LIGHT CURVES OF 20–100 km KUIPER BELT OBJECTS USING THE HUBBLE SPACE TELESCOPE

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ABSTRACT
We report high-precision photometry of three small and one larger Kuiper Belt objects (KBOs) obtained with the Advanced Camera for Surveys on board the Hubble Space Telescope. The three small bodies are the smallest KBOs for which light-curve measurements are available. The object 2003 BF$_{91}$ has a diameter of 20 km (assuming 10% albedo) and a 1.09 mag, 9.1 hr light curve that is feasible explained by the rotation of an elongated, coherent body supported by material strength and best imagined as an icy outer solar system analog to asteroid (243) Ida. Two other small KBOs, 2003 BG$_{91}$ and 2003 BH$_{91}$ (diameters 31 and 18 km, with albedo 10%), exhibit an unremarkable light curve and no detectable photometric variation, respectively. For the larger KBO 2000 FV$_{53}$ (116 km diameter, assuming 10% albedo) we strongly detect a nonsinusoidal periodic (7.5 hr) brightness variation with a very small amplitude (0.07 mag). This KBO may be nearly spherical, a result that might not be unusual in the Kuiper Belt but would be remarkable among outer solar system satellites of similar size. Light curves may be caused by variations in albedo or shape, and we carry out a study of possible physical states and bulk densities under the assumptions of both fluid equilibrium and finite, nonzero internal friction. Under most assumptions, the densities for these KBOs are likely in the range 1–2 g cm$^{-3}$, and a plausible solution for 2000 FV$_{53}$ is a rubble pile of this density that is held slightly out of the minimum-energy shape by internal friction among constituent blocks that are relatively small. Our interpretation of 2000 FV$_{53}$ as a pulverized but essentially primordial object and 2003 BF$_{91}$ as a collisional fragment is consistent with models of collisional timescales in the outer solar system. We compile all published KBO light-curve data to date and compare our results to the larger population.

Key words: Kuiper Belt — minor planets, asteroids
Online material: color figures, machine-readable tables

1. INTRODUCTION
The Kuiper Belt, a remnant debris disk that surrounds the planetary realm of our solar system, is a relatively pristine record of the prevailing conditions during the formation of the solar system. Subsequent evolution has overprinted this original state such that present-day observations allude to the combination of accretion and eons of collisions. Observations of individual Kuiper Belt objects (KBOs) allow explorations of bodies with aged but primordial compositions. Studies of binary KBOs (Veillet et al. 2002; Noll et al. 2002, 2004a, 2004b; Osip et al. 2003; Stansberry et al. 2005; Stephens & Noll 2006) provide albedo constraints, usually under a density assumption, and may increase what little is known about the internal composition and structure of KBOs.

Small solar system body light curves have been studied for many years, principally for asteroids (Pravec et al. 2002) and comets (see, e.g., Jewitt 1991; Samarasinha et al. 2004). Light curves of small objects are often interpreted as manifestations of reflections from irregularly shaped objects, and light-curve information has been shown to correspond well with radar-derived shape models (see, e.g., Ostro et al. 2002). With the continued increase in the number of known KBOs (and hence bright KBOs) and access to improving observing technologies, KBO light curves can now be studied. Published light-curve data exist for 65 KBOs and Centaurs, with approximately half showing light curves greater than around 0.1 mag, with a typical amplitude around 0.5 mag. The object 2001 QG$_{298}$ has the largest known KBO light-curve amplitude, 1.14 mag (Sheppard & Jewitt 2004). KBO light curves are thought to imply either heterogeneous albedo distributions or else asphericities, with the extreme case of the latter potentially being contact binary KBOs (Sheppard & Jewitt 2004). The KBO light-curve literature is tabulated and analyzed in § 6.3.

Here we report high-precision photometry for four KBOs observed with the Hubble Space Telescope (HST) (§ 2). The capabilities of HST and the extended duration of this study permit, for the first time, the study of photometric variations of very faint and therefore small KBOs and the detection of very small (<0.1 mag) variations of modest-sized KBOs. Two of these KBOs show clear periodic variation, a third shows a somewhat less significant periodic variation, and the fourth has no distinguishable periodic signature (§ 3). We discuss interpretations of these data in §§ 4 and 5 and the implications in § 6.

2. OBSERVATIONS
We have carried out a large (125 orbits) HST Advanced Camera for Surveys (ACS) observing program to search for very faint KBOs. The primary results of this program—the discovery of a substantial deficit of classical and excited KBOs at small sizes—are reported in Bernstein et al. (2004). Here we briefly summarize the relevant technical details of the observations and data reduction (see Bernstein et al. [2004] for complete discussions). Our observations were divided into two epochs, the “discovery epoch” (UT 2003 January 26.014–31.341), in which 55 × 400 s
exposures were taken at each of the six pointings, and the “recovery epoch” (2003 February 05.835–09.703), in which an additional 40 × 400 s exposures were taken at each pointing. During the discovery epoch, a given pointing is sampled sporadically, with intervals as small as 8 minutes, over a time span of approximately 24 hr; the pointing is revisited 2 days later with the same sporadic sampling. Approximately 7 days later, the entire cycle repeats for the recovery epoch. Consequently, we obtained ≈95 independent measurements of each KBO observed, over a time baseline of around 12 days, with sampling as fine as minutes in some cases but with windows of several days (or more) in which no observations of a given KBO were made.

Bernstein et al. (2004) detected three new KBOs (2003 BF₉₁, 2003 BG₉₁, and 2003 BH₉₁), as well as a previously known KBO (2000 FV₅₃) that was targeted in the observations. The object 2000 FV₅₃ was detected with signal-to-noise ratio (S/N) ≥ 80 in each of its individual exposures; hence, the photometry is quite precise. The objects 2003 BG₉₁, 2003 BF₉₁, and 2003 BH₉₁ were discovered with S/Ns in individual exposures of typically 7.5, 2.7, and 2.4, respectively. The discovery of the last object required the use of “digital tracking,” in which exposures are shifted at rates corresponding to all valid KBO orbits before summing and searching for flux peaks that exceed the detection threshold.

Photometry for each object was extracted by fitting a model of a moving point source to relevant exposures. We measured the point-spread function (PSF) for the ACS Wide Field Camera (WFC) in exposures of a globular cluster field. In the moving point-source model fitting, this PSF was smeared before fitting to the relevant pixels to account for the (slight) trailing expected on each exposure. We fitted the entire stack of images simultaneously,

### Table 1
**Photometry for 2003 BG₉₁**

| MJD          | Flux (counts s⁻¹) |
|--------------|-------------------|
| 52666.1767   | 0.3777 ± 1.8490   |
| 52666.1803   | 0.8904 ± 0.1151   |
| 52666.1860   | 0.8166 ± 0.1134   |
| 52666.1918   | 0.7036 ± 0.1110   |
| 52666.1975   | 0.8721 ± 0.1173   |
| 52666.2033   | 0.8127 ± 0.1168   |
| 52666.2421   | 0.6223 ± 0.0983   |
| 52666.2487   | 0.8509 ± 0.1043   |
| 52666.2552   | 0.9279 ± 0.1058   |
| 52666.2618   | 0.8789 ± 0.1041   |

**Note.—** Table 1 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Fluxes and MJD are reported for individual exposures. The zero points (the magnitude of a star that produces 1 count s⁻¹ in the given filter) for ACS WFC F606W are 26.486 in the AB magnitude system and 26.655 in the ST magnitude system.

### Table 2
**Photometry for 2003 BF₉₁**

| MJD          | Flux (counts s⁻¹) |
|--------------|-------------------|
| 52665.8549   | −1.2230 ± 1.8355  |
| 52665.8585   | 0.2728 ± 0.1085   |
| 52665.9086   | 0.3598 ± 0.1063   |
| 52665.9143   | 0.3964 ± 0.1044   |
| 52665.9201   | 0.4106 ± 0.1024   |
| 52665.9764   | 0.3061 ± 0.1063   |
| 52665.9826   | 0.3144 ± 0.0944   |
| 52665.9891   | 0.3846 ± 0.1639   |
| 52666.0438   | 0.3133 ± 0.0930   |
| 52666.0503   | 0.2163 ± 0.0939   |

**Note.—** Table 2 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Fluxes and MJD are reported for individual exposures. The zero points (the magnitude of a star that produces 1 count s⁻¹ in the given filter) for ACS WFC F606W are 26.486 in the AB magnitude system and 26.655 in the ST magnitude system.

### Table 3
**Photometry for 2003 BH₉₁**

| MJD          | Flux (counts s⁻¹) |
|--------------|-------------------|
| 52666.1635   | 0.7434 ± 1.8236   |
| 52666.1671   | 0.1931 ± 0.1010   |
| 52666.1728   | 0.1785 ± 0.0956   |
| 52666.1786   | 0.2867 ± 0.1315   |
| 52666.1843   | 0.1527 ± 0.0918   |
| 52666.1901   | 0.3753 ± 0.1033   |
| 52666.2289   | 0.1168 ± 0.0864   |
| 52666.2355   | 0.1277 ± 0.0861   |
| 52666.2420   | 0.2216 ± 0.0892   |
| 52666.2486   | 0.1254 ± 0.0832   |

**Note.—** Table 3 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Fluxes and MJD are reported for individual exposures. The zero points (the magnitude of a star that produces 1 count s⁻¹ in the given filter) for ACS WFC F606W are 26.486 in the AB magnitude system and 26.655 in the ST magnitude system.

### Table 4
**Photometry for 2000 FV₅₃**

| MJD          | Flux (counts s⁻¹) |
|--------------|-------------------|
| 52664.8329   | 21.1105 ± 0.3022  |
| 52664.8386   | 21.9243 ± 0.3048  |
| 52664.8444   | 21.3123 ± 0.3072  |
| 52664.8917   | 20.4094 ± 0.2961  |
| 52664.9005   | 19.8693 ± 0.2640  |
| 52664.9093   | 19.5699 ± 0.2652  |
| 52664.9619   | 19.8776 ± 0.2658  |
| 52664.9760   | 19.7707 ± 0.2660  |
| 52665.0304   | 20.9440 ± 0.2697  |
| 52665.0370   | 20.7644 ± 0.2685  |

**Note.—** Table 4 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Fluxes and MJD are reported for individual exposures, excluding measurements from from nine exposures that exhibit cosmic rays or image defects close to the KBO image. The zero points (the magnitude of a star that produces 1 count s⁻¹ in the given filter) for ACS WFC F606W are 26.486 in the AB magnitude system and 26.655 in the ST magnitude system.
with the free parameters being the six relevant degrees of freedom (dof) in the KBO orbit plus an unknown flux for each exposure. The best-fit photometry and orbit are thus solved simultaneously.

The S/N per exposure for 2000 FV53 is so high that we use a slightly different approach, allowing the position to be a free parameter on each exposure rather than forcing positions to obey a common orbit. Without this approach, we find that small (milliarcsecond) errors in the astrometric solutions for the WFC cause excess variance in the flux determinations. For the fainter three KBOs, the flux errors due to these ~5 mas astrometric errors are a few hundredths of a magnitude, well below the noise levels. The slow brightening due to the decreasing illumination phase of the KBOs is too small to be detected in our data.

The fitting process produces uncertainties for each flux measurement. We find that the best-fit sinusoidal light curves give \( \chi^2 \) dof \(^{-1} \) near unity for the three faint bodies (see below), suggesting that our error estimates are reliable. The \( \chi^2 \) for the best sinusoidal fit for 2000 FV53 is too high, partly because the light curve is clearly not sinusoidal (see below) but also because various systematic effects (e.g., pointing jitter) may affect the PSF fitting at the 0.01 mag level. The formal errors on the magnitudes may also be underestimated, as is common for very high S/N photometry.

The midpoint time of each exposure is corrected for light-travel time from the target. The time-series photometry for these four objects is presented in Tables 1–4.

3. ANALYSIS

We analyze the time-series photometry of these four KBOs for periodic variations by searching for the best-fit sinusoidal light-curve variation to the observed data. We search periods \( P \geq 0.1 \) days with uniform steps in frequency \( (1/P) \) of 0.01 days \(^{-1} \); shorter periods would tend to be badly aliased by the 96 minute \( HST \) orbital period. For each of the newly discovered KBOs, we fitted all the individual photometric measurements. Because the S/N for each individual 2000 FV53 measurement is so high, we exclude flux values from nine exposures that exhibit cosmic rays or image defects close to the KBO image, leaving 87 valid flux measurements. The resulting periodograms are plotted in Figure 1. The best-fit solutions are plotted in Figure 2 as a function of phase and listed in Table 5 (together with estimated uncertainties in derived amplitude). None of the three new KBOs show any evidence for double-peaked light curves, but the sinusoidal periods we derive could easily represent a half-rotation (as in the aspherical case; see § 5.1) rather than a complete rotation period (as in the albedo case; see § 4.1). The best-fit period solution for 2000 FV53 appears double peaked, although half this period may also be a valid solution (see below).

To determine the significance of each best-fit solution, we randomly scramble the time tags of the flux measurements for a given object and repeat the search for a best-fit sinusoid. For each KBO we fit 100 randomizations of the data, with the resulting best \( \chi^2 \) dof \(^{-1} \) of each trial plotted in Figure 3. Best-fit solutions to randomized 2003 BF91 and 2000 FV53 data are clearly less good than the best-fit solution to observed data at >99% confidence in both cases. The best-fit solution to the observed 2003 BF91 data is marginally significant (90% confidence level), while the best fit for 2003 BH91 data is no better than the best fits to randomized data.

3.1. 2003 BF91

The object 2003 BF91 has a best-fit sinusoidal solution with a period of 4.2 hr and an amplitude of 0.18 mag. Similar but less good solutions are found for 4.5, 4.6, and 4.9 hr; these periods are not obviously aliases of each other. In the discussion that follows we refer only to the best-fit period of 4.2 hr and, regardless of period solution, draw no significant conclusions about the internal properties of KBOs from this body’s light curve.

3.2. 2003 BH91

The periodogram for 2003 BF91 shows two clear solutions that are nearly equivalently good fits: 9.1 hr and, secondarily, 7.3 hr (Fig. 1). Both solutions have amplitudes of 1.09 mag. The secondary peak is nonresonant with the best fit, i.e., not an obvious harmonic of the best-fit period, and is also quite significant compared to the randomized data. We therefore searched further for a best-fit solution that consisted of two independent sinusoids with independent phases, amplitudes, and periods, although the periods were restricted to a small range around each of best fits.
100 randomized trials of the 2003 BH 91 data. We therefore con-
derived above. Formally, the \( \chi^2 \) improves significantly through
allowing a two-sine fit, but the data may not warrant attaching
too much importance to a multiple rotation pole interpretation. In
the following analysis we use the single-sinusoid better fitting
9.1 hr period. None of our conclusions depend on the choice be-
tween the two best-fit single-sinusoid periods, nor particularly
on the choice of a single- over a double-sinusoid fit.

3.3. 2003 BH91
The best-fit sinusoid solution to the photometry of 2003 BH91
has a period of 2.8 hr and an amplitude of 0.42 mag. However,
the significance of this solution is only 46\% when compared to
100 randomized trials of the 2003 BH91 data. We therefore con-
clude that we failed to detect significant periodic variability for
2003 BH91. To place an upper limit on the amplitude of an un-
detected periodic variation, we augmented the 2003 BH91 data
with synthetic light curves with various amplitudes and periods
of 4 hr (a typical KBO photometric variation period) and carried
out the best-fit solution search described above. We successfully
recovered all synthetic light curves with amplitudes larger than
around 15\%. We can therefore place an upper limit on possible
light-curve amplitudes for 2003 BH91, requiring that any such
variation must have an amplitude less than 0.15 mag to be un-
dected by us. The albedo variations and/or asphericity of this
body must be less than 15\%.

3.4. 2000 FV53
The best-fit solution for 2000 FV53 gives a period of 7.5 hr.
There is a peak of nearly equal significance at 3.79 hr, almost
exactly half the best solution. The amplitude of the light curve is
identical (0.07 mag) for both solutions. We compare the 2000 FV53
observed data phased at each of these two periods in Figure 4. The
phased data in Figure 4 (top) appear double peaked, with maxima
at phases of 0.3–0.35 and 0.95–1.0. These two peaks have dif-
dent shapes and are not 0.5 phase units apart, so we conclude that
this light curve is double peaked and nonsinusoidal and that 7.5 hr
is the true rotation period of 2000 FV53. (We note a low-signal
maximum for 2000 FV53 in Fig. 1 at 15 hr, which could be an alias
of the 7.5 hr rotation period.) However, we include the 3.79 hr
period in discussions below for completeness; this light curve
(Fig. 4, bottom) is also significantly nonsinusoidal. Arguably,
the true photometric period could be 3.79 hr, with 7.5 hr an alias

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**TABLE 5**

**BEST-FIT SOLUTIONS FOR KBO LIGHT CURVES**

| OBJECT       | MEAN F606W MAGNITUDE (STMAG) | 10% Albedo | 4% Albedo | PERIOD (hr) | AMPLITUDE (mag) | SIGNIFICANCEb |
|--------------|-------------------------------|------------|-----------|-------------|----------------|---------------|
| 2003 BG91    | 26.95 ± 0.02                  | 31         | 48        | 4.2         | 0.18 ± 0.075   | 90            |
| 2003 BF91    | 28.15 ± 0.04                  | 20         | 31        | 9.1         | 1.09 ± 0.25    | >99           |
| 2003 BH91    | 28.38 ± 0.05                  | 18         | 28        | ...         | <0.15          | ...           |
| 2000 FV53    | 23.41 ± 0.01                  | 116        | 183       | 7.5         | 0.07 ± 0.02    | >99           |

a From Bernstein et al. (2004) and erratum. Assumes spherical bodies.
b Significance of the best-fit solution compared to 100 randomizations of the data; that is, the number of the 100 random data trials that
provide worse \( \chi^2 \) dof\(^{-1} \) than the observed data (see § 3 and Fig. 3).
c Here we list our derived upper limit, which corresponds to no detection of periodic variation (§ 3.3).
of this true photometric period. We discuss the implications of the nonsinusoidal light curve below.

4. LIGHT-CURVE MODULATIONS PRODUCED BY SURFACE FEATURES

Observations of KBOs are necessarily conducted with the line of sight very close to the direction of illumination: in our case, 1.4 and 1.7° for the new bodies and 2000 FV53, respectively. In this case we can ascribe light-curve variations to some combination of (1) variation in surface composition and/or albedo that rotates through the observed hemisphere, (2) small-scale irregularities (“facets”) that rotate through (un)favorable orientations for reflecting radiation to the observer, or (3) changes in the projected area of the rotating body due to its gross shape, often approximated as an ellipsoid.

We examine in turn these possible causes for the photometric variations of our measured KBOs, with the goal of extracting any possible constraints on their internal structure or surface composition. We focus primarily on the objects 2003 BF91 and 2000 FV53 because their exceptionally large and small photometric variations, respectively, provide the most interesting constraints. The light curves of 2003 BG93 and 2003 BH91 are relatively unremarkable and do not help differentiate among possible physical models, so they are not discussed further.

4.1. Albedo Effects

If the large observed light-curve variation of 2003 BF91 is due entirely to albedo variations, surface patches with albedos that differ by a factor of 2.5 are required if the body has two distinct hemispheres and the rotation pole is perpendicular to the line of sight. If either of these two assumptions are relaxed, the required albedo range of the surface materials is even higher.

Little is known about KBO albedos. The few data points suggest a range from a few percent to perhaps 20% or more (Altenhoff et al. 2001, 2004; Jewitt et al. 2001; Fernández et al. 2002; Groussin et al. 2004; Brown & Trujillo 2004; Noll et al. 2004b; Stansberry et al. 2004, 2005; Cruikshank et al. 2005). The canonical (but unsupported; see Altenhoff et al. [2004] and others) KBO albedo of 4%, which is based on comet albedos, is more than 4 times smaller than the 17% albedo observed for (55565) 2002 AW197 (Cruikshank et al. 2005). This large albedo range could therefore plausibly exist on 2003 BF91, although this possibility seems extreme and is not consistent with the existing sparse KBO albedo data. The range of albedos on Pluto’s surface exceeds a factor of 5 (Stern et al. 1997), although Pluto’s atmosphere contributes substantially to this effect, and 2003 BF91 would not be expected to have any atmosphere (because of its small size). The two hemispheres of Lapetus have albedos differing by a factor of 7, although this is likely due both to being tidally locked to Saturn and to contamination from other satellites.

These considerations favor shape over albedo as the primary cause of the variability of 2003 BF91, more so because the mainbelt asteroid (243) Ida provides a (rocky) example of the shape needed to produce this light curve (§ 6.4).

On the other hand, albedo and shape could be correlated, as would be the case with a large, fresh, bright crater. Furthermore, a crater or albedo feature could potentially dominate the majority of a hemisphere of a small body such as 2003 BF91, so we cannot exclude the possibility of a wide range of surface reflectance on 2003 BF91. In addition, KBO surfaces likely incorporate volatiles that could potentially be mobilized either through collisions or potentially even seasonal thermal variations. The migration of volatiles could plausibly create patchy surfaces with albedo variations.

The small photometric variations for the other three bodies could easily be explained by albedo variations on the surface. We note that light curves from albedo variations need not be symmetric, and the nonsinusoidal light curve of 2000 FV53 suggests the rotation of (two) bright spots past the subobserver point. However, it is unlikely that albedo variations would conspirse to reduce the amplitude of an otherwise large, shape-derived light curve (this would require a dark long axis and bright short axis of an elongated rotating body). Therefore, the possibility of albedo variation does not invalidate the geophysical arguments presented below.

4.2. Facets on KBOs

A second possible explanation of the KBO light curves arises from the study of small bodies of the inner solar system. Complex shape models have been determined for a number of asteroids and near-Earth objects (NEOs), not only from spacecraft observations (e.g., Thomas et al. 1999; Wilkison et al. 2002) but also from radar studies (see Ostro et al. 2002 for a review). Good light curves have been measured for many asteroids and NEOs whose shapes are known, and several NEOs are observed to have light-curve amplitudes substantially larger or smaller than their elongated shapes would naively suggest (Pravec et al. 1998; Benner et al. 1999; Benner 2002).

Because asteroids, KBOs, and comets are all heavily cratered bodies, nonuniform facets (reflecting faces and partially concave shapes) can potentially mask the true shape of the body. The scenario in which faceted KBOs show light curves larger than their gross shape would otherwise suggest cannot be ruled out. Thus, 2003 BF91 could have a complicated topography that produces a light curve that—at least during our observing season—is substantially larger than its gross shape might otherwise indicate. Conversely, the gross shape of 2000 FV53 may be less regular than its small-amplitude light curve suggests, a caveat to bear in mind for the analyses below. Facets on 2000 FV53 could also produce the observed nonsinusoidal light curve.

5. GEOPHYSICAL CONSIDERATIONS

In this section we regard the photometric variation as primarily a result of the gross shape of the KBO and examine the constraints on internal strength and density that may be derived from the rotation properties. We focus primarily on the constraints imposed by the small 0.07 mag amplitude of the 2000 FV53 light curve.

5.1. A Simple Shape Model

Observed KBO brightness variations may be the result of the gross aspherical shape of the body. A KBO may generally be thought of as having three primary axes, a, b, and c, where a ≥ b ≥ c and rotation takes place about c in the minimized energy and angular momentum state. If this body is viewed equatorially, the ratio a/b determines the magnitude of the observed light-curve modulation as Δm = 2.5 log (a/b). Lacerda & Luu (2003) present a formalism for calculating an observed magnitude variation (for essentially Lambertian bodies) as a function of body shape and the viewing angle θ between the rotation axis and the (coincident) lines of sight and illumination (their eq. [2]).

The conditions in which amplitudes smaller than 0.07 mag are produced correspond to bodies of any shape seen nearly pole-on
(θ ≈ 0) and nearly spherical bodies (a ≈ b ≈ c) seen at any angle. Note that for a KBO in pole-on rotation, the coincidence of illumination, line-of-sight, and rotation axes drives the light-curve amplitude to zero regardless of the body shape or surface properties. In this configuration, the low amplitude of the 2000 FV53 light curve would allow no definitive constraints on its properties (although a useful constraint can still be derived from the photometric period; see below). If 2000 FV53 is significantly aspherical and exactly pole-on at present, its light-curve amplitude should increase as it proceeds along its 250 yr orbit; a 20 yr observational baseline could provide a pole-Earth angle change of ~30°, potentially revealing the equatorial aspect and therefore the shape of the body. However, 2000 FV53 was targeted without regard to potentially revealing the equatorial aspect and therefore the shape of the body for a Jacobian ellipsoid—is shown in Figure 5.

Chandrasekhar (1969) tabulates the relationship between b/a, c/a, and ω²/(πGρ) (what Chandrasekhar writes as Ω we write here as ω, the angular rotation rate). We therefore can derive the relationship between b/a, c/a, and ρ and consequently between b/a, c/a, and τ. From b/a and the observed Δm, we calculate the required viewing angle θ following equation (2) of Lacerda & Luu (2003), deriving θ as a function of τ. Finally, we introduce L(θ) = (1 − cos θ), which is the probability, from simple geometric arguments, that a randomly oriented rotation pole has an orientation angle less than or equal to θ. We show L(θ) as a function of τ in Figure 5.

We exclude L(θ) < 0.1 solutions as improbable. For 2000 FV53, L(θ) ≥ 0.1 corresponds to a/b = 2.8, a/c = 3.3, and ρ ≤ 1.0 g cm⁻³ (Fig. 5). Thus, for Jacobian solutions—the only fluid solutions in which the photometric light curve is derived from the gross aspherical shape of the body—the bulk density of 2000 FV53 must be 0.67–1.0 g cm⁻³ (Fig. 5, solid red line).

By comparison, assigning Pluto’s density of 2 g cm⁻³ (Tholen & Buie 1997) to 2000 FV53 and assuming a Jacobian solution, we find a/b ≈ 5.6 and a/c ≈ 6.1, a long, thin body whose shape would be the most extreme in the solar system: asteroid (216) Kleopatra (the “dogbone asteroid”) has a/b around 2.3 (Ostro et al. 2000; Hestroffer et al. 2002).

5.2. Fluid Solutions

Chandrasekhar (1969), Hubbard (1984), and Tassoul (2000) have discussed the energy distributions and shapes of rotating, equilibrium, fluid bodies, and we apply their analyses here. The physical state of a rotating, fluid (strengthless) body depends on the angular momentum and distribution of matter. Nonrotating or slowly rotating fluid bodies are generally spherical. Moderate rotation produces a Maclaurin spheroid in which a = b ≥ c, and faster rotation results in a triaxial Jacobian ellipsoid in which a > b ≥ c. Hubbard defines the dimensionless rotation rate Ω as

$$\Omega^2 = \frac{\omega^2}{2\pi G\rho}, \tag{1}$$

where ω is the angular rotation rate and ρ is the bulk density of the body; in this formalism, the transition from Maclaurin to Jacobian bodies occurs at the bifurcation point Ω² = 0.19.

The maximum value for the dimensionless rotation rate (Ω) is reached at the bifurcation point. Thus, the minimum density for a fluid 2000 FV53 is 0.67 g cm⁻³ for a rotation period of 7.5 hr. All densities greater than this produce two theoretically viable solutions, one representing the Jacobian ellipsoid branch of solutions and one the Maclaurin spheroid branch. Here we consider each branch in turn.

5.2.1. Jacobian Ellipsoid Solution

If we assume that the observed 2000 FV53 light curve is derived from the gross shape of the body, then we require the branch of solutions corresponding to a triaxial Jacobian ellipsoid in which a > b. The rotation period must be 7.5 hr: if the best-fit solution of 7.5 hr is used, its double-peaked nature implies that it is a complete rotation period, whereas if the second-best-fit solution of 3.79 hr is used its single peak implies that 3.79 hr corresponds to only a half-period (since the light curve is shape-derived for a Jacobian body). Hence, we know ω (the angular rotation rate).

Tassoul introduces τ, which describes the energy state of a rotating body and is the ratio of rotational kinetic energy (K) to the absolute value of the gravitational potential energy (|W|): τ = K/|W|, where τ is small for nearly spherical bodies and increases for bodies with increasing asphericities (Fig. 5). Tassoul shows the relationship between Ω² and τ; from equation (1) and our knowledge of ω, we can convert this relationship to ρ as a function of τ. This result—bulk density as a function of the energy state of the body for a Jacobian ellipsoid—is shown in Figure 5 (right, red line).

To summarize, if 2000 FV53 is strengthless (fluid), there are two primary solutions; both of which will be surprising: (1) 2000 FV53 is a triaxial body with ρ in the range 0.67–1.0 g cm⁻³, implying a very high ice fraction or very high porosity; or (2) 2000 FV53 is an oblate spheroid with a “bright
Fig. 5.—Density vs. energy state for geophysical equilibrium fluid solutions for 2000 FV53, where \( \tau \) is the ratio of rotational kinetic energy \( (K) \) to the absolute value of the gravitational potential energy \( (W) \). The thick vertical line at \( \tau = 0.1375 \) marks the bifurcation point between Maclaurin and Jacobian solutions. Red curves show solutions for a rotation period of 7.5 hr. The green curve shows the solution for a 3.79 hr period, possible in the Maclaurin branch. The blue curve shows \( L(\leq \theta) \), the probability of the orientation required for a given \( \tau \) (this probability is plotted between 0 and 1 using the labels on the vertical axis). The hatched region indicates \( L(\leq \theta) < 0.1 \), which we consider unlikely. The only likely Jacobian solutions (solid red line) have densities of 0.67–1.0 g cm\(^{-3}\) (as indicated by the red bar along the vertical axis). The dashed red curve in the right-hand side of the figure shows unlikely Jacobian solutions (low geometric probability). The dashed red curve in the left-hand side of the figure shows solutions that are unlikely because a double-peak light curve is unlikely to reflect the true rotational period of a Maclaurin body. Instead, the green curve shows the possible densities for Maclaurin solutions (indicated by the green bar along the vertical axis). The approximate relationships among \( a \), \( b \), and \( c \) are given to lend intuition to the solution shapes described.

5.3. KBOs with Nonzero Internal Friction

In the previous section we found that the fluid solutions for 2000 FV53 require surprising densities (or may be geometrically unlikely). However, if KBOs are rubble piles made of rocks and ice, we can relax the fluid assumption by allowing these rotating bodies to have intrinsic strength. Holsapple (2001) has studied the effects on body shapes and rotation rates of allowing cohesionless rubble piles to experience internal friction akin to the strength exhibited by a pile of sand. The results are described in terms of \( \phi \), the angle of internal friction (or angle of repose). Fluids necessarily have \( \phi = 0^\circ \); typical terrestrial soils have \( \phi \approx 30^\circ \). Allowing bodies to have nonzero internal friction allows shapes that depart from the Maclaurin-Jacobian spheroid/ellipsoid sequence. We must assume a density to constrain internal friction; we first consider 2000 FV53 and assume \( \rho = 1 \) g cm\(^{-3}\).

We consider the prolate spheroid case \( a > b = c \) (e.g., Holsapple 2001, Figs. 3 and 5), assumed to be rotating about \( c \) with a rotation period of 7.5 hr. Holsapple assumes equatorial viewing, which we are not restricted to in our analysis. Instead, we may consider a range of axis ratios, where each value of \( b/a \) implies a specific viewing angle \( \theta \) as constrained by the observed light-curve amplitude. Holsappel’s dimensionless rotation rate [which he defines as \( \Omega = \omega (\rho G)^{1/2} \)] is determined by our assumption of \( \rho \) and knowledge of \( \omega \). If we require \( L(\leq \theta) > 0.1 \), then \( b/a \) for 2000 FV53 must be in the range 0.36–0.93. Throughout this range, \( \phi \approx 5^\circ \) (Fig. 6).

We now relax our density assumption. Carrying out the same analysis for \( \rho = 2 \) g cm\(^{-3}\), we find that \( \phi \) is less than 15° for all orientations with \( L(\leq \theta) \geq 0.10 \) (Fig. 6). However, for \( \rho = 0.5 \) g cm\(^{-3}\), the minimum \( \phi \) is around 13° and probable orientations require large \( \phi \).

We thus find that the internal friction for 2000 FV53 can reasonably be small but nonzero. In addition, densities much less than 1 g cm\(^{-3}\) have solutions that increasingly require \( \phi > 30^\circ \), an unlikely physical scenario. Therefore, the physical picture that emerges is the following: 2000 FV53 can readily be a rubble pile with density 1–2 g cm\(^{-3}\) and small angles of internal friction. This solution does not require excessive porosity (from
density estimates). This weak rubble-pile body—multiply impacted into a collection of blocks that has only small internal friction—may be nearly, but not quite, relaxed to geophysical fluid equilibrium configuration. This interpretation also allows for the small but significant nonsinusoidal component of the observed 2000 FV53 light curve, as rock and ice rubble blocks in the body may be slightly out of fluid equilibrium.

For 2003 BF91, \( \rho = 0.5 \) g cm\(^{-3} \) produces solutions for \( \phi \) of generally less than 15°. The 2003 BF91 solutions for \( \rho = 1.0 \) and 2.0 g cm\(^{-3} \) increasingly include \( \phi \)-values of 18°–25°, as well as narrow regions (in b/a) of acceptably low internal friction and very high internal friction (see Holsapple 2001, Fig. 3). We conclude that no combination of density and internal friction is precluded for 2003 BF91, although a \( \phi \)-value of 25° is larger than is observed for most asteroids (Holsapple 2001). This may indicate that 2003 BF91 is more likely to be kept out of equilibrium by monolithic strength and is similar to the facets discussed above—could produce the nonsinusoidal light curve observed for 2000 FV53.

The pressure at the center of a planetary body may be approximated as \( GM^2/r^4 \), where \( M \) and \( r \) are the mass and radius of the body. When \( b/a \) for 2003 BF91 is in the range 0.3–0.9, the overburden pressure produced by the asymmetric shape is 1–10 kbars. The strength of clean laboratory ice is approximately 10 kbars, and that of snow is 0.01–0.1 kbars (E. Asphaug 2005, private communication). Thus, the central stress in 2003 BF91 could easily be supported by its material strength. The object 2003 BF91 could easily be a rotating, coherent monolith with a substantially aspherical shape.

### 6. DISCUSSION

#### 6.1. Summary of Constraints

The object 2000 FV53 is a modest-sized KBO of diameter 116 km if the albedo is 0.10. There is a small chance that the low amplitude of the 2000 FV53 light curve is attributable to pole-on rotation, but otherwise it must be a remarkably spherical body. Topography is allowed by strength arguments, but the size of 2000 FV53 suggests that it should have been impacted many times (Durda & Stern 2000; see below) and hence be a rubble pile, not a monolithic body. The solutions for a fluid body require either a surprisingly low (<1 g cm\(^{-3} \)) or high (>2.7 g cm\(^{-3} \)) density, likely requiring 2000 FV53 to be a remnant of a differentiated body. The former solution may imply a remarkably large porosity.

A more plausible solution is that 2000 FV53 is a rubble pile of density 1–2 g cm\(^{-3} \), held slightly out of the minimum-energy shape by internal friction among constituent blocks that are relatively small. The nonsinusoidal light curve of 2000 FV53 requires surface inhomogeneity or a departure from ellipsoidal shape, but either effect need only be slight, and the latter is easily allowed by a nearly relaxed rotating body with nonzero internal friction.

The flux from the small body 2003 BF91 (20 km diameter for an albedo of 10%) varies by a factor of >2.5 over the light curve. Such large-amplitude variation is achievable if the body is an irregularly shaped collisional remnant consisting of one or a small number of coherent fragments supported by material strength. Alternately, extreme albedo variations would be required to explain the 1.09 mag light-curve variation, perhaps with one impact-generated clean ice hemisphere contrasting with a darker (5%–10% albedo, consistent with that measured for other KBOs and Centaurs) hemisphere.

The ACS data for 2003 BG31 and 2003 BH31 do not allow the placement of any interesting constraints on surface or internal composition.

#### 6.2. Collisions in the Kuiper Belt

The Kuiper Belt is generally thought of as a collisionally evolved population. This environment can readily produce facets on KBOs; impacts likely can also produce albedo features on KBOs through cratering, and elongated objects can be produced through fragmentation. However, the nearly spherical 2000 FV53 must also be created through, or survive, collisional evolution.

Durda & Stern (2000) have calculated the timescale for disruptive collisions based on the present environment in the Kuiper Belt and assuming the pre-Bernstein et al. (2004) understanding (i.e., overestimation) of the small-end size distribution. They found that the timescale for disrupting a 100 km KBO is substantially longer.
than the age of the solar system. Thus, 2000 FV$_{53}$ is likely not a fragment that was recently created. Instead, the size of 2000 FV$_{53}$ likely records the timescale and efficiency of accretion in the Kuiper Belt: 2000 FV$_{53}$ represents an intermediate product of the accretion process that formed Kuiper Belt giants like Quaoar and Pluto. Leinhardt et al. (2000) showed that the pairwise accretion of rubble piles can produce both spherical and aspherical bodies. Thus, both 2000 FV$_{53}$ and Quaoar, which potentially has a 10% asphericity as indicated by its light curve (Ortiz et al. 2003b), can have gross shapes that are the direct result of rubble pile accretion. In addition, 2000 FV$_{53}$ may have been impacted many times since its formation, resulting in a completely shattered body (consistent with Pan & Sari 2005); we note that early in the solar system’s history, the space density of bodies in the Kuiper Belt was higher than today, and the impact rate was higher than at present.

Multiple collisions can produce the small internal friction values we derived in § 5.3. A consistent picture for 2000 FV$_{53}$ is therefore that of a body that accreted to approximately its present size, has been substantially shattered due to extensive collisions, has little internal friction due to its rubble pile nature, and is nearly, but not completely, relaxed, thus nearly attaining a rotating fluid equilibrium state.

Durda & Stern (2000) find that the disruption timescale for a 30 km body is also longer than the age of the solar system, implying that formally a 30 km KBO would reflect primordial growth, not collisional disruption. Including the Bernstein et al. (2004) results will increase the disruption timescale for bodies of this size because of the dearth of small bodies. Thus, the picture for 2003 BF$_{91}$ may be somewhat complicated, as an elongated body is implied by its light-curve amplitude. The object 2003 BF$_{91}$ may be a fragment from an unusual, but not wildly improbable, collision between 50–100 km bodies. Furthermore, this collision could have occurred billions of years ago, when the space density of KBOs was higher, before later dynamical sculpting and mass loss (e.g., Morbidelli et al. 2003; Gomes et al. 2005). Our interpretation of the 2003 BF$_{91}$ data is that the body is an elongated KBO (though not necessarily a monolithic body), and the collisional fragment solution is appealing in this case.

Alternately, 2003 BF$_{91}$ may have a complicated surface that produces a light curve larger than its gross shape would suggest. Eons of impacts certainly could produce arbitrarily complicated surface topographies, although Korycansky & Asphaug (2003) show that cumulative small impacts on rotating asteroids tend to lead to oblate shapes, which cannot produce the observed light curve. Understanding this object, in the absence of many comparably small KBOs, requires us to look elsewhere in the solar system (§ 6.4).

6.3. Comparison to other KBOs

We list in Table 6 the 65 KBOs and Centaurs (excluding comets) for which light-curve measurements or upper limits have been published; 37 of these have reported periodic light-curve amplitudes, typically greater than \( \sim \)0.1 mag. Most of these bodies have implied rotational periods (or half-periods for double-peaked light curves) in the range 3–10 hr, similar to the periods derived for our HST ACS KBO observations. Note that these surveys certainly do not represent a complete nor random sample: some nondetections are likely unreported, and these observations represent mostly the brightest (largest) KBOs, so biases certainly exist in this compiled literature sample. Nevertheless, interesting results can be derived.

The amplitude we derive for 2003 BF$_{91}$, together with the recently measured amplitude of 1.14 mag for 2001 QG$_{298}$ (Sheppard & Jewitt 2004), are the largest amplitude variations (to date) for KBOs and Centaurs. In addition, our data show light curves for the faintest (and therefore smallest) KBOs to date. However, neither the large light-curve amplitude of 2003 BF$_{91}$ nor the fact that the small bodies 2003 BF$_{91}$ and 2003 BG$_{91}$ have light curves are particularly remarkable in the solar system, as many small asteroids are known to have light-curve variations larger than 1 mag, including some kilometer-sized NEOs (Pravec et al. 2002).

Pravec & Harris (2000) derive a simple expression that approximates the critical (minimum) period \( (P_c, \text{ in hours}) \) for a rotating body as a function of density and light-curve amplitude (in magnitudes):

\[
P_c \approx 3.3 \sqrt{\frac{1 + \Delta m}{\rho}}.
\]

This relation assumes a fluid body, that is, \( \phi = 0 \). Although more rigorous treatments of light-curve data are possible, as shown above, we here make this assumption to allow ready comparisons among bodies (and to the main-belt asteroid and NEO populations). Following Pravec & Harris (2000), we plot light-curve amplitudes and observed periods for all currently known KBO and Centaur data, including our new HST data for 2003 BF$_{91}$, 2003 BG$_{91}$, and 2000 FV$_{53}$ (Fig. 7). The rotation periods of most KBOs and Centaurs could be either the observed photometric period (Fig. 7, open symbols) or twice the photometric period (filled symbols). For cases in which the true periods are known from double-peaked light curves, only this true period is plotted (filled symbols).

In Figure 7 we also show solutions corresponding to critical periods for densities spanning the range of plausible values for icy/rocky bodies. Remarkably, there is an apparent “rotation rate barrier” in that there appear to be no KBOs or Centaurs whose densities must be greater than 1 or 1.5 g cm$^{-3}$; this conclusion is derived from the case in which the rotation periods are identical to the photometric periods. Similarly, assuming that the rotation periods are twice the photometric periods shows that there are no KBOs or Centaurs whose densities must be greater than 0.5 g cm$^{-3}$. This does not preclude larger densities but means that no KBOs or Centaurs are observed to have rotations that require larger densities. Furthermore, Pravec & Harris (2000) interpret their results for NEOs by saying that the density that corresponds to the “rotation rate barrier” is likely the maximum bulk density for that population. While it seems unlikely that the maximum density for KBOs is less than 1 g cm$^{-3}$, it is nevertheless remarkable that no KBOs or Centaurs require densities larger than around 0.5 or 1.5 g cm$^{-3}$. For comparison, we note that (47171) 1999 TC$_{30}$ has a density around 0.5 g cm$^{-3}$ (Stansberry et al. 2005), that the “rotation rate barrier” for comets is around 0.6 g cm$^{-3}$ (Weissman et al. 2004), and that this “barrier” for NEOs is 2–3 g cm$^{-3}$ for bodies larger than 200 m (Pravec & Harris 2000).

Since KBOs and Centaurs are expected to be a mixture of ice (density around 1 g cm$^{-3}$) and rock (density perhaps around 3 g cm$^{-3}$), we can roughly estimate that porosity may be important at the level of tens of percent (see below). A further implication is that KBOs and Centaurs in this size range generally may not have significant tensile strength, which would allow stable KBO solutions to the upper left of the critical lines shown in Figure 7 (recall that the discussion in § 5.3 refers to cohesionless bodies). This is further confirmation that KBOs and Centaurs larger than 25 km in diameter are likely to be rubble piles. Our general conclusion from this analysis—that the bulk densities
| Designation | Number | Name   | Period$^a$ (hr) | Amplitude (mag) | Reference$^b$ |
|-------------|--------|--------|-----------------|-----------------|-------------|
| 2003 EL$_{31}$ | ...    | ...    | 153.6$^c$       | 0.33            | -1          | 1           |
| 2003 VB$_{12}$ | 90377  | Sedna  | 10.3            | 0.02            | 1.6         | 3           |
| 2002 LM$_{40}$ | 50000  | Quaor  | 17.7$^d$        | 0.13            | 2.6         | 4           |
| 2001 KX$_{76}$ | 28978  | ...    | ...             | <0.05           | 3.2         | 5           |
| 2002 TX$_{300}$ | 55636  | ...    | 7.89, 8.12, 12.10 | 0.08, 0.09     | 3.3         | 5, 6        |
| 2002 UX$_{25}$ | 55637  | ...    | 14.4$^d$, 16.8$^d$ | 0.2            | 3.6         | 7           |
| 2000 WR$_{106}$ | 20000  | Varuna | 6.34$^d$        | 0.42            | 3.7         | 8, 9        |
| 2002 TX$_{200}$ | 55638  | ...    | ...             | 1.14, 1.16     | 6.3         | 17          |
| 2000 EC$_{98}$ | 60558  | ...    | 26.8$^d$        | 0.24            | 9.6         | 18          |

$^a$ Periods are given in hours.

$^b$ Reference numbers are listed for each entry.

$^c$ Values are estimated.

$^d$ Values are measured.
The curves represent solutions for critical rotation periods (these two solutions, but we omit these connecting lines for other data for clarity. Represented here, as most KBO light curves do not allow us to distinguish between dashed to suggest that the light curve likely is double peaked and that the 3.79 hr dashed line densities (in grams per cubic centimeter): 0.5 (for single-peaked solutions) or perhaps 0.5 g cm$^{-3}$ (for double-peaked solutions) is suggested by the clustering of points up to but not beyond the curves for those densities. Compare to Fig. 8 of Pravec & Harris (2000).

of KBOs and Centaurs likely lie in the range 0.5–1.5 g cm$^{-3}$—is not surprising and confirms results that we have shown above. Finally, we note that the percentage of small KBOs with detected light curves is significantly greater than the percentage of large KBOs with detected light curves (Table 6). This is consistent with the arguments presented above: more small KBOs are likely to be fragments than large KBOs, fragments are more likely to be nonspherical than primordial bodies, light curves are likely to be produced by nonspherical bodies, and therefore, a greater percentage of small KBOs should show significant light-curve variations than large KBOs. We again restate that the data presented in Table 6 are certainly biased against null results and biased toward the detection of small-amplitude light curves for big (but not small) KBOs.

Nevertheless, if taken at face value the data presented in Table 6 therefore support the theoretical models described above, with the largest bodies remaining undisrupted since accretion and smaller bodies representing collisionally derived fragments.

6.4. Comparison to other Solar System Bodies

The KBOs and Centaurs shown in Figure 7 are generally hundreds of kilometers in diameter, as is 2000 FV$_{53}$, but 2003 BG$_{91}$ and 2003 BF$_{91}$ have diameters a factor of 5 smaller; gravity may be important in rounding bodies larger than a few hundred kilometers in diameter but does not prohibit smaller bodies from maintaining various extreme shapes (e.g., Richardson et al. 2002). Therefore, the same physical processes and interpretations may not be relevant across size regimes within the Kuiper Belt, and it is possible that better analogies of individual objects are found elsewhere in the solar system, despite differing collision rates and ice/rock fractions.

Outer planet satellites may be useful analogies to hundred-kilometer-diameter KBOs; indeed, some outer planet satellites may be captured KBOs (Johnson & Lunine 2005). Jupiter’s moon Amalthea has a/b = 1.8, a/c around 2, and a derived density of less than 1.0 g cm$^{-3}$ (Anderson et al. 2005). (Compare this result to the plausible solutions for 2000 FV$_{53}$, shown in Fig. 5.) The best interpretation for this modest-sized body—with mean radius around 80 km, Amalthea is close in size to 2000 FV$_{53}$—is a porosity of tens of percent even when the satellite is largely water ice. The physical state of this body is not currently understood, so we can draw no useful analogy from it other than to say that extremely low densities in the solar system [including

### Table 6—Continued

| Designation | Number | Name   | Period$^a$ (hr) | Amplitude (mag) | $H^b$ | References |
|-------------|--------|--------|----------------|----------------|-------|------------|
| 1999 UG$_{53}$ | 31824  | Elatus | 13.25          | 0.24           | 10.1  | 29         |
| 2003 BG$_{91}$ | 52872  | Okyrhoe | 4.2            | 0.18           | 10.7  | This work  |
| 1998 SG$_{95}$ | 9.1, 7.3 | 0.2    | 11.7           | This work |
| 2003 BF$_{91}$ | <0.15  | 11.9   | This work |

**Notes.**—Multiple measurements have been made for several bodies. For nondetections, we cite here only the most sensitive measurement.

$^a$ Photometric periods except for double-peaked light curves, where the (perspective) rotation period is listed.

$^b$ Absolute magnitude: the hypothetical magnitude the object would have at zero phase angle and geocentric and heliocentric distances of 1 AU. Values are from the Minor Planet Center database.

**References.**—(1) Buie et al. 1997; (2) Rabinowitz et al. 2005; (3) Gaudi et al. 2005; (4) Ortiz et al. 2003b; (5) Sheppard & Jewitt 2003; (6) Ortiz et al. 2004; (7) Rousselot et al. 2005; (8) Jewitt & Sheppard 2002; (9) Sheppard & Jewitt 2002; (10) Hainaut et al. 2000; (11) Ortiz et al. 2003a; (12) Romanishin & Tegler 1999; (13) Osip et al. 2003; (14) Romanishin et al. 2001; (15) Peixinho et al. 2002; (16) Collander-Brown et al. 2001; (17) Sheppard & Jewitt 2004; (18) Davies et al. 1998; (19) Bus et al. 1989; (20) Collander-Brown et al. 1999; (21) Buie & Bus 1992; (22) Farnham et al. 2005; (23) Tegler et al. 2005; (24) Chorny & Kavelaars 2004; (25) Rousselot et al. 2003; (26) Choi et al. 2003; (27) Kern et al. 2000; (28) Farnham & Davies 2003; (29) Gutiérrez et al. 2001; (30) Bauer et al. 2003.

**Fig. 7.**—Amplitudes and periods for all KBOs and Centaurs (excluding comets) with observed light-curve variations (data from Table 6). Diamonds represent our *HST* observations, and circles represent data from other sources. Open symbols indicate photometric periods, and filled symbols indicate rotation periods that are twice the observed photometric period. Objects known to have double-peaked light curves are plotted only as filled symbols. Horizontal lines connect photometric and twice photometric solutions for our double-peaked light curves are plotted only as filled symbols. Horizontal lines connect photometric and twice photometric solutions for our double-peaked light curves are plotted only as filled symbols. Horizontal lines connect photometric and twice photometric solutions for our double-peaked light curves are plotted only as filled symbols.
The maximum asphericity of 2000 FV$_{53}$ may be only a few percent (barring pole-on alignment or a pathological combination of dark surface regions along the long axis and bright surface regions along the short axis of an elongated body). The size of 2000 FV$_{53}$ is similar to a number of outer solar system moons. Uranus’ moon Puck’s axis ratio is close to unity (Karkoschka 2001), but all of these other satellites—which are presumably captured and are perhaps fragments of disrupted bodies—are known to be at least 10% aspherically irregular, although we note that viewing geometries may play some role (outer planet satellites, except those of Uranus, tend to be viewed close to equatorially, maximizing light curve variations, whereas KBOs are assumed to have randomized obliquities that are more likely to hide their true shapes).

Furthermore, Sheppard & Jewitt (2002) compile a list of aspherical solar system objects larger than 200 km and suggest that the four KBOs they observed to have light-curve variations—all larger than 200 km—may also be irregular, with asphericities of tens of percent. It is thus remarkable that even the modest asphericity of the 116 km 2000 FV$_{53}$ is unlikely based on our photometry (barring a pole-on orientation). Perhaps impacts have more thoroughly pulverized 2000 FV$_{53}$ (and KBOs) than satellites of giant planets. The object 2000 FV$_{53}$ would therefore have small internal friction and would be more relaxed and closer to the fluid equilibrium state. We note that approximately half the KBOs that have been searched for photometric variability show no such signal, typically with sensitivities around 0.1 mag. This 50% null result could be interpreted as suggesting that many hundred kilometer-sized KBOs are less than 10% aspherical. A significant difference between KBOs and outer solar system satellites may be implied.

We can look to the comet population for relevant analogies for the smaller KBOs. Jewitt et al. (2003) studied shapes of comet nuclei, which are an order of magnitude smaller than the HST KBOs and 2 orders of magnitude smaller than most other well-studied KBOs. They conclude that the primary cause of comet nuclei asphericity likely is extensive mass loss. We suspect that such a process is not significant for classical KBOs, such as the four we observed with HST, that never approach closer to the Sun than ~35 AU, but could be important for Centaurs, which can have semiaxes as small as ~15 AU.

Weissman et al. (2004) compiled rotation periods and projected axis ratios ($a/b$) for 13 short-period comets and carried out an analysis similar to our § 6.3 and Figure 7. They found an apparent “rotation rate barrier” that corresponds to an upper limit density around 0.6 g cm$^{-3}$, similar to the upper limit we derive from the double-period solutions for KBOs (Fig. 7, filled circles). Comets clearly have nongravitational forces (e.g., jets) that can affect both shape and rotation periods, so this apparent agreement should not be overemphasized. Nevertheless, the idea that short-period (Jupiter family) comets derive from the Kuiper Belt (e.g., Levison & Duncan 1997) may be supported by this agreement.

Finally, the asteroid belt includes bodies throughout the size range of KBOs and may prove useful for understanding the physical properties of KBOs. The object 2000 FV$_{53}$ has no good close analag among main-belt asteroids (using absolute magnitude, light-curve amplitude, and period as criteria). However, 2003 BF$_{91}$ may have a good and easily imagined analog in the main asteroid belt, based on light-curve amplitude and approximate size: asteroid (243) Ida, which has maximum and minimum dimensions of 55.3 and 14.6 km, asymmetry (area-weighted average of the ratio of the radii) of 1.48, and an observed light curve around 0.8 mag (Simonelli et al. 1996; Thomas et al. 1996). Ida has clearly been much affected by disruptive collisions, as suggested by its membership in the Koronis dynamical family, by the presence of its (presumably impact-generated) satellite, Dactyl, and by its much-cratered appearance (Greenberg et al. 1996). All evidence suggests that Ida is a collisional fragment of the (former) Koronis parent body. Note that Ida’s significant aspect ratio demonstrates, at least in concept, that fragmentary results of collisional events can have substantially aspherical shapes and, consequently, large-amplitude light curves. We note that the asteroid belt has a higher space density of bodies and larger impact speeds than the Kuiper Belt. Perhaps, however, it is not inappropriate to imagine an icy Ida when picturing 2003 BF$_{91}$.

7. CONCLUSIONS

We have derived best-fit light curves for four KBOs imaged in the HST ACS KBO survey (Bernstein et al. 2004). The object 2003 BF$_{91}$ is found to experience large-amplitude periodic brightness variations, whereas, significantly, 2000 FV$_{53}$ is found to undergo very small but nonzero amplitude periodic brightness variations that are nonsinusoidal. Our primary conclusions are the following:

1. Plausibly, based on the range of suggested and measured albedos for KBOs, an albedo range of at least a factor of 2.5 could exist on 2003 BF$_{91}$, although such unlikely and extreme albedo ranges on single bodies in the outer solar system are seen only in unusual situations. However, albedo and shape could be correlated, as would be the case with a large, fresh, bright crater. Furthermore, it may be easier for a crater or albedo feature to dominate the majority of a hemisphere of a small body like 2003 BF$_{91}$, so we cannot exclude the possibility of a wide range of surface reflectance on 2003 BF$_{91}$.

2. The object 2003 BF$_{91}$ could have a complicated topography that produces light curves that—at least during our observing season—are substantially larger than their gross shapes might otherwise indicate. Facets on 2000 FV$_{53}$ could produce a small-amplitude light curve that suggests a body more spherical than its true shape. In addition, the relatively small deviations from sphericity required to produce the observed 2000 FV$_{53}$ light curve may be readily explained by topography—facets—in the presence of low surface gravity.

3. The conditions in which small-amplitude light curves are produced (e.g., 2000 FV$_{53}$) include bodies of any shape seen nearly pole-on ($\theta \approx 0$) and nearly spherical bodies ($a \approx b \approx c$) seen at any angle. For Jacobian solutions—the only non-pole-on fluid solutions in which the photometric light curve is derived from the gross aspherical shape of the body—the bulk density of 2000 FV$_{53}$ must be 0.67–1.0 g cm$^{-3}$. For Maclaurin solutions (rotating spot model), as well as for pole-on orientations, the minimum density is 2.7 g cm$^{-3}$. The simplest solution arises from allowing nonzero internal friction: 2000 FV$_{53}$ can readily be a rubble pile with density 1–2 g cm$^{-3}$ and small (but nonzero) internal friction.

The emerging picture for 2000 FV$_{53}$ is that of a body that accreted to approximately its present size, has been completely shattered due to extensive collisions, has little internal friction

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\[ b/a = 0.8 \] (Porco et al. 2003) and Amalthea has $b/a = 0.58$ (Thomas et al. 1998). Saturn: Phoebe, which has a retrograde orbit possibly implying capture from the asteroid belt or Kuiper Belt, is 10%–20% aspherical (Kruse et al. 1986; Bauer et al. 2004; Porco et al. 2005). Epimetheus has $b/a = 0.80$, while Janus has $b/a = 0.98$ and $c/a = 0.79$ (Thomas 1989). Neptune: Despina and Galatea have $b/a = 0.82$ and $b/a = 0.9$, respectively, while Larissa has $b/a = 0.94$ but $c/a = 0.78$ (Karkoschka 2003).
due to its rubble-pile nature (a small but likely nonzero), and is nearly, but not completely, relaxed, thus nearly attaining a rotating fluid equilibrium state. This conclusion is consistent with the idea that the timescale for disruptive collisions among 100 km KBOs is longer than the solar system. The nonsinusoidal light curve could be produced by facets or surface topography, or simply as a result of 2000 FV35 being nearly, but not quite, in rotational fluid equilibrium.

The object 2003 BF91 (as well as 2003 BG91) is likely a single coherent fragment, the result of an unusual, but not wildly improbable, collision between 100 km bodies.

We combine the new light-curve data presented here with all other reported KBO photometry to understand the physical properties of the KBO population. Our general conclusion from this analysis is that the bulk densities of KBOs and Centaurs likely lie in the range 0.5–1.5 g cm\(^{-3}\). This is consistent with the results of the detailed modeling we carried out for the HST ACS KBOs and roughly consistent with the average bulk density for short-period comets. This agreement may strengthen the proposed genetic link between KBOs and short-period comets. We furthermore show that the percentage of small KBOs with light-curve variations is greater than that for large KBOs, implying that small KBOs are nonspherical fragments produced by collisions.

Outer solar system satellites of the size of 2000 FV35 almost all have asphericities greater than 10%. Perhaps 50% of similarly sized KBOs show no variability at the 10% level, suggesting a significant difference between the evolutions of KBOs and outer solar system satellites.

The most helpful and easily imagined solar system analog for 2003 BF91 may be the main-belt asteroid (243) Ida, which has size, axis ratios, and shape similar to those we derive for 2003 BF91. Ida has clearly been much affected by disruptive collisions and is a fragment of a larger parent body, further suggesting that 2003 BF91 could be a collisionally shaped body. Perhaps it is not inappropriate to imagine an icy Ida when picturing the small KBO 2003 BF91.

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