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CIRCUMSTANCES FOR PLUTO–CHARON MUTUAL EVENTS IN 1988

DAVID J. THOLEN, MARC W. BUIE, AND CATHERINE E. SWIFT[a)]
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822

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ABSTRACT

Circumstances are tabulated for 89 Pluto–Charon mutual events occurring during the 1988 opposition. All superior events will be total, as in 1987, but only slightly more than half of the inferior events will be total. 1988 is the last year during which total events will occur. Two new stars have been selected as comparison stars for events occurring before opposition in 1988. The primary star is located at R. A. $14^{\mathrm{h}}58^{\mathrm{m}}05^{\mathrm{s}}.92$ and Dec. $+00^\circ12'15''.2$, and the check star is located at R. A. $14^{\mathrm{h}}57^{\mathrm{m}}46^{\mathrm{s}}.27$ and Dec. $+00^\circ02'29''.9$ (mean equator and equinox of 1950.0). Standardization of the comparison star 1987 Primary has yielded the following preliminary magnitudes: $B = 12.3093 \pm 0.0013$ and $V = 11.4215 \pm 0.0013$. Two transformation stars have also been selected so that observers can determine the necessary color terms to convert their instrumental magnitudes to the standard system. The designations, positions, and preliminary magnitudes and colors of these stars are: SA 82-18, R. A. $14^{\mathrm{h}}17^{\mathrm{m}}37^{\mathrm{s}}.56$ and Dec. $+15^\circ24'25''.4$ (1950.0), $B = 13.133$, $B - V = 1.080$; SA 82-22, R. A. $14^{\mathrm{h}}18^{\mathrm{m}}33^{\mathrm{s}}.44$ and Dec. $+15^\circ24'01''.7$ (1950.0), $B = 13.135$, $B - V = 0.460$.

I. INTRODUCTION

Three years have now elapsed since the beginning of the Pluto–Charon mutual-event season. In several earlier publications, we and others have mentioned the enormous potential of these events for improving our meager knowledge of this remote planetary system. This potential is beginning to be realized, as evidenced by the growing number of publications on Pluto. Three different sets of orbital and physical parameters for the Pluto–Charon system have been published, based on independent analyses of mutual-event observations taken during the 1985 and 1986 oppositions (Dunbar and Tedesco 1986; Reinsch and Pakull 1987; Tholen *et al.* 1987a). Although the differences in mean densities derived by these three groups are large (1.6 to 2.1 g cm^{-3}), all indicate that the Pluto–Charon system has a substantial rock component, which comes as a surprise to those who expected a water-ice-dominated composition and a density near 1.0 g cm^{-3}.

The physical parameters derived from the mutual events have served as input quantities for the theoretical calculations of other groups. The first of these works to appear in the literature are by Stern (1987) and Trafton *et al.* (1987). The total superior events of 1987 were put to good use by Marcialis *et al.* (1987), Buie *et al.* (1987), Fink and DiSanti (1988), and Sawyer *et al.* (1987) to detect the presence of water ice and the absence of methane frost on the Pluto-facing hemisphere of Charon. Also, the combination of mutual-event data and *IRAS* thermal measurements of Pluto has been analyzed by three different groups (Tedesco *et al.* 1987; Aumann and Walker 1987; Sykes *et al.* 1987), but with strikingly different conclusions, with the existence of a substantial atmosphere being the issue in question.

Much more can be done, however, and 1988 is a critical year, because it represents the last opportunity to study Pluto uncontaminated by the light of Charon (at least for another 120 yr). This paper presents the circumstances of the 89 observable mutual events occurring during the 1988 opposition. It is the third in a series, being preceded by similar papers that described the events in 1986 (Tholen 1985) and 1987 (Tholen *et al.* 1987b). These earlier papers will hereafter be referred to as Paper I and Paper II, respectively.

II. MUTUAL EVENTS IN 1988

The circumstances for events occurring in 1988 are given in Table I. The format of this table is identical to that used in Paper II for the 1987 circumstances. The columns contain the following information:

1—UT date corresponding to the time of maximum depth or mid-totality.
2—Universal Time of first contact (beginning of event).
3—Universal Time of second contact (beginning of totality).
4—Universal Time of third contact (end of totality).
5—Universal Time of fourth contact (end of event).
6—Universal Time of maximum depth or mid-totality.
7—approximate depth of event in Johnson *B*.
8—1950.0 right ascension at the time given in column 6.
9—1950.0 declination at the time given in column 6.
10—heliocentric distance in astronomical units.
11—geocentric distance in astronomical units.
12—phase angle in degrees.
13—Johnson *B* magnitude (out of eclipse).
14—window duration for 30° north latitude.
15—window duration for 30° south latitude.
16—range of east longitudes from which at least a portion of the event can be observed.
17—type of event (inferior or superior).

If a time in column 2 or 3 is printed in italics, it refers to the time on the previous UT date; similarly, if a time in column 4 or 5 is printed in italics, it refers to the time on the following UT date. The word totality, as used in this paper, refers to the time when the surface area that is physically blocked from view or in shadow is constant. All superior events will be total in 1988, as they were in 1987, with the duration of totality ranging from 68 to 93 min. More than half of the inferior events in 1988 will be total; that is, both Charon and Charon's shadow will be completely encompassed by the disk of Pluto. For those events in which the geometry does not produce totality, the second- and third-contact entries in Table I are marked with a dash.

The tabulated *B* magnitude of Pluto is the brightness the system would have at the time of maximum depth or mid-

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[a)] Summer research assistant at the Institute for Astronomy; present address at California Institute of Technology, Pasadena, CA 91125.

TABLE I. Circumstances for Pluto–Charon mutual events occurring during the 1988 opposition.

	Contacts				Max. Depth		R.A. (1950.0) DEC.										Windows			
UT Date	(1)	(2)	(3)	(4)	UT	Mag	h	m	s	°	′	″	r	Δ	α	B Mag	30° N	30° S	Long. Range	Event Type
1987 Dec 12	13:53	15:45	16:35	18:37	16:10	0.42	14	53	18.2	−00	05	02	29.674	30.407	1.25	14.86	—	—	—	Inf
15	18:32	20:11	21:44	23:16	20:57	0.17	14	53	42.6	−00	05	56	29.674	30.372	1.32	14.77	0:14	—	89-163	Sup
19	*23:10*	01:02	01:46	03:54	01:24	0.44	14	54	06.1	−00	06	41	29.674	30.335	1.39	14.86	0:28	—	16- 94	Inf
22	03:48	05:32	07:00	08:32	06:16	0.17	14	54	28.9	−00	07	18	29.674	30.296	1.46	14.77	0:42	—	304- 25	Sup
25	08:27	10:18	10:55	13:10	10:36	0.45	14	54	50.6	−00	07	46	29.673	30.255	1.52	14.86	0:56	—	231-316	Inf
28	13:05	14:52	16:16	17:48	15:34	0.17	14	55	11.6	−00	08	06	29.673	30.212	1.57	14.77	1:09	—	159-247	Sup
31	17:44	19:39	20:01	22:26	19:50	0.47	14	55	31.5	−00	08	17	29.673	30.168	1.63	14.86	1:22	—	87-177	Inf
1988 Jan 04	*22:23*	00:11	01:32	03:04	00:51	0.17	14	55	50.5	−00	08	21	29.673	30.122	1.68	14.77	1:35	—	14-108	Sup
07	03:02	—	—	07:43	05:06	0.47	14	56	08.3	−00	08	16	29.673	30.074	1.72	14.85	1:48	—	301- 38	Inf
10	07:41	09:28	10:48	12:21	10:08	0.17	14	56	25.1	−00	08	03	29.673	30.026	1.76	14.76	2:01	0:03	228-329	Sup
13	12:19	—	—	16:59	14:22	0.47	14	56	40.6	−00	07	42	29.672	29.976	1.80	14.85	2:13	0:19	155-259	Inf
16	16:58	18:45	20:04	21:37	19:24	0.17	14	56	55.1	−00	07	12	29.672	29.925	1.83	14.76	2:25	0:35	83-189	Sup
19	21:37	—	—	*02:15*	23:39	0.47	14	57	08.2	−00	06	35	29.672	29.874	1.85	14.84	2:37	0:50	10-119	Inf
23	02:16	04:02	05:20	06:53	04:41	0.17	14	57	20.1	−00	05	50	29.672	29.821	1.87	14.75	2:49	1:06	297- 50	Sup
26	06:55	—	—	11:31	08:56	0.46	14	57	30.7	−00	04	58	29.672	29.768	1.89	14.84	3:01	1:22	225-340	Inf
29	11:34	13:18	14:36	16:09	13:57	0.17	14	57	40.0	−00	03	59	29.672	29.715	1.90	14.74	3:12	1:38	152-270	Sup
Feb 01	16:14	—	—	20:47	18:14	0.45	14	57	47.9	−00	02	53	29.671	29.662	1.90	14.83	3:23	1:54	80-199	Inf
04	20:53	22:34	23:52	*01:25*	23:13	0.17	14	57	54.5	−00	01	39	29.671	29.608	1.90	14.73	3:33	2:11	7-129	Sup
08	01:32	—	—	06:03	03:31	0.45	14	57	59.8	−00	00	21	29.671	29.556	1.90	14.82	3:44	2:27	294- 59	Inf
11	06:11	07:51	09:08	10:41	08:29	0.17	14	58	03.7	+00	01	05	29.671	29.502	1.88	14.73	3:55	2:43	222-348	Sup
14	10:50	—	—	15:19	12:49	0.44	14	58	06.2	+00	02	36	29.671	29.450	1.87	14.81	4:05	2:59	149-278	Inf
17	15:29	17:07	18:24	19:57	17:45	0.17	14	58	07.3	+00	04	13	29.671	29.398	1.84	14.72	4:14	3:15	77-208	Sup
20	20:08	—	—	*00:35*	22:07	0.43	14	58	07.1	+00	05	54	29.670	29.348	1.81	14.80	4:24	3:30	4-137	Inf
24	00:47	02:24	03:40	05:13	03:02	0.17	14	58	05.5	+00	07	40	29.670	29.297	1.78	14.71	4:33	3:46	291- 66	Sup
27	05:27	—	—	09:51	07:26	0.43	14	58	02.6	+00	09	30	29.670	29.249	1.74	14.79	4:43	4:02	218-356	Inf
Mar 01	10:06	11:40	12:56	14:29	12:18	0.17	14	57	58.4	+00	11	24	29.670	29.201	1.70	14.70	4:52	4:17	146-285	Sup
04	14:45	—	—	19:07	16:44	0.42	14	57	52.9	+00	13	21	29.670	29.155	1.65	14.78	5:01	4:32	74-214	Inf
07	19:23	20:57	22:12	23:45	21:34	0.17	14	57	46.1	+00	15	21	29.670	29.110	1.60	14.69	5:10	4:48	1-144	Sup
11	00:01	—	—	04:24	02:03	0.41	14	57	38.2	+00	17	22	29.669	29.068	1.54	14.77	5:19	5:03	288- 73	Inf
14	04:39	06:14	07:27	09:02	06:50	0.17	14	57	29.0	+00	19	26	29.669	29.027	1.48	14.68	5:28	5:18	215- 3	Sup
17	09:18	—	—	13:40	11:22	0.41	14	57	18.7	+00	21	31	29.669	28.988	1.42	14.76	5:36	5:33	142-292	Inf
20	13:56	15:30	16:43	18:18	16:06	0.17	14	57	07.3	+00	23	37	29.669	28.950	1.35	14.67	5:45	5:48	70-222	Sup
23	18:34	—	—	22:56	20:41	0.40	14	56	54.9	+00	25	43	29.669	28.916	1.28	14.75	5:53	6:02	357-153	Inf
27	*23:13*	00:47	01:59	03:34	01:23	0.17	14	56	41.4	+00	27	48	29.669	28.883	1.20	14.65	6:02	6:17	284- 84	Sup
30	03:51	—	—	08:12	06:00	0.39	14	56	27.1	+00	29	53	29.668	28.853	1.13	14.74	6:10	6:32	212- 15	Inf
Apr 02	08:29	10:04	11:16	12:51	10:40	0.17	14	56	11.9	+00	31	57	29.668	28.826	1.05	14.65	6:18	6:47	139-306	Sup
05	13:08	—	—	17:29	15:20	0.38	14	55	55.8	+00	33	58	29.668	28.801	0.98	14.73	6:27	7:01	66-237	Inf
08	17:46	19:21	20:32	22:07	19:56	0.17	14	55	39.1	+00	35	58	29.668	28.778	0.90	14.64	6:35	7:16	353-167	Sup
12	*22:24*	—	—	02:46	00:38	0.37	14	55	21.7	+00	37	55	29.668	28.758	0.83	14.72	6:44	7:30	280- 98	Inf
15	03:03	04:39	05:48	07:26	05:13	0.17	14	55	03.7	+00	39	48	29.668	28.742	0.76	14.63	6:52	7:45	207- 29	Sup
18	07:41	09:43	10:16	12:06	09:59	0.35	14	54	45.1	+00	41	38	29.668	28.727	0.69	14.71	7:01	7:59	134-320	Inf
21	12:20	13:56	15:04	16:46	14:30	0.17	14	54	26.1	+00	43	23	29.667	28.716	0.64	14.62	7:09	8:12	61-251	Sup
24	16:58	18:56	19:42	21:27	19:19	0.34	14	54	06.7	+00	45	05	29.667	28.708	0.59	14.71	7:18	8:16	347-179	Inf
27	21:37	23:13	*00:24*	*02:07*	23:48	0.17	14	53	47.1	+00	46	40	29.667	28.703	0.57	14.62	7:26	8:16	274-106	Sup
May 01	02:15	04:10	04:58	06:47	04:34	0.34	14	53	27.3	+00	48	11	29.667	28.700	0.56	14.71	7:35	8:16	201- 33	Inf
04	06:54	08:31	09:48	11:27	09:09	0.17	14	53	07.3	+00	49	36	29.667	28.700	0.57	14.62	7:29	8:16	128-320	Sup
07	11:32	13:26	14:15	16:07	13:50	0.34	14	52	47.3	+00	50	54	29.667	28.704	0.59	14.71	7:22	8:16	55-247	Inf
10	16:11	17:49	19:10	20:47	18:29	0.17	14	52	27.3	+00	52	06	29.667	28.710	0.64	14.62	7:14	8:16	342-175	Sup
13	20:50	22:42	23:31	*01:27*	23:06	0.35	14	52	07.4	+00	53	12	29.666	28.719	0.69	14.71	7:05	8:16	269-102	Inf
17	01:28	03:07	04:32	06:07	03:49	0.17	14	51	47.7	+00	54	10	29.666	28.731	0.75	14.63	6:54	8:16	195- 29	Sup
20	06:07	08:00	08:48	10:47	08:24	0.37	14	51	28.3	+00	55	01	29.666	28.745	0.82	14.72	6:42	8:16	122-316	Inf
23	10:46	12:25	13:53	15:27	13:09	0.17	14	51	09.2	+00	55	44	29.666	28.763	0.90	14.64	6:26	8:16	49-243	Sup
26	15:25	17:17	18:04	20:06	17:40	0.39	14	50	50.6	+00	56	19	29.666	28.783	0.97	14.73	6:11	8:10	338-170	Inf
29	20:03	21:43	23:13	*00:46*	22:28	0.17	14	50	32.4	+00	56	47	29.666	28.805	1.05	14.65	5:55	7:57	267- 97	Sup
Jun 02	00:42	02:35	03:21	05:25	02:58	0.41	14	50	14.8	+00	57	06	29.666	28.830	1.13	14.74	5:40	7:44	197- 24	Inf
05	05:21	07:01	08:33	10:05	07:47	0.17	14	49	57.7	+00	57	17	29.665	28.858	1.20	14.65	5:24	7:31	127-311	Sup
08	10:00	11:53	12:37	14:44	12:15	0.42	14	49	41.4	+00	57	20	29.665	28.888	1.28	14.75	5:10	7:18	57-239	Inf
11	14:39	16:20	17:52	19:24	17:06	0.17	14	49	25.8	+00	57	15	29.665	28.920	1.35	14.66	4:56	7:06	347-166	Sup
14	19:18	21:11	21:54	*00:03*	21:32	0.44	14	49	11.1	+00	57	01	29.665	28.954	1.42	14.76	4:41	6:53	277- 93	Inf
18	*23:57*	01:38	03:10	04:42	02:24	0.17	14	48	57.1	+00	56	39	29.665	28.991	1.49	14.68	4:27	6:40	208- 20	Sup
21	04:36	06:29	07:11	09:21	06:50	0.46	14	48	44.2	+00	56	08	29.665	29.029	1.55	14.77	4:13	6:26	138-307	Inf
24	09:15	10:57	12:28	14:00	11:42	0.17	14	48	32.2	+00	55	28	29.665	29.069	1.61	14.69	4:00	6:12	69-234	Sup
27	13:53	15:47	16:27	18:39	16:07	0.47	14	48	21.2	+00	54	41	29.665	29.111	1.66	14.78	3:48	5:59	359-161	Inf
30	18:32	20:16	21:46	23:18	21:01	0.17	14	48	11.2	+00	53	45	29.664	29.155	1.71	14.70	3:35	5:45	290- 88	Sup
Jul 04	*23:11*	01:05	01:44	03:57	01:24	0.48	14	48	02.4	+00	52	42	29.664	29.199	1.76	14.79	3:23	5:31	220- 15	Inf
07	03:50	05:35	07:03	08:36	06:19	0.17	14	47	54.7	+00	51	30	29.664	29.245	1.80	14.71	3:10	5:17	151-302	Sup
10	08:29	10:23	11:00	13:14	10:41	0.49	14	47	48.1	+00	50	11	29.664	29.293	1.84	14.80	2:59	5:03	81-229	Inf
13	13:09	14:53	16:20	17:53	15:36	0.17	14	47	42.8	+00	48	43	29.664	29.341	1.87	14.72	2:48	4:49	12-156	Sup
16	17:48	19:41	20:17	22:31	19:59	0.50	14	47	38.6	+00	47	09	29.664	29.390	1.90	14.81	2:38	4:35	303- 83	Inf
20	*22:27*	00:11	01:37	03:10	00:54	0.17	14	47	35.7	+00	45	27	29.664	29.440	1.92	14.73	2:27	4:21	234- 10	Sup
23	03:06	04:58	05:33	07:48	05:15	0.50	14	47	34.1	+00	43	38	29.664	29.491	1.94	14.82	2:16	4:07	164-297	Inf
26	07:45	09:29	10:54	12:27	10:11	0.17	14	47	33.7	+00	41	43	29.663	29.542	1.95	14.73	2:07	3:53	95-224	Sup
29	12:24	14:15	14:49	17:05	14:32	0.50	14	47	34.6	+00	39	41	29.663	29.593	1.96	14.83	1:58	3:40	26-152	Inf
Aug 01	17:03	18:47	20:11	21:43	19:29	0.17	14	47	36.7	+00	37	33	29.663	29.645	1.96	14.74	1:48	3:26	317- 79	Sup
04	21:42	23:33	*00:05*	*02:22*	23:49	0.50	14	47	40.2	+00	35	20	29.663	29.696	1.96	14.83	1:39	3:12	247- 6	Inf
08	02:21	04:05	05:27	07:00	04:46	0.17	14	47	44.9	+00	33	00	29.663	29.748	1.95	14.75	1:30	2:59	178-293	Sup
11	07:00	08:53	09:20	11:38	09:06	0.50	14	47	50.9	+00	30	36	29.663	29.799	1.94	14.84	1:22	2:46	109-220	Inf
14	11:39	13:22	14:44	16:16	14:03	0.17	14	47	58.2	+00	28	06	29.663	29.849	1.92	14.75	1:13	2:33	40-147	Sup
17	16:18	18:14	18:35	20:54	18:24	0.50	14	48	06.7	+00	25	33	29.663	29.899	1.89	14.85	1:05	2:20	331- 75	Inf
20	20:57	22:39	*00:00*	*01:32*	23:19	0.17	14	48	16.5	+00	22	54	29.663	29.949	1.87	14.76	0:56	2:07	262- 2	Sup
24	01:36	03:36	03:49	06:10	03:42	0.49	14	48	27.5	+00	20	13	29.662	29.997	1.83	14.85	0:48	1:53	193-289	Inf
27	06:15	07:55	09:16	10:48	08:35	0.17	14	48	39.7	+00	17	27	29.662	30.045	1.79	14.76	0:40	1:39	124-216	Sup
30	10:54	—	—	15:26	12:59	0.48	14	48	53.1	+00	14	40	29.662	30.091	1.75	14.86	0:32	1:26	54-143	Inf
Sep 02	15:33	17:12	18:32	20:04	17:52	0.17	14	49	07.6	+00	11	49	29.662	30.137	1.71	14.77	0:25	1:12	345- 71	Sup
05	20:13	—	—	*00:41*	22:17	0.47	14	49	23.2	+00	08	56	29.662	30.180	1.66	14.86	0:17	0:58	276-358	Inf
09	00:52	02:27	03:47	05:19	03:07	0.17	14	49	40.0	+00	06	01	29.662	30.223	1.60	14.77	0:09	0:44	207-285	Sup
12	05:31	—	—	09:57	07:35	0.45	14	49	57.8	+00	03	05	29.662	30.263	1.54	14.86	0:01	0:30	138-212	Inf
15	10:10	11:43	13:02	14:34	12:22	0.17	14	50	16.7	+00	00	07	29.662	30.302	1.48	14.77	—	0:15	69-139	Sup
18	14:48	—	—	19:12	16:52	0.44	14	50	36.5	−00	02	50	29.662	30.339	1.42	14.86	—	0:01	0- 66	Inf

totality if there were no event. If for some reason an observer is unable to obtain photometry of the system immediately prior to or following an event, then this value can be used to estimate the depth of the event. The *V* magnitude is 0.84 mag brighter.

As in both Paper I and Paper II, we used 2.5 airmasses and astronomical twilight as the limits for defining the length of the observing window. Note that the 1987 December 12 event has no window as seen from either the northern or southern hemisphere. This particular event was included in the table because it is observable from Mauna Kea, where we have successfully observed Pluto to in excess of 5.0 airmasses, which makes our window as long as 40 min.

We emphasize that the longitude range given in the second-to-last column refers to east longitudes. Also, the inclusion of a particular longitude within the tabulated range means that at least a portion of the event can be observed from either 30° north or 30° south latitude, but not necessarily both.

The orbital and physical parameters used to generate these circumstances are shown in Table II and are based on an analysis of data accumulated through 1987 June 26 (Tholen and Buie 1987). Although this particular set of parameters does not represent a complete analysis of the data, they do adequately represent the times of contacts of all observed events and should therefore be sufficient for accurately extrapolating to the times of the various contacts in 1988. Once again, the computations were performed at a time resolution of 1 min, so round-off/truncation error intrinsically limits the accuracy of the listed times to 1 or 2 min. The accuracy of the orbital and physical parameters is still the limiting factor in the accuracy of the times of contacts. Our ongoing modeling efforts suggest adjustments to the model parameters that favor a slightly longer duration of totality than tabulated, but the times should be good to better than 5 min for all contacts and all events.

The depths of the superior events will be correct to about 0.01 mag if the observations are made with a filter approximating Johnson *B*. Longer wavelengths will yield shallower depths, given the color difference for superior events found by Tholen *et al.* (1987a) and examined in greater detail by Fink and DiSanti (1988). On the other hand, the depths of the inferior events are quite uncertain, which should come as no surprise, given the surface-albedo distribution that Pluto must have to produce its light curve (see Buie and Tholen (1988) for a model of the surface albedo distribution that successfully reproduces the light curve). For this particular set of circumstances, we used the albedo that reproduces the depth of the 1987 March 19 event and extrapolated to 1988. During that event, Charon transited the equatorial region of Pluto, which we believe has a comparatively low albedo, and its shadow covered the north polar region, which presumably has a higher albedo. (As in earlier papers, we define north to lie in the direction of the angular-momentum vector.) During 1988, the equatorial region will be occulted or eclipsed once again, along with portions of the south polar region, which we believe also has a high albedo. If the albedos of the north and south polar caps are roughly equal, then the depths listed in Table I should be approximately correct, given that the geometry of many 1988 events represents a crude mirror image of the corresponding 1987 event on the opposite side of the opposition date. Although the actual absolute depths of the events may differ somewhat from those tabulated, the relative depths (i.e., the change in depth from one inferior event to the next) should be fairly accurate, unless there is a very sharp, high-contrast discontinuity in Pluto's surface-albedo distribution.

TABLE II. Orbital and physical parameters used to generate the circumstances.

Semimajor axis	19 130 km
Eccentricity	0.0
Inclination[a]	98°.1
Ascending node[a]	222°.342
Argument of periapsis[a]	0°.0
Mean anomaly	259°.85
Epoch	JD 2446600.5 = 1986 June 19
Period	6.387217 days
Pluto radius	1122.7 km
Charon radius	600 km
Pluto blue geometric albedo	0.505
Charon blue geometric albedo	0.367

[a] Referred to the mean equator and equinox of 1950.0.

The geometry of Pluto, Charon, and shadow is shown for both inferior and superior events in Fig. 1 for three times in 1988: preopposition quadrature, opposition, and postopposition quadrature. The effects of parallax are at their maximum near quadrature, with Charon's disk covering the southernmost latitudes on Pluto preopposition and the northernmost latitudes postopposition. Opposition represents the time when shadowing effects are at their minimum.

From one inferior event to the next, the position of Charon's shadow with respect to Pluto is slowly and monotonically moving from right to left (in Fig. 1); this motion is strictly due to Pluto's orbital motion around the Sun. On the other hand, between preopposition and postopposition quadrature (approximately), the position of Charon itself with respect to Pluto will be moving from left to right; this motion is primarily due to the Earth moving around its orbit (parallax). Before and after this interval, Charon moves more rapidly from right to left. With this information, one should be able to estimate the geometry for any particular event. For a look backward in time, see Fig. 1 of Paper II.

III. COMPARISON STARS

We have an ongoing program of selecting and standardizing comparison stars specifically for use by those observing Pluto–Charon mutual-event light curves. Our selection of the stars for use before opposition in 1988 is based on observations of 20 stars collected on 1987 February 17 and 18 UT with the 2.24 m University of Hawaii telescope on Mauna Kea. Once again, we chose the two stars having the best combination of brightness, color match, and proximity to Pluto, with the brighter of the two being designated as the primary comparison star. The positions were measured on print copies of the Palomar Sky Survey and should be accurate to better than 2 arcsec, although the unknown proper motions could make the 1988-epoch positions somewhat less accurate.

Table III lists the positions and initial magnitude and color measurements for these two stars along with the same information for the 1987 comparison stars, which should be used starting with the May 4 event.

Standardization of the various comparison stars used in previous years is also being continued. Table IV shows the currently adopted magnitudes and colors for the primary comparison stars used in 1987, with the uncertainties shown directly above the magnitudes and colors in units of the least significant digit. These uncertainties represent the standard deviation of the weighted mean of 27 nights of observation of

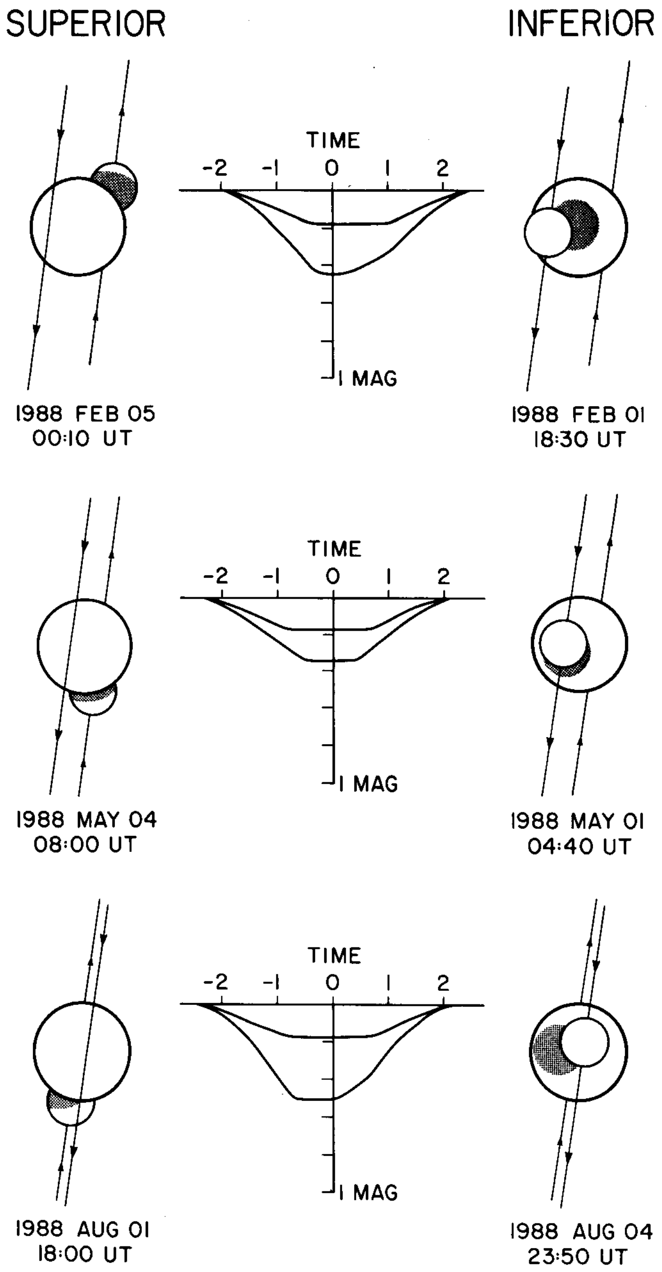

FIG. 1. The geometry of the Pluto-Charon system is shown in the leftmost and rightmost panels for three times in 1988: preopposition quadrature (top), opposition (middle), and postopposition quadrature (bottom). Equatorial north is up in all views. The middle vertical panel shows the predicted light-curve shapes for the inferior and superior event on either side. The time axis is in hours from minimum separation. In all cases, the deeper of the two light curves corresponds to the inferior event depicted on the right, whereas the shallower light curve corresponds to the superior event depicted on the left.

TABLE III. Comparison stars for use in 1988.

	R. A.	(1950.0) Dec.		
Star	h m s	° ′ ″	B	$B-V$
1987 Primary	14 47 24.23	+01 00 31.9	12.309	0.885
1987 Check	14 48 20.69	+01 09 28.2	12.877	0.879
1988 Primary	14 58 05.92	+00 12 15.2	12.259	0.930
1988 Check	14 57 46.27	+00 02 29.9	13.236	0.707

Note to TABLE III

1988 Primary should be used prior to opposition, and 1987 Primary should be used starting with the May 4 event.

1986 Primary and six nights of data on 1987 Primary. The $B-V$ colors are not exactly equal to the differences between the B and V magnitudes because of the weighting procedure, but the discrepancies are smaller than the uncertainties and can therefore be ignored. The B magnitude for 1986 Primary differs from the one tabulated in Paper II, which was based on only 22 nights of data, by 0.0018 mag ($>2\sigma$). The larger than expected difference is entirely due to one presumably excellent measurement in 1987 that shows a residual of 0.007 mag. Because the tabulated magnitude is a weighted mean, this particular measurement is probably carrying more weight than it should at the present time.

IV. TRANSFORMATION STARS

As we noted in Paper II, the Johnson *UBV* system is not internally accurate to the millimagnitude level, so we are establishing a network of comparison stars that will ultimately be standardized to a precision about an order of magnitude better than the Johnson system. Such an improvement in the magnitude scale will also require a concomitant improvement in the effective wavelength, given that it is impossible to have all comparison stars match Pluto's color to a few millimag, nor will all observers have instrumental systems providing the same effective wavelengths. To this end, we have also chosen a blue-red pair of stars so that those observers working at the Johnson B and V wavelengths can determine accurate color terms for the transformation to this high-precision variant of the Johnson *UBV* system (which we have been informally calling the Johnson-Pluto system).

There is no particular necessity for having these stars in close proximity to either Pluto or the network of comparison stars, so rather than using valuable telescope time to hunt for a suitable blue-red pair, we simply selected a relatively nearby pair of stars from a previously published standard-star network that the first author was involved in establishing (Tedesco *et al.* 1982, using stars from Purgathofer 1969). The positions, magnitudes, and colors of these stars are shown in Table V. The magnitudes and colors are based on five nights of data from 1987. As described in Paper II, all of these values are relative to the adopted B and V magnitudes of SAO 120107. We anticipate publishing the final results for the magnitudes and colors of all comparison and transformation stars sometime around the end of the mutual-event season.

V. COMMENTS

The Earth will pass through Charon's orbital plane (Pluto's equatorial plane) three times during the 1988 opposition, on 1987 November 14, 1988 June 20, and 1988 September 4. Coincidentally, Pluto and Charon will pass through

TABLE IV. Standard magnitudes for primary comparison stars used in 1987.

Star	B	V	$B-V$
1986 Primary	8 13.1256	13 12.3905	8 0.7346
1987 Primary	13 12.3093	13 11.4215	30 0.8852

TABLE V. Transformation stars.

	R. A.		(1950.0)		Dec.			
Star	h	m	s	°	′	″	B	$B-V$
							15	12
SA 82-18	14	17	37.56	+15	24	25.4	13.1333	1.0801
							14	14
SA 82-22	14	18	33.44	+15	24	01.7	13.1351	0.4596

the Earth's equatorial plane on 1987 November 12, 1988 February 26, and 1988 September 5; that is, the true declination of Pluto will change sign on these dates. That the first and last of these plane-crossing dates agree to within two days (out of the 90 000 + day orbital period of Pluto) is truly extraordinary!

The mutual-event season will conclude with the superior event of 1990 October 15, based on the orbital and physical parameters listed in Table II. Further improvements to these parameters are unlikely to affect this ending date by more than a few events, so the very shallow events occurring in 1990 September, just before Pluto moves into conjunction with the Sun, will be the last observable events.

Several different experiments can be performed with the geometry produced in 1988. For example, spectral observations of Charon only, such as the ones performed by Marcialis *et al.* (1987), Buie *et al.* (1987), Fink and DiSanti (1988), and Sawyer *et al.* (1987) are made possible by the occurrence of total superior events. 1988 is the last year of the current season in which total superior events will occur, so the importance of total superior events is quite high. Also, the numerous total inferior events will provide an opportunity to look for longitudinal albedo variegation on the Charon-facing hemisphere of Pluto. 1988 represents the last year during which total inferior events will occur as well.

High-precision measurements of total superior events at a full range of phase angles should permit the phase coefficients of Pluto and Charon to be determined separately, potentially providing information on the scattering properties of their respective surfaces.

Several observers of these events have not been using the comparison stars suggested in this series of papers, for understandable reasons. For example, those observing with two-star photometers or CCDs are often using a local comparison star instead (one within the travel limits of the second beam of a two-star photometer, or one that falls on the CCD frame along with Pluto). Under such circumstances, we strongly recommend, however, that the suggested comparison stars be observed either immediately preceding or following an event so that the observations can be properly tied into the photometric system. The internal accuracy of the network of comparison stars should eventually reach 0.001 mag. Observations made relative to some random field star are unlikely to benefit from this careful standardization of the comparison-star network.

Unless the observing window is too narrow to permit it, proper coverage of the out-of-eclipse light curve immediately preceding or following an event is also important. The rotational light curve of the Pluto-Charon system is slowly evolving with time, and, without such coverage, the true depth of an event will depend on an interpolation of the out-of-eclipse brightness determined from other observations, thereby compromising the accuracy of the data. A half hour of coverage should be regarded as a lower limit; an hour or more would be desirable.

Additional comments and some basic guidelines for observing these mutual events can be found in Sec. IV of both Paper I and Paper II.

As before, more detailed circumstances for any particular event can be obtained by writing to the first author, specifying the nights for which more information is desired. When requesting such information, please include observatory coordinates so that airmass and twilight information can be properly computed.

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REFERENCES

Aumann, H. H., and Walker, R. G. (1987). Astron. J. **94**, 1088.

Buie, M. W., Cruikshank, D. P., Lebofsky, L. A., and Tedesco, E. F. (1987). Nature (in press).

Buie, M. W., and Tholen, D. J. (1988). Icarus (submitted).

Dunbar, R. S., and Tedesco, E. F. (1986). Astron. J. **92**, 1201.

Fink, U., and DiSanti, M. A. (1988). Astron. J. (in press).

Marcialis, R. L., Rieke, G. H., and Lebofsky, L. A. (1987). Science **237**, 1349.

Purgathofer, A. T. (1969). Lowell Obs. Bull. **VII**, 98.

Reinsch, K., and Pakull, M. W. (1987). Astron. Astrophys. **177**, L43.

Sawyer, S., Barker, E., Cochran, A., and Cochran, B. (1987). IAU Circ. No. 4401.

Stern, S. A. (1987). Icarus (in press).

Sykes, M. V., Cutri, R. M., Lebofsky, L. A., and Binzel, R. P. (1987). Science **237**, 1336.

Tedesco, E. F., Tholen, D. J., and Zellner, B. (1982). Astron. J. **87**, 1585.

Tedesco, E. F., Veeder, G. J., Jr., Dunbar, R. S., and Lebofsky, L. A. (1987). Nature **327**, 127.

Tholen, D. J. (1985). Astron. J. **90**, 2639.

Tholen, D. J., and Buie, M. W. (1987). Bull. Am. Astron. Soc. (in press).

Tholen, D. J., Buie, M. W., Binzel, R. P., and Frueh, M. L. (1987a). Science **237**, 512.

Tholen, D. J., Buie, M. W., and Swift, C. E. (1987b). Astron. J. **93**, 244.

Trafton, L., Stern, S. A., and Goldstone, R. (1987). Icarus (in press).