consistent with the periods of Buie and Bus (1992) and Farnham (2001), 9.9825 ± 0.004 and 9.9823 ± 0.0012 h. Buie and Bus found maxima of almost equal brightness while minima differed by 0.04 mag. They found the two minima were spaced by half a rotational phase as were the two maxima.

In Fig. 2b, we present a plot of extinction corrected, B-band, instrumental magnitude, b_o, vs rotational phase for our 9.980 h period (solid circles). The larger error bars in Fig. 2b compared to Fig. 2a are the result of the extraordinary red color of Pholus.

3.2. Pole position and axial ratios

Although the period of rotation has not changed over the last 11 years, the amplitude of the lightcurve has increased from 0.15 mag (Buie and Bus, 1992) to 0.39 mag (Farnham, 2001) to 0.60 mag (the work we report here). Davies et al. (1998) observed Pholus in May, 1997; however, they did not obtain a complete lightcurve and so they do not have an accurate amplitude measurement. Like Farnham, we assume the changing aspect that Pholus presents to us as it orbits the Sun is responsible for the increase in amplitude.

Here we use the three observed lightcurve amplitudes and an amplitude-aspect model (cf. Magnusson, 1986) to determine the shape as well as the rotational pole position of Pholus. In our model, we assume Pholus is a triaxial ellipsoid in simple rotation (i.e., its rotation axis is fixed relative to the stars). We let a, b, and c be the principal axes of the ellipsoid where $a \geqslant b \geqslant c$ and the c-axis is the axis of rotation. We define the aspect angle, ψ, as the Earth–Pholus–north pole angle. At the near zero solar phase angles of Pholus

(Earth–Pholus–Sun angle), $\alpha \sim 2°$, and a given ψ, the projected area of Pholus perpendicular to the line of sight varies between two extreme values,

$$(\text{Area})_{\max} = \pi a \left(b^2 \cos^2 \psi + c^2 \sin^2 \psi\right)^{1/2} \tag{3}$$

and

$$(\text{Area})_{\min} = \pi b \left(a^2 \cos^2 \psi + c^2 \sin^2 \psi\right)^{1/2}. \tag{4}$$

The lightcurve amplitude, Δm, is then given by

$$\Delta m = 2.5 \log\left[\frac{(\text{Area})_{\max}}{(\text{Area})_{\min}}\right]. \tag{5}$$

By substituting Eqs. (3) and (4) into Eq. (5), we get the lightcurve amplitude as a function of the aspect angle and the axial ratios,

$$\Delta m = 1.25 \log\left[\frac{(\frac{b^2}{c^2}) \cos^2 \psi + \sin^2 \psi}{(\frac{b^2}{c^2}) \cos^2 \psi + (\frac{b^2}{a^2}) \sin^2 \psi}\right], \tag{6}$$

where the aspect angle is given by

$$\psi = 90 - \arcsin\left[\sin \beta_{se} \sin \beta_p + \cos \beta_{se} \cos \beta_p \cos(\lambda_{se} - \lambda_p)\right]. \tag{7}$$

The quantities λ_{se} and β_{se} are the ecliptic longitude and latitude of the sub-Earth point in the Pholus-centered reference frame and λ_p and β_p are the ecliptic longitude and latitude of the pole. The ecliptic longitude and latitude of the sub-Earth point are given by

$$\lambda_{se} = \lambda_a \pm 180 \tag{8}$$

so that $0 \leqslant \lambda_{se} \leqslant 360$ and

$$\beta_{se} = -\beta_a \tag{9}$$

where λ_a and β_a are the ecliptic longitude and latitude of Pholus.

Using the three positions of Pholus in its orbit about the sun, corresponding to the three observed lightcurve amplitudes, we carried out a grid search for the quantities λ_p, β_p, a/b, and c/b in Eq. (6) that gave three Δm values with the smallest χ^2 fit to the three observed lightcurve amplitudes. We searched $0.5 \leqslant c/b \leqslant 1.0$ and $1.0 \leqslant a/b \leqslant 2.0$, both at intervals of 0.1. We searched the entire sky for λ_p and β_p at intervals of 5°.

The amplitude-aspect method gives four pole solutions, two centered across the orbital plane of Pholus along with their 180° opposite solutions. Our smallest χ^2 value occurs for pole position $(\lambda_p, \beta_p) = (155°, +5°)$ and its 180° opposite, $(335°, -5°)$. These two solutions give Δm values of 0.14, 0.39, and 0.59 mag. The pole solution across the orbital plane of Pholus, $(145°, +30°)$, and its 180° opposite, $(325°, -30°)$, give a slightly larger χ^2 value and Δm values of 0.16, 0.40, and 0.59 mag. All four poles give Δm values $\leqslant$0.01 mag different than the observed Δm values. All four pole solutions require $a/b = 1.9$ and $c/b = 0.9$.

How do our solutions agree with solutions in the literature? Quite well. Farnham (2001) used the epoch method to eliminate two 180° opposite poles. He found one solution at $(337°, -5°)$ with axial ratios of $a/b = 1.9$ and $c/b = 0.9$, and another solution at $(149°, +26°)$ with axial ratios of $a/b = 1.8$ and $c/b = 1.0$, i.e., remarkable agreement with our solutions. The uncertainties in our observations do not allow us to distinguish between our four poles; therefore, we use the pole, $(145°, +30°)$, closest to Farnham's preferred pole.

3.3. Density

If we assume Pholus is a rubble pile, then perhaps its nonspherical shape is due to rotational distortion. Chandrasekhar (1969) tabulated the relationship between axial ratios, rotation period, and density of a rotating, strengthless, self-gravitating body (a Jacobi ellipsoid). If we use the axial ratio b/a from the lightcurve amplitude, and the period from above with Chandrasekhar's formalism, we find Pholus would be in hydrostatic equilibrium if its density is $0.5\ \text{g cm}^{-3}$. The assumption of strengthless material that goes into this analysis is clearly an oversimplification for real Solar System bodies (cf. Holsapple, 2004). Pholus cannot be completely strengthless, as the c/a axial ratio differs slightly from the equilibrium value, and the lightcurve is not perfectly symmetric. However, internal stresses would be minimized for a density near $0.5\ \text{g cm}^{-3}$.

It is intriguing to note that this density is similar to those found for the similarly-sized saturnian moons Janus, Epimetheus, Prometheus, and Pandora (Jacobson and French, 2004). Such a density is suggestive of a porous (and probably ice-rich) interior.

3.4. $B - R$ color

We derived the $B - R$ color as a function of phase for Pholus by combining the data in Figs. 2a and 2b. Specifically, we used the cubic spline fit to the R-band data in Fig. 2a to interpolate between the r_o points to arrive at r_o values at the phases of b_o measurements; thereby eliminating any effects of brightness variations on the $B - R$ colors. We then calculated $(b_o - r_o)$ using the 94 b_o values in Fig. 2b and their interpolated counterparts in Fig. 2a. Next, we inserted the $(b_o - r_o)$ instrumental colors into Eq. (2) to derive Kron–Cousins $(B - R)$ colors. In Fig. 2c, we present a plot of $B - R$ color as a function of phase for our 9.980 h period. The horizontal solid line at $B - R = 1.94$ is the average of the 94 measurements over the entire rotational phase. The horizontal dashed lines above and below the average are plus and minus one standard deviation, $\sigma = 0.06$ mag. We conclude there is no $B - R$ color variation over the surface of Pholus larger than 0.06 mag. Any color variation smaller than 0.06 mag is far smaller than the observed color range among KBOs and Centaurs, $1.0 < B - R < 2.0$.

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Table 1
$V-R$ color for Pholus

Date (UT)	Sub-Earth lat (°)	$V-R$	Reference
1992 Jan 09	−52	0.75	a
1992 Jan 23	−52	0.66	b
1992 Feb 22–Feb 24	−51	0.81 ± 0.006	c
1993 Mar 27	−66	0.84 ± 0.07	d
1995 Nov 27	−57	0.78 ± 0.04	e
1997 May 07	−53	0.75 ± 0.02	f
2000 May 02–May 05	−31	0.71 ± 0.03	g
2004 Apr 20	−11	0.76 ± 0.04	h

[a] Mueller et al. (1992).
[b] Tholen, see Mueller et al. (1992).
[c] Buie and Bus (1992).
[d] Luu and Jewitt (1996).
[e] Romanishin et al. (1997).
[f] Davies et al. (1998).
[g] Farnham (2001).
[h] This work.

Another interesting question is whether there is any long term change in the $B-R$ color of Pholus. On 1992 January 23, Tholen made a preliminary measurement of $(B-R) = 2.01$ (see Table I of Mueller et al., 1992). On 1995 November 27, we obtained three 600 s exposures through each of B, V, and R filters and found $B-R = 1.97 \pm 0.11$ (Romanishin et al., 1997). Here, we report $B-R = 1.94 \pm 0.01$. From eight 180 s exposures through each of the B and R filters on 2004 April 20 data, we found $B-R = 1.94 \pm 0.07$. Over the past 12 years, it appears Pholus has exhibited a constant $B-R$ color.

3.5. $V-R$ color

Our $V-R$ measurements suggest a constant color for Pholus over almost nine years. On 1995 November 27 UT, we obtained $V-R = 0.78 \pm 0.04$ (Romanishin et al., 1997). On 2004, April 20 UT, we found $V-R = 0.76 \pm 0.04$.

In Table 1, we compare our $V-R$ colors with values in the literature. If we average all the $V-R$ values in Table 1, with the exception of Tholen's value of 0.66 which the footnote to Table I in Mueller et al. refers to as "preliminary reductions," we find $(V-R)_{avg} = 0.77$. Five of the seven $V-R$ values in Table 1 appear consistent with the average. Only the Buie and Bus (1992) value of 0.81 ± 0.006 and the Farnham (2001) value of 0.71 ± 0.03 do not overlap the average of 0.77.

3.6. $U-B$ color

We are unaware of any previous $U-B$ color measurements for extraordinary red Centaurs or KBOs. On 2004 April 24 UT, we found $U-B = 0.59 \pm 0.10$ mag for Pholus. For comparison, the Sun has $U-B = 0.20$ mag (Hardorp, 1980). The S-type asteroids of the inner belt, M-type asteroids of the central belt, and the C-type asteroids of the outer belt have $U-B$ values of 0.42, 0.23, and 0.3 mag, respectively (Bowell and Lumme, 1979). Trojan asteroids have $U-B = 0.24$ (Degewij et al., 1978). There are only two KBOs with $U-B$ color measurements, 1996 TL_{66} and 1996 TO_{66} exhibit $U-B = 0.23$ and 0.28 mag, respectively (Barucci et al., 1999). Both of these objects are gray, 1996 TL_{66} and 1996 TO_{66} have $B-R = 1.10 \pm 0.02$ and 1.12 ± 0.05 (Tegler and Romanishin, 1998).

3.7. Axial lengths

We derived lengths for each of the axes as follows. We can write a second expression for the maximum area that Pholus projects onto the sky in 2003 May by using the definition of albedo, p,

$$p\Phi(\alpha)(\text{Area})_{max} = 7 \times 10^{16} r^2 \Delta^2 10^{0.4(m-V)}, \qquad (10)$$

where m is the apparent solar magnitude in V band (−26.74), V is the magnitude of Pholus in V band, r is the heliocentric distance (17.84 AU), and Δ is the geocentric distance (16.93 AU). We assume an albedo of 0.04. The phase function is given by

$$\Phi(\alpha) = (1-G)\Phi_1(\alpha) + G\Phi_2(\alpha) \qquad (11)$$

and

$$\Phi_i(\alpha) = \exp\left[-A_i\left(\tan\frac{1}{2}\alpha\right)^{B_i}\right], \qquad (12)$$

where $i = 1, 2$, $A_1 = 3.33$, $B_1 = 0.63$, $A_2 = 1.87$, $B_2 = 1.22$, and $G = 0.15$ (Bowell et al., 1989). For 2003 May, $\alpha = 1.4°$ and $\Phi(1.4°) = 0.84$. From Fig. 2a, the brightest r_o is −4.813 mag. Substitution of the brightest r_o and a $B-R$ color of 1.94 into Eq. (1) gives $R = 19.319$ at its brightest. By combining R with $V-R$ of 0.77, we obtain $V = 20.089$ at its brightest for Pholus during 2003 May. When we substitute these values into Eq. (10), we find $(\text{Area})_{max} = 3.53 \times 10^4$ km^2. If we insert $(\text{Area})_{max} = 3.53 \times 10^4$ km^2, $\psi = 105°$, $a = 1.9b$, and $c = 0.9b$ into Eq. (3), we find $2a \times 2b \times 2c = 310 \times 160 \times 150$ km.

4. 2004 DW (90482) analysis

We have surface color measurements for one additional object over a significant time interval, the KBO 2004 DW (90482), a Plutino in the 2:3 mean motion resonance with Neptune. As we show below, we do not have coverage over a complete rotational phase, but our measurements do allow us to say something about color variation over a part of its surface, and so we include it here.

On 2004 February 27 UT, we obtained ∼7 h of continuous observations of (90482) using the 2.3-m Bok telescope on Kitt Peak, the facility CCD camera, and B-band and R-band filters. Because there were thin clouds (∼0.3 mag at most), we could not derive Johnson–Kron–Cousins colors, but we could look for evidence of a lightcurve and color variations.

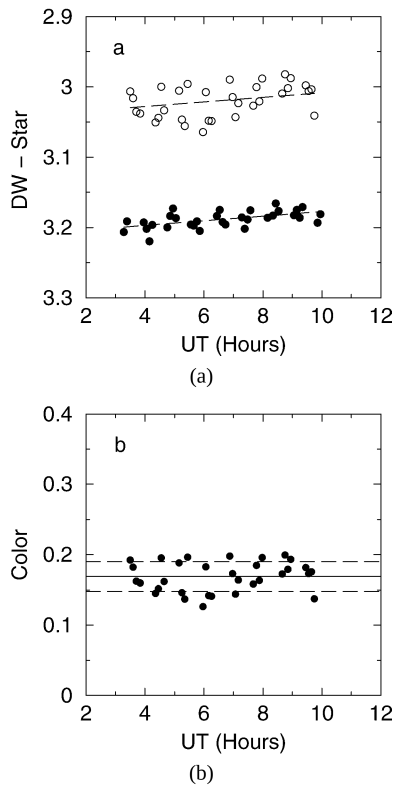

Fig. 3. (a) Difference between the instrumental magnitude of 2004 DW (90482) and the instrumental magnitude of the summed flux of two comparison, field stars vs universal time (UT). Neither field star exhibited any variability. The filled and open circles represent R-band and B-band measurements. We find that (90482) brightened by 0.02 mag in both B and R filters over seven hours. (b) Magnitude difference between the B-band and R-band values in (a). Such a magnitude difference gives us the color of (90482) relative to the colors of the comparison stars. The solid line is the average of the 32 points in the figure. The dashed lines are plus/minus one standard deviation, $\sigma = 0.02$ mag. We find any color variation over the surface of (90482) must be smaller than 0.02 mag during the seven hour time interval.

In Fig. 3a, we present the difference between the instrumental magnitude of (90482) and the instrumental magnitude of the summed flux of two comparison, field stars vs universal time (UT). Neither comparison star exhibited any variability. The filled and open circles represent R-band and B-band measurements. From the figure, we see that (90482) brightened by 0.02 mag in both B and R filters over 7 h. Obviously, we cannot say whether (90482) has a very long period, high amplitude lightcurve or a low amplitude lightcurve. We can rule out a high amplitude lightcurve with a period of hours as in the case of Pholus.

In Fig. 3b, we present the magnitude difference between the B-band and R-band values in Fig. 3a. Such a magnitude difference gives us the color of (90482) relative to the colors of the comparison stars. The solid line is the average of the 32 points in the figure. The dashed lines are plus/minus one standard deviation, $\sigma = 0.02$ mag. Although we have much less rotational phase coverage than Pholus, we can say any color variation over the surface of (90482) must be smaller than 0.02 mag during the 7 h time interval.

5. Discussion

We sum up our major findings about Pholus as follows. First, we find a rotation period of 9.980 ± 0.002 h which is consistent with the periods of Buie and Bus (1992) and Farnham (2001). The consistency of period measurements over more than a decade suggests Pholus is in a state of simple rotation (i.e., the rotation axis is fixed with respect to the stars).

Second, we find a lightcurve peak-to-peak amplitude of 0.60 mag which is larger than the 0.15 and 0.39 peak-to-peak amplitudes found by Buie and Bus (1992) and Farnham (2001). Using the three observed amplitudes and an amplitude-aspect model, we derive four pole positions and axial ratios of $a/b = 1.9$ and $c/b = 0.9$.

Third, if we assume Pholus is a strengthless rubble-pile and its non-spherical shape is due to rotational distortion, our axial ratios and period indicate Pholus has a density of $0.5\ \mathrm{g\,cm^{-3}}$, suggestive of a an ice-rich, porous interior.

Fourth, if we use our pole position closest to Farnham's favorite pole position, (145°, +30°), at the time of our 2003 observations, the sub-Earth point was 15° from the equator of Pholus. We expect the lightcurve peak-to-peak amplitude to grow as large as 0.70 mag when the sub-Earth point reaches a Pholus-centered latitude of 0° in 2007.

Fifth, we find any $B - R$ color variation with rotational phase must be smaller than 0.06 mag. Our observation of a homogeneous color over the surface of Pholus is consistent with the result of Buie and Bus (1992). They found any $V - R$ color variation must be less than 0.04 mag over half of a rotational cycle. We do not confirm the color variation seen in $V - R$ by Farnham (2001). The feature Farnham sees (an increase in $V - R$ by ∼0.1 mag between $0.4 <$ rotational phase < 0.6 in his Fig. 3) is a 1.5σ detection. The feature occurs near a brightness minimum where the signal-to-noise ratio is the smallest. In addition, Farnham was able to make lightcurve corrections for only two of the six points making up the feature. Although Farnham's feature is tantalizing, we do not confirm its existence.

Sixth, we see no evidence of any color variation between the northern and southern hemispheres of Pholus. In column 2 of Table 1 and Fig. 4, we give the Pholus-centered latitude of the sub-Earth point for the $V - R$ color measurements (i.e., the arcsin term in Eq. (7) for a pole of 145°, +30°). We see no evidence of a trend of $V - R$ color with latitude of the sub-Earth point. Since our 2004 April measurement probes the northern hemisphere more so than any other previous measurement, and since we find a $V - R$ value in agreement with the average of the literature, we do not confirm Farnham's suggestion that the northern hemisphere of Pholus contains bluer features than the southern hemisphere.

Our observation of a homogeneous surface color for (1) Pholus and (2) at least a part of the surface of (90482), adds to a growing body of evidence that collisional graying and radiation reddening are not responsible for the wide range of colors we see among Centaurs and KBOs. If colli-

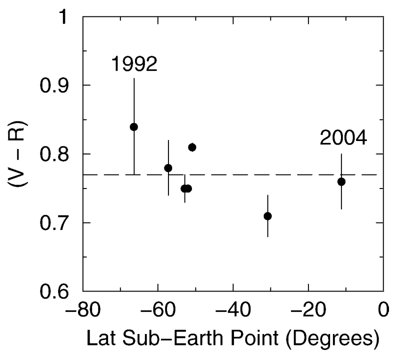

Fig. 4. $V - R$ color and corresponding Pholus-centered latitude of the sub-Earth point for the $(145°, +30°)$ pole (Table 1). The dashed line represents the average of the seven $V - R$ measurements, 0.77. Early measurements in 1992 primarily probed the southern hemisphere. Our recent measurement in 2004, saw more of the northern hemisphere than an previous measurements. Both hemispheres appear to have the same $V - R$ color.

sional resurfacing were the primary cause for the color range among Centaurs and KBOs $(1.0 < B - R < 2.0)$, we should see a similar range or a significant fraction of the one magnitude range over the surface Pholus and (90482). Instead, the color variation of Pholus and (90482) appears less than 0.06 and 0.02 mag.

What other mechanisms could produce homogeneous surface colors for individual objects, yet provide a range of colors among the entire population of Centaurs and KBOs? Stern suggests collisions could still be responsible, if each collision produces a vapor that coats an entire individual object (private communication). Our group suspects a temperature-induced, primordial, composition gradient is responsible for Centaur and KBO colors. Unlike resurfacing mechanisms, a primordial composition gradient is more capable of explaining why Centaurs divide into two distinct color groups (Peixinho et al., 2003; Tegler et al., 2003).

Acknowledgments

We thank the NASA Planetary Astronomy program for financial support of this research and the Vatican Observatory for consistent allocation of telescope time.

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