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PLUTO-CHARON STELLAR OCCULTATION CANDIDATES: 1996–1999

S. W. McDonald[1] and J. L. Elliot[2,3]

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
Electronic mail: mcdonald@astron.mit.edu, jle@mit.edu

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ABSTRACT

With the hope of finding stellar occultation events that can be used to answer fundamental questions about Pluto and Charon, we have extended our previous search for stellar-occultation candidates for these bodies to include the years 1996 to 1999. The data for this work are CCD strip scans to about 17.5 R magnitude for stars close to Pluto's and Charon's ephemerides (DE403). We list 60 stars within 1.0 arcsec of Pluto's ephemeris and 64 within 1.0 arcsec of Charon's ephemeris over these four years. In addition, we list our predictions for stars that have been previously published as Pluto and/or Charon occultation candidates [Mink *et al.* AJ, 101, 2255 (1991); Dunham *et al.* AJ, 102, 1464 (1991)]. Four events involve stars brighter than 15th magnitude and minimum separations less than 0.31 arcsec. An appulse with a minimum geocentric separation less than 0.35 arcsec will result in a stellar occultation observable from Earth, but further astrometry and photometry will be necessary to refine individual predictions for identification of actual occultations. Finder charts are included to aid in further studies and prediction refinement. © *1996 American Astronomical Society.*

1. INTRODUCTION

Despite considerable attention from observers in recent years, several fundamental properties of the Pluto-Charon system remain unknown. Pluto's surface radius is one of these, with values determined from the mutual events being somewhat less (Tholen & Buie 1990; Young & Binzel 1994) than those determined from the 1988 stellar occultation, under the assumption of a clear atmosphere (Elliot & Young 1992; Millis *et al.* 1993). This uncertainty in surface radius limits the accuracy with which we know Pluto's bulk density, now that different methods are converging on similar values for the Charon-to-Pluto mass ratio (Foust *et al.* 1996; Null & Owen 1996; Young *et al.* 1994). Another uncertainty in our knowledge of Pluto is whether the sharp drop in the occultation light curve obtained with the KAO (Elliot *et al.* 1989) is due to extinction or large thermal gradient in Pluto's atmosphere (Elliot & Young 1992; Stansberry *et al.* 1994). This issue must be resolved before we can use stellar occultation data to establish the surface radius. Simultaneous occultation observations at two well-separated wavelengths and of sufficient signal-to-noise ratio could distinguish between these two possibilities. Plans continue on a flyby mission to the system (Staehle *et al.* 1996), which will give us a great deal of information about the structure and composition of the atmosphere and surface. But stellar occultations remain the only method we have to observe changes in the structure of Pluto's atmosphere over the next few decades, during which the atmospheric structure may change as the system recedes from the sun.

Similarly, the radius of Charon from the mutual events remains uncertain within a sizable range (Tholen & Buie 1990; Young & Binzel 1994). The stellar occultation by Charon in 1980 was observed only by Walker (1980), so that only a lower limit on Charon's radius (Elliot & Young 1991) could be established from that event. Multiple chords from a future stellar occultation observation could give a much more accurate value and perhaps also resolve the issue of a possible atmosphere (Elliot & Young 1991). Occultations of the same star by Pluto and Charon visible from Earth would provide a strong constraint on Charon's orbit about Pluto.

In this paper we report the results of CCD strip scans (Dunham *et al.* 1991; McDonald & Elliot 1992; McDonald & Elliot 1995), which reach fainter magnitudes than photographic searches (Mink *et al.* 1991) and allow us to identify candidates that would yield good signal to noise if the events prove to be visible from a large telescope. Our present work covers the period 1996–99, and we use the latest Pluto ephemeris available (DE403).

2. OBSERVATIONS AND ANALYSIS

The methods that we used in this search for occultation candidates are essentially the same as those described for our search for Triton occultation candidates (McDonald & Elliot 1995), and similar to that used in our previous search for Pluto and Charon occultation candidates (Dunham *et al.* 1991). The few differences are described here in a brief over-

[1]Bldg. 54-427, M.I.T., Cambridge, MA 02139.
[2]Bldg. 54-422, M.I.T., Cambridge, MA 02139.
[3]Also Department of Physics, M.I.T. and Lowell Observatory.

view of the procedure. See the previous papers for more details about the analysis, the equipment, and the errors in the occultation predictions.

We used the SNAPSHOT CCD camera (Dunham *et al.* 1985) in strip-scanning mode to observe the star field through which Pluto-Charon will travel. The observations were made from the 61 cm telescope at MIT's Wallace Observatory with no filter to maximize the number of stars detected (the CCD itself has a response similar to a Kron-Cousins *R* filter, Dunham *et al.* 1991, and we term magnitudes derived from this system "CCD magnitudes"). Stellar images typically had a full width at half maximum of 2 pixels, with an image scale of 2.28 arcsec/pixel. The individual strip-scan images overlapped each other by 50%, as in our previous work, in order to give redundant coverage of the fields.

The images were flattened in IRAF and processed by IRAF's DAOPHOT routines to identify and measure stars down to the limiting magnitude. For an astrometric secondary network we used a set of stars provided to us by Doug Mink, measured by Arnold Klemola for their photographic occultation candidate search (Mink *et al.* 1991). These reference stars were also used to very roughly calibrate the magnitudes of our resulting candidates. After astrometric calibration, those stars near the ephemerides of Pluto or Charon were identified as candidates.

For this project we used the DE403 ephemeris, provided by JPL's Navigation Ancillary Information Facility (Acton 1990). As in our 1995 Triton occultation candidate search, we changed our search criteria based on our previous experience. Our nominal criteria for inclusion in our candidate lists is a minimum separation between star and planetary body of less than 1.0 arcsec and a solar angle at event time of greater than 20°. However, we have also included any stars that appeared in previous occultation candidate lists (Mink *et al.* 1991; Dunham *et al.* 1991) even if we find a minimum separation greater than our 1.0 arcsec limit, so that our candidate lists can be compared with the results of those previous searches. The difference in minimum separation with the list of Mink *et al.* (1991) comes from differences in the astrometry and the fact that we are using a newer ephemeris. Differences with Dunham *et al.* (1991) arise only from the newer ephemeris, since common candidates were not remeasured.

TABLE 1. Some strips were observed more than once; we distinguished the different observations of an area with a letter (a, b, c). The gain of SNAPSHOT CCD camera is about 7 electrons per ADU. For reference, the bias of the SNAPSHOT was around 570 ADU, and the CCD chip is linear to about 10 000 ADU. The limiting magnitudes are estimates based on detected star abundance vs CCD magnitude.

Strip	Date taken (yy mm dd)	limiting magnitude (~R Mag)
49A	90 06 13	17.6
50	90 06 02	17.5
51	90 06 02	17.5
52	90 06 02	17.4
53a	91 03 09	17.1
54a	91 03 09	17.5
55a	91 03 09	17.8
56a	91 03 09	17.9
57a	91 04 08	17.6
58a	91 04 12	17.9
59a	91 04 12	18.0
60a	91 04 12	18.0
61a	91 04 12	18.0
62a	91 04 12	17.9
63a	91 04 12	17.3
64a	91 04 19	17.5
64b	91 05 11	17.4
65a	91 04 19	17.3
66a	91 04 19	17.5
67a	91 04 19	17.3
68a	91 04 19	17.1
69a	91 04 19	17.1
70a	91 04 19	17.0
70b	91 06 03	16.9
70c	91 06 06	16.8
70d	91 06 07	17.1
70e	91 06 08	16.2
70f	91 06 14	16.9
70g	91 06 20	17.0
70h	91 07 09	16.7
71a	91 04 19	17.0
72a	91 04 24	17.4
72b	91 05 11	16.9
72c	91 05 21	16.8
73a	91 04 24	17.2
73b	91 05 11	17.0
74a	91 04 24	17.1
75a	91 04 24	17.1
76a	91 04 24	17.0
77a	91 04 24	16.9
77b	91 05 20	16.9
78a	91 05 05	17.8
79a	91 05 05	17.4
79b	91 05 16	17.6
80a	91 05 05	17.1
80b	91 05 16	17.3
81a	91 05 05	16.8
81b	91 05 16	16.9
82a	91 05 08	16.7
83a	91 05 08	16.6

3. RESULTS AND DISCUSSION

Table 1 provides information on each of the strip scan images used in this occultation candidate search. Tables 2 and 3 give information about each occultation candidate we found in our search for Pluto and for Charon, respectively. Pluto candidates have an identification label beginning with "P" and followed by a sequenced number while Charon candidates are labeled with an initial "C." This continues the labeling system we used in Dunham *et al.* (1991); those candidates that also appear in Mink *et al.* (1991) are given the same identification label used in that paper, and the new candidates have been given decimal numbers to fit sequentially in between. The next columns show the data and time of the occulting body's closest approach to the star and the minimum separation and position angle (measured north

TABLE 2. Occultation candidates for Pluto. The CCD magnitude and the S/N columns are explained in the text.

	Closest approach											
Star ID	Date yyyy mm dd	UT hh:mm	Min. sep. (arcsec)	PA of Pluto (deg)	CCD mag *	Shadow velocity (km/s)	S/N *	Solar dist. (deg)	Right Ascension (J2000)	Declination (J2000)	East long. (deg)	Strip numbers
P30	1996 04 17	04:17	0.25	19	15.6	18.3	3	143	16 12 58.053	-07 30 48.58	-27	51,52
P30.01	1996 04 20	17:23	1.20	18	16.9	19.3	1	146	16 12 40.716	-07 29 21.78	133	51
P30.02	1996 05 05	21:24	0.52	193	17.7	22.2	<1	159	16 11 16.518	-07 23 35.80	58	51
P30.03	1996 05 08	13:38	1.82	12	15.0	22.6	5	161	16 11 00.293	-07 22 44.55	171	50,51
P30.04	1996 06 03	12:43	0.00	0	15.7	22.9	3	162	16 08 15.239	-07 16 36.43	159	50
P30.05	1996 06 15	22:07	0.11	2	16.7	21.2	1	153	16 06 59.302	-07 15 41.68	5	49,49A,50
P30.06	1996 06 22	15:23	0.69	178	16.6	19.8	1	147	16 06 21.160	-07 15 48.02	99	49,49A,50
P30.07	1996 06 27	22:51	1.18	355	16.4	18.5	2	142	16 05 53.120	-07 16 14.34	-18	49,50
P30.08	1996 07 18	00:11	1.06	159	17.0	12.5	1	124	16 04 28.737	-07 20 15.38	-58	50,51
P30.09	1996 07 24	00:21	1.66	150	16.0	10.6	3	118	16 04 11.408	-07 22 12.92	-66	50,51
P31	1996 07 28	03:32	0.10	141	15.7	9.5	4	114	16 04 01.961	-07 23 46.70	-118	50,51
P32	1996 07 28	09:23	0.97	322	16.0	9.4	3	114	16 04 01.509	-07 23 53.30	154	50,51
P32.01	1996 08 19	13:33	1.11	71	15.8	9.0	4	93	16 03 47.066	-07 34 35.42	69	52,53a
P32.02	1996 08 23	13:04	0.01	236	17.1	10.2	1	90	16 03 51.266	-07 36 52.37	73	53a
P33	1996 09 06	22:19	1.76	40	16.2	15.6	2	76	16 04 23.171	-07 45 53.61	-80	53a,54a
P34	1996 09 19	14:18	0.85	31	15.9	20.7	2	65	16 05 12.920	-07 54 28.98	28	55a,56a
P34.01	1996 09 26	13:33	0.57	207	17.6	23.4	<1	58	16 05 48.371	-07 59 20.76	32	55a,56a
P34.02	1996 10 31	00:12	0.79	197	17.5	33.7	<1	27	16 09 52.250	-08 23 04.47	-160	58a,59a
P34.04	1996 11 07	03:09	0.90	16	18.3	34.9	<1	21	16 10 53.282	-08 27 33.87	149	59a,60a
P34.05	1996 11 07	06:28	0.19	16	18.6	34.9	<1	21	16 10 54.500	-08 27 38.22	99	59a,60a
P34.07	1997 01 10	14:43	0.62	183	17.4	27.3	1	47	16 20 12.572	-08 51 20.17	-86	62a,63a
P35	1997 01 10	23:15	0.58	183	16.1	27.2	2	47	16 20 15.116	-08 51 22.00	146	62a,63a
P35.01	1997 01 13	18:18	0.42	182	17.8	26.1	<1	50	16 20 34.696	-08 51 33.69	-143	63a
P35.02	1997 01 17	22:55	0.68	180	17.8	24.5	<1	54	16 21 02.675	-08 51 42.18	144	62a,63a
P35.03	1997 01 27	03:30	0.39	357	17.5	20.7	1	63	16 21 57.656	-08 51 29.17	66	62a,63a
P36	1997 02 22	10:22	1.52	153	15.5	8.8	5	88	16 23 38.983	-08 46 55.03	-62	62a,63a
P37	1997 05 09	04:46	1.44	12	16.5	22.4	1	159	16 20 26.034	-08 19 21.59	-54	58a,59a
P38.01	1997 06 14	08:45	0.53	1	18.2	22.0	<1	157	16 16 37.244	-08 12 45.08	-150	58a
P38.03	1997 10 28	08:49	0.55	197	16.9	32.6	1	31	16 18 23.294	-09 14 32.89	75	65a,66a
P38.04	1997 10 30	10:20	0.31	197	14.1	33.0	10	30	16 18 40.134	-09 15 50.24	51	65a,66a
P38.05	1997 11 10	15:59	0.26	14	17.5	35.0	<1	20	16 20 16.064	-09 22 32.57	-45	67a
P38.07	1997 12 20	18:51	0.91	7	14.2	33.8	9	25	16 26 19.445	-09 39 59.46	-126	69a,70b,c,d,e,f,g,h
P38.08	1997 12 29	17:26	0.47	6	16.8	31.8	1	33	16 27 35.629	-09 42 07.94	-113	69a,70a,b,c,d,f,g,h
P38.09	1997 12 30	05:13	0.63	185	16.3	31.6	1	34	16 27 39.686	-09 42 12.71	70	69a,70a,b,c,d,e,f,g,h
P38.10	1998 01 01	09:01	0.81	5	16.6	31.1	1	36	16 27 57.301	-09 42 38.21	11	69a,70a,b,c,d,e,f,g,h
P38.12	1998 01 17	03:51	0.95	181	15.8	25.8	2	51	16 29 55.362	-09 44 17.72	73	69a,70a,b,c,d,e,f,g,h
P39	1998 01 25	13:18	0.97	178	15.3	22.4	4	59	16 30 48.859	-09 44 18.41	-77	69a,70a,b,c,d,e,f,g,h
P40	1998 02 28	12:12	1.23	146	17.1	7.2	1	92	16 33 00.071	-09 38 46.06	-93	68a,69a,70c,f
P40.02	1998 05 20	05:37	0.99	8	17.2	23.2	1	165	16 28 46.222	-09 12 03.44	-75	65a,66a
P40.03	1998 06 15	01:30	0.24	182	16.8	22.3	1	159	16 26 01.002	-09 08 33.72	-39	64a,b,65a
P42	1998 07 09	22:33	0.14	170	14.1	16.7	14	137	16 23 45.138	-09 10 24.55	-20	65a,66a
P43	1998 08 07	13:24	0.21	311	16.3	8.1	3	110	16 22 17.394	-09 19 05.53	89	66a,67a
P43.01	1998 08 08	17:39	0.62	306	17.6	7.8	1	109	16 22 15.836	-09 19 35.47	24	67a
P43.02	1998 08 19	21:24	0.93	265	15.4	7.6	6	98	16 22 09.560	-09 24 44.21	-44	67a
P43.03	1998 09 02	16:24	0.90	229	16.5	11.5	2	85	16 22 24.180	-09 32 06.70	18	68a
P43.04	1998 09 09	06:47	0.45	41	16.4	14.0	2	79	16 22 39.890	-09 35 58.31	156	68a,69a
P44	1998 09 21	14:59	0.59	30	16.4	19.1	2	68	16 23 24.197	-09 43 32.70	21	69a,70a,b,c,d,f,g,h
P44.01	1998 09 29	14:09	0.32	26	17.2	22.4	1	60	16 24 02.617	-09 48 35.60	25	70a,b,f,g,71a

TABLE 2. (continued)

Star ID	Closest approach Date yyyy mm dd	UT hh:mm	Min. sep. (arcsec)	PA of Pluto (deg)	CCD mag *	Shadow velocity (km/s)	S/N *	Solar dist. (deg)	Right Ascension (J2000)	Declination (J2000)	East long. (deg)	Strip numbers
P44.02	1998 10 06	23:59	0.20	23	15.9	25.2	2	53	16 24 44.712	-09 53 19.82	-129	70a,b,d,e,f,g,h,71a,72c
P44.03	1998 10 11	04:34	0.69	22	17.2	26.7	1	49	16 25 11.029	-09 56 00.52	158	72a,b
P44.04	1998 10 30	01:07	0.37	17	17.0	32.3	1	32	16 27 29.199	-10 07 41.18	-168	72a,73a,b
P44.05	1998 11 10	09:26	0.59	14	17.4	34.5	<1	22	16 29 04.520	-10 14 10.70	56	73a,b,74a
P44.06	1999 01 12	15:47	0.79	183	13.5	28.3	19	44	16 38 18.981	-10 35 19.72	-99	76a,77a,b
P45	1999 02 01	18:16	0.55	357	14.3	20.4	11	63	16 40 28.888	-10 35 25.68	-156	76a,77a,b
P45.01	1999 02 05	03:58	0.17	175	16.7	18.9	1	66	16 40 46.587	-10 35 07.24	55	76a,77a
P45.03	1999 02 20	22:59	0.94	164	16.9	11.5	1	82	16 41 49.906	-10 32 40.44	115	76a
P46	1999 02 27	22:19	0.88	154	15.3	8.3	7	88	16 42 07.435	-10 31 06.74	118	76a
P46.01	1999 05 11	08:41	0.78	10	17.2	21.9	1	157	16 39 08.413	-10 08 31.93	-109	73a,b
P47	1999 05 25	01:40	0.46	7	15.1	23.4	5	167	16 37 43.155	-10 05 28.61	-18	72a,b,c,73a,b
P47.01	1999 05 25	03:46	0.98	187	16.3	23.4	2	167	16 37 42.602	-10 05 26.23	-50	72a,b,73a,b
P47.02	1999 06 06	06:03	0.99	4	17.3	23.4	1	167	16 36 24.321	-10 03 44.90	-96	72a,73a
P48	1999 07 11	23:25	0.04	172	16.7	16.9	1	138	16 32 58.399	-10 05 08.29	-33	72a,b,c,73a,b
P48.01	1999 07 21	18:07	0.61	164	17.0	13.9	1	128	16 32 17.901	-10 07 19.58	37	72a,73a,b
P48.02	1999 08 13	09:23	0.07	301	17.1	7.4	1	107	16 31 24.151	-10 15 12.02	145	73a,b,74a
P48.03	1999 09 15	05:47	0.14	35	17.0	15.3	1	76	16 32 01.230	-10 32 01.51	167	76a,77a
P49	1999 09 26	00:25	1.00	28	11.5	19.7	145	66	16 32 43.591	-10 38 23.60	-123	76a,77a
P49.01	1999 09 30	18:35	0.42	205	18.0	21.6	<1	62	16 33 06.768	-10 41 14.12	-40	78a
P49.02	1999 10 26	16:22	0.23	17	17.9	30.7	<1	38	16 35 54.531	-10 56 42.22	-31	80b
P49.05	1999 11 06	18:43	0.72	15	17.9	33.4	<1	28	16 37 23.844	-11 02 53.75	-77	80a,b
P49.07	1999 12 27	09:31	0.34	6	15.9	33.5	2	26	16 44 59.119	-11 22 46.89	13	82a,83a

through east) of the body relative to the star at event time for a geocentric observer. The CCD magnitude of the star in the next column is estimated based on the magnitude relative to the stars in our secondary network. This is followed by the velocity of the occultation shadow on the fundamental plane.

The next column carries an estimate of the signal to noise (S/N) that might be expected by observing with a 0.9 m telescope with a CCD detector, based on our observation of the P8 occultation with the KAO (Elliot *et al.* 1989). For Pluto, the S/N refers to that achievable over a time corresponding to a shadow motion of 60 km—approximately the scale height of its atmosphere (the relevant dimension for analysis). For Charon, the S/N refers to that achievable over a distance of 10 km (a few times the Fresnel diffraction scale). Background limited performance has been assumed, which may lead to an overestimate of S/N for the brightest sources. Potential observers should evaluate the S/N for their own photometric equipment. We have retained candidates in this list with low estimated S/N because other factors will affect the actual S/N. First, if an occultation should be visible from a larger telescope, the signal to noise will be much improved. Also, we have not yet measured the colors of any of these stars; an extremely red or blue star may provide a greater S/N in the UV or IR.

The angular distance of Pluto-Charon from the Sun at event time is in the next column. The measured coordinates of the star comes next, in J2000 equinox. The second-to-last column is the sub-Earth longitude of the star at the midtime of the event; the sub-Earth latitude is the same as the star's Declination. The CCD strip images on which the candidate was measured are listed in the final column.

Finder charts for each candidate are provided in Fig. 1. Figure 2 is provided to assist in locating potential observation locations for viewing the appulse or occultation event. It depicts a view of the Earth from Pluto-Charon at the time of closest approach; the shadow shows the area from which the Sun is more than 12° below the horizon. Many of the events listed occur while Pluto and Charon are fairly close to the sun (20° was the limit for our search); these events will be difficult to observe except possibly in the IR.

Dunham *et al.* (1991) have discussed the sources of error in predictions derived from candidate searches with CCD strip scans of this type. The components of the error are: random error in a star position from an individual strip scan (~0.1 arcsec, Foust *et al.* 1996), field distortion (not measured), difference between the secondary network and ephemeris reference frames (unknown), color-dependent refraction (~0.3 arcsec, Dunham *et al.* 1991), uncertainty in Pluto's position relative to the center of mass (~0.03 arcsec), and errors in the DE403 ephemeris (unknown, and will increase with time). Although several of the components of the total error are not known, we can estimate their combined

TABLE 3. Occultation candidates for Charon. The CCD magnitude and the S/N columns are explained in the text.

Star ID	Closest approach Date yyyy mm dd	UT hh:mm	Min. sep. (arcsec)	PA of Charon (deg)	CCD mag *	Shadow velocity (km/s)	S/N *	Solar dist. (deg)	Right Ascension (J2000)	Declination (J2000)	East long. (deg)	Strip numbers
C30	1996 04 17	04:24	0.54	200	15.6	18.4	1	143	16 12 58.053	-07 30 48.58	-29	51,52
C30.01	1996 04 20	17:19	1.90	18	16.9	19.1	<1	146	16 12 40.716	-07 29 21.78	134	51
C30.04	1996 06 03	12:38	0.87	5	15.7	22.9	1	162	16 08 15.239	-07 16 36.43	160	50
C30.05	1996 06 15	22:01	0.86	1	16.7	21.2	<1	153	16 06 59.302	-07 15 41.68	7	49,49A,50
C30.06	1996 06 22	15:19	0.20	358	16.5	19.8	1	147	16 06 21.160	-07 15 48.02	100	49,49A,50
C30.07	1996 06 27	22:45	1.41	356	16.4	18.5	1	142	16 05 53.120	-07 16 14.34	-16	49,50
C30.08	1996 07 18	00:12	0.21	160	17.0	12.4	<1	124	16 04 28.737	-07 20 15.38	-58	50,51
C30.09	1996 07 24	00:22	0.97	151	16.0	10.5	1	118	16 04 11.408	-07 22 12.92	-67	50,51
C31	1996 07 28	03:16	0.90	143	15.7	9.5	2	114	16 04 01.961	-07 23 46.70	-114	50,51
C32	1996 07 28	09:05	0.25	322	16.0	9.4	1	114	16 04 01.509	-07 23 53.30	158	50,51
C32.01	1996 08 19	14:08	1.28	71	15.8	9.1	2	93	16 03 47.066	-07 34 35.42	60	52,53a
C32.02	1996 08 23	12:49	0.36	241	17.1	10.0	<1	90	16 03 51.266	-07 36 52.37	76	53a
C34	1996 09 19	14:29	1.26	31	15.9	20.7	1	65	16 05 12.920	-07 54 28.98	25	55a,56a
C34.01	1996 09 26	13:42	0.10	28	17.6	23.5	<1	58	16 05 48.371	-07 59 20.76	30	55a,56a
C34.03	1996 11 01	13:32	0.52	17	18.1	33.9	<1	26	16 10 05.341	-08 24 06.10	-2	59a
C34.04	1996 11 07	03:05	0.13	16	18.3	34.9	<1	21	16 10 53.282	-08 27 33.87	150	59a,60a
C34.05	1996 11 07	06:24	0.59	196	18.6	34.9	<1	21	16 10 54.500	-08 27 38.22	100	59a,60a
C34.06	1996 12 18	06:17	0.53	188	18.1	33.8	<1	26	16 17 04.875	-08 46 47.91	63	62a
C35.01	1997 01 13	18:19	0.36	2	17.8	26.2	<1	50	16 20 34.696	-08 51 33.69	-143	63a
C35.02	1997 01 17	22:59	0.79	180	17.8	24.5	<1	54	16 21 02.675	-08 51 42.18	143	62a,63a
C35.03	1997 01 27	03:26	0.81	358	17.5	20.7	<1	63	16 21 57.656	-08 51 29.17	67	62a,63a
C35.04	1997 02 09	23:43	0.62	350	14.9	14.4	3	76	16 23 02.111	-08 49 46.01	110	62a,63a
C36.01	1997 02 24	05:05	0.44	329	12.9	8.1	25	90	16 23 42.642	-08 46 28.30	15	62a
C38	1997 06 04	22:48	1.03	4	16.3	23.1	1	163	16 17 36.035	-08 13 29.76	9	57a,58a
C38.01	1997 06 14	08:39	0.84	2	18.2	22.0	<1	157	16 16 37.244	-08 12 45.08	-149	58a
C38.02	1997 10 24	18:00	0.29	18	17.9	31.6	<1	35	16 17 54.439	-09 12 16.64	-59	65a,66a
C38.03	1997 10 28	08:51	0.12	18	16.9	32.7	<1	31	16 18 23.294	-09 14 32.89	75	65a,66a
C38.04	1997 10 30	10:14	0.95	197	14.1	33.0	4	30	16 18 40.134	-09 15 50.24	52	65a,66a
C38.05	1997 11 10	15:58	0.65	15	17.5	35.1	<1	20	16 20 16.064	-09 22 32.57	-45	67a
C38.06	1997 11 11	09:46	0.98	15	16.2	35.1	1	20	16 20 22.608	-09 22 58.64	48	66a,67a
C38.07	1997 12 20	18:47	0.12	8	14.2	33.7	4	25	16 26 19.445	-09 39 59.46	-125	69a,70b,c,d,e,f,g,h
C38.09	1997 12 30	05:17	0.14	5	16.3	31.7	1	34	16 27 39.686	-09 42 12.71	69	69a,70a,b,c,d,e,f,g,h
C38.10	1998 01 01	08:57	0.69	5	16.6	31.1	<1	36	16 27 57.301	-09 42 38.21	12	69a,70a,b,c,d,e,f,g,h
C38.11	1998 01 09	12:10	0.97	3	17.3	28.4	<1	43	16 29 00.689	-09 43 47.78	-44	70a,f,g
C38.12	1998 01 17	03:56	0.94	181	15.8	25.8	1	51	16 29 55.362	-09 44 17.72	72	69a,70a,b,c,d,e,f,g,h
C39	1998 01 25	13:18	0.18	179	15.3	22.5	2	59	16 30 48.859	-09 44 18.41	-77	69a,70a,b,c,d,e,f,g,h
C40.01	1998 05 10	19:24	0.99	11	17.6	22.3	<1	159	16 29 44.708	-09 14 28.06	88	66a
C40.03	1998 06 15	01:29	0.59	1	16.8	22.2	<1	159	16 26 01.002	-09 08 33.72	-39	64a,b,65a
C41	1998 06 27	04:49	0.72	177	16.1	20.0	1	148	16 24 49.622	-09 08 45.74	-101	64a,65a
C42	1998 07 09	22:30	0.76	351	14.1	16.7	6	137	16 23 45.138	-09 10 24.55	-19	65a,66a
C42.01	1998 07 13	23:07	0.93	349	15.6	15.6	2	133	16 23 27.604	-09 11 14.63	-33	65a,66a
C43	1998 08 07	13:04	0.55	130	16.3	8.1	1	110	16 22 17.394	-09 19 05.53	93	66a,67a
C43.01	1998 08 08	17:13	0.31	308	17.6	7.7	<1	109	16 22 15.836	-09 19 35.47	30	67a
C43.02	1998 08 19	20:54	0.62	266	15.4	7.6	3	98	16 22 09.560	-09 24 44.21	-36	67a
C43.04	1998 09 09	06:32	0.14	220	16.4	13.9	1	79	16 22 39.890	-09 35 58.31	159	68a,69a
C44	1998 09 21	14:47	0.06	211	16.4	19.1	1	68	16 23 24.197	-09 43 32.70	24	69a,70a,b,c,d,f,g,h
C44.01	1998 09 29	14:14	0.15	26	17.2	22.3	<1	60	16 24 02.617	-09 48 35.60	24	70a,b,f,g,71a
C44.02	1998 10 07	00:08	0.72	23	15.9	25.2	1	53	16 24 44.712	-09 53 19.82	-131	70a,b,d,e,f,g,h,71a,72c
C44.03	1998 10 11	04:29	0.04	204	17.2	26.6	<1	50	16 25 11.029	-09 56 00.52	159	72a,b
C44.04	1998 10 30	01:02	0.40	197	17.0	32.2	<1	32	16 27 29.199	-10 07 41.18	-167	72a,73a,b

TABLE 3. (continued)

Star ID	Closest approach Date yyyy mm dd	UT hh:mm	Min. sep. (arcsec)	PA of Charon (deg)	CCD mag *	Shadow velocity (km/s)	S/N *	Solar dist. (deg)	Right Ascension (J2000)	Declination (J2000)	East long. (deg)	Strip numbers
C44.05	1998 11 10	09:21	0.49	15	17.4	34.6	<1	22	16 29 04.520	-10 14 10.70	57	73a,b,74a
C44.06	1999 01 12	15:43	0.48	183	13.5	28.4	8	44	16 38 18.981	-10 35 19.72	-98	76a,77a,b
C45	1999 02 01	18:09	0.06	359	14.3	20.3	4	63	16 40 28.888	-10 35 25.68	-154	76a,77a,b
C45.01	1999 02 05	04:05	0.47	355	16.7	18.9	1	66	16 40 46.587	-10 35 07.24	54	76a,77a
C45.02	1999 02 05	21:13	0.93	175	16.2	18.6	1	67	16 40 50.126	-10 35 01.23	156	76a,77a,b
C45.04	1999 02 21	06:15	0.72	345	17.2	11.3	<1	82	16 41 50.860	-10 32 38.97	6	76a
C46	1999 02 27	22:21	1.75	154	15.3	8.2	3	88	16 42 07.435	-10 31 06.74	118	76a
C46.01	1999 05 11	08:33	0.86	10	17.2	21.9	<1	157	16 39 08.413	-10 08 31.93	-107	73a,b
C47.01	1999 05 25	03:40	0.19	187	16.3	23.3	1	167	16 37 42.602	-10 05 26.23	-48	72a,b,73a,b
C48	1999 07 11	23:29	0.89	171	16.7	17.0	1	138	16 32 58.399	-10 05 08.29	-34	72a,b,c,73a,b
C48.01	1999 07 21	18:06	0.29	343	17.0	13.8	<1	128	16 32 17.901	-10 07 19.58	37	72a,73a,b
C48.02	1999 08 13	08:51	0.55	121	17.1	7.3	1	107	16 31 24.151	-10 15 12.02	153	73a,b,74a
C48.03	1999 09 15	05:42	0.39	215	17.0	15.1	<1	76	16 32 01.230	-10 32 01.51	168	76a,77a
C49	1999 09 26	00:15	0.82	29	11.5	19.8	59	66	16 32 43.591	-10 38 23.60	-120	76a,77a
C49.01	1999 09 30	18:41	0.26	26	18.0	21.8	<1	62	16 33 06.768	-10 41 14.12	-41	78a
C49.02	1999 10 26	16:23	0.82	17	17.9	30.8	<1	38	16 35 54.531	-10 56 42.22	-32	80b
C49.03	1999 10 28	16:13	0.91	17	14.3	31.2	4	36	16 36 09.946	-10 57 51.95	-31	79a,b,80a,b
C49.04	1999 10 28	22:43	0.64	17	15.3	31.2	1	36	16 36 12.061	-10 58 00.97	-129	79a,b,80a,b
C49.06	1999 11 14	14:12	0.53	193	17.6	34.9	<1	21	16 38 31.161	-11 06 55.53	-17	80b,81b
C49.07	1999 12 27	09:36	0.53	6	15.9	33.4	1	26	16 44 59.119	-11 22 46.89	12	82a,83a

effect, based on our experience with this method to identify two occultations by Triton (Tr60 and Tr148) and three appulses by Pluto (P17, P20, and P28, Dunham *et al.* 1991). The geocentric closest approach of Triton to Tr60 and Tr148 turned out to be, respectively, 0.06 arcsec further south and 0.15 arcsec further south (Olkin 1996) than given in the original candidate lists (McDonald & Elliot 1992; McDonald & Elliot 1995), although the interpretation of the Tr148 results is problematic because the star turned out to be an unresolved double (Olkin 1996). For these comparisons, the final astrometry of the Pluto appulses was less accurate ($\pm\sim$0.1 arcsec) than for the observed Triton occultations ($\pm\sim$0.01 arcsec) because we terminated the prediction effort after it became clear that no occultation would be visible from Earth and an impact parameter determined from occultation chords will be more accurate than one determined from appulse astrometry (Olkin 1996). The geocentric closest approach of Pluto to P17, P20, and P28 turned out to be, respectively, 0.45 arcsec further north, 0.50 arcsec further north, and 0.57 arcsec further north (Olkin 1996) than that given in the original candidate lists (Dunham *et al.* 1991).

The apparent size of the Earth at the distance of Pluto-Charon plus the apparent size of Pluto or Charon is approximately 0.35 arcsec. Stars which are closer than that to the ephemeris of Pluto or Charon will be occulted by that body as viewed from somewhere on the Earth. Expected inaccuracies in our astrometry and in the ephemerides forces us to include in our candidate list stars with larger separations, but we can estimate how many of our candidates will produce occultations. There are 60 stars within 1.0 arcsec of Pluto's ephemeris and 64 stars within 1.0 arcsec of Charon's ephemeris and greater than 20° from the Sun at event time. Taking the ratio of 0.35 to 1.0 arcsec, statistically we would expect that 21 of these stars will be occulted by Pluto, 22 by Charon. Unfortunately, many of these stars are either faint or will be too close to the sun for most telescopes to observe. There are few good candidates during this period, but to evaluate changes in Pluto's atmosphere observers will need to take advantage of any events available.

We cannot say with certainty which of these candidates will be occulted, but we can note the candidates of particular interest. The brightest stars in our candidate lists (<14.0 mag) are P49/C49, C36.01, and P44.06/C44.06. The events with less than 9 km/s sky plane velocity are C36.01, P46/C46, P43.02/C43.02, P36, P43/C43, P40, P48.02/C48.02, and P43.01/C43.01, in order of decreasing brightness. There are four events with stars brighter than 15.0 mag and low minimum separation: P38.04, P42, C38.07, and C45; unfortunately P38.04 and C38.07 occur when Pluto is near the sun and have very small zones of visibility in darkness. Finally, some candidates have similar minimum separations to both Pluto and Charon. This is interesting because a single star could produce occultations by both Pluto and Charon, separated by just a few minutes. The following candidates have minimum separations from Pluto and Charon that are similar to each other (within 0.2 arcsec): P35.02/C35.02, P38.10/

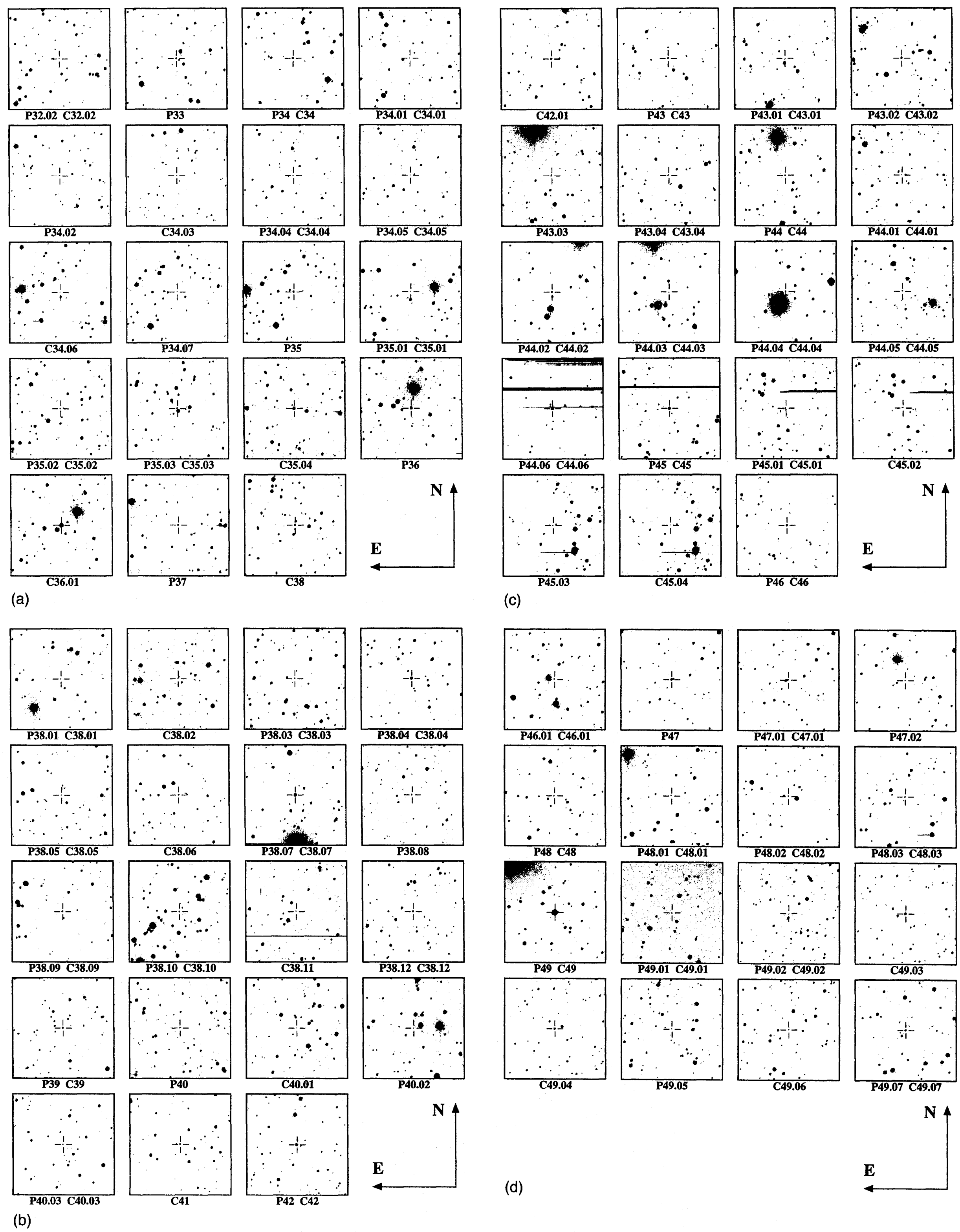

FIG. 1. Finder charts for Pluto and Charon occultation candidates. These images were extracted directly from the flattened strip-scan images. Each box is 6.88 arcmin on a side, and the occultation candidate is marked. The event labels correspond to those in Tables 2 and 3.

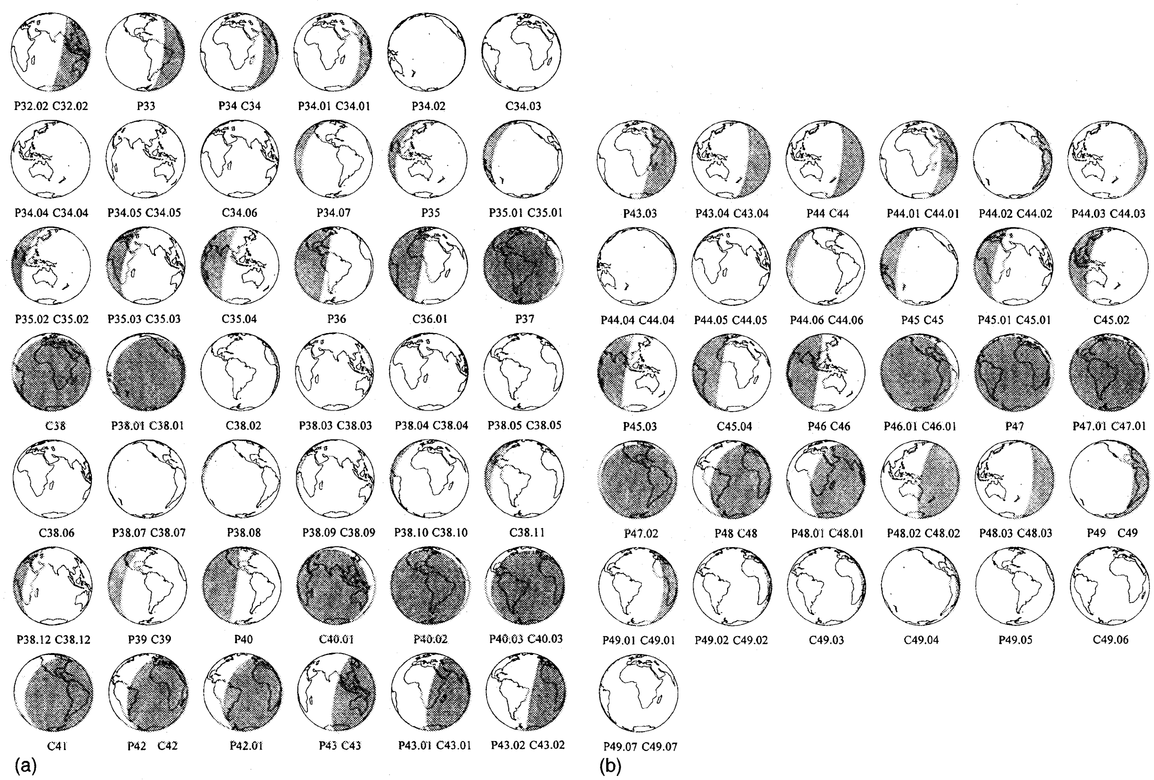

FIG. 2. Visibility zones for potential Pluto and Charon occultations. Each frame in this figure shows the Earth as seen from Pluto-Charon near the occultation midtime for the indicated star. The shaded region is the part of the Earth where the Sun is more than 12° below the horizon, and the center of each globe is the sub-event point.

C38.10, P38.12/C38.12, P44.01/C44.01, P44.05/C44.05, P46.01/C46.01, P49/C49, and P49.07/C49.07.

4. CONCLUSIONS

Our lists contain 60 occultation candidates for Pluto and 64 candidates for Charon, within 1.0 arcsec of their respective ephemerides. We can expect Pluto and Charon to actually occult around 21 of the candidates between 1996 and 1999, though many of these events will only be visible in daylight or from inaccessible locations. Comparison with previous occultation candidate lists shows a number of significant differences. As an example, P31 was listed in our previous paper (Dunham *et al.* 1991) with a minimum separation from Pluto of 0.77 arcsec, while in this work we find a minimum separation of 0.10 arcsec and that the event would occur 49 min later. The same stellar measurements were used in both cases; the difference comes entirely from using a newer ephemeris (DE403). Mink *et al.* (1991) gave a minimum separation of 0.86 arcsec for P31; the additional difference is due to differences in the astrometry. The two older candidate searches that listed P31 used the DE130 ephemeris for Pluto. The DE403 ephemeris for Pluto is based on many more observational positions than was the DE130, making it much more accurate. Even so, we expect that projections of the DE403 forward will develop deviations from reality within a few years.

Again we emphasize that this work identifies only occultation candidates and that the limitations of our astrometric accuracy and Pluto's ephemeris prevent us from making specific predictions from the data at hand. Further astrometry of specific candidates should be undertaken to predict specific occultation circumstances. Photometry of the candidates to better determine magnitude and color will help in predicting the signal-to-noise ratio of occultation events, and will allow choosing the best filter to improve the signal to noise. We encourage efforts to improve the astrometry and photometry of promising occultation candidates.

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