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# PHYSICAL OBSERVATIONS OF 2005 UD: A MINI-PHAETHON

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## ABSTRACT

Planet-crossing object 2005 UD is dynamically similar to purported Geminid meteor-stream parent 3200 Phaethon, suggesting an association between the two. We present new physical observations taken to characterize 2005 UD when at 1.6 AU from the Sun. Assuming equal albedos, 2005 UD is about 4 times smaller than 3200 Phaethon, with a diameter of $\sim$1.3 $\pm$ 0.1 km. The body shows periodic brightness variations of 0.4 mag that are compatible with an aspherical nucleus in rotation with a period near 5.2 hr. At optical wavelengths, 2005 UD is similar to or slightly bluer than the Sun. This property is relatively uncommon among near-Earth objects but is shared by Phaethon, strengthening the association between the two. No evidence for ongoing mass loss at rates as small as 0.01 kg s$^{-1}$ is found in the surface brightness profile, and we conclude that the fraction of the surface that is losing mass is not greater than $10^{-4}$. Overall, we conclude that the dynamical similarities between 2005 UD and 3200 Phaethon are matched by physical similarities between these bodies, except that the former contains only about 2% of the mass of the latter. Phaethon, 2005 UD, and the Geminid meteoroids may be fragments produced by the breakup of a precursor object.

*Key words:* comets: general — Kuiper Belt — minor planets, asteroids

## 1. INTRODUCTION

Meteor streams consist of macroscopic debris ejected from the nuclei of comets. Asteroid 3200 Phaethon (formerly 1983 TB) has long been recognized as the likely parent of the Geminid stream, based on a pronounced orbital similarity (Whipple 1983). One puzzle is that 3200 Phaethon, which has a Tisserand parameter with respect to Jupiter of $T_J = 4.5$, is dynamically associated with the main-belt asteroids (which have $T_J > 3$), not with the comets ($T_J \leq 3$). Perhaps this body has been deflected inward from the outer main belt, causing residual ices to sublimate and producing the Geminid stream. It is tempting to speculate that 3200 Phaethon may be a dynamically and thermally evolved main-belt comet (Hsieh & Jewitt 2006), although we currently lack the data to test this possibility.

Planet-crossing asteroid 2005 UD was discovered on UT 2005 October 22 by the Catalina Sky Survey (McNaught et al. 2005) and was found to show orbital similarity to both Phaethon and the Geminids, suggesting that a genetic relationship may connect all three (Ohtsuka et al. 2006). If this is so, it is to be expected that the colors and other physical properties of the two bodies should be similar. Observations showing a clear difference between Phaethon and 2005 UD would be difficult to understand if these objects share a common origin, given that the orbits, solar heating, and space-weathering environments are essentially the same. Our aim in this short paper is to present physical observations of 2005 UD that may have bearing on the purported relationship with 3200 Phaethon.

## 2. OBSERVATIONS

We observed using the University of Hawaii 2.2 m telescope on Mauna Kea on the nights of UT 2005 November 19–22, inclusive. A Tektronix 2048 $\times$ 2048 pixel charge-coupled device (CCD) was employed at the f/10 Cassegrain focus, with an image scale of 0."219 pixel$^{-1}$ and a field of view of approximately 7.'5 $\times$ 7.'5. We obtained integrations 300 s in duration through Kron-Cousins *BVRI* filters, with the telescope autoguided on a fixed star and offset to follow the motion of 2005 UD at nonsidereal rates (about 41" hr$^{-1}$ relative to background stars). This nonsidereal tracking caused sidereal objects to trail by about 3."4 in the individual integrations.

Images were corrected by subtracting a bias image and dividing by a bias-subtracted flat-field image, the latter constructed from scaled, dithered images of the evening twilight sky. Photometric calibration was obtained from images of standard stars PG 0231+51E, Mark A1, PG 0918+029A and C, and PG 2213−006A from the catalog by Landolt (1992). The full width at half-maximum (FWHM) of untrailed star images in data taken close in time to 2005 UD varied from $\sim$0."8 to 1."0. A journal of observations is presented in Table 1.

## 3. OBSERVATIONAL RESULTS

Object 2005 UD appeared pointlike in all images (Fig. 1), justifying the simple aperture photometry listed in Table 2. The magnitudes in the table were measured within synthetic, circular apertures of 3."3 (15 pixel) radius, with sky subtraction from a contiguous annulus with an outer radius of 6."6 (30 pixels). We estimated the photometric uncertainty, about $\pm$0.03 mag, from repeated measurements of field stars in consecutive exposures having integrated brightness close to that of 2005 UD. This is consistent with other measurements taken using the same instrument over the past two decades and is further consistent with the scatter seen in the photometry of 2005 UD.

Inspection of Table 2 shows systematic variations in brightness that are large compared to the photometric uncertainties. To examine their cause, we first corrected the photometry for variations in the viewing geometry (see Table 1), assuming that the asteroid obeys the inverse square law. The night-by-night corrections [$\Delta m_R = 5 \log_{10}(R\Delta) + \beta\alpha$, where $R$ and $\Delta$ are the heliocentric and geocentric distances in AU, $\alpha$ is the phase angle in degrees, and $\beta$ is the linear phase law coefficient, taken to be $\beta = 0.04$ mag deg$^{-1}$], are given in the last column of Table 1. As can be seen from the table, the increase in the distance to 2005 UD from November 19 to November 22 should result in a fading by about 0.2 mag.

TABLE 1

Journal of Observations

| UT Date | Integration (s) | Filter | $R^a$ (AU) | $\Delta^b$ (AU) | $\alpha^c$ (deg) | $\Delta m^d$ (mag) |
|---|---|---|---|---|---|---|
| 2005 Nov 19...... | 300 | 6*R* | 1.571 | 0.916 | 35.9 | 2.226 |
| 2005 Nov 20...... | 300 | 1*V*, 5*R*, 1*I* | 1.582 | 0.938 | 35.8 | 2.289 |
| 2005 Nov 21...... | 300 | 2*B*, 2*V*, 13*R*, 2*I* | 1.592 | 0.960 | 35.8 | 2.353 |
| 2005 Nov 22...... | 300 | 16*R* | 1.602 | 0.982 | 35.7 | 2.412 |

[a] Heliocentric distance.
[b] Geocentric distance.
[c] Phase angle.
[d] Magnitude correction to $R = 1$ AU, $\Delta = 1$ AU, and $\alpha = 0°$.

The average value of the magnitude of 2005 UD reduced to unit heliocentric and geocentric distance and zero phase angle is $m_R(1,\ 1,\ 0) = 17.19 \pm 0.03$. This is about 3 mag fainter than the corresponding quantity measured for 3200 Phaethon, $m_R(1,\ 1,\ 0) \sim 14.3 \pm 0.1$ (Green et al. 1985; Dundon 2005), indicating that (for equal albedos) 2005 UD must be about 4 times smaller. Green et al. (1985) used optical and thermal data to estimate the geometric albedo of Phaethon, $p_R = 0.11 \pm 0.02$, and equivalent circular diameter, $D_e = 4.7 \pm 0.5$ km. Scaling from these numbers under the assumption that the albedos of Phaethon and 2005 UD are comparable, we estimate that the equivalent circular diameter of 2005 UD is $D_e = 1.3 \pm 0.1$ km. The quoted uncertainty reflects only the formal error in the adopted albedo, and the true uncertainty must surely be larger. The mass contained in 2005 UD, assuming equal density, is only about 2% of the mass of 3200 Phaethon.

A search for periodicity was conducted using the phase-dispersion minimization (PDM) technique. The PDM analysis shows a number of possible light-curve periods. We constructed light curves for each period allowed by the PDM calculation and evaluated them visually. The most convincing solution corresponds to a single-peaked light curve of period $P_0 = 2.6246$ hr, but the phased data look better if the light curve is two-peaked, in which case the true rotation period is $P_{\rm rot} = 2P_0 = 5.2492$ hr. The phased light curve using this period is shown in Figure 2. We note that there is a hint that the light curve of 2005 UD might not be singly periodic: the phased data from UT 2005 November 19 are fainter than the data from UT 2005 November 21 by about 0.05 mag (Fig. 2). The discrepancy is small, given the photometric uncertainties and the unknown phase function. If it is real, it could indicate multiple periodicity in the light curve, perhaps due to precession of the nucleus. However, better data would be needed to establish this case, and we work under the assumption that the photometry is well enough described by a singly periodic (simple rotation) function. Other plausible rotation periods are related to $P_{\rm rot}$ by the 24 hr periodicity in the sampling of the light curve

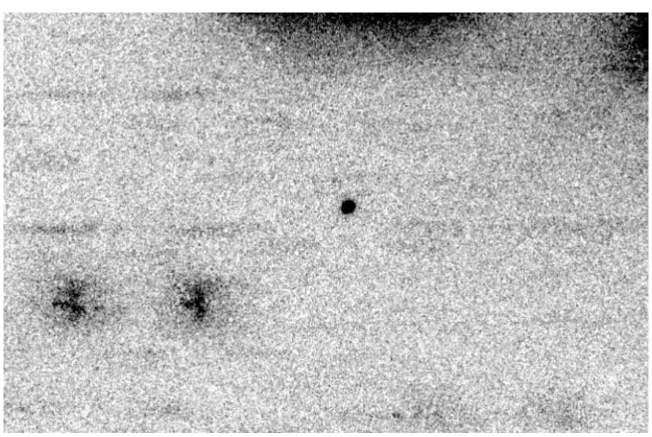

Fig. 1.—Clipped median *R*-band image of 2005 UD (*center*) having a total integration time of 1800 s and recorded on UT 2005 November 21. The image has been rotated so that the motion of the object relative to the fixed stars lies along a horizontal. The region shown is approximately 150″ in width. The light at the top of the image is from two very bright stars just outside the region shown. The double blobs to the lower left of 2005 UD are residuals from another bright field star.

TABLE 2

Photometry

| *N* | Date (UT 2005) | Midtime[a] | Filter | Magnitude[b] |
|---|---|---|---|---|
| 1...................... | Nov 19 | 8.9654 | *R* | 19.61 |
| 2...................... | Nov 19 | 9.0781 | *R* | 19.60 |
| 3...................... | Nov 19 | 9.1906 | *R* | 19.52 |
| 4...................... | Nov 19 | 9.3031 | *R* | 19.46 |
| 5...................... | Nov 19 | 9.4173 | *R* | 19.38 |
| 6...................... | Nov 19 | 9.5300 | *R* | 19.33 |
| 7...................... | Nov 20 | 31.5239 | *R* | 19.43 |
| 8...................... | Nov 20 | 31.6367 | *R* | 19.53 |
| 9...................... | Nov 20 | 31.7471 | *R* | 19.58 |
| 10.................... | Nov 20 | 31.8593 | *I* | 19.28 |
| 11.................... | Nov 20 | 32.0838 | *V* | 20.03 |
| 12.................... | Nov 20 | 32.1975 | *R* | 19.75 |
| 13.................... | Nov 20 | 32.3098 | *R* | 19.63 |
| 14.................... | Nov 21 | 53.9403 | *R* | 19.46 |
| 15.................... | Nov 21 | 54.0528 | *R* | 19.40 |
| 16.................... | Nov 21 | 54.1650 | *R* | 19.38 |
| 17.................... | Nov 21 | 54.2761 | *I* | 19.06 |
| 18.................... | Nov 21 | 54.3883 | *B* | 20.35 |
| 19.................... | Nov 21 | 54.5006 | *V* | 19.70 |
| 20.................... | Nov 21 | 54.6145 | *R* | 19.35 |
| 21.................... | Nov 21 | 54.7264 | *R* | 19.38 |
| 22.................... | Nov 21 | 54.8389 | *R* | 19.36 |
| 23.................... | Nov 21 | 55.5548 | *R* | 19.69 |
| 24.................... | Nov 21 | 55.6670 | *R* | 19.69 |
| 25.................... | Nov 21 | 55.7795 | *R* | 19.81 |
| 26.................... | Nov 21 | 55.8914 | *R* | 19.78 |
| 27.................... | Nov 21 | 56.5639 | *R* | 19.48 |
| 28.................... | Nov 21 | 56.6764 | *R* | 19.46 |
| 29.................... | Nov 21 | 56.7917 | *I* | 19.09 |
| 30.................... | Nov 21 | 56.9044 | *B* | 20.43 |
| 31.................... | Nov 21 | 57.0164 | *V* | 19.72 |
| 32.................... | Nov 21 | 57.1353 | *R* | 19.32 |
| 33.................... | Nov 22 | 77.6617 | *R* | 19.45 |
| 34.................... | Nov 22 | 77.7739 | *R* | 19.39 |
| 35.................... | Nov 22 | 77.9081 | *R* | 19.38 |
| 36.................... | Nov 22 | 78.0189 | *R* | 19.37 |
| 37.................... | Nov 22 | 79.0581 | *R* | 19.70 |
| 38.................... | Nov 22 | 79.1703 | *R* | 19.71 |
| 39.................... | Nov 22 | 79.3011 | *R* | 19.86 |
| 40.................... | Nov 22 | 79.4289 | *R* | 19.81 |
| 41.................... | Nov 22 | 79.5412 | *R* | 19.79 |
| 42.................... | Nov 22 | 79.6534 | *R* | 19.79 |
| 43.................... | Nov 22 | 80.6311 | *R* | 19.44 |
| 44.................... | Nov 22 | 80.7437 | *R* | 19.39 |
| 45.................... | Nov 22 | 80.8561 | *R* | 19.42 |
| 46.................... | Nov 22 | 80.9681 | *R* | 19.48 |
| 47.................... | Nov 22 | 81.0806 | *R* | 19.48 |
| 48.................... | Nov 22 | 81.1928 | *R* | 19.51 |

[a] Time of the middle of each integration, expressed in hours since UT 2005 November 19.0000.
[b] Apparent red magnitude within a circle of projected radius of 15 pixels, where 1 pixel = 0.″219. The 1 $\sigma$ uncertainty on each measurement is approximately 0.03 mag.

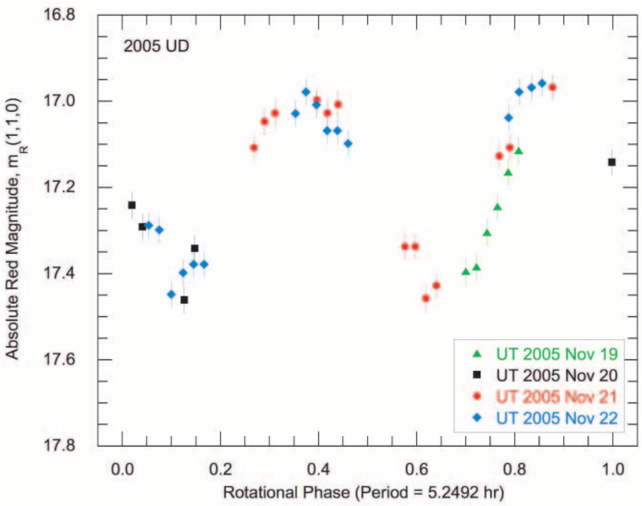


FIG. 2.—*R*-band photometry of 2005 UD taken at the University of Hawaii 2.2 m telescope on four nights in 2005 November and phased to a rotation period of 5.2492 hr. Magnitudes have been corrected for changes in the observing geometry to UT 2005 November 19. The resulting light curve has a range of 0.4 mag.

imposed by the day-night cycle. The most convincing of these aliases occurs at $P_{\rm rot} = 6.719$ hr. We cannot completely eliminate the possibility that the latter is the true rotation period. In either case, however, the rotation of 2005 UD appears to be significantly slower than the rapid rotation of Phaethon ($P_{\rm rot} = 3.59$ hr; Dundon 2005). The implications of this dissimilarity for ascertaining whether Phaethon and 2005 UD share a common origin, however, are unclear. For the purposes of this paper, we adopt 5.249 hr as the nucleus rotation period for 2005 UD. The mean rotation period of asteroids with diameters $D \sim 1$ km is $5.0 \pm 0.6$ hr (Pravec et al. 2002). The period of 2005 UD is unremarkable in the sense that it is within 1 $\sigma$ of this mean.

The peak-to-peak photometric range of the light curve of 2005 UD is $\Delta m_R = 0.40 \pm 0.05$ mag. Assuming that this is due to the rotational modulation of the scattering cross section of an elongated body (and not due to surface albedo variation), the ratio of the axes of 2005 UD projected on the plane of the sky is given by

$$\frac{a}{b} = 10^{0.4\Delta m_R} = 1.45 \pm 0.06. \tag{1}$$

This is a lower limit to the true axis ratio of the body because of projection effects. Approximating 2005 UD as a prolate ellipsoid, this gives approximate nucleus dimensions of 1.1 km × 1.6 km. Using the rotational period we calculated for this body, we can also estimate a critical bulk density from

$$\rho_c \approx 1000\left(\frac{3.3\ \rm hr}{P_{\rm rot}}\right)^2\left(\frac{a}{b}\right), \tag{2}$$

where, for a given $P_{\rm rot}$ in hours, $\rho_c$ is the minimum density required for the self-gravity of a rubble pile to exert enough centripetal acceleration to prevent nucleus disintegration due to rotation (Harris 1996). For 2005 UD, we calculate $\rho_c \approx 570$ kg m$^{-3}$. For comparison, faster spinning Phaethon has $\rho_c \approx 1200$ kg m$^{-3}$. As these values are minimum densities only, however, we can still draw no definitive conclusions as to a possible common origin of these two bodies.

Next, we sought evidence for a coma, which would indicate ongoing mass loss from 2005 UD. For this purpose, we visually examined all 40 *R*-band images (Table 2) and selected those with the best combination of image quality (measured by the FWHM of field stars) and background contamination. For proper comparison with field stars, our chosen images also all had to have been observed on the same night. Six *R*-band images taken on the night of UT 2005 November 21 (combined integration of 1800 s) were selected for the profile determination. The images were rotated so that the direction of motion of 2005 UD was horizontal, then aligned on the object using a fifth-order polynomial for pixel interpolation, and finally median-combined into a single image. The resulting rotated, shifted image has a FWHM of 0.″78, compatible with the seeing in the individual images used to make the composite. A one-dimensional surface brightness profile was measured in the direction perpendicular to the trail (vertical in the rotated image). For reference, we measured the corresponding one-dimensional surface brightness profiles of nearby field stars in the same way. The agreement between the 2005 UD and field star profiles is generally good. Small differences between the profiles can be attributed to background objects, which passed behind 2005 UD and are imperfectly removed in a combination of only six images, and real differences in the point-spread function over the field of the CCD (the latter probably due to diffraction around dust particles and other imperfections on the filter, which is located near the focal plane).

Limits on the presence of a near-nucleus coma were set using a convolution model (Luu & Jewitt 1992). We convolved the two-dimensional point-spread function determined from field stars with simple "coma plus nucleus" models. In the models the nucleus was represented by a single pixel and the coma by a circularly symmetric function with surface brightness varying inversely with distance from the nucleus. The primary parameter used to distinguish models was $\eta$, defined as the ratio of the signal from the coma when integrated out to a radius of 50 pixels (10.″95) to the signal from the nucleus. If the nucleus and coma grains have the same albedo, then $\eta$ gives the ratio of the scattering cross sections of the coma and nucleus, with $\eta = 0$ indicating no coma and $\eta = 1$ indicating equal areas in the coma and the nucleus. The degree to which this model is useful rests on the accuracy of the assumed coma surface brightness variation. A coma that is much more centrally condensed (i.e., has a steeper surface brightness profile) than assumed could go undetected with a larger $\eta$. A coma that is not circularly symmetric in the plane of the sky would likewise be imperfectly modeled. The current model is a useful way to quantify limits to the coma given the complete absence of other observational constraints.

Convolution models are plotted in Figure 3, from which it may be inferred that a coma with $\eta > \eta_{\rm lim} = 0.2$ would be detected in the 2005 UD surface brightness profile if it were present. Under the assumption of isotropic ejection, the mass-loss rate can be related to $\eta$ by (Luu & Jewitt 1992)

$$\frac{dM}{dt} = \frac{0.001\pi\rho\bar{a}\eta_{\rm lim}r_e^2}{\phi R^{1/2}\Delta}, \tag{3}$$

where $\rho = 1000$ kg m$^{-3}$ is the assumed grain density, $\bar{a} = 0.5 \times 10^{-6}$ m is the assumed weighted mean grain radius, $r_e = 650$ m is the effective radius, $\phi$ is the projected photometry radius in arcseconds, and $R$ and $\Delta$ are given in Table 1. With $\eta_{\rm lim} \sim 0.2$, we obtain $dM/dt \sim 0.01$ kg s$^{-1}$. At $R = 1.6$ AU, perfectly absorbing water ice exposed at the subsolar point of 2005 UD (neglecting heat loss by conduction and the effects of rotation but including the cooling effect of sublimation) would have a temperature of 198 K and would sublimate at the rate $dm/dt = 1.7 \times 10^{-4}$ kg m$^{-2}$ s$^{-1}$. This is the maximum temperature and

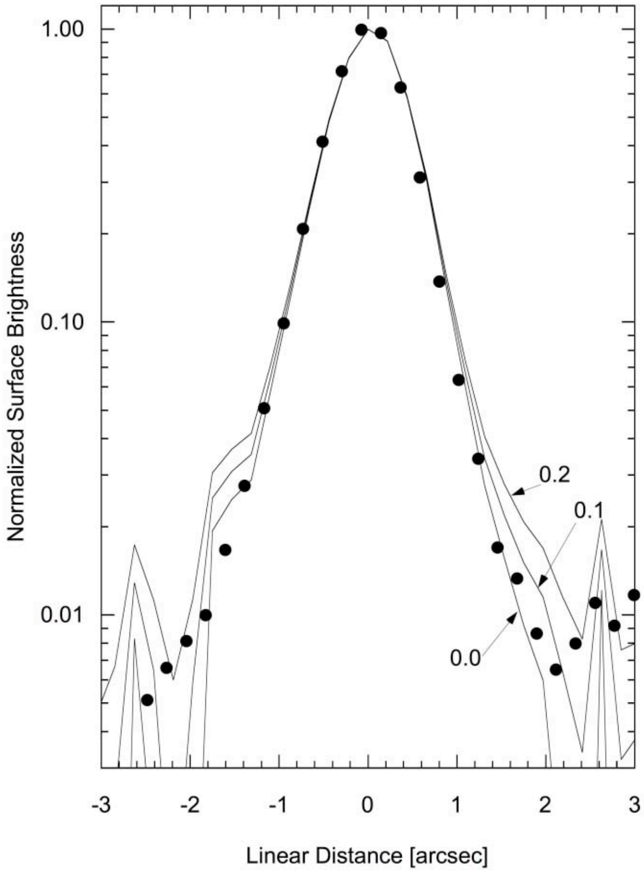


FIG. 3.—Surface brightness profiles of 2005 UD and a field star from UT 2005 November 21. Solid curves show convolution models with coma-to-nucleus ratios of 0.0, 0.1, and 0.2, as marked.

sublimation rate likely to be found on 2005 UD at this heliocentric distance. It corresponds, for example, to the case for which the rotation axis of 2005 UD is pointed at the Sun so that heating of the pole is unmodulated by rotation. To estimate the minimum temperature and sublimation rate, we also consider the isothermal case in which heat from the Sun is assumed to be spread uniformly over the surface of the body. Then, we find that the temperature (again depressed by sublimation) is 186.6 K, and the sublimation rate is $\sim 2 \times 10^{-5}$ kg m$^{-2}$ s$^{-1}$. From the minimum and maximum calculated specific sublimation rates we find that the sublimating area needed to supply 0.01 kg s$^{-1}$ is then in the range of 60–500 m$^2$. The larger of these two, expressed as a fraction of the surface area of 2005 UD, corresponds to an active fraction $f \leq 10^{-4}$. For comparison, the median active fraction measured in 27 periodic comets is $f = 0.1$ (Tancredi et al. 2006). The upper limit to the active fraction on 2005 UD is an order of magnitude beneath the smallest value reported for a periodic comet, namely, $f \sim 10^{-3}$ for 28P/Neujmin 1 (Tancredi et al. 2006).

We used the light curve from Figure 2 to correct for rotational variations in the photometry when determining broadband colors. Results are given in Table 3, in which we have listed the best estimate of the $R$-band magnitude interpolated to the time of each $B$-, $V$-, and $I$-filter measurement. Because of the time sampling of the $R$-band data, uncertainties in the interpolated magnitudes are effectively no larger than for the individual $R$-band measurements and may in fact be smaller because of the smoothing effect of the interpolations. Uncertainties in the colors as listed in the table are calculated by propagation of errors. Within the uncertainties, measurements from UT 2005 November 20 and 21 are consistent in showing optical colors that are very similar to those of the Sun, or slightly bluer (Table 3).

The colors of 3200 Phaethon are also bluer than the Sun (Luu & Jewitt 1990; Skiff et al. 1996; Lazzarin et al. 1996; Hicks et al. 1998; Dundon 2005), and this object has been classified as an F-type asteroid by Tholen (1985) and a B-type asteroid by Green et al. (1985), both considered to be blue spectral types. (We discount a single, unconfirmed report that Phaethon is a red S-type object [Cochran & Barker 1984].) In Figure 4 we compare the broadband colors of 2005 UD measured here with the reflection spectrum of 3200 Phaethon from Lazzarin et al. (1996). The optical reflectivity gradients of the two objects are consistent in showing slightly blue slopes.

This in itself is an interesting result because blue near-Earth objects (NEOs) are uncommon. For example, Luu & Jewitt (1990) found only 1 of 19 NEOs in their sample to have a reflectivity gradient $S' \leq 0\%$ kÅ$^{-1}$. Dandy et al. (2003) found that 3 out of 56 NEOs were blue. Binzel et al. (2002) listed 10 B- or F-class NEOs out of $\sim$230 that are spectrally classified, corresponding to 1 out of every 23 NEOs. In the largest study of a more heterogeneous sample, Bus & Binzel (2002) reported 63 blue-sloped asteroids (not just NEOs) in a sample of 1447, again corresponding to 1 out of every 23 asteroids. Taking 1/23 as the blue fraction, the likelihood that two blue objects (3200 Phaethon and 2005 UD) would be found by randomly drawing from the NEO population is $(1/23)^2 \sim 1/530$. We conclude, at a level of confidence corresponding to about 3 $\sigma$, that the blueness of these two objects is not a chance result. Given that 3200 Phaethon exists

TABLE 3

COLOR PHOTOMETRY

| $N$ | Date (UT 2005) | Midtime[a] | $R$[b] | $B - R$[c] | $V - R$[c] | $R - I$[c] |
|---|---|---|---|---|---|---|
| 1 | Nov 20 | 31.8593 | 19.63 | ... | ... | 0.35 ± 0.04 |
| 2 | Nov 20 | 32.0838 | 19.70 | ... | 0.33 ± 0.04 | ... |
| 3 | Nov 21 | 54.2761 | 19.37 | ... | ... | 0.31 ± 0.04 |
| 4 | Nov 21 | 54.3883 | 19.36 | 0.99 ± 0.03 | ... | ... |
| 5 | Nov 22 | 54.5006 | 19.35 | ... | 0.35 ± 0.04 | ... |
| 6 | Nov 22 | 56.7917 | 19.42 | ... | ... | 0.33 ± 0.04 |
| 7 | Nov 22 | 56.9044 | 19.39 | 1.04 ± 0.03 | ... | ... |
| 8 | Nov 22 | 57.0164 | 19.35 | ... | 0.37 ± 0.04 | ... |
| Average colors | | | | 1.01 ± 0.02 | 0.35 ± 0.02 | 0.33 ± 0.02 |
| Solar colors | | | | 1.03 | 0.36 | 0.35 |

[a] Time of the middle of each $B$-, $V$-, or $I$-band integration expressed in hours since UT 2005 November 19.0000.
[b] $R$-band magnitude at the time of the $B$-, $V$-, or $I$-filter measurement, determined from the light curve in Fig. 2.
[c] Instantaneous color index obtained by referencing all photometry to the $R$-band light-curve data.

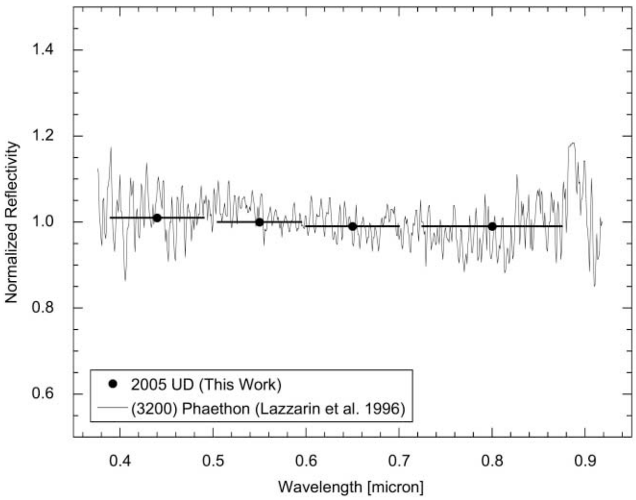


FIG. 4.—Normalized reflectivity as a function of wavelength, for 2005 UD (*filled circles*) and 3200 Phaethon (*line*; Lazzarin et al. 1996). Error bars on the 2005 UD data are about the size of the symbols. Horizontal bars mark the FWHM of the $B$, $V$, $R$, and $I$ filters.

and is blue, the likelihood that 2005 UD would also be blue if drawn at random from the NEO distribution of the colors is $\sim$1/23. This is not so small that we can prove on statistical grounds that the two objects share a common origin. However, the data are consistent with this interpretation.

Known properties of 2005 UD and 3200 Phaethon are compared in Table 4. The dynamical similarities between 2005 UD and 3200 Phaethon are consistent with a common origin for both, presumably as pieces of a larger object that broke up to produce the Geminid meteor stream (Ohtsuka et al. 2006). The new physical observations are compatible with this inference but provide no direct clue about the mechanism behind the breakup. A few conjectures are nevertheless possible. The timescale on which heat deposited on the surface of a body of radius $r_e$ is conducted to the center is of order $\tau \sim r_e^2/\kappa$, where $\kappa$ is the thermal diffusivity, equal to the conductivity divided by the density and the specific heat capacity. For dielectric solids of the type likely to constitute the bulk of the NEOs, we can take $\kappa \sim 10^{-6}$ m$^2$ s$^{-1}$. Porosity might reduce $\kappa$ to $\sim 10^{-7}$ m$^2$ s$^{-1}$. With $r_e = 650$ m for 2005 UD, we estimate $\tau \sim 10^4$–$10^5$ yr. Even the longer of these timescales is short compared to the million-year dynamical lifetimes of bodies in planet-crossing orbits (Froeschle et al. 1995). As a result, we expect that enough time has elapsed for the deep interior of 2005 UD to have been warmed by heat conducted from the surface. Under these circumstances we can, to a first level of approximation, consider the nucleus as a thermal integrator. The core temperature can be estimated by equating the average power input to the body around its orbit to the radiative losses, or

$$4\pi r_e^2 \epsilon \sigma T_c^4 = \frac{\pi r_e^2 (1 - A)}{P} \int \frac{L_\odot}{4\pi r^2(t)}\, dt, \tag{4}$$

where $T_c$ is the core temperature, $\sigma = 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$ is the Stefan-Boltzmann constant, $r_e$ is the spherical equivalent radius, $\epsilon$ and $A$ are the effective emissivity and the Bond albedo, respectively, $L_\odot = 4 \times 10^{26}$ W is the power of the Sun, $r(t)$ is the time-dependent heliocentric distance, and $P$ is the orbit period. We computed $r(t)$ from Kepler's equation and hence evaluated the integral in equation (4), finding $T_c = 295$ K. This is far too hot for water ice to persist in the deep interior of 2005 UD and suggests a mechanism for the disintegration of the precursor body. The partial pressure in water vapor at 295 K is $P_w \sim 3000$ N m$^{-2}$. The central hydrostatic pressure in a spherical, nonrotating body is $P_c \sim G\rho^2 r_e^2$, where $G = 6.7 \times 10^{-11}$ N kg$^{-2}$ m$^2$ is the gravitational constant. We note that $P_w > P_c$ for $r_e > (P_w/G)^{1/2}/(\rho)$. Substituting $P_w = 3000$ N m$^{-2}$ and $\rho = 1000$ kg m$^{-3}$, we obtain $r_e > 7000$ m. Any body in a 2005 UD or Phaethon-like orbit and smaller than about 7 km in radius would have gravity insufficient to overcome the water vapor pressure corresponding to the core temperature. Both 2005 UD and Phaethon are smaller than this critical size, suggesting that they could have been produced by gas pressure disintegration of a precursor body. Essentially, this model has been invoked to explain breakup of cometary nuclei, but the larger distances and lower temperatures of some cometary breakups require the sublimation of ices more volatile than water in order to generate sufficient pressures (Samarasinha 2001). As with the comets, we possess no proof that this is the method of breakup, and reasonable arguments can clearly be made that

TABLE 4
PHAETHON AND 2005 UD COMPARED

| Quantity | Symbol | 2005 UD | 3200 Phaethon |
|---|---|---|---|
| Semimajor axis | $a$ | 1.275 | 1.271 |
| Perihelion | $q$ | 0.163 | 0.140 |
| Eccentricity | $e$ | 0.872 | 0.890 |
| Inclination | $i$ | 28.75 | 22.16 |
| Absolute red magnitude | $H_R$ | 17.13 ± 0.03 | 14.3 ± 0.1[a] |
| Red geometric albedo | $p_R$ | 0.11[b] | 0.11 ± 0.02[a] |
| Equivalent circular diameter (km) | $D_e$ | 1.3 ± 0.1 | 4.7 ± 0.5 |
| Color | $B - V$ | 0.66 ± 0.03 | 0.59 ± 0.01[c] |
| Color | $V - R$ | 0.35 ± 0.02 | 0.35 ± 0.01[c] |
| Color | $R - I$ | 0.33 ± 0.02 | 0.32 ± 0.01[c] |
| Rotation period (hr) | $P_{\rm rot}$ | 5.249 | 3.59[c] |
| Photometric range (mag) | $\Delta m_R$ | 0.40 ± 0.05 | 0.4[c] |
| Minimum critical density (kg m$^{-3}$) | $\rho_c$ | 570 | 1200 |

NOTE.—Unlabeled numbers are from the present work, except for the orbital data from Ohtsuka et al. (2006).
[a] Green et al. (1985).
[b] Assumed value.
[c] Dundon (2005).

gas pressure would be incapable of detonating a body in which cracks, fractures, and the overall permeability to gas flow prohibit dramatic pressure buildup. Still, the possibility is interesting and would be consistent with the expected thermal shock on a main-belt comet following a dramatic reduction in the perihelion distance from >3 AU (Hsieh & Jewitt 2006) to $\sim$0.15 AU.

The mass of the Geminids is near $1.6 \times 10^{13}$ kg (Hughes & McBride 1989), and the stream is young, with an age estimated to lie between 600 and 2000 yr (Gustafson 1989; Williams & Wu 1993). With $\rho = 1000$ kg m$^{-3}$, the mass of 2005 UD must be near $1 \times 10^{12}$ kg, and it may be appropriate to think of this object as a particularly large fragment produced by the breakup of a hypothetical parent body. Formation by breakup of a larger (presumably rubble-pile) body should leave 2005 UD in a rotationally excited state. The young age is short compared to the timescale for internal damping toward principal axis rotation, and therefore, it is reasonable to expect that 2005 UD should show motion in an excited state. However, the available light-curve data (Fig. 2) are too limited and remain consistent with principal axis rotation. Longer photometric time series taken at the next apparition might show deviations from singly periodic rotation.

## 4. SUMMARY

New optical observations of 2005 UD lead to the following conclusions:

1. The nucleus has an absolute red magnitude $m_R(1, 1, 0) = 17.13 \pm 0.03$, about 3 mag fainter than that of 3200 Phaethon. If the geometric albedo and density are the same as Phaethon's, then the equivalent diameter of 2005 UD is $D_e = 1.3 \pm 0.1$ km, and the ratio of the masses is approximately 50:1.

2. At wavelengths from 4500 to 8500 Å, the nucleus is neutral to slightly blue relative to the Sun, as is 3200 Phaethon, and thus qualifies spectrally as a B-type asteroid. Spectral B types are uncommon among near-Earth objects. The fact that both 2005 UD and 3200 Phaethon are blue strongly suggests a physical association between these objects.

3. The light curve of 2005 UD is periodic, with range $\Delta m_R = 0.40 \pm 0.05$ mag and best-fit period 5.249 hr, suggesting a projected axis ratio of $\sim 1.45 \pm 0.06$ and a minimum density needed to keep the body in internal compression of 570 kg m$^{-3}$.

4. The data provide no evidence for ongoing mass loss. An upper limit from detailed analysis of the surface profile is set at 0.01 kg s$^{-1}$, corresponding to an upper limit to the fraction of the surface area that could be occupied by freely sublimating water ice of $f \leq 10^{-4}$. This is an order of magnitude smaller than the least active short-period comets.

5. We conjecture that 3200 Phaethon, 2005 UD, and the Geminids are pieces of a main-belt comet precursor that disrupted, perhaps due to unsustainable internal gas pressures, following deflection into a Sun-approaching orbit.

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## REFERENCES

Binzel, R. P., Lupishko, D., di Martino, M., Whiteley, R. J., & Hahn, G. J. 2002, in Asteroids III, ed. W. F. Bottke, Jr., et al. (Tucson: Univ. Arizona Press), 255
Bus, S. J., & Binzel, R. P. 2002, Icarus, 158, 146
Cochran, A. L., & Barker, E. S. 1984, Icarus, 59, 296
Dandy, C. L., Fitzsimmons, A., & Collander-Brown, S. J. 2003, Icarus, 163, 363
Dundon, L. 2005, M.S. thesis, Univ. Hawaii
Froeschle, C., Hahn, G., Gonczi, R., Morbidelli, A., & Farinella, P. 1995, Icarus, 117, 45
Green, S. F., Meadows, A. J., & Davies, J. K. 1985, MNRAS, 214, 29P
Gustafson, B. A. S. 1989, A&A, 225, 533
Harris, A. W. 1996, Lunar Planet Sci., 27, 493
Hicks, M. D., Fink, U., & Grundy, W. M. 1998, Icarus, 133, 69
Hsieh, H. H., & Jewitt, D. 2006, Science, 312, 561
Hughes, D. W., & McBride, N. 1989, MNRAS, 240, 73
Landolt, A. U. 1992, AJ, 104, 340
Lazzarin, M., Barucci, M. A., & Doressoundiram, A. 1996, Icarus, 122, 122
Luu, J. X., & Jewitt, D. C. 1990, AJ, 99, 1985
———. 1992, Icarus, 97, 276
McNaught, R. H., et al. 2005, Minor Planet e-Circ., 2005-U22
Ohtsuka, K., Sekiguchi, T., Kinoshita, D., Watanabe, J.-I., Ito, T., Arakida, H., & Kasuga, T. 2006, A&A, 450, L25
Pravec, P., Harris, A. W., & Michalowski, T. 2002, in Asteroids III, ed. W. F. Bottke, Jr., et al. (Tucson: Univ. Arizona Press), 113
Samarasinha, N. H. 2001, Icarus, 154, 540
Skiff, B. A., Buie, M. W., & Bowell, E. 1996, BAAS, 28, 1104
Tancredi, G., Fernández, J. A., Rickman, H., & Licandro, J. 2006, Icarus, 182, 527
Tholen, D. J. 1985, IAU Circ., 4034, 2
Whipple, F. L. 1983, IAU Circ., 3881, 1
Williams, I. P., & Wu, Z. 1993, MNRAS, 262, 231