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10199 CHARIKLO STELLAR OCCULTATION CANDIDATES: 1999–2005

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ABSTRACT

The Flagstaff Astrometric Scanning Transit Telescope was used to scan the sky in search of occultation candidates through which the Centaur 10199 Chariklo (formerly 1997 CU_{26}) will pass in 1999–2005. Positions for 96,397 stars (magnitudes $7.5 < V < 17.3$) were determined using differential reductions to the ACT catalog of star positions and proper motions, and accuracies of ± 30 mas were achieved for well-exposed images. The ephemeris for 10199 Chariklo was improved by including the new positions presented in this paper and, second, by correcting older positions taken from the literature for systematic errors. During this time period, 10199 Chariklo passes within 2″ of 117 of these stars, which are identified as occultation candidates in this paper. Among these, 28 candidates have magnitudes $V < 15.0$, making them the best choices for observing programs using portable telescopes. Circumstances for each occultation are given. Because the angular radius of 10199 Chariklo is only about 15 mas, the astrometry provided in this paper is only accurate enough for identifying possible occultation events and is not sufficient for predicting individual shadow paths across the surface of Earth, although representative cases are given. Last-minute astrometry with a large-aperture telescope will be needed to refine each prediction.

Key words: astrometry — occultations

1. INTRODUCTION

Studies of Centaur asteroids have become popular in recent years, because these objects are believed to be Kuiper belt objects (KBOs) that have been perturbed recently into the outer solar system (Jewitt & Luu 1993; Jewitt, Luu, & Trujillo 1998). Kuiper belt objects are interesting, inasmuch as they contain ices and hydrocarbons left over from the collapse of the solar nebula, which when studied can give important new information about the early evolution of the solar system and short-period comets. Unfortunately, all the KBOs are very distant and, as a result, extremely faint ($V > 21$ mag), making them difficult to observe with means other than broadband photometry. On the other hand, Centaurs are much closer (residing between the orbits of Jupiter and Neptune) and accordingly can be observed with much greater precision. Only nine Centaurs are currently known. This is not surprising, since according to Hahn & Bailey (1990) and Asher & Steel (1993), many will be ejected from the solar system after close encounters with Jovian planets, whose orbits they cross. This process can be quite rapid (about a million years), according to numerical simulations. Others will become short-period comets (Levison & Duncan 1997).

Observations of Centaurs show the same color diversity characteristic of KBOs (Luu & Jewitt 1996; Tegler & Romanishin 1998), and spectrophotometric analyses of their surfaces find three classes of features: hydrocarbon ices (5145 Pholus), water ices (10199 Chariklo), and featureless (2060 Chiron), according to Brown & Koresko (1998). Moreover, at least one (2060 Chiron) shows cometary activity, and others are expected to do so if their heliocentric distances become less than ∼9 AU.

Besides photometry and spectroscopy, another important method for studying Centaurs (and by inference KBOs) is with stellar occultations, whereby the Centaur passes in front of a background star, whose light is dimmed by the event. If accurate photometric measurements are taken, then the resulting data can give the physical size and shape of the Centaur (if several chords are observed by different telescopes along the occultation path), as well as its albedo and evidence of possible cometary activity. For example, Elliot et al. (1995) and Bus et al. (1996) observed occultations by 2060 Chiron in 1993 and 1994, respectively, and found evidence for jets emitting from its nucleus and for an extended coma. A lower limit for the radius of Chiron (≃80 km) was found also. Unfortunately, Centaurs are very small (radius ∼100 km) and distant, meaning a good occultation prediction requires an extremely accurate position for the occultation star, as well as a very well determined ephemeris for the occulting Centaur. Previous attempts at identifying possible Centaur occultations have included 2060 Chiron (Bus et al. 1996; Person et al. 1996) and 5145 Pholus (Stone, McDonald, & Elliot 1999). Also, lists of candidates have been prepared for Triton (McDonald & Elliot 1995) and Pluto (McDonald & Elliot 1996), which are believed to be related to or are former KBOs. As discussed in Stone et al.

(1999), it is now possible to determine positions of candidate occultation stars with accuracies of about ±20 mas in each coordinate using wide-field telescopes, CCD observations, and differential reductions for position with reference stars taken from the ACT star catalog (Urban, Corbin, & Wycoff 1998). Moreover, similar observations of Centaurs can dramatically improve their ephemerides, thereby improving any prediction further.

This paper presents stellar occultation candidates determined along the path of the Centaur 10199 Chariklo over the time period 1999.5–2006.0. A permanent numerical designation (10199) and name (Chariklo) have been recently assigned to this object, while in the older literature it is referred to as 1997 CU_{26}. This Centaur was discovered in 1997 with the 0.9 m Spacewatch telescope (Scotti 1997), has an orbital eccentricity of $e = 0.169$, and is currently at a heliocentric distance of ~13.4 AU. Brown & Koresko (1998) found infrared absorption features in its spectrum that they interpret as indicating 3% of its surface being covered with water ice. Moreover, Jewitt & Kalas (1998) found an albedo of 5%, as well as a photometric diameter of 302 ± 30 km, making 10199 Chariklo the largest of the known Centaurs. Considering its large distance from the Sun, 10199 Chariklo is probably not active; however, detailed observations would be needed to explore that possibility further.

As discussed in the following sections, this paper presents a list of candidate stars that might be occulted by 10199 Chariklo in 1999.5–2006.0 based on accurate positions (±30 mas) determined in the International Celestial Reference System (ICRS), the choice for all modern astrometric observations according to IAU resolution (Arias et al. 1995). This is a coordinate system defined at equator and equinox J2000. The practical realization of the ICRS is the International Celestial Reference Frame (ICRF), consisting of ~600 well-calibrated radio sources (Ma et al. 1998). In the optical domain, the ICRF is defined by the *Hipparcos* catalog of positions and proper motions (ESA 1997, p. 319). Furthermore, new positions in the ICRF are presented for 10199 Chariklo in order to improve its ephemeris. Both these sets of modern data can be used to significantly improve predictions for future 10199 Chariklo occultation events. In particular, bright occultation stars ($V < 14$) might be identified, which are the most suitable for occultation observations using portable 0.35 m telescopes (see, e.g., Bus et al. 1996). Notwithstanding these improvements, the data presented in this paper will not be sufficient by themselves for precisely predicting future 10199 Chariklo occultation events. Nevertheless, this paper gives a list of candidates worthy of further investigation (true occultation events constitute a subset of the given list). Last-minute astrometry with a large-aperture telescope will be needed to refine each of the predictions and to determine which of them will actually produce viable events.

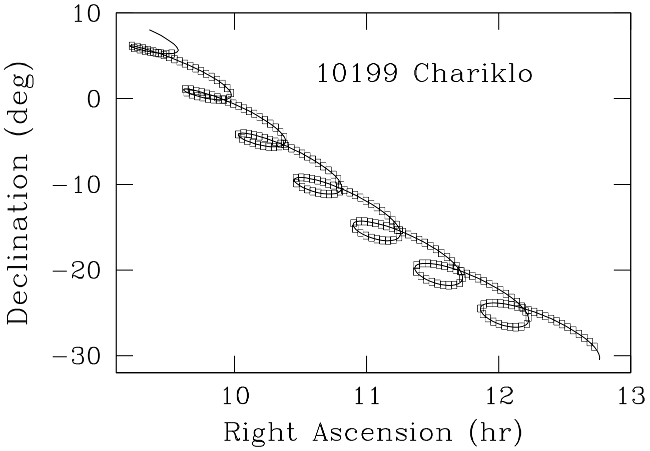


FIG. 1.—Orbital path of 10199 Chariklo in 1999.5 to 2006.0, shown along with overlapping FASTT scan boxes used to identify stars that might be occulted by the Centaur. Each box is 38'.2 × 50'.7 in size. The boxes shown in the diagram were each scanned twice, and then the process was repeated with a second set of boxes, whose centers were shifted by 50% relative to the first set. In all, each star was observed about four times.

Section 2 of the paper discusses the CCD observations taken and their reduction to positions in the ICRF, § 3 presents and discusses the list of stellar occultation candidates found along the path of 10199 Chariklo in 1999.5–2006.0, and in § 4, the conclusions of this paper are summarized.

2. OBSERVATIONS AND REDUCTIONS

2.1. *Occultation Stars*

In order to make a good occultation prediction, accurate astrometry is needed for both the target object, 10199 Chariklo in this paper, and for the candidate background occultation star. In most cases, the existing astrometry is quite poor, since historically the reference-star catalogs used to reduce the observations contained systematic errors in position that could easily exceed ±0''.6. The random errors in these catalogs are large as well. This paper presents new positions for 10199 Chariklo and background stars along its path in 1999.5–2006.0 (from which stellar occultation candidates can be identified) using modern CCD observations and reductions using the ACT catalog (Urban et al. 1998) of accurate star positions and motions at epoch J2000. The ACT star positions are referenced to the ICRF by means of the Tycho catalog of star positions (Høg 1997), and the ACT catalog contains accurate proper motions as well.

All of the observations were taken with the Flagstaff Astrometric Scanning Transit Telescope (FASTT), which is a 20 cm automated telescope (scale = 99'' mm^{-1}) equipped with a front-illuminated Ford/Loral 2048^2 CCD (15 μm pixels) that has a field of view of 50'.7 × 50'.7. The chosen passband was 4700–7300 Å (light was filtered with a *Hubble Space Telescope* F606W filter), and field flattening was achieved by illuminating a flat screen inside the telescope enclosure. The telescope and its instrumentation are described more fully in Stone et al. (1996). The methods of observation and reduction for the background stars along the path of 10199 Chariklo in 1999.5–2006.0 are identical to those discussed in Stone et al. (1999) for the Centaur 5145 Pholus. Consequently, they will be discussed only briefly in this paper. Namely, overlapping short exposure CCD scans, hereafter referred to as scan boxes, were taken along the path of 10199 Chariklo in 1999.5–2006.0, wherein the chosen exposure was 50 s, each scan box was 38'.2 × 50'.7 in area, adjacent boxes overlapped by 5%, and the magnitude limit reached was $V \sim 17.3$. Figure 1 shows the placements of the first set of these scan boxes along the path of 10199 Chariklo. After the first set of overlapping scan boxes were taken, a second set was taken with field centers offset by 50% with respect to the first set. This procedure was used to reduce systematic errors in star position. Both sets of scan boxes were repeated, and as a consequence, each star was observed typically four times. Table 1 gives more details about the FASTT observations.

After each scan box was observed, a local-maximum search algorithm was used to find all the measurable stars within it, and then each of these stars was centered with a two-dimensional Gaussian fit. Next, the pixel positions of ACT stars in each scan box were matched with their standard coordinates (computed from their ACT catalog positions and proper motions), and least-squares differential reductions (allowing for changes in zero point, scale, and orientation) were used to determine the transformations between the pixel and standard coordinate systems (see Stone et al. 1999 for more details). Finally, positions in the system of ICRF were computed using these transformations for each of the stars. In general, there were four positions determined for each star (from overlapping scans), which were averaged and had formal errors computed. These are the star positions and errors presented in this paper.

In all, positions were determined for 96,397 stars along the path of 10199 Chariklo in 1999.5–2006.0, with accuracies of ±30 mas in each coordinate for the brighter stars and ±200 mas for the faintest ones ($V \sim 17.5$) observed. These errors are tabulated in Table 2 and plotted in Figure 2 as a function of magnitude. When compared with the positional accuracies achieved for 5145 Pholus (Stone et al. 1999), using similar observations and reduction techniques, the positions obtained in this paper are about 30% less accurate. This results from the poorer seeing conditions prevalent when the 10199 Chariklo data were taken. As a check on the accuracy of the reductions, FASTT-minus-ACT differences in positions in each coordinate were computed for the ACT stars found in the 852 scans observed with FASTT. These differences are plotted in Figures 3 and 4 against right ascension, declination, and magnitude. In both coordinates, there is no evidence of systematic trends in the FASTT star positions, indicating that the reductions were performed properly.

2.2. *Positions for 10199 Chariklo*

2.2.1. *Modern Positions*

Unfortunately, many of the existing positions used to compute an ephemeris for 10199 Chariklo are quite poor ($>0''.5$ errors), and as a consequence, its predicted position at modern epochs is very uncertain. Most of the reductions for these positions used reference stars taken from the Guide Star Catalog (GSC), version 1.1 (Lasker et al. 1990; Russell et al. 1990), which is known to have large systematic and random errors. Moreover, since the observations for the GSC were taken in ~1983, and no proper motions are included in the catalog, additional errors caused by secular and Galactic motions have compounded since then. In order to ameliorate this problem, new positions for 10199 Chariklo were determined with the US Naval Observatory (Flagstaff Station) Strand 1.5 m astrometric reflector using a Tektronix 2048^2 (24 μm pixels) thinned CCD, giving a field of view of $11'.1 \times 11'.1$. FASTT could not make these observations, since 10199 Chariklo, currently at $V \sim 18$ mag, was too faint to observe. On the other hand, the small sky coverage of the Tektronix CCD (0.034 deg^2) would include only about one ACT reference star typically, and as a result, the reduction for position could not be made because of a lack of reference stars. As discussed previously, there are other

TABLE 1

Characteristics of the FASTT Star Observations

Characteristic	Value
10199 Chariklo orbital time coverage……	1999.5–2006.0
CCD scan frames taken …………………	852
Exposure ………………………………	50 s
Stars surveyed …………………………	96,397
CCD images per star ……………………	3.85
Mean epoch of observation ……………	1999.05
Range in R.A. (ICRF)……………………	$9^{\mathrm{h}}11^{\mathrm{m}}.9$ to $12^{\mathrm{h}}44^{\mathrm{m}}.9$
Range in decl. (ICRF) …………………	$-29°23'$ to $6°35'$
Total area scanned ………………………	97 deg^2
Central Galactic coordinates (l, b) ………	$(264°.7, 42°.8)$
Range in V magnitude…………………	7.5–17.3
Magnitude completeness ………………	$V \lesssim 16.5$

TABLE 2

Mean Accuracy of the FASTT Star Positions and Magnitudes

V	σ(R.A.) cos δ (mas)	σ(decl.) (mas)	$\sigma(V)$ (mag)	Number of Stars
7.5–8.0 ……..	34	31	0.085	20
8.0–8.5 ……..	29	34	0.066	80
8.5–9.0 ……..	21	33	0.047	105
9.0–9.5 ……..	23	32	0.033	177
9.5–10.0 …….	24	35	0.023	226
10.0–10.5……	24	31	0.023	372
10.5–11.0……	30	36	0.029	557
11.0–11.5……	38	49	0.032	740
11.5–12.0……	40	53	0.031	1055
12.0–12.5……	41	52	0.032	1565
12.5–13.0……	41	53	0.031	2235
13.0–13.5……	41	53	0.031	3268
13.5–14.0……	43	55	0.033	4393
14.0–14.5……	46	56	0.034	5955
14.5–15.0……	52	61	0.037	7819
15.0–15.5……	61	70	0.041	10194
15.5–16.0……	77	86	0.048	12899
16.0–16.5……	105	114	0.060	15932
16.5–17.0……	143	151	0.079	17519
17.0–17.5……	183	193	0.102	10135
17.5–18.0……	221	208	0.128	1140

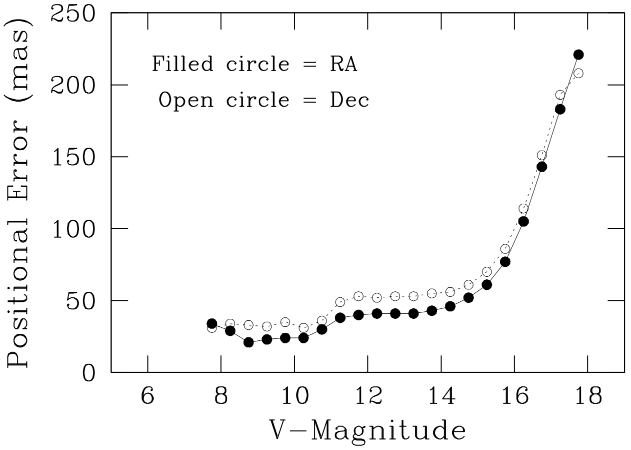


Fig. 2.—Accuracy of FASTT star positions in both right ascension and declination as a function of visual magnitude. The FASTT positions are quite accurate (±50 mas or better), except for the faintest stars observed.

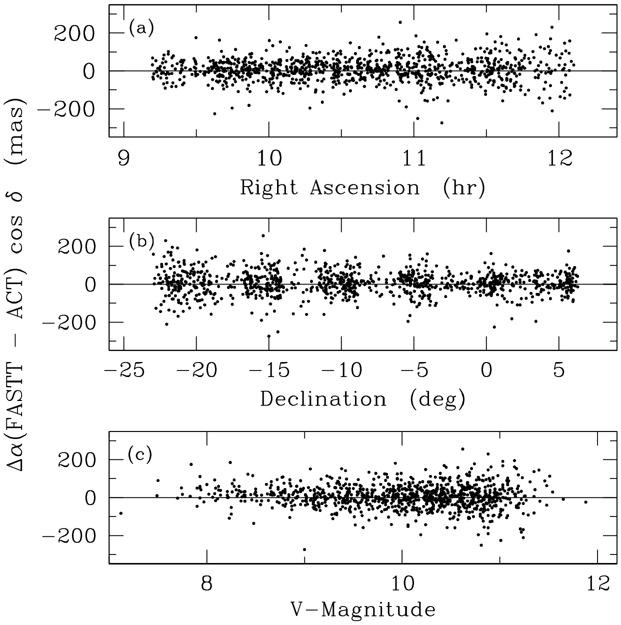


FIG. 3.—Differences between FASTT and ACT catalog right ascensions plotted against (*a*) right ascension, (*b*) declination, and (*c*) magnitude. There is no evidence of systematic trends in any of the plots, and the scatter can be explained by FASTT observational and known ACT catalog errors. The clustering of points in (*b*) is caused by the retrograde loops shown in Fig. 1.

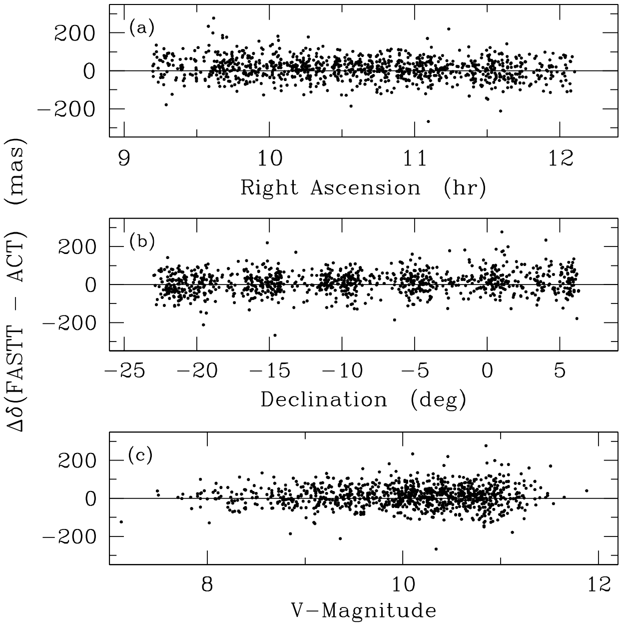


FIG. 4.—Similar to Fig. 3, but showing (FASTT − ACT) differences in declination plotted against equatorial coordinates and magnitude. Again, there is no evidence of systematics in the FASTT star positions, and the scatter in declination can be explained by FASTT observational and ACT catalog errors.

catalogs of star positions containing much higher densities of stars, but these were not considered, because of their poor accuracies. To solve this problem, the densified star positions (reduced with the ACT star catalog and accurate to ±30 mas) discussed in § 2.1 were used instead, which gave 15–17 reference stars on each Tektronix CCD frame. These data were reduced in the usual astrographic manner (see Green 1985, p. 310, for details), using terms allowing for changes in zero point, scale, and orientation, and positions were derived for each of the CCD images of 10199 Chariklo taken with the Strand 1.5 m telescope.

The reduced topocentric positions for 10199 Chariklo are presented in Table 3, where column (1) gives the date and time of each Strand 1.5 m observation; columns (2) and (3) present the derived topocentric equatorial positions in the ICRF coordinate system; the computed visual magnitude, exposure time, and number of reference stars used in each reduction are listed respectively in columns (4) to (6); and columns (7) and (8) give (geocentric minus topocentric) corrections that when added to the coordinate positions given in columns (2) and (3) convert these positions to geocentric places. By knowing the positional accuracy of the densified

TABLE 3

MODERN TOPOCENTRIC POSITIONS FOR 10199 CHARIKLO DETERMINED IN THE ICRF WITH THE US NAVAL OBSERVATORY (FLAGSTAFF STATION) STRAND 1.5 m REFLECTOR

UTC (1)	R.A. (ICRF) (2)	Decl. (ICRF) (3)	V (mag) (4)	Exposure (minutes) (5)	$N_{\rm ref}$ (6)	$\Delta\alpha(g-t)$ (arcsec) (7)	$\Delta\delta(g-t)$ (arcsec) (8)
1999 Mar 24:							
5:44:41.0......	9 14 28.4860	5 54 26.266	18.24	2	17	0.164	0.339
5:54:05.0......	9 14 28.4300	5 54 26.555	18.25	4	17	0.183	0.340
6:02:30.0......	9 14 28.3799	5 54 26.789	18.24	4	17	0.203	0.340
6:09:09.0......	9 14 28.3415	5 54 26.979	18.25	4	17	0.218	0.341
1999 Apr 12:							
3:50:35.0......	9 12 38.0920	6 05 09.532	18.51	2	15	0.072	0.329
3:56:58.0......	9 12 38.0878	6 05 09.790	18.29	5	15	0.083	0.329
1999 Apr 22:							
4:22:19.0......	9 12 19.4344	6 08 38.754	18.30	4	15	0.232	0.330
4:29:08.0......	9 12 19.4310	6 08 38.804	18.30	4	15	0.247	0.331
4:35:36.0......	9 12 19.4280	6 08 38.892	18.29	4	15	0.261	0.331
4:42:08.0......	9 12 19.4243	6 08 38.940	18.26	4	15	0.275	0.332

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

reference-star positions determined with FASTT (see § 2.1 for details) and the accuracy of the Tektronix on-chip astrometric reductions, the overall accuracy of the positions given in Table 3 can be estimated ($\sigma \sim \pm 50$ mas in each coordinate). Moreover, the Strand 1.5 m observations of 10199 Chariklo were purposely spaced over ~ 30 days in order to reduce systematic errors caused by the placement of reference stars in each Tektronix CCD frame, i.e., different sets of reference stars were in the reductions that corresponded with the different dates of observation.

2.2.2. *Older Positions*

With few exceptions, the early positions for 10199 Chariklo were determined from CCD observations and differential reductions using reference stars taken from the GSC (version 1.1). These data and the modern positions in the ICRF described in § 2.2.1 were used to compute an orbit with the ephemeris integrator maintained by E. B. and L. Wasserman at Lowell Observatory. The modern observations presented in this paper were assigned different weights in order to ascertain the stability of the computed orbit. The older observations were always assigned unit weight ($w = 1$). After this was done, it was found that the assigned weights could significantly change the outcome of the prediction. Namely, when orbital positions (computed with the modern observations, given respective weights of 1 and 10) were extrapolated to 2006.0 (the last date considered in this paper for identifying possible occultation stars), they differed by 1".1 and 0".6, respectively, in right ascension and declination. Most probably, these differences are caused by systematic errors in the reference frame of the GSC (known to have large systematic errors in many cases). In order to test this possibility, the older 10199 Chariklo star positions were converted to the ICRF by applying (ICRF − GSC) corrections in each coordinate. These corrections were computed by comparing ACT (on the system of ICRF) and GSC star positions along the path of 10199 Chariklo in 1989–1999 and determining (ACT − GSC) mean differences as a function of position in the sky. Figure 5 shows the derived corrections in both coordinates for each of the known 10199 Chariklo observations. The positions obtained in 1988–1989 are prediscovery positions measured from Palomar Observatory Sky Survey (POSS) II photographic plates. As can be seen, these corrections are typically −0".2 in both coordinates and can vary significantly in differing parts of the sky, i.e., they show a regional dependence.

After the old positions for 10199 Chariklo were converted to the ICRF using the corrections discussed above, new ephemerides were computed using the same weighting scheme as described above. The results showed a significant improvement, wherein the orbit extrapolations to epoch 2006.0 differed now by only 0".8 and 0".2, respectively, in right ascension and declination. Moreover, the scatter of the observations around each computed orbit was reduced by about 10% in each coordinate. A further refinement would require the identification of all the GSC reference stars used to reduce each observation of 10199 Chariklo in 1988–1999 and then have individual corrections applied to them. Only global corrections were used in this paper. This refined analysis would be very difficult, since many of the records of the early observations are hard to obtain, and the process would be very tedious. As a result, it was not done for this paper. Rather, the globally corrected old and modern positions described above were used to compute a new ephemeris for 10199 Chariklo. The modern positions were assigned weight $w = 10$ in this solution. As will be discussed in the following section, the resulting ephemeris and the accurate positions of stars discussed in § 2.1 can be used to identify possible occultation stars along the path of 10199 Chariklo.

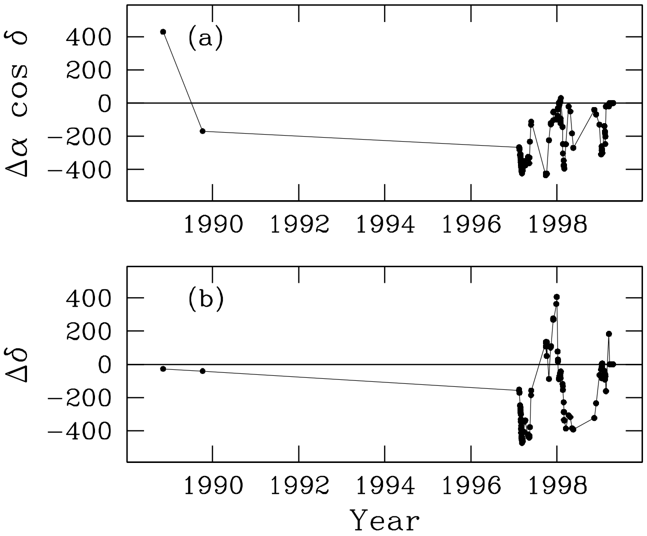


FIG. 5.—Corrections (ICRF − GSC) for converting old GSC (version 1.1) positions of 10199 Chariklo into the ICRF reference frame. The two observations taken prior to 1997 are prediscovery positions measured from POSS II plates. As can be seen, the typical correction is −0".2 in both coordinates. Most likely, these corrections result from systematic errors in the Guide Star Catalog and are needed to compute an accurate ephemeris for 10199 Chariklo (see text).

2.3. *Magnitudes*

Accurate magnitudes were determined for each of the stars discussed in § 2.1 and for the modern Strand 1.5 m observations of 10199 Chariklo discussed in § 2.2.1 using aperture photometry (see Stone et al. 1999 for details). The errors in magnitude are tabulated in Table 2 as a function of apparent magnitude, and in general, accuracies of ± 0.03 mag for the brighter stars and ± 0.10 mag for the faintest ones were achieved. As expected, these errors become greater at fainter magnitudes because of reduced count rates. Moreover, the errors for the very brightest stars ($V < 9$) are larger than expected, since the central count levels in their images were near photometric saturation.

None of these magnitudes are rigorously placed in the standard Johnson *UBV* photometric system, since the required transformation would require knowledge of the $B-V$ color for each object. Colors are not known generally for the stars discussed herein or for 10199 Chariklo, and no colors were determined in this paper, because FASTT can observe only in a single passband. Rather, a $B-V = 0.7$ value was assumed for all objects, which is representative of stars in the same part of the sky as 10199 Chariklo. Hence, these magnitudes are affected by a systematic error amounting to $\Delta V = V - V_{\rm FASTT} = 0.363[(B-V) - 0.7]$ mag, where $B-V$ is the true stellar color (see Stone et al. 1999 for more details). The magnitudes can be corrected to the Johnson system with the above formula, if colors should eventually become known. Based on statistical considerations, the

TABLE 4

Possible Occultations by 10199 Chariklo in 1999.5–2006.0

Star ID	Event Date	UTC	Minimum Separation (arcsec)	Position Angle (deg)	Star Mag. (*V*)	Shadow Velocity (km s^{-1})	Solar Angle (deg)	R.A. (ICRF)	Decl. (ICRF)	East Long. (deg)	Dist. to Chariklo (AU)	Chariklo Mag. (*V*)
10199-1	1999 Jul 1	0118	0.23	19	16.3	29.6	43	09 22 18.925	+05 33 09.47	−158	14.170825	18.1
10199-2	1999 Jul 11	0027	0.34	19	16.4	32.5	35	09 25 03.337	+05 19 16.56	−154	14.266402	18.1
10199-3	1999 Jul 12	1942	1.40	200	17.1	32.9	33	09 25 34.399	+05 16 34.86	−85	14.281505	18.1
10199-4	1999 Sep 19	1623	1.87	29	14.4	34.4	30	09 46 38.654	+02 57 02.71	−98	14.273994	18.1
10199-5	1999 Sep 26	1946	1.91	31	17.4	32.8	36	09 48 35.152	+02 40 27.26	−155	14.207275	18.1
10199-6	1999 Oct 17	1441	0.15	37	14.5	26.4	55	09 53 28.119	+01 52 53.20	−98	13.954089	18.1
10199-7[a] ...	2000 Jan 2	2219	1.69	347	15.7	13.9	130	09 56 11.103	−00 04 39.45	72	12.721877	17.9
10199-8	2000 Jan 6	2204	1.89	351	16.8	15.1	134	09 55 35.655	−00 06 24.72	72	12.671202	17.9
10199-9	2000 Jan 17	0950	1.28	359	16.6	18.1	144	09 53 46.322	−00 08 39.15	−116	12.555063	17.8
10199-10...	2000 Jan 27	1803	1.21	184	17.7	20.3	154	09 51 40.052	−00 07 38.04	111	12.467881	17.7
10199-11...	2000 Feb 19	1103	1.98	12	17.3	22.1	167	09 46 29.278	+00 03 59.26	−168	12.385159	17.6
10199-12...	2000 Mar 24	0037	0.09	203	14.6	16.1	141	09 39 39.772	+00 34 35.09	−47	12.544093	17.8
10199-13...	2000 May 30	0548	1.56	8	15.0	14.6	78	09 38 56.974	+01 05 40.23	169	13.490919	18.1
10199-14...	2000 Jun 9	1433	1.20	191	16.2	19.2	69	09 40 37.499	+01 01 23.06	28	13.647850	18.1
10199-15...	2000 Jun 15	0807	0.17	193	15.1	21.6	63	09 41 43.465	+00 57 44.47	119	13.730352	18.1
10199-16...	2000 Jun 25	2311	0.41	196	13.7	25.7	54	09 44 03.254	+00 48 44.38	−116	13.872600	18.1
10199-17...	2000 Sep 21	0158	1.63	30	16.1	35.8	26	10 09 57.510	−01 56 26.44	122	14.168241	18.0
10199-18...	2000 Sep 23	0535	0.19	210	16.9	35.5	28	10 10 34.776	−02 01 49.21	66	14.152535	18.0
10199-19...	2000 Sep 28	1429	1.06	32	16.5	34.4	32	10 12 05.213	−02 15 24.53	−72	14.108612	18.0
10199-20...	2000 Oct 14	1158	0.32	215	16.2	30.3	46	10 16 08.680	−02 55 43.92	−49	13.942121	18.0
10199-21...	2000 Oct 16	0830	1.51	216	13.4	29.7	47	10 16 34.324	−03 00 22.86	1	13.919427	18.0
10199-22...	2000 Oct 16	1942	0.49	37	13.4	29.6	48	10 16 40.598	−03 01 34.94	−167	13.913629	18.0
10199-23...	2000 Oct 16	2217	1.65	217	12.8	29.5	48	10 16 42.147	−03 01 49.51	154	13.912282	18.0
10199-24...	2000 Oct 19	2125	0.34	38	16.4	28.5	51	10 17 21.411	−03 09 17.27	164	13.874437	18.1
10199-25...	2000 Oct 24	0209	1.78	219	15.0	27.2	54	10 18 14.133	−03 19 40.90	89	13.818284	18.1
10199-26...	2000 Nov 17	1942	0.42	55	17.3	17.7	77	10 22 01.737	−04 17 10.20	162	13.439657	18.0
10199-27...	2001 Jan 7	1128	0.37	161	17.2	13.5	127	10 21 05.202	−05 32 02.25	−124	12.630452	17.9
10199-28...	2001 Jan 22	1404	0.17	357	13.8	17.6	141	10 18 37.815	−05 38 17.93	−179	12.452526	17.8
10199-29...	2001 Feb 22	2201	1.22	13	14.3	22.0	164	10 11 47.254	−05 27 08.78	29	12.271119	17.6
10199-30...	2001 Feb 23	1505	0.63	193	14.9	21.9	164	10 11 37.403	−05 26 32.69	133	12.270331	17.6
10199-31...	2001 Mar 12	1214	0.38	199	15.9	20.5	158	10 07 51.311	−05 10 09.39	158	12.296239	17.7
10199-32...	2001 Apr 8	2058	0.29	32	17.1	13.5	133	10 03 11.482	−04 38 19.73	−1	12.505435	17.8
10199-33...	2001 Jun 22	1818	0.35	11	16.2	21.4	65	10 06 45.486	−04 08 01.32	−34	13.594461	18.0
10199-34...	2001 Jul 8	1333	0.07	197	16.1	27.5	51	10 10 24.451	−04 21 07.06	22	13.801168	18.0
10199-35...	2001 Jul 8	2314	1.06	196	13.3	27.6	51	10 10 30.648	−04 21 32.05	−123	13.805964	18.0
10199-36...	2001 Jul 22	0329	0.09	18	12.4	31.5	40	10 14 05.103	−04 38 04.58	161	13.947037	18.0
10199-37...	2001 Aug 1	1527	1.82	21	15.4	34.1	32	10 17 10.973	−04 54 34.45	−28	14.035185	18.0
10199-38...	2001 Aug 7	0102	0.57	22	16.6	35.3	28	10 18 50.448	−05 04 05.22	−177	14.071313	18.0
10199-39...	2001 Oct 20	1200	0.54	217	17.0	31.1	44	10 41 16.723	−08 05 27.86	−49	13.858359	18.0
10199-40...	2001 Oct 26	0028	0.64	39	9.9	29.7	49	10 42 33.411	−08 20 27.93	119	13.792638	18.0
10199-41...	2001 Nov 11	1659	0.32	47	15.7	24.0	64	10 45 47.030	−09 04 37.40	−144	13.563583	18.0
10199-42...	2001 Nov 25	1536	1.07	237	16.2	18.7	77	10 47 37.082	−09 38 53.35	−137	13.345934	18.0
10199-43...	2001 Nov 28	0336	0.93	240	15.3	17.7	79	10 47 51.368	−09 44 41.27	41	13.305324	18.0
10199-44...	2001 Dec 14	0304	0.55	265	16.1	12.3	94	10 48 40.183	−10 18 15.15	33	13.041242	18.0
10199-45...	2001 Dec 24	0733	1.36	291	16.7	10.8	104	10 48 32.233	−10 35 58.13	−44	12.874980	17.9
10199-46...	2001 Dec 27	0003	1.72	296	16.7	10.8	107	10 48 25.060	−10 40 05.33	65	12.832239	17.9
10199-47...	2002 Feb 6	2245	0.93	182	15.8	19.3	147	10 42 34.023	−11 09 45.56	42	12.306020	17.7
10199-48...	2002 Feb 26	2307	0.05	11	16.4	21.8	160	10 38 04.067	−11 00 35.07	16	12.199959	17.6
10199-49...	2002 Mar 22	0535	1.91	203	13.8	20.1	155	10 32 52.413	−10 35 39.33	−106	12.223505	17.7
10199-50...	2002 Mar 25	1621	1.55	25	17.2	19.4	152	10 32 10.902	−10 31 10.82	89	12.240281	17.7
10199-51...	2002 Apr 10	0025	1.36	213	13.3	15.7	139	10 29 33.236	−10 10 03.59	−47	12.352532	17.7
10199-52...	2002 Jun 5	1834	0.82	170	16.2	11.4	88	10 28 32.899	−09 14 06.57	−16	13.122427	18.0
10199-53...	2002 Jun 27	1448	0.01	180	16.3	20.1	69	10 32 01.142	−09 14 49.78	20	13.454073	18.0
10199-54...	2002 Jul 11	2202	1.95	193	15.7	25.7	56	10 35 14.439	−09 23 35.77	−102	13.648993	18.0
10199-55...	2002 Jul 16	0036	0.83	194	17.7	27.5	53	10 36 16.857	−09 27 20.62	−144	13.699949	18.0
10199-56...	2002 Jul 18	1225	1.25	15	16.6	28.3	51	10 36 55.967	−09 29 52.99	36	13.729595	18.0
10199-57...	2002 Oct 30	0146	1.63	219	16.9	31.1	46	11 08 17.788	−13 22 37.66	102	13.774345	18.0
10199-58...	2002 Nov 2	1234	1.96	41	15.8	30.5	49	11 09 06.162	−13 32 33.61	−63	13.734199	18.0
10199-59...	2002 Nov 2	2045	1.33	221	16.6	30.4	49	11 09 10.992	−13 33 29.77	174	13.730116	18.0
10199-60...	2002 Nov 14	0616	0.74	226	16.4	26.2	59	11 11 32.856	−14 05 45.07	20	13.582425	18.0
10199-61...	2003 Jan 4	1635	1.72	296	14.2	11.5	107	11 15 07.637	−16 04 17.91	176	12.777349	17.9
10199-62...	2003 Jan 5	0719	1.13	118	13.1	11.5	107	11 15 05.391	−16 05 15.35	−46	12.767854	17.9
10199-63...	2003 Feb 6	2209	1.27	355	16.1	17.4	138	11 10 50.224	−16 35 24.81	58	12.340565	17.7
10199-64...	2003 Mar 4	0323	0.19	13	17.5	21.5	157	11 05 19.473	−16 28 23.37	−46	12.169475	17.6

TABLE 4—*Continued*

Star ID	Event Date	UTC	Minimum Separation (arcsec)	Position Angle (deg)	Star Mag. (*V*)	Shadow Velocity (km s^{-1})	Solar Angle (deg)	R.A. (ICRF)	Decl. (ICRF)	East Long. (deg)	Dist. to Chariklo (AU)	Chariklo Mag. (*V*)
10199-65	2003 Mar 9	2244	1.00	196	16.1	21.5	159	11 03 57.706	−16 23 20.56	17	12.155026	17.6
10199-66	2003 Apr 11	0040	0.85	212	13.8	17.7	145	10 57 14.353	−15 40 44.34	−45	12.248875	17.7
10199-67	2003 May 12	1150	1.35	251	17.0	8.9	118	10 53 57.360	−14 53 03.81	116	12.583959	17.8
10199-68	2003 Jun 17	2343	0.74	169	14.0	13.5	85	10 55 54.893	−14 20 34.87	−98	13.128386	18.0
10199-69	2003 Jun 19	0708	1.40	352	16.8	14.1	84	10 56 06.009	−14 20 11.77	150	13.148588	18.0
10199-70	2003 Jun 26	0416	1.64	359	17.3	16.8	78	10 57 11.189	−14 18 53.21	−174	13.253845	18.0
10199-71	2003 Jul 2	0214	1.69	182	13.3	18.8	73	10 58 16.337	−14 18 58.76	−149	13.342358	18.0
10199-72	2003 Oct 24	2227	0.68	216	16.6	34.9	35	11 32 46.987	−17 47 50.05	163	13.877411	18.0
10199-73	2003 Nov 16	0330	0.04	225	16.6	29.3	53	11 38 24.414	−18 53 28.95	67	13.644844	18.0
10199-74	2003 Dec 7	1109	1.29	56	14.4	21.8	72	11 42 06.163	−19 53 58.33	−68	13.346752	18.0
10199-75	2003 Dec 22	0610	0.22	252	16.6	16.5	85	11 43 27.120	−20 31 34.92	−7	13.115304	18.0
10199-76	2004 Jan 14	1901	1.49	119	14.9	11.9	108	11 43 18.889	−21 18 59.86	137	12.744927	17.9
10199-77	2004 Jan 25	0431	0.34	323	17.0	12.7	117	11 42 22.625	−21 33 38.47	−16	12.594098	17.8
10199-78	2004 Jan 31	0335	0.27	335	16.5	13.7	123	11 41 36.881	−21 39 59.84	−8	12.514279	17.8
10199-79	2004 Feb 4	1916	1.83	341	16.0	14.6	127	11 40 54.947	−21 43 53.81	112	12.456089	17.8
10199-80	2004 Feb 9	0533	0.65	167	15.8	15.6	131	11 40 10.304	−21 46 38.99	−47	12.404478	17.8
10199-81	2004 Feb 12	1113	1.28	172	16.4	16.7	134	11 39 35.166	−21 48 08.09	−135	12.369278	17.8
10199-82	2004 Feb 27	2234	0.60	6	16.9	19.5	147	11 36 21.909	−21 48 42.87	38	12.234173	17.7
10199-83	2004 Mar 15	1211	1.46	16	12.0	21.0	156	11 32 29.556	−21 38 03.37	177	12.158617	17.6
10199-84	2004 Mar 19	1008	1.50	198	17.0	21.1	157	11 31 33.940	−21 33 57.50	−157	12.151976	17.6
10199-85	2004 Jul 18	0824	0.99	6	16.9	22.8	67	11 28 37.240	−19 15 28.76	109	13.452612	18.0
10199-86	2004 Aug 3	0705	0.39	193	14.0	28.4	53	11 32 46.384	−19 24 54.71	114	13.660342	18.0
10199-87	2004 Aug 15	1238	1.88	196	11.8	31.5	44	11 36 25.511	−19 38 08.44	20	13.794096	18.0
10199-88	2004 Aug 16	2200	1.73	17	15.7	32.5	43	11 36 51.560	−19 40 00.93	−122	13.807645	18.0
10199-89	2004 Aug 19	1933	1.19	198	16.7	33.1	41	11 37 47.062	−19 44 00.44	−88	13.834662	18.0
10199-90	2004 Aug 23	1025	0.48	199	15.3	34.1	38	11 38 57.238	−19 49 23.39	46	13.866106	18.0
10199-91	2004 Oct 27	1205	0.28	35	12.9	36.4	32	12 00 57.297	−22 22 29.98	−38	13.924006	18.0
10199-92	2004 Nov 3	2038	1.26	37	14.8	34.5	37	12 03 09.306	−22 44 08.48	−172	13.867965	18.0
10199-93	2004 Nov 26	0747	0.26	225	15.4	28.8	55	12 08 53.533	−23 51 09.91	−1	13.629319	18.0
10199-94	2004 Dec 16	2104	1.68	238	15.0	21.5	73	12 12 24.943	−24 49 46.34	141	13.342591	18.0
10199-95	2004 Dec 26	2237	0.94	248	17.0	17.9	82	12 13 24.561	−25 15 58.91	108	13.188093	18.0
10199-96	2004 Dec 31	0025	1.04	73	15.9	16.5	86	12 13 39.708	−25 25 55.91	77	13.124325	18.0
10199-97	2005 Jan 23	0144	0.08	119	14.7	12.0	108	12 13 27.555	−26 12 44.78	35	12.767941	17.9
10199-98	2005 Feb 12	2232	1.36	161	16.6	14.6	127	12 10 58.982	−26 37 33.06	61	12.486618	17.8
10199-99	2005 Apr 2	1213	1.16	203	13.3	21.5	156	12 00 14.651	−26 19 45.88	166	12.187633	17.6
10199-100...	2005 May 7	2142	1.92	47	14.6	15.9	136	11 53 33.134	−25 19 31.20	−13	12.366382	17.8
10199-101...	2005 May 9	0543	0.62	229	16.7	15.3	135	11 53 23.490	−25 16 59.73	−135	12.379089	17.8
10199-102...	2005 Jul 8	0150	1.68	168	16.7	15.9	83	11 54 55.313	−23 55 20.55	−135	13.198272	18.0
10199-103...	2005 Jul 20	1542	0.51	359	14.3	20.5	73	11 57 23.055	−23 51 43.62	5	13.387151	18.0
10199-104...	2005 Jul 30	0243	0.83	185	16.8	24.1	65	11 59 38.087	−23 52 44.48	−169	13.521724	18.0
10199-105...	2005 Aug 29	0023	0.90	16	17.2	33.4	41	12 08 32.902	−24 17 22.18	−161	13.870832	18.0
10199-106...	2005 Sep 1	1808	1.23	198	15.2	34.2	39	12 09 48.472	−24 22 33.54	−71	13.903759	18.0
10199-107...	2005 Sep 3	2333	1.83	18	16.9	34.3	37	12 10 34.203	−24 25 57.35	−154	13.922035	18.0
10199-108...	2005 Sep 12	1524	1.82	20	17.1	36.4	31	12 13 35.698	−24 40 21.20	−40	13.983209	18.0
10199-109...	2005 Sep 13	1502	0.74	21	15.3	36.5	31	12 13 56.783	−24 42 07.64	−35	13.989140	18.0
10199-110...	2005 Nov 5	0633	1.52	214	16.9	36.5	32	12 32 31.993	−26 49 46.24	45	13.973856	18.0
10199-111...	2005 Nov 6	0529	0.91	34	16.7	36.4	33	12 32 50.370	−26 52 32.97	60	13.967511	18.0
10199-112...	2005 Nov 8	1452	0.60	34	15.4	35.3	34	12 33 35.849	−26 59 25.34	−83	13.950714	18.0
10199-113...	2005 Nov 22	0906	1.78	39	15.4	32.8	45	12 37 39.635	−27 39 42.13	−9	13.830520	18.0
10199-114...	2005 Dec 4	0001	1.10	44	15.2	29.2	54	12 40 36.251	−28 13 52.68	117	13.700526	18.0
10199-115...	2005 Dec 7	0318	0.40	45	15.7	28.3	57	12 41 18.825	−28 23 02.60	65	13.661581	18.0
10199-116...	2005 Dec 10	2206	0.55	227	15.6	27.0	60	12 42 06.539	−28 33 57.89	139	13.612646	18.0
10199-117...	2005 Dec 26	0102	0.51	57	14.4	21.5	73	12 44 38.226	−29 16 08.21	81	13.399754	18.0

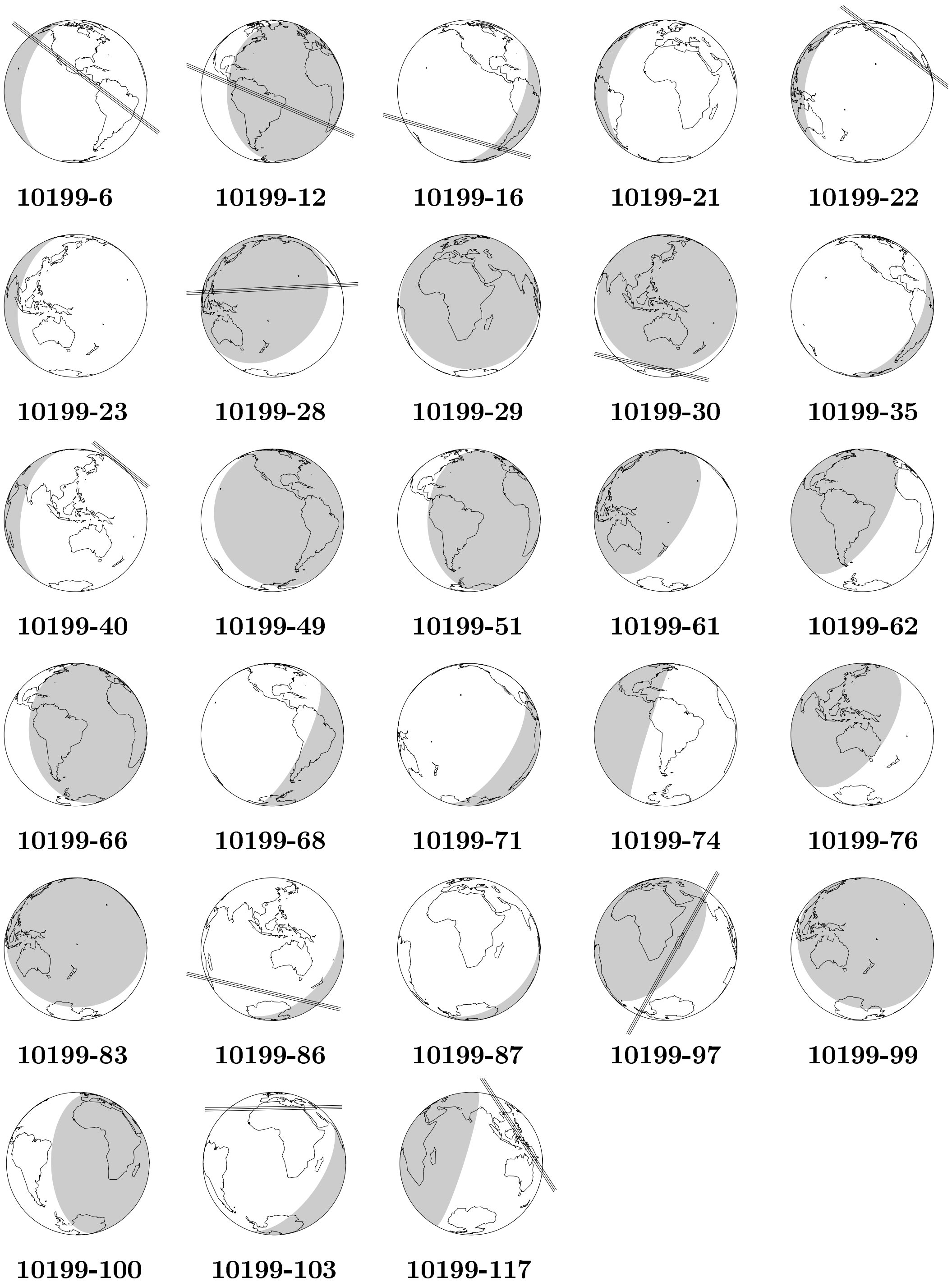
[a] Possibly nonstellar.

color-dependent error discussed above should be $|\Delta V| < 0.15$ mag in most cases. Even without this correction, the computed magnitudes are certainly accurate enough for the purposes of this paper.

3. RESULTS AND DISCUSSION

The list of measured star positions was compared with our revised ephemeris, and all stars within 2″.0 of the ephemeris were designated as occultation candidates. The large 2″.0 limit was chosen because of the increasing uncertainty in the orbit of 10199 Chariklo in the later years of our occultation search. Events with solar elongations less than 25° were eliminated from the candidate list, since they would be difficult to observe under daylight conditions.

Table 4 lists the occultation candidates for 10199 Chariklo from 1999 July through 2005. In previous work we have designated each star with a combination of one or two



10199-6 10199-12 10199-16 10199-21 10199-22

10199-23 10199-28 10199-29 10199-30 10199-35

10199-40 10199-49 10199-51 10199-61 10199-62

10199-66 10199-68 10199-71 10199-74 10199-76

10199-83 10199-86 10199-87 10199-97 10199-99

10199-100 10199-103 10199-117

FIG. 6.—Maps of Earth as viewed from 10199 Chariklo at the midtime of each potential occultation for the brightest occultation stars ($V < 15.0$) in Table 4 that are 40° or more from the Sun at appulse time. The shaded region of each globe represents that portion of Earth for which the Sun is more than 12° below the local horizon. Nominal occultation tracks for 10199 Chariklo that cross Earth are shown with widths equal to ± 1 Chariklo radius. For those globes with no shadow paths plotted, one can establish the orientation of the path from the position angle of 10199 Chariklo at the time of closest approach given in Table 4. As discussed in the text, the predicted paths are quite uncertain because of errors in the ephemeris of 10199 Chariklo, and as a consequence, any of the events shown in the figure could produce an observable occultation, notwithstanding the shown paths.

letters and a number, the letters taken from the name of the object. In this paper, we use the assigned numerical designation for the Centaur along with a sequential number. Thus, each star is designated as 10199-*n*, wherein *n* is a sequential number. The date and time indicate the estimated time of closest approach of the asteroid to the star. The minimum separation, position angle of the Centaur relative to the star at closest approach, geocentric velocity of the occultation shadow, and solar angle of the star during the appulse are all included in the table. The coordinates of each star are given in the ICRF reference frame (equator and equinox J2000), and their accuracies are discussed in § 2.1. The "East Long." column indicates Earth longitude of the star during the appulse. The final two columns give the distance from Earth and magnitude of 10199 Chariklo at event time.

Two objects were removed from the list of occultation candidates after they were examined on the Digitized Sky Survey. These two objects have a fuzzy appearance and are most likely galaxies. One other object, 10199-7, has a slightly odd appearance but was retained in the candidate list. It may be nonstellar and should be examined more carefully before trying to observe the appulse of the Centaur associated with this star.

The uncertainty in the orbit of 10199 Chariklo is the primary source of error in the occultation predictions presented here. Section 2 contains a detailed discussion of the errors in the astrometric analysis of the star positions and the positions of the Centaur that were used to calculate the ephemeris. However, even after attempting to correct the historical positions for 10199 Chariklo in order to improve its ephemeris, the uncertainty in its ephemeris is still around $0''.1$ in 2000 January and increases to around $1''.5$ during elongation in 2005. The apparent radius of Earth from the typical distance of this Centaur from Earth ranges from $0''.65$ to $0''.70$. An appulse with a minimum separation less than this will be visible as an occultation from somewhere on Earth. The limit of $2''.0$ minimum separation, chosen for our candidate list, should include all occultations through 2005 unless future observations indicate that the ephemeris is in greater error than we have estimated.

The best occultation results will come from events with bright stars and low shadow velocities. The errors in the ephemeris and stellar astrometry prevent determining which of these stars will actually be occulted at this time. However, the most promising potential events can be listed. The events with the lowest apparent shadow velocities (<12 km s^{-2}) are 10199-67, -45, -46, -52, -61, -62, and -76, given in order of increasing velocity. Unfortunately, none of these are brighter than $V = 13.1$ or have an expected minimum separation less than $0''.82$. The brightest candidates ($V < 13.0$), listed in order of increasing minimum separation, are 10199-36, -91, -40, -83, -23, and -87. The stars brighter than magnitude $V = 14.0$ and with low minimum separations ($<0''.65$) are 10199-36, -28, -91, -16, -22, and -40.

Figure 6 shows views of Earth as seen from 10199 Chariklo at the times of the brighter appulses ($V < 15.0$) given in Table 4 with solar elongations exceeding 40°. These are the events best suited for occultation observation, because of the apparent brightnesses of the background stars. Each globe is intended to show what areas of Earth might be able to view a particular event. Many of the globes include also a set of tracks marking the nominal track and northern and southern limits of the occultation shadow. Where tracks are not included, the appulse is not currently expected to produce an occultation on Earth. It is very important to note that the nominal tracks depicted are based on the current ephemeris for 10199 Chariklo and the star positions given in Table 4. Astrometric errors parallel to the track will affect the time at which an occultation occurs, and errors perpendicular to the track will shift the track north or south. For appulses closer to year 2005, the uncertainty in the ephemeris is larger than the apparent radius of Earth, so the nominal track should only be used as a guide for visualizing the orientation of the path. Because of uncertainties in the ephemeris for 10199 Chariklo, any of the events shown in Figure 6 could produce an observable occultation, notwithstanding the shown (or not shown) shadow paths. Finder charts for the occultation candidate stars are not included, because of the current availability of the Digitized Sky Survey, which observation planners can use to create their own finder charts for objects of interest.

Further observations of 10199 Chariklo and astrometry of specific occultation candidates will allow improved appulse predictions and identifications of impending occultation events. Given the small angular radius of this Centaur (~ 15 mas) and the uncertainty in its ephemeris, it may not be possible to predict the observability of individual events at specific sites until very shortly before the occultation, using last-minute differential astrometry. The authors plan to update information on the occultation candidates whenever we obtain further data. Interested investigators may contact any of the authors for more information.

4. CONCLUSIONS

This paper presents accurate astrometry for 96,367 stars ($7.5 < V < 17.3$), whose positions have been searched for possible occultation by the Centaur 10199 Chariklo in 1999.5–2006.0. The positions are accurate to ± 30 mas in each coordinate for well-exposed images. According to current theories, this object is a former KBO that has been recently perturbed into the inner solar system, making it interesting from an observational standpoint because of its relative brightness. The ephemeris for 10199 Chariklo was improved by incorporating the new positions presented in this paper (accurate to ± 50 mas) and by transforming older positions taken from the literature into the International Celestial Reference Frame. With the new ephemeris and accurate star positions, 117 occultation candidates were identified satisfying the selection criteria that Centaur-star separations were under $2''.0$ at closest approach and the solar elongations exceeded 25°. Particulars about each potential occultation are given in Table 4, including the dates and times of each event, positions, magnitudes, and solar shadow velocities. Among these events, those with minimum spacings under $0''.65$ will always produce an occultation somewhere on the surface of Earth.

Many of the identified candidates are very faint, rendering them difficult to observe with portable telescopes, and the likelihood of one of them being observed from an observatory at a fixed site is very remote. Among these stars, the most promising candidates are those with magnitudes $V < 15.0$ and solar elongations exceeding 40°. Visibility zones for these potential events are shown in Figure 6, and the brightest of these candidates are 10199-40 ($V = 9.9$), -87 (11.8), -83 (12.0), -23 (12.8), and -62 (13.1).

Because of the small angular radius of 10199 Chariklo, which is about 15 mas, the width of its shadow path across Earth will be very narrow. The astrometry provided in this paper is not accurate enough for precisely predicting individual occultation events. Rather, it was intended only to identify which stars might be occulted by the Centaur in the coming years. A much more accurate prediction would require last-minute astrometry, wherein both 10199 Chariklo and a candidate occultation star, taken from Table 4, are imaged in the same CCD frame using a large-aperture telescope just prior to the event. In order to further improve each prediction, random errors in position can be greatly reduced by taking many CCD frames. This procedure of follow-up last-minute astrometry has produced successfully observed occultations of 2060 Chiron and Triton in the past years.

In order to compute the catalog corrections discussed in § 2.2.2, particulars about individual observations of 10199 Chariklo were solicited. We would like to thank the Klet, Steward (Spacewatch), Palomar, and Sormano astronomical observatories for their help in this endeavor. We would like to thank also the scientific staff at the US Naval Observatory (Flagstaff Station) for assisting in the taking of the observations presented in this paper. Finally, this work was supported in part by NASA grant NAG 5-3940 (at MIT).

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