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PLUTO-CHARON STELLAR OCCULTATION CANDIDATES: 2000–2009

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ABSTRACT

We have completed a search for candidates for occultations by Pluto and Charon over the years 2000 through 2009. Using the DE405 ephemeris and the Plu006 orbit model for Pluto and Charon, we searched for stars that lie within 1″.0 of their respective apparent motions. The images used were CCD strip scans taken at the George R. Wallace Astrophysical Observatory, reaching a depth of 15th to 17th magnitude. As Pluto-Charon enter the Galactic plane, a dramatic increase in the number of stellar appulses will occur. We identify 486 appulses by Pluto and 479 appulses by Charon over this period, with the frequency peaking in 2007. Further astrometry will be necessary to determine which of these appulses will have minimum separations small enough (less than 0″.34 for Pluto or 0″.31 for Charon) to produce an occultation visible from Earth.

Key words: astrometry — occultations — planets and satellites: individual (Charon, Pluto)

1. INTRODUCTION

Pluto's atmosphere has not been probed by a stellar occultation since 1988, when an extensive set of occultation light curves were recorded with a variety of telescopes (Millis et al. 1993), including the Kuiper Airborne Observatory (KAO; Elliot et al. 1989). This data set, ground-based spectroscopy (Owen et al. 1993), and the resulting modeling of Pluto's atmosphere (see Yelle & Elliot 1997 for a review) led to the conclusion that Pluto's atmosphere is composed primarily of N_2 that is in vapor-pressure equilibrium with surface N_2 frost. Well above the surface, the atmospheric temperature is maintained at ~ 100 K by a small amount of CH_4 that acts as a "thermostat" through absorption of solar radiation in the 2.3 and 3.3 μm bands and emission in the 7.8 μm band. One intriguing feature of the light curve recorded from KAO, however, is a sharp drop just below half-light that has been interpreted in two ways: either as the result of a thin, absorbing haze layer (Elliot et al. 1989) or as the onset of a large thermal gradient (Hubbard, Yelle, & Lunine 1990).

In principle one could determine which of these two competing models is correct through observation of a subsequent occultation simultaneously in the visible and the infrared. If the thermal gradient model is correct, the light-curve drop would be due to differential refraction, and the two light curves would appear virtually identical. On the other hand, if the haze model is correct, the light-curve drop would be due to absorption (which, for the small particles that could be suspended in Pluto's atmosphere, would be different at different wavelengths), and the two light curves would differ. A further issue to be addressed with Pluto occultation data is whether its pressure is changing, as has been established for Triton (Elliot et al. 1998, 1999). This goal does not require infrared observations and could be accomplished with a network of small telescopes equipped with high-speed photometers.

Charon has been probed only once by a stellar occultation, with a single light curve observed by Walker (1980). The signal-to-noise ratio (S/N) for this event was high, but the integration time for the data recording was rather long for an occultation: 2.0 s. From these data a (3 σ) lower limit on Charon's radius of 601.5 km was established (Elliot & Young 1991), which is consistent with some values determined from the mutual events, but not with others (Tholen & Buie 1997). Furthermore, the 1980 stellar occultation shows tantalizing evidence (at the 2 σ level) for absorption just prior to and after the main occultation, which could be due to a thin atmosphere or other material near Charon's surface (Elliot & Young 1991). A well-observed stellar occultation by this body could provide an accurate radius and yield more information about possible additional material.

In order to pursue these issues with further stellar occultation data, we have identified appulses for Pluto and Charon that may be visible as occultations from Earth over the next decade: 2000 through 2009. During this time Pluto and Charon will be crossing the Galactic plane, offering a larger number of potentially observable occultations compared with the previous decade (Mink, Klemola, & Buie 1991; Dunham, McDonald, & Elliot 1991; McDonald & Elliot 1996).

2. OBSERVATIONS AND ANALYSIS

A search for occultation candidates could be performed with a known catalog of stars or by astrometric reduction of images of the relevant portion of the sky. Although a catalog search is more convenient and could be accomplished much more quickly, a serious drawback of catalogs is that the positions are based on star positions from an epoch that may be decades old (as is the case for the USNO-A2.0 catalog, which is derived from photographic plates up to 50 years old). During the intervening time between the epoch of the catalog and the time of the potential occultations, the proper motion of the candidates can introduce significant error in the stellar positions. A second potential problem with a catalog search is that the catalog may not be complete to the magnitude depth of interest. In view of the importance of identifying all potential occultations by Pluto and Charon as accurately as possible, we chose to use newly exposed CCD strip scans for this project.

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The procedures for observation and analysis for this project were nearly identical to those described in our recent search for Triton occultation candidates (McDonald & Elliot 2000), and therefore we will present only a brief synopsis of the procedures here. A set of CCD strip scans covering the path of Pluto and Charon during the period 2000–2009 was recorded with our Portable CCD Camera (PCCD; Buie et al. 1993) mounted on the 61 cm telescope at MIT's Wallace Astrophysical Observatory (Westford, Massachusetts). Neighboring strip-scan fields (Fig. 1) overlapped by 50% in order to obtain redundant coverage of the star field around the Pluto-Charon projected orbit. Each image was flattened and processed by IRAF (Tody 1986) to produce a list of star positions on the image and then registered against the US Naval Observatory's A2.0 star catalog to convert to right ascension and declination. Although, as mentioned above, these catalog positions are inaccurate as a result of proper motion over several decades, we expect the proper motions to be in random directions, so that the overall USNO-A2.0 catalog serves as a good astrometric reference standard (since we use thousands of catalog stars on each image). The star coordinates were further refined by fitting Fourier series to the residuals plotted against right ascension (essentially a time axis on CCD strip scans) using Mathematica 3.0 (Wolfram 1996), to correct for systematic time-variable deviations (as discussed in McDonald & Elliot 2000). Observed magnitudes were calibrated to the USNO-A2.0 catalog, again using Fourier series to remove the time-variable deviations. The documentation of the USNO-A1.0 catalog says that the internal photometric accuracy of the catalog is believed to be 0.15 mag, though systematic errors due to plate-to-plate differences could be as large as 0.5 mag. The USNO-A2.0 catalog has better photometric accuracy than the USNO-A1.0 at the brighter end. The internal photometric accuracy of our CCD photometry is a few tenths of a magnitude.

The resulting stellar coordinates were then compared with the Pluto and Charon ephemerides to identify appulses. The DE405 ephemeris provided the orbits of Earth and the Pluto-Charon barycenter, and the Plu006 orbital model provided the offset of Pluto and Charon from the barycenter. This ephemeris uses a Charon-to-Pluto mass ratio of 0.14185. Both ephemerides were supplied by JPL's Navigation and Ancillary Information Facility (Acton 1990). Stars from our images found to be within 1″.0 of the Pluto or Charon ephemeris and more than 25° from the Sun at the time of the appulse were designated occultation candidates. We visually examined each candidate on our images and on the Digitized Sky Survey and removed from our list a few objects that were clearly nonstellar. Other nonstellar objects with small apparent sizes ($\sim 3''$ or less) may still be among our occultation candidates.

The quality of the images used for this project varied widely. In many cases we did not achieve our goal of reach-

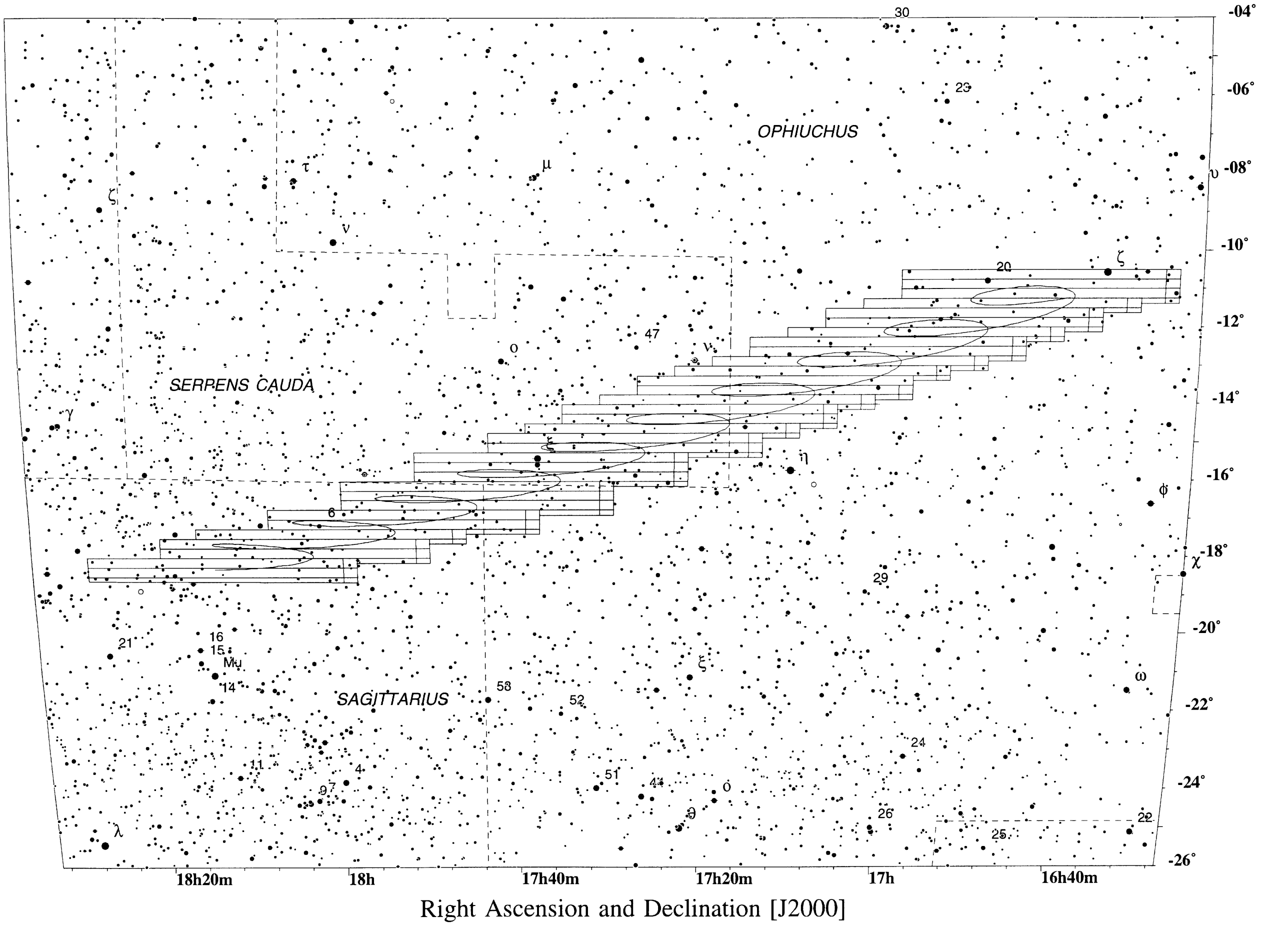

FIG. 1.—Layout of strip-scan fields. The odd-numbered fields are depicted; even-numbered fields overlap the odd-numbered fields by 50% on each side. Each field is about 15′ wide. Pluto's orbit is plotted from 2000 (in the upper right fields) through 2009 (lower left fields).

ing 17th magnitude. The PCCD detector has a linear response over its entire range (up to 64K ADU), but noise from high background counts degraded some of our observations. However, we were able to reach a depth of at least 16.0 mag over the entire star field near Pluto's apparent motion during this decade. Information about individual images can be found in Table 1. Each field was assigned a number, with letters differentiating separate observations of each field. The even-numbered fields overlap the neighboring odd-numbered fields by 50%; the layout of the odd-numbered strip-scan fields is shown in Figure 1.

3. RESULTS AND DISCUSSION

Our results are 486 Pluto occultation candidates and 479 Charon occultation candidates within our search criteria. Since the full tables of candidates would run many pages in length, we have selected only the potential occultation events with high signal-to-noise ratios for publication in the print version of the paper. Table 2 contains the Pluto occultation candidates with potential signal-to-noise values (using HOPI on SOFIA; see below) greater than 100. Occultation events with listed signal-to-noise

TABLE 1

STRIP SCANS USED IN SEARCH

Strip	Date	Mag. Limit	Notes
03a......	1996 Jun 6	17.4	
03b......	1998 Jul 19	18.1	
04a......	1996 Jun 6	17.1	
05b......	1998 Jul 19	17.4	
06a......	1996 Jun 6	17.9	
06b......	1998 Jul 25	17.8	
07b......	1998 Jul 25	17.7	
07c......	1999 May 11	17.1	1
08d......	1999 May 11	17.6	
08e......	1999 May 16	17.8	
09b......	1998 Aug 2	17.7	1
09c......	1999 May 11	17.6	
09d......	1999 May 16	17.6	
10b......	1998 Aug 2	17.7	1
10c......	1999 May 11	17.1	
10d......	1999 May 17	17.6	
11b......	1998 Jun 30	16.9	2
11c......	1999 May 11	17.3	
11d......	1999 May 17	17.4	
12a......	1996 Jun 15	16.7	3
12b......	1998 Aug 2	17.8	1
13b......	1999 May 10	17.1	
14b......	1999 May 10	16.9	
15b......	1999 May 17	17.7	
16a......	1996 Jun 15	16.8	3
16b......	1999 May 10	17.5	
17b......	1999 May 17	17.3	
17c......	1999 Jul 6	16.4	1, 2
18b......	1999 May 11	17.5	
18c......	1999 May 18	17.5	1
18d......	1999 Jul 6	16.8	1
19b......	1996 Jun 26	16.2	1, 4
19c......	1996 Jun 26	16.2	4
20a......	1996 Jun 26	16.2	4
20b......	1996 Jun 26	14.8	1, 4
21a......	1996 Jun 26	15.3	4
21b......	1998 Jul 14	17.4	1
22a......	1996 Jun 27	15.4	2, 5
22b......	1996 Jun 27	15.9	1, 4
23a......	1996 Jun 27	15.5	1, 4
23b......	1999 May 15	17.8	
23c......	1999 May 18	17.6	
24a......	1996 Jun 27	15.6	4
24b......	1999 May 15	17.7	
24c......	1999 May 21	17.8	
25a......	1996 Jul 6	17.4	
25b......	1999 May 21	17.3	
26a......	1996 Jul 7	17.7	
26b......	1999 May 21	17.4	
27b......	1996 Jul 11	17.5	
28a......	1996 Jul 11	16.6	
28b......	1999 May 21	17.4	
29a......	1996 Jul 11	16.9	
29b......	1999 May 21	17.4	
30a......	1996 Jul 12	16.5	4
30b......	1999 May 15	17.2	
30c......	1999 May 22	17.0	1
31a......	1996 Jul 12	17.0	
32a......	1996 Jul 12	16.8	
32b......	1999 May 22	17.1	1
33a......	1996 Jul 12	16.0	2
33b......	1999 May 15	16.7	
33c......	1999 May 22	16.8	1, 2
34a......	1996 Jul 12	15.0	1, 2
34b......	1996 Jul 22	16.6	2
34c......	1998 Aug 23	16.1	
35a......	1996 Jul 22	16.6	2
35c......	1999 May 15	16.7	
35d......	1999 May 22	16.3	1, 2
36a......	1996 Jul 23	17.1	
37a......	1996 Jul 23	17.1	
37b......	1999 May 22	16.4	1, 2
38a......	1996 Jul 23	16.6	
38c......	1999 Jun 23	16.4	1
38d......	1999 Jul 6	15.9	1, 2
39a......	1996 Jul 23	16.7	
39b......	1999 Jun 23	16.6	1
39c......	1999 Jul 6	15.5	1
40a......	1996 Jul 25	16.1	5
40b......	1999 Jun 23	16.3	1
41a......	1996 Jul 25	15.6	5
41b......	1998 Jul 22	16.4	
42b......	1998 Aug 22	16.7	
42c......	1999 Jul 8	16.0	
43a......	1996 Aug 5	15.5	
43c......	1999 Jul 8	16.0	
44a......	1996 Jun 15	16.3	
44b......	1996 Jul 6	16.2	1
45a......	1996 Aug 6	16.4	
45c......	1999 Jul 8	16.2	
46a......	1996 Aug 6	16.5	
46b......	1999 Jun 19	15.8	1, 3
46c......	1999 Jun 24	15.8	5
46d......	1999 Jul 8	16.0	
47a......	1996 Aug 6	16.5	
47b......	1999 Jun 19	16.3	
48a......	1996 Aug 7	16.2	
48b......	1999 Jun 19	16.4	
49a......	1996 Aug 7	16.4	
49b......	1999 Jun 19	16.3	
50a......	1996 Aug 7	16.3	
50b......	1999 Jun 19	16.2	
51c......	1996 Aug 8	16.4	
51d......	1998 Jul 21	16.6	
52a......	1996 Aug 7	16.4	
52b......	1999 Jun 20	15.0	5, 6
52d......	1999 Jul 8	16.4	
53a......	1996 Aug 8	16.7	
53b......	1999 Jun 20	15.5	5, 6
53c......	1999 Jun 24	16.2	5
53d......	1999 Jul 8	16.1	5, 7
54a......	1996 Aug 8	16.4	
54b......	1999 Jun 20	15.6	5, 6
54c......	1999 Jun 24	15.5	5, 6
54d......	1999 Jul 11	16.0	
55a......	1996 Aug 9	16.3	2
55b......	1999 May 17	16.2	
55d......	1999 Jun 20	16.0	5
55e......	1999 Jul 11	15.8	
56a......	1996 Aug 9	16.1	6
56b......	1999 May 17	16.1	
56c......	1999 Jun 20	16.3	1, 2
56d......	1999 Jun 25	15.4	5, 6
56e......	1999 Jul 11	16.2	
57a......	1996 Aug 12	16.2	1, 2
57e......	1999 Jul 11	16.0	
58a......	1996 Aug 21	16.3	1
58e......	1999 Jul 11	16.1	
59a......	1996 Aug 21	16.4	1
59b......	1999 May 18	16.2	
59e......	1999 Jul 11	16.1	7
60a......	1996 Aug 7	16.0	
60b......	1999 Jun 23	15.3	5
60c......	1999 Jul 11	15.7	1, 7
61a......	1996 Jul 11	15.6	
61b......	1998 Jun 30	16.1	6
61c......	1999 Jun 25	15.4	5
62a......	1996 Aug 6	16.0	
62b......	1999 Jun 23	15.4	5, 6
62c......	1999 Jul 14	16.2	1
63a......	1996 Aug 18	16.2	1
63e......	1999 Jul 14	15.7	1

NOTES.—(1) High background (>15% of saturation); (2) haze or clouds; (3) bad CCD clock rate; (4) focus problems; (5) very high background (>30% of saturation); (6) part of image washed out; (7) low altitude.

TABLE 2

Possible Occultations by Pluto

	Closest Approach												
Event	Date	UT	Minimum Separation (arcsec)	P.A. of Pluto (deg)	Shadow Velocity (km s^{-1})	CCD Mag.	S/N[a]	Solar Angle (deg)	East Long. (deg)	R.A. (J2000)	Decl. (J2000)	Distance (AU)	Strips
P60	2000 Sep 25	0931	0.01	206	18.7	14.7	121	68	103	16 41 43.831	−11 29 27.77	30.66	07b, c, 08d, 09c
P74	2001 Feb 12	0020	0.74	174	17.5	13.3	341	69	107	16 59 22.716	−12 13 22.00	30.69	13b, 14b
P95	2001 Oct 3	1830	0.45	203	20.9	14.1	180	63	−37	16 51 20.578	−12 23 31.69	30.87	15b, 16a, b
P102......	2002 Jan 1	1811	0.77	184	33.1	13.7	190	27	−118	17 03 31.727	−12 59 40.06	31.34	19b, c, 20a, b
P107......	2002 Feb 14	0718	0.69	354	17.5	14.9	107	68	3	17 08 31.243	−13 00 30.35	30.83	19b, c, 20a, b, 21a, b
P130......	2002 Aug 5	1249	0.18	336	11.1	14.5	184	122	109	16 59 17.698	−12 45 59.21	30.00	17b, c, 18c, d, 19b, c
P139......	2002 Nov 7	0234	0.39	193	31.8	12.3	459	33	171	17 04 01.833	−13 27 59.71	31.40	23a, b, c, 24a, b, c
P178......	2003 Oct 5	2054	0.90	22	19.5	14.4	149	66	−71	17 09 22.333	−13 59 01.77	31.10	27b, 28a, b
P186......	2004 Jan 6	0100	0.73	3	33.2	14.1	143	26	140	17 21 42.691	−14 29 57.93	31.62	31a, 32a, b, 33a, b, c
P188......	2004 Jan 7	0755	0.86	183	33.0	13.4	233	27	35	17 21 53.750	−14 30 05.01	31.61	31a, 32a, b, 33a, b, c
P190......	2004 Jan 17	1332	0.99	182	30.3	13.2	276	37	−59	17 23 18.102	−14 30 54.56	31.53	32a, b, 33a, b, c
P207......	2004 Feb 18	1204	0.57	175	17.8	13.0	408	68	−68	17 26 43.084	−14 29 57.25	31.12	31a, 32a, b, 33a, b, c
P208......	2004 Feb 21	1103	0.68	354	16.4	14.9	110	70	−55	17 26 56.397	−14 29 38.98	31.08	31a, 32a, b, 33a, b
P211......	2004 Mar 17	2014	0.73	141	4.3	14.7	253	95	142	17 28 03.701	−14 25 43.54	30.66	31a, 32a, b
P248......	2004 Oct 16	0836	0.88	197	23.1	13.2	316	57	105	17 19 16.546	−14 48 49.76	31.39	34a, b, c, 35a, c, d
P254......	2004 Nov 11	2006	0.80	11	31.9	13.5	222	32	−93	17 22 23.021	−14 59 18.04	31.71	35a, c, d, 37b
P257......	2004 Nov 16	0239	0.33	10	32.9	13.8	178	28	165	17 22 58.351	−15 00 47.72	31.74	35c, d, 36a, 37a, b
P275......	2005 Feb 4	0902	0.69	179	24.5	14.0	179	52	−7	17 34 22.113	−15 13 14.47	31.50	37a, 38a, c, d
P276......	2005 Feb 13	1127	0.48	356	20.7	14.4	145	61	−52	17 35 16.141	−15 12 42.31	31.38	37a, 38a, d
P289......	2005 May 14	1107	0.46	4	19.7	14.2	173	149	−135	17 34 50.371	−14 59 49.87	30.08	35a, c, d, 36a, 37a, b
P292......	2005 May 22	1304	0.26	3	21.5	10.7	1272	156	−173	17 34 04.929	−14 59 08.44	30.02	35a, c, d, 36a, 37b
P306......	2005 Jun 22	0531	0.34	358	23.4	14.2	158	169	−91	17 30 50.363	−14 58 53.63	29.97	35a, c, d
P341......	2005 Nov 12	2351	0.99	189	31.5	14.4	118	33	−147	17 31 18.301	−15 41 41.18	31.85	41b
P342......	2005 Nov 14	1356	0.78	189	31.9	14.2	136	32	0	17 31 31.135	−15 42 11.70	31.87	41a, b, 42b
P360......	2006 Mar 16	0529	0.87	342	6.9	14.9	170	89	10	17 46 03.827	−15 49 48.92	31.09	43a
P362......	2006 Mar 26	2357	0.73	118	2.4	16.1	105	99	83	17 46 15.253	−15 48 14.45	30.91	42b
P364......	2006 Apr 14	1419	0.68	15	8.2	14.0	309	118	−151	17 45 58.536	−15 45 33.59	30.62	41a, b, 43a
P365......	2006 Apr 19	1209	0.16	192	10.3	14.8	151	122	−123	17 45 46.812	−15 44 52.85	30.55	41a
P373......	2006 May 13	1232	0.47	184	18.7	14.5	141	146	−153	17 44 11.463	−15 42 18.12	30.27	41a, b, 42b
P379......	2006 May 31	1435	0.55	1	22.6	14.7	110	162	158	17 42 28.465	−15 41 28.04	30.15	41a, b, 42b
P383......	2006 Jun 8	0338	0.86	180	23.4	14.5	126	169	−46	17 41 40.928	−15 41 26.32	30.13	41a
P385......	2006 Jun 22	2117	0.12	358	23.6	14.5	126	170	35	17 40 05.554	−15 42 06.43	30.13	41a, b, 42b
P388......	2006 Jul 3	2154	0.11	354	22.5	13.5	264	162	14	17 38 55.770	−15 43 11.45	30.17	41a, b
P395......	2006 Jul 26	1021	0.46	349	17.5	13.4	319	141	165	17 36 51.785	−15 47 00.43	30.36	41a, 43a
P398......	2006 Jul 29	0825	0.51	348	16.6	13.7	268	138	−169	17 36 38.474	−15 47 38.90	30.39	42b, 43a
P399......	2006 Aug 8	2052	0.51	162	13.0	10.5	1803	128	−6	17 35 57.359	−15 50 12.94	30.52	42b, c, 43a
P403......	2006 Sep 10	1822	0.31	64	6.1	14.8	196	96	−2	17 35 11.514	−16 00 25.39	31.04	43a, 44a, b, 45c
P406......	2006 Sep 28	0618	0.33	27	12.9	15.1	106	79	162	17 35 44.267	−16 06 37.98	31.35	44a, b, 45a, c
P415......	2006 Oct 31	0355	0.24	191	26.7	13.9	184	48	166	17 38 28.780	−16 18 05.47	31.85	46a, c, 47a, b
P421......	2006 Nov 12	0011	0.83	9	30.5	14.1	149	36	−149	17 39 55.343	−16 21 46.03	31.99	46a, a, c, d, 47a, b, 48a, b
P425......	2006 Nov 18	0718	0.14	188	32.2	14.3	125	30	98	17 40 45.836	−16 23 31.84	32.05	46a, c, 47a, b, 48a, b
P434......	2007 Feb 1	1105	0.85	359	27.4	11.7	683	45	−30	17 51 36.784	−16 32 35.89	31.93	48a, b, 49a
P435......	2007 Feb 3	0937	0.65	359	26.7	13.3	276	46	−10	17 51 50.411	−16 32 31.66	31.91	48a, 49a, b
P446......	2007 Mar 28	1329	0.21	309	2.2	14.7	353	98	−119	17 55 16.638	−16 27 16.43	31.10	47a, 48a
P450......	2007 Apr 29	2324	0.89	6	13.4	14.2	209	130	60	17 54 22.965	−16 23 39.42	30.62	47a, b, 48a, b
P456......	2007 May 12	0231	0.02	0	17.6	13.5	298	142	1	17 53 32.019	−16 22 46.66	30.48	46a, d, 47a, 48a
P458......	2007 May 18	2213	0.26	181	19.6	14.0	200	148	59	17 52 57.566	−16 22 27.69	30.42	46a, d, 47a, b, 48a, b
P461......	2007 Jun 1	0810	0.79	360	22.3	13.6	248	161	−104	17 51 40.599	−16 22 17.87	30.33	46c, d, 47a, 48a
P470......	2007 Jun 15	0140	0.13	177	23.7	14.2	157	172	−21	17 50 13.860	−16 22 44.64	30.29	46a, 47b, 48a

TABLE 2—*Continued*

	Closest Approach												
Event	Date	UT	Minimum Separation (arcsec)	P.A. of Pluto (deg)	Shadow Velocity (km s^{-1})	CCD Mag.	S/N[a]	Solar Angle (deg)	East Long. (deg)	R.A. (J2000)	Decl. (J2000)	Distance (AU)	Strips
P476.......	2007 Jun 26	0105	0.03	180	23.6	14.8	100	170	−23	17 49 02.774	−16 23 37.11	30.30	46a
P478.......	2007 Jun 28	0204	0.27	176	23.4	14.7	108	169	−40	17 48 49.690	−16 23 49.72	30.31	46a, 47a, b, 48a, b
P482.......	2007 Jul 3	0748	0.30	355	22.9	14.7	109	165	−131	17 48 16.544	−16 24 27.25	30.33	47a, b, 48a, b
P486.......	2007 Jul 5	2142	0.22	175	22.7	14.8	102	162	18	17 48 00.537	−16 24 47.44	30.34	47a, b, 48a, b
P493[b]......	2007 Jul 25	1922	0.90	170	18.4	13.6	273	144	33	17 46 08.679	−16 28 14.42	30.49	47a, b, 48a, b
P500.......	2007 Aug 9	0604	0.43	343	13.7	13.9	257	130	−142	17 45 06.748	−16 31 36.60	30.67	48a, b, 49a, b
P501.......	2007 Aug 9	1402	0.05	164	13.6	15.1	103	130	98	17 45 05.554	−16 31 41.18	30.67	48a, b, 49a, b
P503.......	2007 Sep 17	1341	0.11	228	7.3	14.7	194	92	65	17 44 18.310	−16 43 16.94	31.29	49a, b, 50a, b
P508.......	2007 Sep 30	1419	0.84	25	12.7	14.9	125	79	42	17 44 46.394	−16 47 34.05	31.52	50a, b, 51c
P513.......	2007 Oct 10	1144	0.22	197	17.1	14.7	127	70	71	17 45 22.393	−16 50 46.82	31.68	50a, b
P518.......	2007 Oct 25	1630	0.35	192	23.6	12.0	628	55	−15	17 46 40.632	−16 55 31.91	31.92	51c, d, 52a, b, d
P539.......	2008 Jan 25	2346	0.12	178	30.3	14.5	111	36	149	17 59 31.057	−17 09 37.83	32.20	53a, c, 54a, b, c, d
P553[b]......	2008 Mar 8	0615	0.12	353	12.7	14.4	185	77	10	18 03 35.114	−17 06 39.52	31.63	52a, d, 53b, c, d
P560[b]......	2008 May 26	0750	0.34	180	21.0	14.4	144	154	−92	18 01 23.933	−17 00 58.13	30.55	51c, 52a, d, 53a, b, c, d
P566.......	2008 Jun 13	1526	0.44	177	23.6	13.5	258	170	136	17 59 31.763	−17 01 47.26	30.47	52a, b, d, 53a, b, c, d, 54a
P570.......	2008 Jun 22	1732	0.65	356	23.8	12.7	422	173	95	17 58 33.078	−17 02 37.83	30.47	52a, b, 53a, b, c, 54a
P581[b]......	2008 Jul 6	0813	0.83	174	22.8	14.7	110	164	−139	17 57 06.399	−17 04 21.52	30.51	52b
P586.......	2008 Jul 18	1440	0.19	172	20.6	14.8	107	152	112	17 55 54.031	−17 06 28.03	30.59	52a, d, 53c, d, 54a
P591[b]......	2008 Jul 28	1139	0.96	169	18.1	13.7	257	143	147	17 55 02.581	−17 08 28.23	30.68	53a, d, 54c
P599.......	2008 Sep 3	1113	0.53	121	5.2	15.3	141	107	117	17 53 14.302	−17 18 04.61	31.21	54d, 55a, b, e
P601.......	2008 Sep 22	1453	0.41	35	8.4	15.2	121	89	43	17 53 24.119	−17 23 46.69	31.54	55a, d, 56a, b, c, d, e
P602.......	2008 Oct 4	1636	0.73	20	13.8	15.1	102	77	6	17 53 55.141	−17 27 23.20	31.74	55a, 56a, b, c, d, e
P605.......	2008 Oct 10	1712	0.03	16	16.5	14.3	175	71	−9	17 54 17.660	−17 29 08.17	31.84	55a, b, e, 56a, b, c, d, 57a
P608.......	2008 Oct 24	1826	0.71	11	22.6	14.4	139	58	−41	17 55 27.061	−17 33 03.99	32.07	56a, b, e, 57a, e
P611.......	2008 Nov 3	2032	0.70	9	26.5	12.4	476	48	−82	17 56 30.262	−17 35 39.07	32.21	56a, b, c, d, e, 57a, e
P615[b]......	2008 Nov 17	0208	0.88	6	30.7	10.7	1065	35	−179	17 58 07.404	−17 38 38.88	32.36	56b, 57a, e, 58a, e
P622[b]......	2009 Feb 10	0706	0.40	357	25.5	10.6	1226	49	25	18 10 09.631	−17 43 54.97	32.23	58e, 59b
P624.......	2009 Mar 2	1925	0.64	355	16.4	14.3	176	69	−179	18 12 02.187	−17 42 13.76	31.94	57e, 58e
P625.......	2009 Mar 4	1534	0.09	355	15.5	12.4	622	71	−123	18 12 09.864	−17 42 02.81	31.91	57e, 58a, e
P626.......	2009 Mar 20	0609	0.97	169	7.7	15.3	116	87	3	18 12 57.676	−17 40 30.84	31.66	57a, e, 58a, e
P627.......	2009 Mar 22	0241	0.83	348	6.7	15.2	135	88	53	18 13 01.264	−17 40 22.07	31.63	57a, e, 58a, e
P631.......	2009 May 12	0713	0.45	360	16.5	14.3	175	138	−66	18 11 44.375	−17 37 21.61	30.88	56b, c, d, e, 57e, 58a, e
P645.......	2009 Aug 9	2327	0.04	344	14.9	14.0	230	133	−40	18 03 15.900	−17 48 50.64	30.99	58a, e, 59b, e
P652.......	2009 Oct 2	0244	0.58	23	11.3	13.8	304	82	−141	18 02 37.603	−18 03 02.29	31.84	60a, b, c, 61a, c
P653.......	2009 Oct 5	1415	0.46	200	12.9	15.0	115	78	42	18 02 47.847	−18 03 56.87	31.90	60a, b, c, 61a, c

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. Only those events with S/N values of at least 100 are shown here.

[a] The signal-to-noise ratio listed is calculated for HOPI on SOFIA (see text)

[b] Star does not match any entry in the USNO-A2.0 catalog within 2″.0 of right ascension and declination.

values of about 100 should produce the same quality of data as the KAO observation of the P8 event in 1988. Table 3 contains the Charon occultation candidates with potential signal-to-noise values greater than 80. The full tables, without any S/N selection, are included in the electronic version of this paper and can also be accessed from our own occultation World Wide Web site.[2] We have continued the naming scheme used in our previous Pluto and Charon occultation search papers, first used by Mink et al. (1991). Pluto candidates are designated by a "P" followed by a number, and Charon candidates are designated by a "C" and a number. Stars that appear on both lists have the same numeric designation, and the numbering starts at the next sequence number after the last occultation candidate in 1999 (McDonald & Elliot 1996). Since Tables 2 and 3 are a subset of our full candidate lists, the numbering sequence will appear to have large gaps. It is important to note that many events that do not appear in the print version of the tables can still provide useful occultation data. Interested observers (especially those with access to larger telescopes) should check the electronic version of the tables for a complete list of potential events.

The date and time of closest approach (UT), minimum separation for a geocentric observer, position angle of the body relative to the star (measured north through east), and velocity of the occultation shadow on the fundamental plane are listed for each candidate. Next is the CCD magnitude, approximately equal to an *R* magnitude (except for very red or blue objects), calibrated to the USNO-A2.0 field stars as described above.

An estimated signal-to-noise ratio for the occultation appears in the next column. This S/N estimate assumes the use of the High-Speed Occultation Photometer and Imager (HOPI; Dunham, Elliot, & Taylor 1998) on the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA; Becklin 1997). For Pluto, the calculation uses the signal expected from the unocculted star over the course of 60 km of shadow motion (approximately the scale height of its atmosphere). For Charon the signal is that expected during 10 km of motion (a few times the Fresnel diffraction scale). For both bodies, the noise used in the calculation is the photon noise expected from the combined light of Pluto, Charon, and the star, since they can be assumed to be unresolved. For a telescope of diameter *D*, the expected error in the chord length of a Charon occultation can be estimated by the equation (2.5 m/D)(14 km)/(S/N), where S/N is the signal-to-noise value from Table 3 (if the detector is not read-noise limited).

The solar elongation of the star at the midtime of the appulse is in the next column, followed by the substar east longitude on Earth at that time. The substar Earth latitude is the same as the star's declination. Next is the right ascension and declination of the star, in J2000 equinox. The distance from Earth to Pluto-Charon at event time is next. The last column is a list of strip scans on which the star was found. More information about specific strip scans can be found in Table 1.

Unlike our previous Pluto-Charon occultation search papers, we have not included a set of finder charts for these occultation candidates. Several resources currently exist that can provide adequate finder charts for stars this faint, including the Digitized Sky Survey. Figure 2 can be used to determine what areas on Earth might be able to view these appulse and occultation events. For each star, Figure 2 depicts a view of Earth from the star at the approximate time of closest approach of Pluto and Charon. The region from which the Sun is more than 12° below the horizon is shaded gray. Occultation paths are not included, because our astrometry and the ephemeris are not accurate enough to make actual occultation predictions.

Over this decade, the mean apparent radius of Earth from Pluto-Charon is 0".285, while the mean apparent radii of Pluto and Charon from Earth are 0".054 and 0".027, respectively. That means that a Pluto appulse with a minimum separation less than about 0".34 or a Charon appulse with less than about 0".31 separation will be visible as an occultation somewhere on Earth. Assuming a random distribution of minimum separations, we would then expect about 165 Pluto occultations and 148 Charon occultations from our full candidate lists. However, the minimum separations listed in Tables 2 and 3 are not accurate enough to determine which candidates will actually be occulted (as visible from Earth). We chose a search width of 1".0 to allow for the uncertainty in our astrometric measurements, in the USNO-A2.0 catalog, and in the Pluto-Charon ephemeris. In particular, the accuracy of the ephemeris is expected to decrease the further into the future it is projected. We believe the total effect of the errors to be a few tenths of an arcsecond, comparable to the apparent radius of Earth, and probably increasing with time. To make accurate occultation predictions, further astrometry and, possibly, upgraded ephemerides will be needed. These candidate lists will allow researchers to select likely candidates for further evaluation.

Since one of our reasons for using the CCD strip scans instead of a catalog search was a concern about completeness of the catalog, we compared our list of candidates with the USNO-A2.0 catalog. Of the 610 individual stars in our full candidate lists, 102 stars do not match star positions in the USNO-A2.0 catalog within 2".0. Expanding the match to 5".0 difference in right ascension and declination still leaves 36 of our candidates unmatched in the USNO-A2.0. Either these stars are missing from the catalog or there is a large discrepancy in the positions of the missing stars. Of the stars that did match the catalog within 2".0, the standard deviation of the position differences is 0".7 in right ascension and 0".7 in declination. Since the errors in our candidate positions for observed occultations have been only a few tenths of an arcsecond (McDonald & Elliot 2000), a large part of the 0".7 differences is likely due to proper motion.

Occultation events with high signal-to-noise ratios would provide the best information about Pluto and Charon. Seven Pluto events in our candidate lists have potential S/Ns from SOFIA higher than 500. In order of decreasing S/N, they are P399, P292, P622, P615, P434, P518, and P625. For Charon, seven events have SOFIA S/Ns greater than 300: C507, C399, C292, C622, C615, C119, and C126. Of these only P292, P625, C292, and C622 have estimated minimum separations small enough to produce occultations. Fortunately, numerous other candidates have fairly high signal-to-noise ratios and low minimum separations, and further astrometry may change individual predictions. At large telescopes, even events with low S/N can provide useful data. The values 500 and 300 were chosen simply to note the very best candidates in terms of potential S/N.

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[2] See http://occult.mit.edu.

TABLE 3

POSSIBLE OCCULTATIONS BY CHARON

	CLOSEST APPROACH												
EVENT	Date	UT	Minimum Separation (arcsec)	P.A. of Charon (deg)	Shadow Velocity (km s^{-1})	CCD MAG.	S/N[a]	SOLAR ANGLE (deg)	EAST LONG. (deg)	R.A. (J2000)	DECL. (J2000)	DISTANCE (AU)	STRIPS
C69	2001 Jan 12	1520	0.61	2	29.5	13.6	88	39	−88	16 56 11.481	−12 13 56.52	31.09	13b, 14b
C119	2002 Jul 1	2156	0.57	356	21.3	11.4	369	154	6	17 01 52.334	−12 38 56.23	29.61	17b, c, 18b, c, d
C126	2002 Jul 20	0039	0.90	349	16.6	12.0	306	137	−53	17 00 18.002	−12 41 41.63	29.78	17b, c, 18b, c, d
C188	2004 Jan 7	0749	0.82	183	33.0	13.4	95	27	37	17 21 53.750	−14 30 05.01	31.61	31a, 32a, b, 33a, b, c
C190	2004 Jan 17	1339	0.52	181	30.4	13.2	113	37	−61	17 23 18.102	−14 30 54.56	31.53	32a, b, 33a, b, c
C207	2004 Feb 18	1215	0.04	172	17.8	13.0	167	68	−70	17 26 43.084	−14 29 57.25	31.12	31a, 32a, b, 33a, b, c
C254	2004 Nov 11	2011	0.50	10	31.8	13.5	91	32	−94	17 22 23.021	−14 59 18.04	31.71	35a, c, d, 37b
C292	2005 May 22	1256	0.07	5	21.5	10.7	519	156	−171	17 34 04.929	−14 59 08.44	30.02	35a, c, d, 36a, 37b
C320	2005 Jul 21	0051	0.90	170	18.2	12.2	262	143	−50	17 28 02.133	−15 02 34.63	30.16	36a, 37a, b
C328	2005 Sep 13	1031	0.90	49	7.9	14.5	89	91	111	17 26 12.784	−15 19 00.80	30.97	38a, c, c, d, 39a, b, c
C333	2005 Oct 19	1542	0.80	195	23.4	13.3	120	56	−2	17 28 27.116	−15 33 02.47	31.56	40a, 41a, b
C339	2005 Nov 10	1922	0.85	10	30.8	13.6	86	35	−78	17 31 00.836	−15 41 00.41	31.83	41a, 42b
C340	2005 Nov 12	2122	0.76	189	31.6	13.1	118	33	−110	17 31 17.453	−15 41 38.60	31.85	41a, b, 42b
C359	2006 Mar 9	2031	0.58	349	10.0	14.4	85	83	151	17 45 49.681	−15 50 41.21	31.20	42b, 43a
C388	2006 Jul 3	2156	0.76	175	22.7	13.5	107	162	14	17 38 55.770	−15 43 11.45	30.17	41a, b
C398	2006 Jul 29	0828	0.37	168	16.7	13.7	109	138	−170	17 36 38.474	−15 47 38.90	30.39	42b, 43a
C399	2006 Aug 8	2103	0.04	162	12.9	10.5	739	128	−9	17 35 57.359	−15 50 12.94	30.52	42b, c, 43a
C418	2006 Nov 6	1942	0.89	190	29.0	11.9	244	41	−77	17 39 16.025	−16 20 10.72	31.93	46a, d, 47a
C434	2007 Feb 1	1114	0.99	359	27.4	11.7	279	45	−32	17 51 36.784	−16 32 35.89	31.93	48a, b, 49a
C445	2007 Mar 7	0411	0.57	172	12.7	13.8	117	78	41	17 54 36.408	−16 29 53.58	31.45	47a, b, 48a, 49b
C446	2007 Mar 28	1357	0.62	129	2.2	14.7	144	98	−126	17 55 16.638	−16 27 16.43	31.10	47a, 48a
C450	2007 Apr 29	2335	0.11	6	13.6	14.2	85	130	57	17 54 22.965	−16 23 39.42	30.62	47a, b, 48a, b
C456	2007 May 12	0243	0.54	182	17.7	13.5	121	142	−2	17 53 32.019	−16 22 46.66	30.48	46a, d, 47a, 48a
C461	2007 Jun 1	0811	0.01	180	22.5	13.6	101	161	−104	17 51 40.599	−16 22 17.87	30.33	46c, d, 47a, 48a
C467	2007 Jun 13	1839	0.92	358	23.8	13.7	91	171	86	17 50 22.224	−16 22 42.09	30.29	46a, c, d, 47b, 48a
C471	2007 Jun 15	2360	0.73	178	23.7	12.6	183	172	3	17 50 07.790	−16 22 47.07	30.29	46a, b, c, d, 47b, 48a
C493[b]	2007 Jul 25	1926	0.17	170	18.3	13.6	112	144	32	17 46 08.679	−16 28 14.42	30.49	47a, b, 48a, b
C500	2007 Aug 9	0616	0.14	163	13.8	13.9	105	130	−145	17 45 06.748	−16 31 36.60	30.67	48a, b, 49a, b
C503	2007 Sep 17	1259	0.46	227	7.1	14.7	80	92	75	17 44 18.310	−16 43 16.94	31.29	49a, b, 50a, b
C507[b]	2007 Sep 27	1822	0.77	208	11.6	9.7	1140	82	−16	17 44 38.454	−16 46 36.30	31.47	49a, 50a, b, 51c, d
C566	2008 Jun 13	1516	0.30	178	23.6	13.5	105	170	138	17 59 31.763	−17 01 47.26	30.47	52a, b, d, 53a, b, c, d, 54a
C570	2008 Jun 22	1740	0.89	355	23.7	12.7	173	173	93	17 58 33.078	−17 02 37.83	30.47	52a, b, 53a, b, c, 54a
C585	2008 Jul 17	0806	0.39	172	20.8	13.6	105	153	−148	17 56 01.158	−17 06 12.79	30.58	52a, b, d, 53b, c, d, 54a
C591[b]	2008 Jul 28	1127	0.63	170	18.1	13.7	105	143	150	17 55 02.581	−17 08 28.23	30.68	53a, d, 54c
C615[b]	2008 Nov 17	0201	0.88	7	30.8	10.7	434	35	−177	17 58 07.404	−17 38 38.88	32.36	56b, 57a, e, 58a, e
C622[b]	2009 Feb 10	0709	0.21	177	25.3	10.6	503	49	24	18 10 09.631	−17 43 54.97	32.23	58e, 59b
C625	2009 Mar 4	1528	0.69	355	15.7	12.4	252	71	−122	18 12 09.864	−17 42 02.81	31.91	57e, 58a, e
C645	2009 Aug 9	2317	0.79	345	14.7	14.0	94	133	−37	18 03 15.900	−17 48 50.64	30.99	58a, e, 59b, e
C652	2009 Oct 2	0230	0.96	23	11.4	13.8	123	82	−138	18 02 37.603	−18 03 02.29	31.84	60a, b, c, 61a, c

NOTE.— Table 3 is presented in its entirety in the electronic edition of the Astronomical Journal. Only those events with S/N values of at least 80 are shown here.

[a] The signal-to-noise ratio listed is calculated for HOPI on SOFIA (see text)

[b] Star does not match any entry in the USNO-A2.0 catalog within 2″.0 of right ascension and declination.

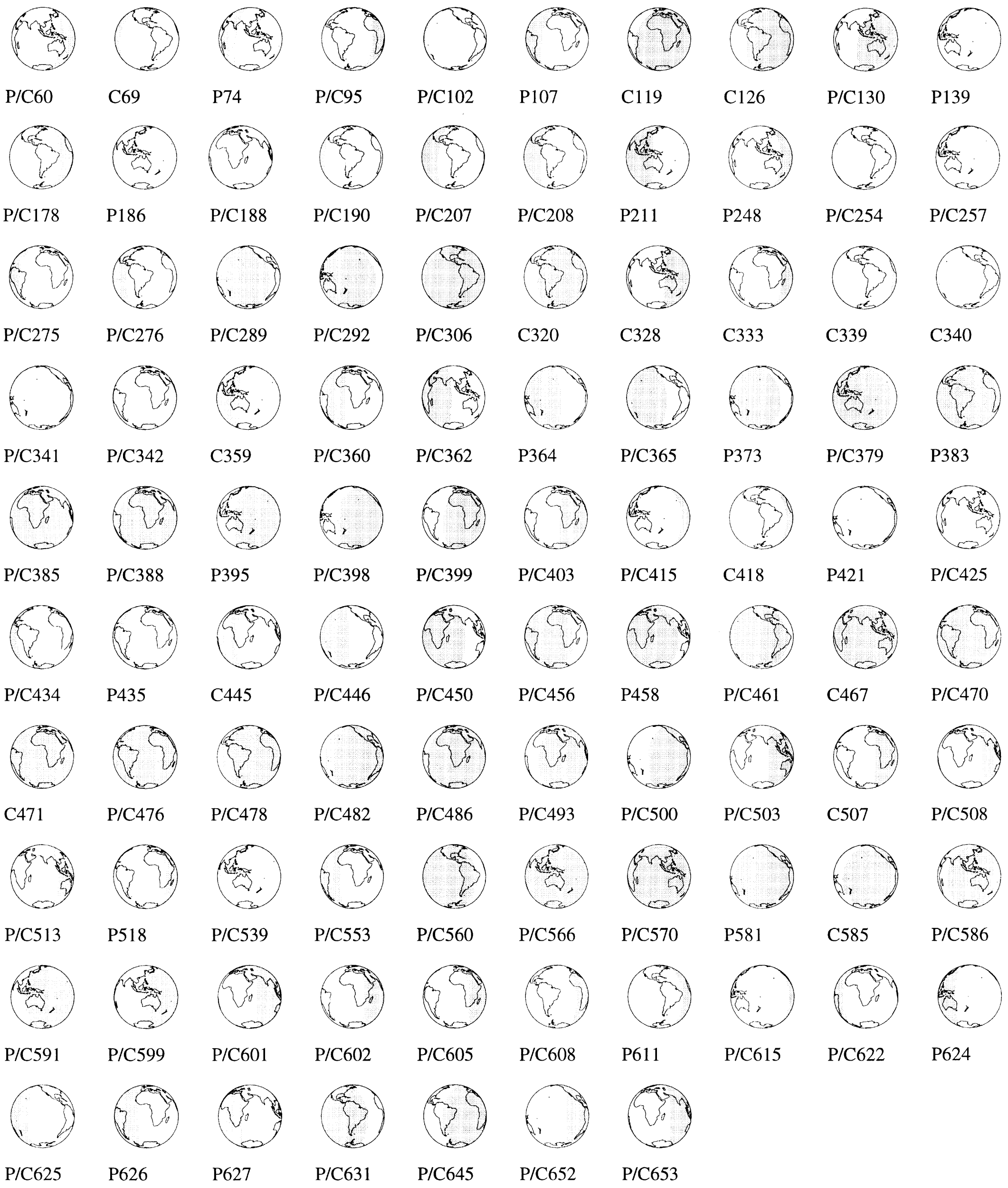

Fig. 2.—Visibility zones for appulse and occultation events. Each frame in this figure shows Earth as seen from the named star at about the time of closest approach by Pluto and/or Charon. Star designations include a " P," " C," or " P/C," for Pluto events, Charon events, and events by both Pluto and Charon, respectively. The shaded region of each globe indicates the areas where the Sun is more than 12° below the horizon at event time.

Of particular interest are those candidates for which the separation of Pluto and Charon perpendicular to the direction of apparent motion is small. For these stars it is possible that occultations by both Pluto and Charon can be observed. The following appulse events have apparent paths of Pluto and Charon that are within 0″.3 of each other and Charon S/Ns greater than 50: P/C188, P/C292, P/C342, P/C385, P/C434, P/C470, P/C566, P/C570, and P/C615. Figure 3 plots our estimated signal-to-noise ratios (taken from Tables 2 and 3) versus the nominal geocentric minimum separation for each event.

During the next decade, Pluto and Charon will be entering the Galactic plane. The frequency of appulse events will increase dramatically as they enter denser star fields. This effect is clearly visible in our occultation candidate lists. Even though we were not able to obtain images as deep as those used in our previous Pluto-Charon occultation searches, the frequency of events in our list is much higher than in those earlier searches. For Pluto, it rises from 13 events in 2000 to a peak of 83 in 2007; Charon has 13 appulse events in 2000 and a peak of 88 in 2007. This should provide excellent opportunities to observe possible changes in Pluto's atmosphere over this time.

4. CONCLUSIONS

We have found 486 stars within 1″.0 of Pluto's ephemeris over the decade 2000–2009 and 479 stars within 1″.0 of Charon's ephemeris over the same period. Full lists of the occultation candidates are available in the electronic

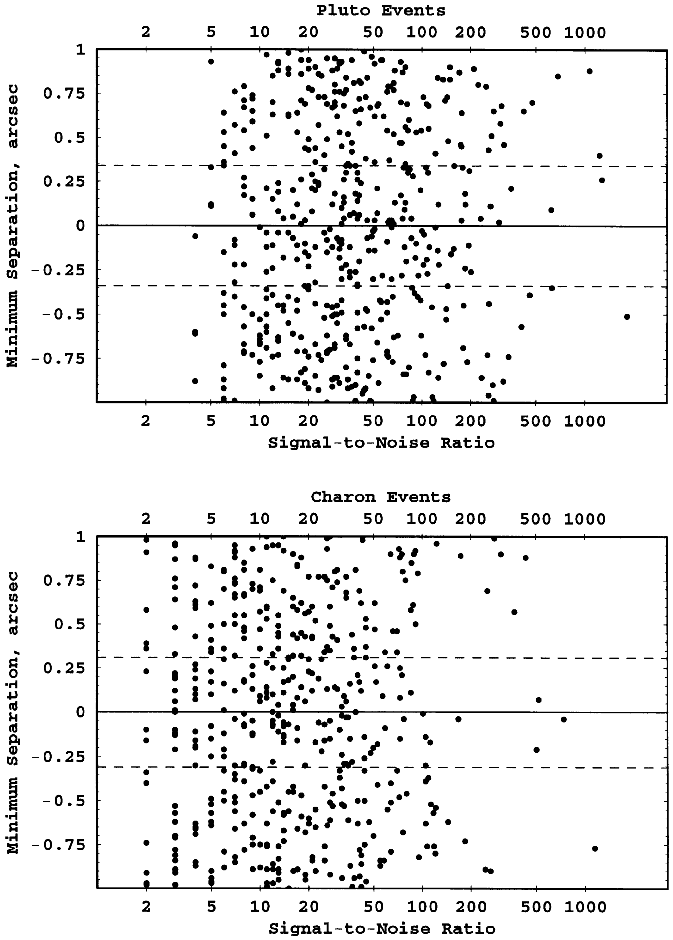

FIG. 3.—Signal-to-noise ratio vs. geocentric minimum separation. The horizontal axis shows the signal-to-noise ratios listed in Tables 2 and 3. Negative values of minimum separation indicate events with position angles greater than 90° and less than 270°, i.e., events that pass south of the center of Earth. Two horizontal lines indicate plus and minus 0″.34 for the Pluto events, and 0″.31 for the Charon events. If our astrometry had no errors, those events between the pairs of dashed lines would be occultations visible from somewhere on Earth, while those outside the lines would be appulses. However, uncertainties in the astrometry and ephemeris mean that the actual minimum separations will differ from those plotted in this figure.

version of this paper, and at our Web site.[3] Pluto occultation candidates with potential signal-to-noise ratios better than 100 and Charon occultation candidates with potential S/N better than 80 are included in the print version. The progress of Pluto-Charon through the dense star fields of the Galactic plane is apparent in the increasing frequency of appulse events, peaking in 2007. The current ephemeris and available astrometry of these stars are insufficient to accurately predict actual occultations; further astrometry will be required to determine whether any specific candidate will be occulted and to make ground-track predictions. Depictions of Earth are presented to aid in identifying events that might be visible from specific locations.

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[3] http://occult.mit.edu.

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