A SEARCH FOR STELLAR OCCULTATIONS BY URANUS, NEPTUNE, PLUTO, AND THEIR SATELLITES: 1990-1999

Grant NAGW-1490

Final Report
For the period 1 January 1989 through 31 December 1990

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Abstract

A search for occultations of stars by Uranus, Neptune, and Pluto between 1990 and 1999 was carried out combining ephemeris information and star positions using very accurate occultation modeling software developed over the past 10 years. Stars from both the Space Telescope Guide Star Catalog and photographic plates taken by Arnold Klemola at Lick Observatory were compared with planet positions from the JPL DE-130 ephemeris, with local modifications for Pluto and Charon. 666 possible occultations by the Uranian rings, 143 possible occultations by Neptune, and 40 possible occultations by Pluto and/or Charon were found among stars with visual magnitudes as faint as 16. Before the star positions could be obtained, the occultation prediction software was used to aid many observers in observing the occultation of 28 Sagitarii by Saturn in July 1989. As a test on other outer solar system objects, 17 possible occultations were found in a search of the Guide Star Catalog for occultations by 2060 Chiron, an interesting object between Saturn and Uranus which shows both cometary and asteroidal properties.

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Introduction

The primary purpose of the occultation prediction project funded by NASA Grant NAGW-1490 from 1 January 1989 through 31 December 1990 was to produce a list of occultations by Uranus, Neptune, and Pluto through the end of 1999. Positions of stars along the tracks of those planets, measured by Arnold Klemola of Lick Observatory under NASA Grant NAGW-1525, were processed and compared with very accurate ephemerides of those planets, and the resulting occultations and appulses were tabulated and published.

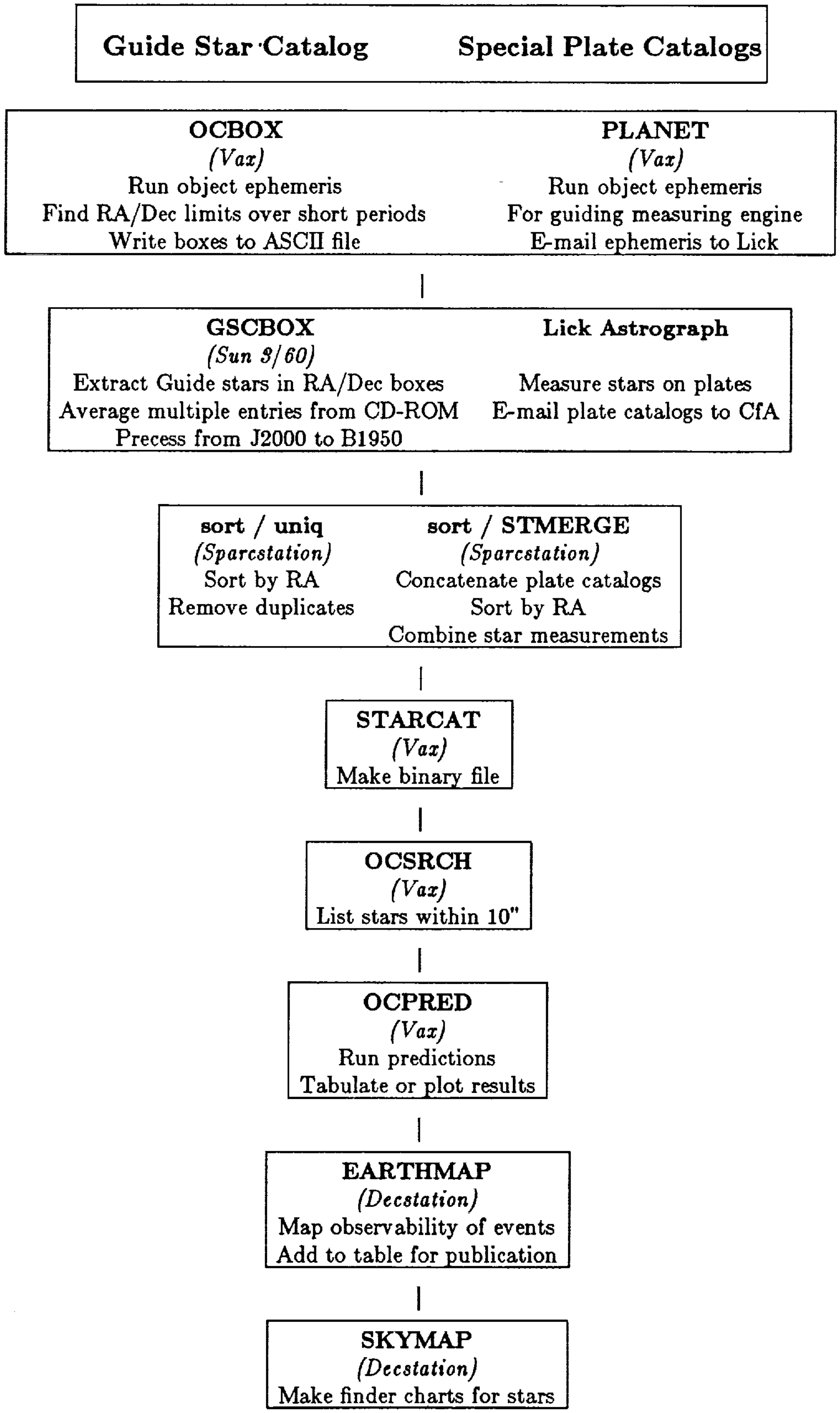
Plate Measurements

Ephemerides of Uranus, Neptune, and Pluto were provided to Arnold Klemola at Lick Observatory, who took photographic plates of the appropriate portions of the sky during May, June, and July, 1990. The plates for Pluto were measured by September 1989, and the Uranus and Neptune plates were completed by March 1990. Details of measurement techniques are in the papers in Appendices A and B.

Occultation Software

Figure 1 summarizes the techniques used for predicting occultations. First a catalog of stars to be searched must be created. Guides to the region along the path of the planet are computed--a set of boxes in right ascension and declination for the Guide Star Catalog, or a simple list of planet positions for photographic plates. Plate centers are chosen based on the ephemerides and star positions are measured along the planet's track. Plate catalogs are merged by assuming that stars within 0.3 arcseconds on the same plate and 1.0 arcsec on different plates are the same. The resulting merged catalogs, one per planet, are sorted by right ascension. Guide Stars within the boxes are extracted and placed in a new

Figure 1. Occultation prediction procedure



catalog. Duplicates resulting from overlapping boxes are eliminated, and the result is sorted by right ascension. These catalogs are then converted to a binary format which allows for fast searches. Several all-sky catalogs, such as the SAO Catalog and the IRAS Point Source Catalog, have been converted to this binary format, as well.

The actual prediction process begins with the OCSRCH program which runs through the star catalog in a manner analogous to the way the Lick measuring engine selects stars on a plate. Additional criteria, such as distance of the event in the sky from the Sun, can be added in this program. The resulting file of star numbers and times of closest approach is used as input to OCPRED, the main prediction program. It can print out tables such as those found in the papers in the appendices or graph the passage of the planet past the star. EARTHMAP plots the areas on the earth where the Sun is down and the planet is above the horizon. For small occulting objects, such as Pluto and Charon, the shadow track can also be plotted. SKYMAP produces finder charts to make it easier for observers to identify the stars which are being occulted.

Space Telescope Guide Star Catalog Search

As the plate measurement was not completed during the year of the grant, alternative catalog sources were needed to provide timely information to occultation observers. Access to the Space Telescope Guide Star Catalogue was provided through a collaboration with Marc Buie at the Space Telescope Science Institute, and a search for occultations by Uranus, Neptune, and Pluto was conducted in early March 1989. This used the same source cataloguing, occultation search, and occultation prediction software as was later used on Arnold Klemola's plate catalogs.

Although the plates go more than a magnitude fainter and provide more accurate positions than the ST Guide Stars, knowing the brighter stars before their 1989 opposition gave Marc Buie time to get UBVRI photometry of some of the Pluto candidate stars. This helped calibrate the star brightnesses derived from the photographic plates. In addition, an examination of systematic differences between Guide Star positions and Klemola's plate positions will aid in understanding the usefulness of the Guide Star Catalogue in future planet astrometry and occultation work. Table 1 summarizes the Guide Star Catalog search statistically, while Table 2 does the same for the plate search.

Table 1. Guide Star occultation search: 1989-1999

Planet	Uranus	Neptune	Pluto
Catalog Entries	99,131	32,602	46,461
Stars (Merged)	55,284	15,533	23,575
Stars within 10"	576	345	218
Events	119 (<5")	27 (<2")	17 (<2")

Table 2. Lick plate occultation search: 1990-1999

Planet	Uranus	Neptune	Pluto/Charon
Measurements	11,780	4,818	6,319
Stars (merged)	8,469	3,631	5,582
Stars within 10"	3,119	1,607	798
Events	666 (<5")	143 (<2")	40 (<1")

Results of the Guide Star search were presented at the August 1989 meeting of the Division on Dynamical Astronomy of the American Astronomical Society ("Automated Occultation Prediction using the Space Telescope Guide Star Catalog", by D.J. Mink and M.W. Buie) and at the November 1989 meeting of the Division for Planetary Astronomy of the American Astronomical Society ("Occultations by Uranus, Neptune, and Pluto: 1990-1999", by D.J. Mink and A.R. Klemola). Abstracts of these presentations are in Appendix 3.

Occultations by Pluto and Charon

The search for Pluto and Charon occultations found 32 stars which may be occulted by Pluto and 28 which may be occulted by Charon. A paper detailing these results, "Occultations by Pluto and Charon: 1990-1999", by D.J. Mink, A.R. Klemola, and M.W. Buie, has been submitted to *The Astronomical Journal,* and preprints have been circulated to active observers. Appendix 1 contains this paper. Figure 2 maps the process. From the track of Pluto obtained from the JPL DE-130 ephemeris in Figure 2a, the stars in Figure 2b were measured at Lick Observatory. Those stars which Pluto and Charon passed within 2 arcseconds remain in Figure 2c. Figure 3 shows a ground track on the earth, and Figure 4, the graphical prediction for a specific observatory for P/C28 on 6 July 1995, when both Charon and Pluto occultations may be observed.

Occultations by Uranus and Neptune

The searches for Neptune and Uranus occultations have been completed, but it took some time to merge the large numbers of stars from multiple photographic plates in a way that provided positions that are as accurate as we have worked with in the past. Steve McDonald's work with our Pluto catalog (E.W. Dunham, S.W. McDonald, and J.L. Elliot, 1990, *Bull.Am.Astron.Soc.*, 22, 1129) provided useful input to this process. A paper ("Occultations by Uranus and Neptune: 1991-1999", by A.R. Klemola and D.J. Mink, in Appendix 2) has been submitted to *The Astronomical Journal.* The results of our search have been circulated among occultation observers, and priorities for observation were discussed at the October 1989 meeting of the Division for Planetary Sciences of the American Astronomical Society. Figures 5 and 6 show the search process for Uranus and Neptune, from the ephemeris through the measured stars to the occultation candidates. Figure 7 is a prediction for the most central Uranus occultation, U148 on 27 August 1998.

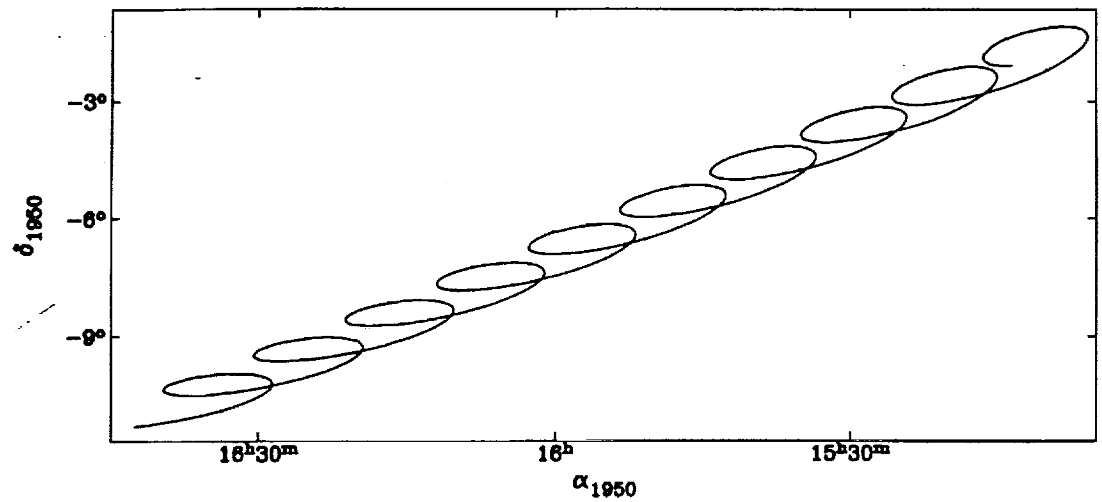


Figure 2a. Pluto from 1 January 1990 to 31 December 1999

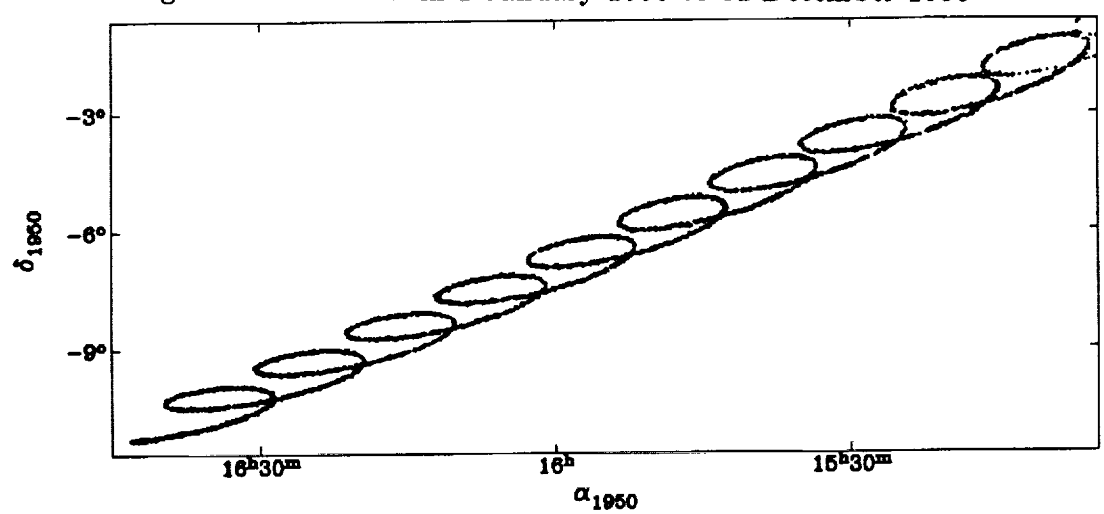


Figure 2b. Stars within 5 arcminutes of Pluto 1990-1999

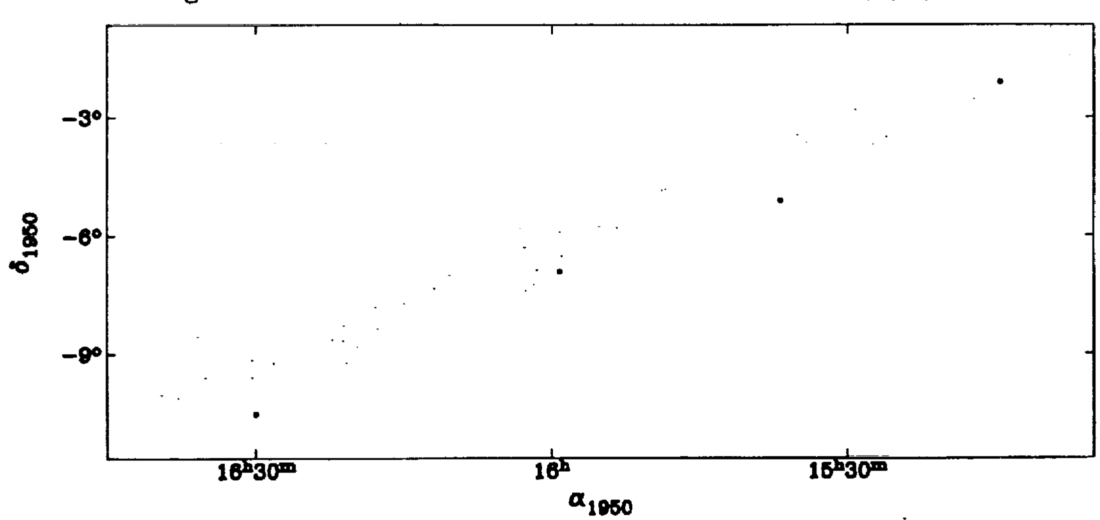


Figure 2c. Pluto and Charon Occultation Candidate Stars 1990-1999

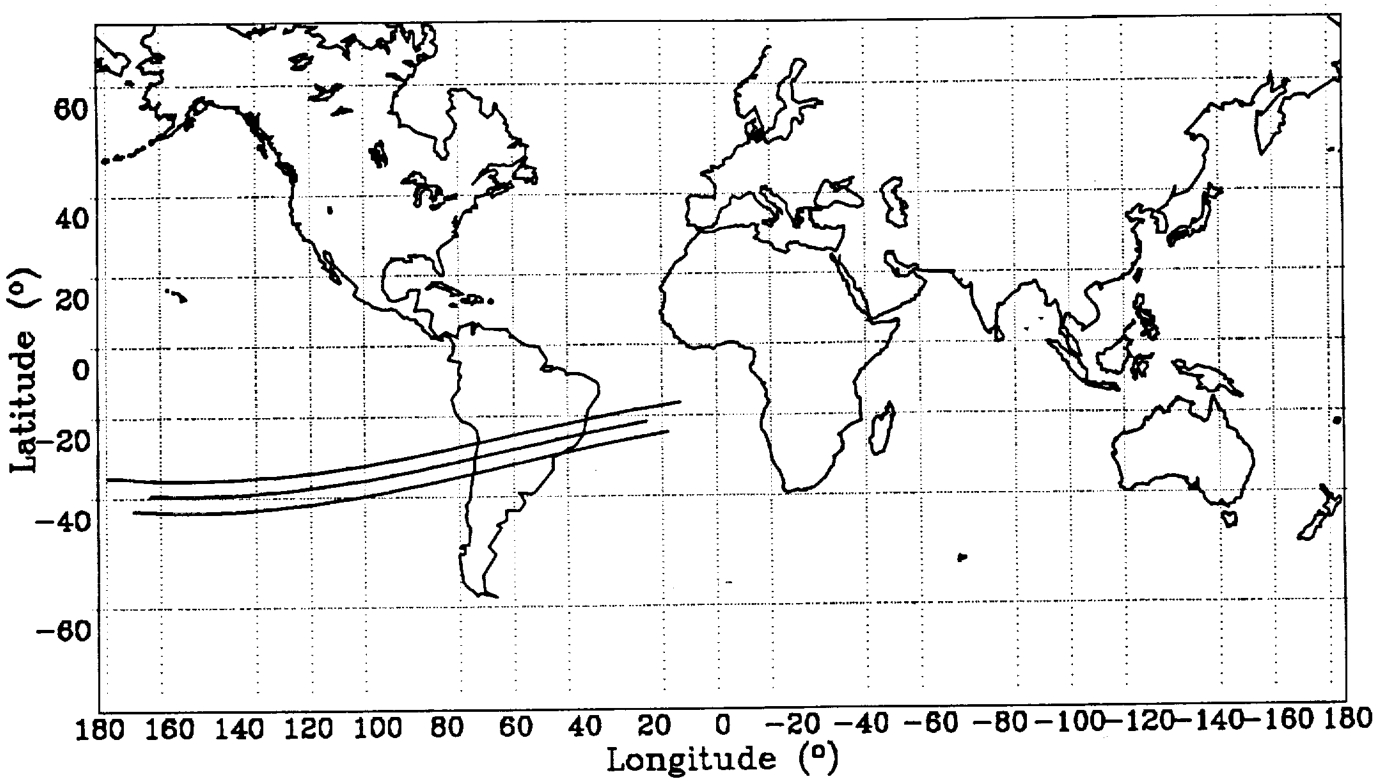


Figure 3. Ground track for occultation of P/C 28 by Charon, 6 July 1995.

```
July 6 1995 Occultation of mkp 28 by Charon
Observed from Rio De Janeiro 46cm Long=  43 13 21.9  Lat= -22 53 42.2
15.68-magnitude star at RA= 15h 55m 39.8965s  Dec= -6d 18' 36.788"
                  (1950) RA= 15h 53m 13.6690s  Dec= -6d 10' 46.870"
Closest at  3:15:54 U.T.
 Radial=     666.5 km  =   0.03"
 Planet=     625.7 km  =   0.03"
 DE=-16.0635 Pole= 83.6107 deg
 V=0.0008  "/s = 15.99 km/s
 D= 29.143069 AU
 ET - UT = 61.5193 sec  DE-130
 P.A.= 170.8 deg.
 Phase =    1.4 deg = 100.0%
 Alt= 38 d, Az= -79 d
 Sun alt=-85 d, Az=  91 d
 Sun:132.9 d, Moon: 41.9 d
 V =0.0008 "/s = 15.99 km/s
 D = 29.143069 A.U.
Doug Mink 19:19 Mar 15 1991
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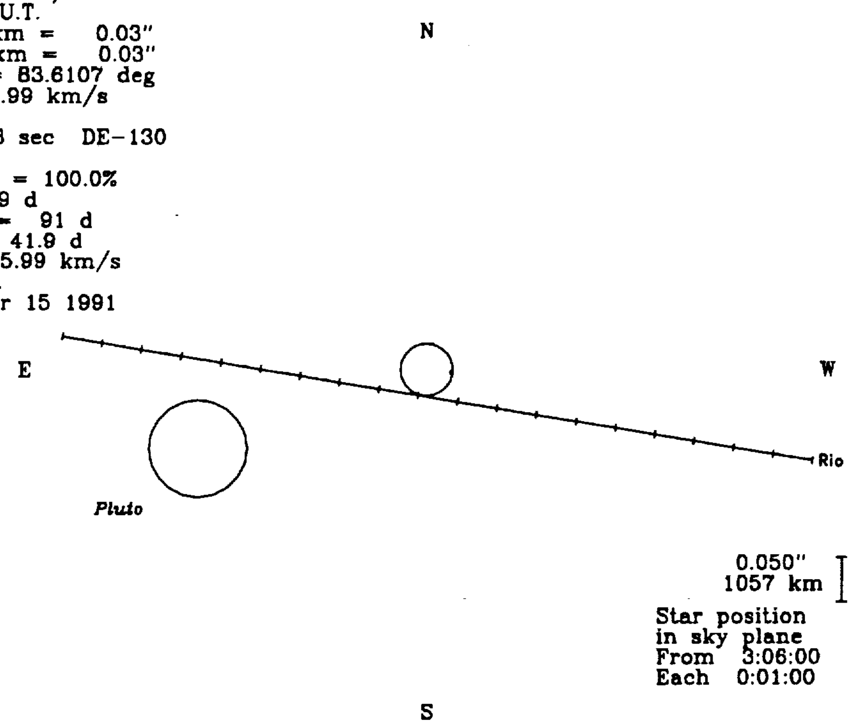

Figure 4. Track of P/C 28 relative to Charon as seen from Rio de Janeiro, Brazil

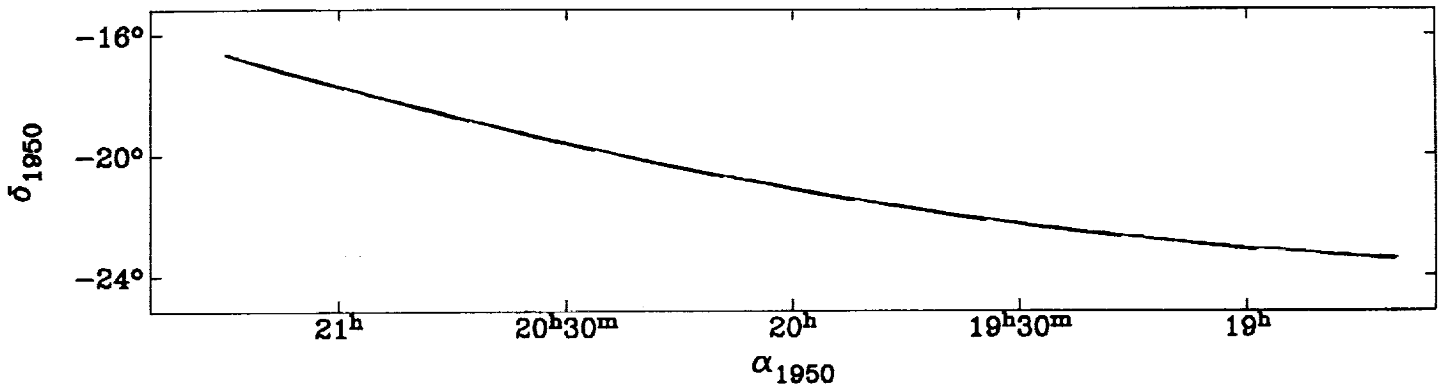

Figure 5a. Uranus from 1 January 1991 to 31 December 1999

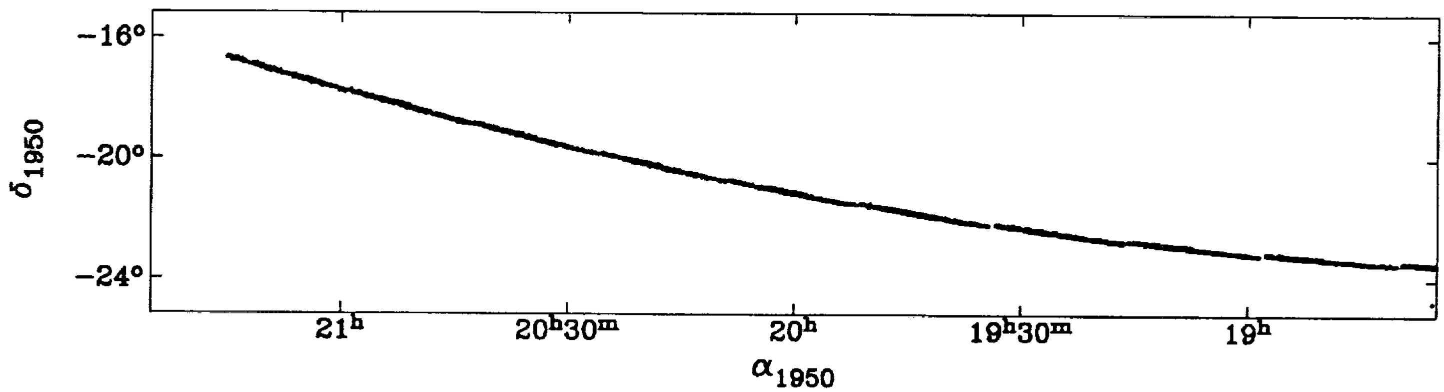

Figure 5b. Stars within 50 arcseconds of Uranus 1991-1999

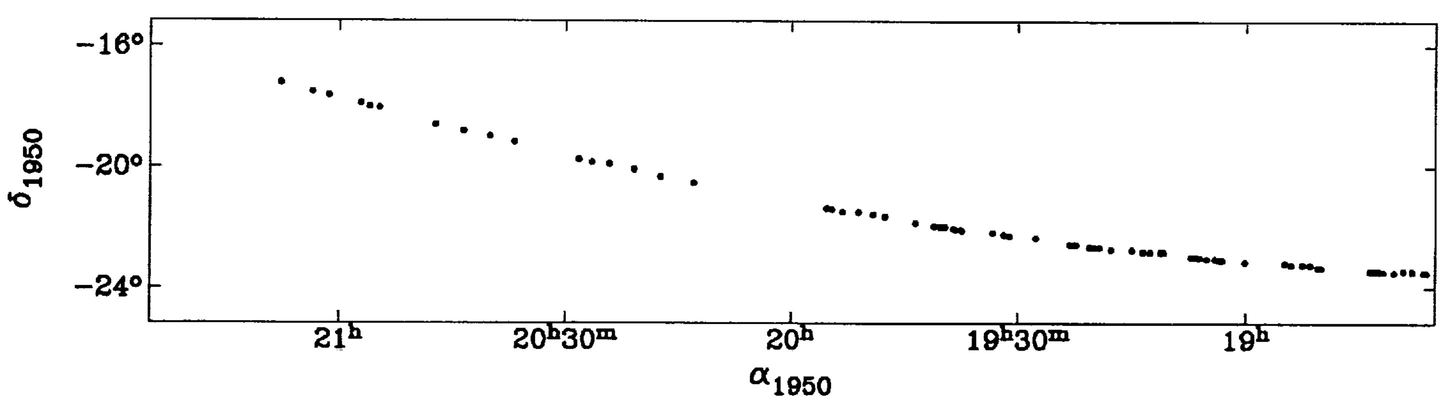

Figure5c. Uranus Ring Occultation Candidate Stars 1991-1999

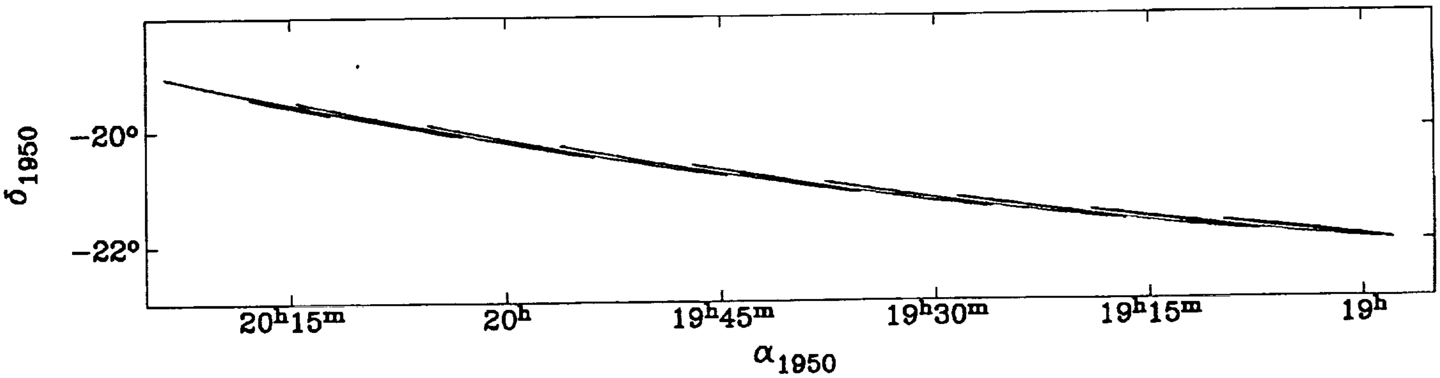

Figure 6a. Neptune from 1 January 1991 to 31 December 1999

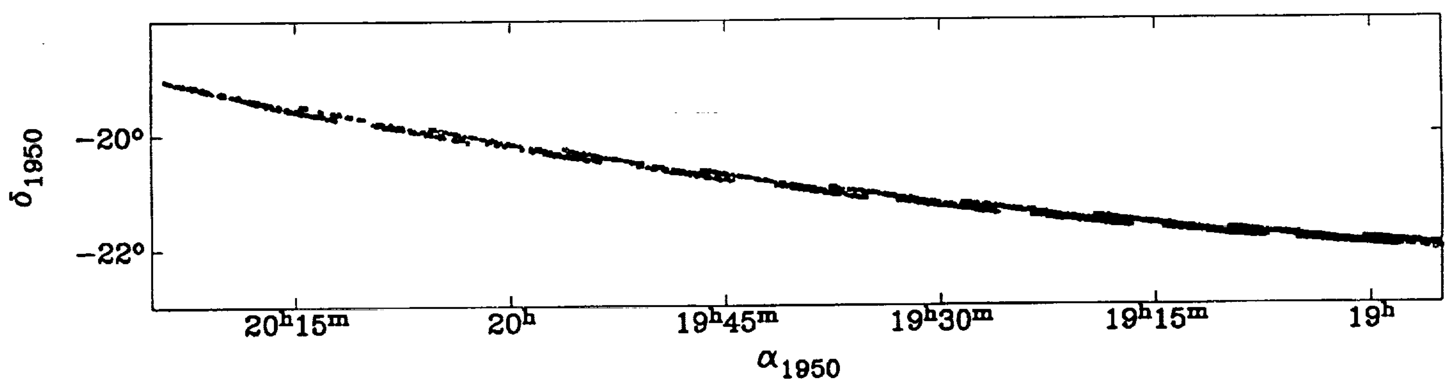

Figure 6b. Stars within 22 arcseconds of Neptune 1991-1999

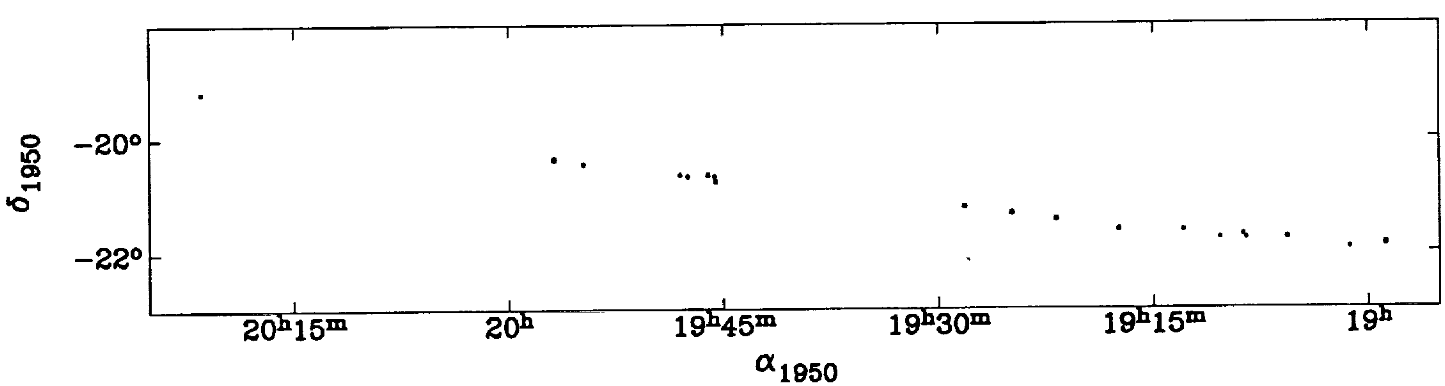

Figure 6c. Neptune Occultation Candidate Stars 1991-1999

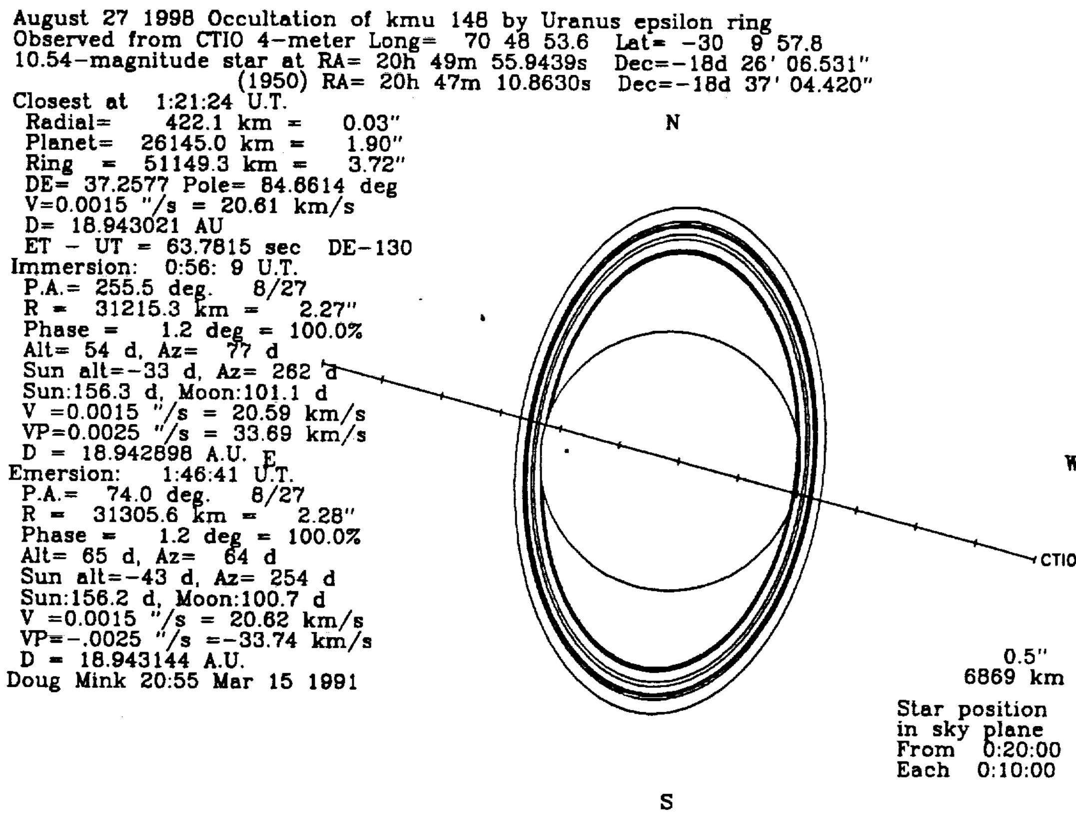

Figure 7. Track of KMU 148 relative to Uranus as seen from Cerro Tololo, Chile

Occultation of 28 Sagitarii by Saturn

Widespread interest in the 3 July 1989 occultation of 28 Sagitarii by Saturn and its ring system created a demand for precise predictions. Updated predictions for this event were sent to observers at the end of January 1989 and again in June 1989 after knowledge of the star's position was improved by the measurement of new photographic plates taken by Arnold Klemola at Lick Observatory. A paper was written for *Sky & Telescope* (in Appendix 4). Diagrams of the event were also provided to *Astronomy* magazine. The occultation fulfilled expectations, drawing attention to planetary astronomy as nothing but comets have in the past. The article in *Sky & Telescope* led to interviews with several newspapers and planetariums around the U.S., and updated predictions were supplied to serious amateurs in the International Occultation Timing Association. Appendix 5 contains the information sheet which was sent to observers on request, and Figure 8 shows a typical prediction for one observatory. Data reduction is still going on a year and a half after this event, and promises to tell us much about the fine structure of Saturn's ring system.

Occultations by 2060 Chiron

Programs to search the Space Telescope Guide Star Catalog CD-ROM have been written outside of this grant to satisfy the needs of astronomers at the Center for Astrophysics. Little additional work was needed to incorporate their output into the occultation search software. A test inclusion of external ephemerides was used to carry out a search for occultations by the interesting asteroid/comet Chiron ("Occultations of Space Telescope Guide Stars by 2060 Chiron: 1990-1995", by D.J.Mink and S.A. Stern, *Bull.Am.Astron.Soc.* 1990). Due to inaccuracies in the Chiron ephemeris used in this search, the specific events found in the original are unlikely to occur, but a more recent ephemeris provided by Lawrence Wasserman of Lowell Observatory was used to carry out the search shown in Figure 9, yielding the appulses in Table 3. The rate of one or two subarcsecond appulses per year shows that there is a good chance the region around Chiron can be probed with occultation observations.

July 3 1989 Occultation of 28 Sgr by F ring (approx.)
Observed from Palomar Obs. 200" Long= 116 51 50.0 Lat= 33 21 22.0
5.40-magnitude K2 star at RA= 18h 45m 43.3142s Dec=-22d 24' 20.307"
(1950) RA= 18h 43m 19.7700s Dec=-22d 26' 46.910"
Closest at 7:40: 4 U.T.
Radial= 5596.7 km = 0.86"
Planet= 60268.0 km = 9.21"
Ring = 140185.0 km = 21.43"
DE= 25.4021 Pole= 6.3158 deg
V=0.0031 "/s = 20.56 km/s
D= 9.021191 AU
ET - UT = 57.1961 sec DE-130
Immersion: 5:59:40 U.T.
P.A.= 261.8 deg. 7/ 3
R = 123935.4 km = 18.94"
Phase = 0.1 deg = 100.0%
Alt= 30 d, Az= 151 d
Sun alt=-29 d, Az= -29 d
Sun:179.0 d, Moon:175.6 d
V =0.0031 "/s = 20.52 km/s
VP=0.0034 "/s = 22.34 km/s
D = 9.021183 A.U.
Emersion: 9:27:34 U.T.
P.A.= 87.0 deg. 7/ 3
R = 132640.4 km = 20.27"
Phase = 0.1 deg = 100.0%
Alt= 31 d, Az= 207 d
Sun alt=-31 d, Az= 25 d
Sun:178.9 d, Moon:174.8 d
V =0.0031 "/s = 20.52 km/s
VP=-.0034 "/s =-22.23 km/s
D = 9.021209 A.U.
Doug Mink 21:12 Mar 15 1991

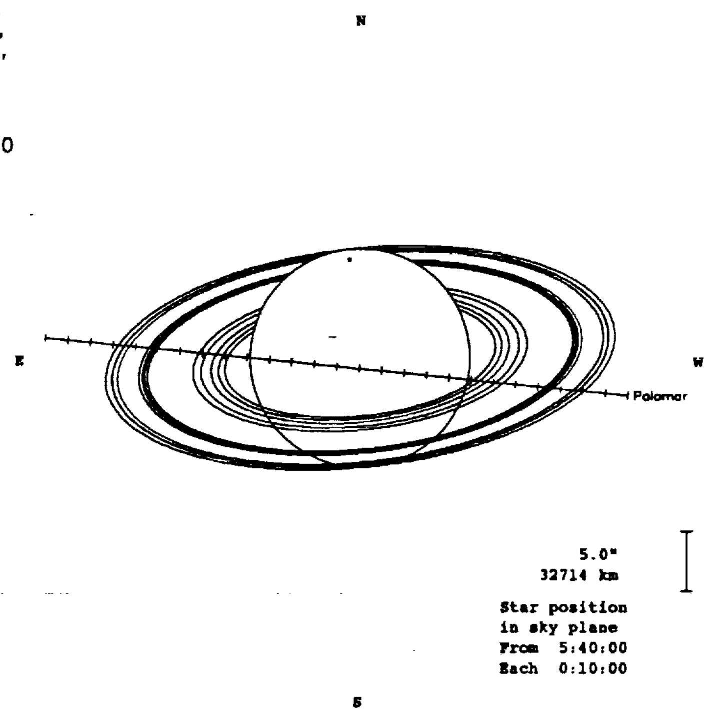

Figure 8. Track of 28 Sgr relative to Saturn as seen from Mt. Palomar

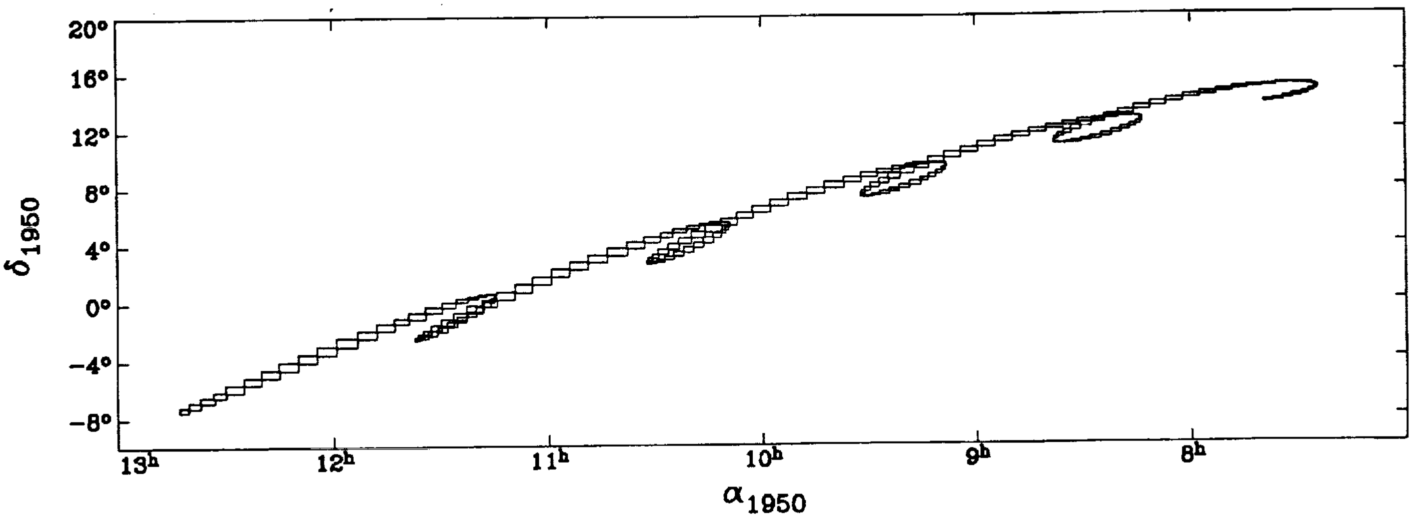

Figure 9a. 2060 Chiron from 1 January 1991 to 31 December 1995
Each rectangular box covers Chiron's motion in 10 days 50 arcseconds wide

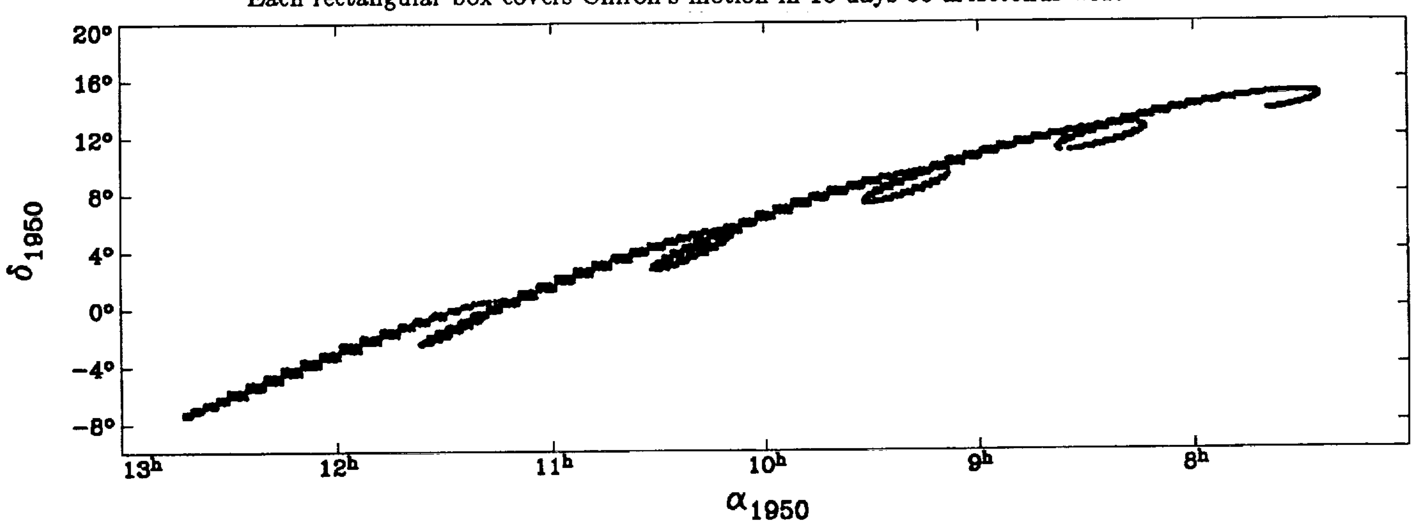

Figure 9b. Space Telescope Guide Stars within 50 arcseconds of Chiron 1991-1995

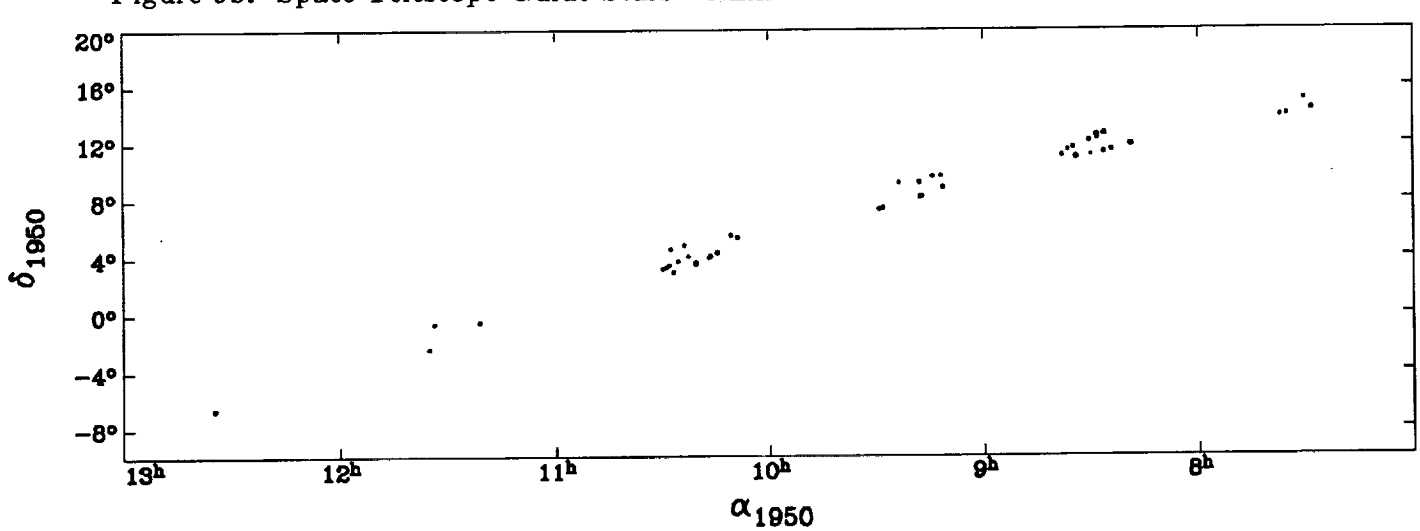

Figure 9c. Chiron Occultation Candidate Stars 1991-1995

Table 3. Possible Guide Star Occultations by 2060 Chiron 1991-1995

Closest Approach Date	U.T.	Distance (")	Sky Plane Velocity (km/sec)	Sun Angle (°)	Transit Longitude (°)	Star Position α_{1950}	δ_{1950}	Mv
	1991							
21 Jan	1:12:10	0.81s	20.50	170	24	7 35 12.102	13 55 56.82	13.77
24 Sep	22:34:13	0.67s	27.26	55	-146	8 28 18.502	12 19 10.46	11.37
19 Nov	1:49:30	1.91s	3.64	106	-45	8 38 06.085	11 06 49.87	14.50
	1992							
11 Jan	5:00:41	1.38s	18.57	161	57	8 30 03.568	11 08 37.96	14.71
5 Jun	12:37:12	0.42s	28.49	52	-44	8 26 14.148	12 37 32.84	11.07
	1993							
4 Jan	9:02:23	0.26n	13.04	141	97	9 29 06.950	7 21 13.53	14.48
15 Feb	14:13:39	0.44s	19.41	170	-141	9 17 42.250	8 11 02.69	12.11
17 Feb	18:48:52	1.28n	19.22	168	-70	9 17 04.922	8 14 34.13	14.08
17 May	17:57:05	0.18s	16.07	81	6	9 12 00.771	9 40 54.47	13.90
7 Nov	13:27:17	0.04s	22.97	68	92	10 25 32.630	3 45 56.29	14.27
21 Nov	14:50:38	0.24n	16.31	81	125	10 29 01.490	3 18 42.55	15.03
	1994							
7 Mar	10:49:45	0.60n	18.26	167	173	10 16 51.692	4 02 14.15	15.59
8 Mar	23:45:47	0.41n	18.07	166	8	10 16 26.459	4 05 16.84	11.38
29 Apr	9:28:08	0.68n	3.63	114	-154	10 08 44.748	5 24 18.55	13.73
23 May	1:24:13	1.19n	10.95	92	108	10 10 45.295	5 33 38.09	15.59
	1995							
4 Feb	5:32:26	0.06s	10.66	139	43	11 35 11.178	-2 24 42.57	14.03
1 Aug	20:43:29	0.71s	33.23	46	87	11 33 47.480	-0 37 26.60	14.27

Recommendations For Future Work

Incorporation of the ephemerides of the Uranian and Neptunian satellites, including those discovered by Voyager, into the occultation software is needed before an occultation survey for those bodies can be done. Current JPL satellite ephemerides only run to 1992. As the satellite software is not yet incorporated into the SAO occultation package, stars measured for 1991 have been passed on to Lawrence Wasserman at Lowell Observatory who has found several possible occultations by Triton. As time allows, the JPL satellite ephemerides will be incorporated into the SAO software.

Astrometric study of the plate catalogs produced for the occultation search has been postponed until the occultation work has been completed. To know how well to trust predictions of occultations of stars toward the faint limit of our catalog, postitions of stars on multiple plates will be compared. In addition, positions of stars found in the Guide Star Catalogue search will be compared to positions of the same stars on Arnold Klemola's plates. This is of interest to many users of the Guide Star Catalog as there has been no other astrometric test for stars fainter than those measured for transit circle catalogs. Results will be published if appropriate.

The catalogs of stars near Uranus, Neptune, and Pluto produced under this grant may be useful for other observations of these planets as well as astrometric references for additional occultation searches.

Much of the occultation software at the Center for Astrophysics is running on computers which are becoming obsolete. Those programs are labeled *(Vax)* in Figure 1. It is imperative that this software be moved to newer machines--crashes of old equipment caused weeks of delay in the current project. Some of the software is running on modern RISC computers--*(Sparcstation)* and*(Decstation)* in Figure 1--and it is hoped that the rest can be transferred in the next year.

For the Pluto and Charon events in Appendix 1, additional plate measurement of the stars and Pluto/Charon will be needed closer to the epoch of the events. Funding should be made available for these plates and the time needed to update the predictions.

Publications
(listed chronologically)

D.W. Dunham, D.W., Porco, C.C., and Mink, D.J. 1989. "Saturn to Occult a Bright Star" *Sky & Telescope*, 77, 638.

Mink, D.J. and Buie, M.W. 1989. "Automated Occultation Prediction using the Space Telescope Guide Star Catalog", *Bulletin of the American Astronomical Society*, 21, 1010.

Mink, D.J. and Klemola, A.R. 1989. "Occultations by Uranus, Neptune, and Pluto: 1990-1999", *Bulletin of the American Astronomical Society*, 21, 919.

Mink, D.J. and Stern, S.A. 1990. "Occultations of Space Telescope Guide Stars by 2060 Chiron: 1990-1995", *Bulletin of the American Astronomical Society*, 22, 1358.

Mink, D.J., Klemola, A.R., and Buie, M.W. 1991. "Occultations by Pluto and Charon: 1990-1999", accepted by *The Astronomical Journal.*

Klemola, A.R. and Mink, D.J. 1991. "Occultations by Uranus and Neptune: 1991-1999", submitted to *The Astronomical Journal*".

APPENDIX 1

OCCULTATIONS BY PLUTO AND CHARON: 1990-1999

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Abstract

The results of a photographic plate search for stars as faint as V=16 which may be occulted by Pluto or Charon between 1 January 1990 and 31 December 1999 are presented. Circumstances for the closest approach of Pluto to 32 stars and Charon to 28 stars are presented. Photometric information is given for some of the brightest stars found in a search of the Space Telescope Guide Star Catalog for Pluto occultations. Finding charts from Space Telescope Guide Star plates are provided for some of the best events. The brightest star (V=12.7) may be occulted by both Pluto and Charon on 26 September 1999.

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomical Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

1. Introduction

Pluto is now on its way out from the Sun, having come closest to the Sun on 7 September 1989 (The Pluto-Charon barycenter was closest on 5 September 1989). The smallest known planet in the solar system and its satellite Charon are slowly yielding their secrets to earth-based observations. Marcialis (1988) and Buie and Tholen (1989) have derived surface albedo maps from single point absolute photometry spanning a period of time from 1954 to 1986. Observations of mutual eclipses by Pluto and Charon (Binzel, *et al.* 1985, Tholen, *et al.* 1987, 1988) have provided information about Charon's orbit and the bulk density of the Pluto-Charon system. Stellar occultations, however, give high instantaneous spatial resolution views of that system, providing tests of models generated by analysis of other data.

Halliday (1963) first proposed conducting an ongoing search for occultations of stars by Pluto in order to determine its diameter. Observation of the event he predicted for 28 April 1965 (Halliday 1965) led to the establishment of an upper limit for Pluto's diameter of 6800 km (Halliday, *et al.* 1966).

Taylor (1978) forecast the close approach of a 13th magnitude star to Pluto on 6 April 1980. Walker (1980) observed an occultation by Charon of that star which set a lower limit of 600 km for Charon's radius. A search of the Palomar Sky Survey covering Pluto's path from 1979 to 1985 (Shelus & Benedict 1978) turned up a promising event on 15 April 1982 which went unobserved. A close approach of Pluto to a 9th magnitude star on 4 April 1983, predicted by diCicco (reported by Millis & Wasserman 1983), was observed but no occultation was seen. Taylor (1984) reported four unobserved possible occultations by Pluto of faint stars in 1984.

Mink and Klemola (1985) searched plates for Pluto occultations between 1985 and 1990. Brosch and Mendelson (1985) observed the second event, MKP2, but the nature of their observation remains uncertain. It appears, using the current Pluto ephemeris, that they may have observed a grazing occultation by Pluto's extended atmosphere. On 9 June 1988, the occultation of MKP8, the eighth event in Mink and Klemola (1985), was recorded by numerous observers in the South Pacific (Blow and Priestly 1988, Elliot *et al.* 1988; Kilmartin *et al.* 1988; Mattram *et al.* 1988; Millis 1988; Page *et al.* 1988; Walker *et al.* 1988b; Watson *et al.* 1988), and indications of an atmosphere on Pluto were seen (Elliot *et al.* 1989, Walker *et al.* 1988a).

This paper carries the occultation search through 31 December 1999, past Pluto's resumption of its title as ninth planet from the Sun on 15 February of that year. As Pluto moves farther out, it will cool, and the structure and composition of its atmosphere may change. Additional occultation observations will monitor these changes. An occultation of Charon at higher time resolution or with multiple observatories will better determine it's shape and size.

2. Astrometric and Photometric Observations: Coarse Selection

Photographic observations were made with the Lick 51-cm Carnegie astrograph, using 17x17-in (6x6 deg) yellow-sensitive Kodak 103aG plates with GG 14 filter. All exposures were 60 minutes in length, permitting stars somewhat beyond yellow magnitude 16 to be measured. The five plates, overlapping by about one degree in right ascension, were taken on three nights for which the mean epoch is 1989.4. The maximum range for the trajectory of Pluto is 26 deg. for the 10-year interval surveyed here. Currently Pluto is entering the Milky Way from Libra to Ophiuchus, with more numerous useful occultations compared to recent decades.

The search for occultation candidate stars was made in a way similar to our previous work (Mink & Klemola 1985). For the present survey a 10-day ephemeris of Pluto was computed using the JPL DE-130 ephemeris (Standish 1987) and used to identify candidate stars on the photographs, using the Lick Gaertner survey machine (Klemola, *et al.* 1987). Most stars in a band 4-5 arcmin across were recorded almost to the plate limit. The purpose of selecting stars in such a wide band is to construct a catalog of secondary reference stars suitable for small field astrometry, such as with large reflector telescopes, possibly employing CCD's as detectors. An example of such use was a search for occultation candidates done at MIT (Dunham *et al.* 1990).

Subsequently, the surveyed stars were measured for precise rectangular coordinates and reduced to equatorial coordinates for equinox 1950 in a way similar to that employed in our earlier survey. Reference stars were taken from the PERTH 70 catalog (Høg & von der Heide 1976). Because of the weakness of images in the last magnitude above the plate limit, the derived coordinates for those stars are less certain.

Measurements with the Lick Gaertner automatic measuring machine (Klemola et al. 1987) also provide photometer readings. These have been converted to approximate V-magnitudes, using mainly stars from the Guide Star Photometric Catalog (Lasker *et al.* 1988) for the Hubble Space Telescope. These stars occupy relatively small areas on Lick astrograph plates, so that needed position-dependent terms could not be included in the photometric reduction model. Consequently, our magnitudes should be regarded only as an approximate guide, particularly for the last magnitude, where extrapolation to the plate limit was required. There is some suggestion that our magnitudes may be too bright by about 0.5 mag. for the faintest stars.

3. The Occultation Survey

The first result of the survey was a catalog of coordinates (B1950) and magnitudes for 6329 stars from the five separately reduced plates. This initial catalog was then merged internally and with the catalog generated in our 1985 survey by combining stars measured on overlapping plates. Stars with coordinates within 0.5 arcsec from overlapping plates were regarded as identical and the separate coordinates averaged. The resulting catalog of 5825 stars was searched for possible occultations by Pluto and by Charon. This plate catalog is available in ASCII format from D. Mink.

The resulting catalog was sorted by right ascension and put into a database format designed for rapid random access. The search was conducted in two stages. A coarse search for stars within 10 arcsec of the paths of Pluto and Charon associated specific stars with specific dates. This search also dropped those stars passed by Pluto and Charon when they will be within 45 degrees of the Sun. Exact occultation circumstances were computed for the remaining candidates, and those stars further than 2 arcsec from the paths of Pluto or Charon were dropped.

Tables 1 and 2 give the results of this search. The events are numbered sequentially in time, and those stars occulted by both Pluto and Charon have the same number. Photometric measurements have been made for those stars which were found in a search of the Space Telescope Guide Star Catalog by Mink and Buie (1989 and below). Due to a lack of time and some questions about the quality of the GSC positions, no search for Charon candidates was carried out until now. No offset has been added to the DE-130 ephemeris other than that appropriate for the orbits of Pluto and Charon around their common center of mass.

In the tables:

- Number is the event number continuing from our previous survey (Mink & Klemola 1985). Stars are numbered sequentially and preceded by a "P" when Pluto passes within one arcsec of the star and a "C" when Charon passes within one arcsec of the star.
- Distance is the closest approach of the planet to the star in arcsec. "s" indicates that the star will appear to pass south of the planet, "n" that the star will pass north of the planet.
- Velocity is that of Pluto relative to the star on the sky plane in km/sec.
- Sun Angle is the angular distance in degrees between the planet and the Sun as seen from Earth. Small numbers mean that the region on the Earth where Pluto is above the horizon and the Sun is below the horizon is small.
- Right ascension and declination are given in B1950 coordinates.
- Mv is an approximate visual magnitude determined from the plate.
- Region of Observability is a brief description of that part of the earth where Pluto is above the horizon and the Sun is below the horizon.

4. Space Telescope Guide Star Search

In order to obtain aperture photometry of some of the candidate stars before the plates had been measured, a deep catalog of the appropriate part of the sky was needed. The Guide Star Catalog (Lasker *et al.* 1989), which contains stars from V=7 to fainter than V=14, was available at the Space Telescope Science Institute. The JPL DE-130 ephemeris was used to generate boxes containing Pluto's track through the sky for half a year at a time. These were written to an appropriately formatted file in Cambridge which was sent by computer network to Baltimore where it was used as input to the GSC search utility. A total of 46,461 entries were found in the search boxes, representing 23,575 point sources after duplicate entries from overlapping boxes were removed and positions from multiple plates were averaged. The remaining sources were sorted by right ascension, and a coarse search revealed 218 sources which Pluto would approach within 10 arcsec; 17 of those were approached within 2 arcsec. Due to an error in the software, the original search was incomplete, and only 9 of those stars were found in the original search and selected for photometric observation. Of those 9, 5006.0365 and 5006.0320, which will be approached by Pluto on 26 January 1990 and 16 September 1991, respectively, turned out to be galaxies rather than stars. As such extended sources are hard to find and may be incompletely occulted, they have been dropped from the prediction tables.

5. Photometry

The Guide Star Catalog search for Pluto occultation candidates yielded a total of 9 stars. These stars were observed by M. Buie at visible wavelengths with the 1.5-m telescope at Cerro-Tololo Interamerican Observatory on the night of 1989 May 28/29. Additional K-band observations were obtained by M. Buie at the United Kingdom Infrared Telescope on 1989 July 3.

The visible wavelength observations were obtained on the CTIO 1.5-m telescope at the f/13.5 Cassegrain focus using the People's Photometer with the Hamamatsu phototube, coldbox #71, and public filter set #3. The R and I filters are from the Kron-Cousins system. All observations were obtained through a 14 arc-sec aperture under dark and photometric skies. The standard stars used in the photometric reductions were taken from Landolt (1983). The photometry for the 9 candidate stars is shown in Table 3. The fit to the standard stars was good to 0.02 mag in the U filter while the other filters were slightly better fit. Two of the objects were known beforehand to be slightly extended objects (galaxies). The surface brightnesses of the galaxies were sufficiently low that a positive identification in the TV finder was not possible and no useful photometry was obtained.

The infrared measurements, also shown in Table 3, were derived from images taken at UKIRT with IRCAM (a 58 by 62 pixel array, infrared imaging camera). The UKIRT staff provided data upon which a linearization correction was applied. This raw data was then corrected by subtracting a bias-frame (zero-exposure frame from the camera), subtracting a dark frame (scaled to the same exposure time as the object image), dividing by a flat-field response image taken from the inside of the telescope dome, and subtracting a sky image from each object frame. The sky image used was taken immediately after each object frame at a position 60 arc-sec to the east of the object. Once each frame was calibrated in this manner, a total object flux was extracted from the image by summing the counts in a 6 pixel (3.6 arc-sec) radius circle centered on the star and subtracting the background determined from an average of the counts in an annulus with inner and outer radii of 10 and 20 pixels (6.2 and 12.4 arc-sec), respectively. The magnitudes listed in Table 3 should be good to 10-15% where the uncertainty estimate is entirely due to systematic errors and is derived from past experience of the UKIRT staff in using IRCAM. The random errors in all measurements were less than 1% in all cases.

6. Recommendations

Because of the faintness of Pluto and Charon, the observation of the occultation of any of the stars within our measurement limits could provide good data if observed with a telescope of large enough aperture. All of these stars are so faint at visible wavelengths that useful observations can best be obtained using 1-meter or larger telescopes.

There are three times when the same star may be occulted by both Pluto and Charon: 8 January 1995 (P/C24), 6 July 1995 (P/C28), and 26 September 1999 (P/C49). P/C24 may be occulted by both Pluto and Charon at some observatories (nominally in Europe). The 6 July 1995 event is most widely observable, the Pluto ground track being north of Charon's. With the nominal tracks over northern South America, a change in star position is likely to move the event toward more observatories. P/C49 is one of the brightest found in the search; it will cast Pluto's shadow less than one Earth diameter north of Charon's.

Among the Pluto events, good events include 1 March 1992 (P16), where a north-south occultation track could hit both Japan and New Zealand, 3 October 1993 (P20), visible in Australia, 17 April 1996 (P30), visible from the eastern U.S. and the Canary Islands, 9 July 1998 (P42), visible over Europe, Africa, and the Atlantic Ocean, and 27 February 1999 (P46), visible over India.

There are several good possibilities among the Charon events. On 20 June 1990 (C12), there is a promising occultation by Charon of a 15th magnitude star, with the nominal ground track across Cape York in Australia, crossing the Pacific near the equator. On 30 January 1992 (C15), Charon's nominal shadow hits the western U.S. The 28 July 1996 (C32) event with slight changes to the star's declination could hit either the east coast of the U.S. or South American observatories, and the 1 February 1999 (C45) event, with a slightly larger star position change, could touch Australia or Japan.

Finder charts for those stars considered to be the best occultation candidates in Tables 1 and 2, that is, those less than 0.5 arcsec from Pluto or Charon and observable from a large enough area to hit several telescopes, are provided in Figure 1. Each finder chart is an extraction from the digital plate catalog at the Space Telescope Science Institute. In all cases the chart covers a 7 by 7 arc-min patch of sky. At the bottom of each chart is the star ID (P for Pluto events and C for Charon events). The extraction was centered at the position on the plate (in the Guide Star Catalog plate coordinate system) that corresponded to the coordinate for each star as shown in Tables 1 and 2. The hollow symbol in each chart was placed at the center of each image and shows the coordinate of each star according to the Guide Star plate catalog solution. In most cases, the agreement is quite good. However, one of the stars does not closely fall in the predicted place according to the Guide Star Catalog. Close re-examination of the photographic plate measurements reported in this work, as well as the coordinates used to extract the portion of the Guide Star Catalog plate, did not reveal any errors. Therefore, we must conclude that there is a large (~3 arc-sec) systematic error in the Guide Star plate coordinates for that star. Further photographic plates will be measured in the future to improve positions and predictions for the stars in Tables 1 and 2.

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TABLE 1. Possible Occultations by Pluto 1990-1999

Number	Closest Approach Date	U.T.	Distance	Velocity (km/sec)	Sun Angle	α_{1950}	δ_{1950}	Mv	Region of Observability
	1990								
P10[a]	9 Jan	23:53	0.25s	21.2	63	15 14 25.440	-2 06 07.31	13.1	India
P11[a]	31 May	2:45	0.70n	21.3	152	15 09 16.333	-1 06 32.66	15.9	E. Americas
P12[a]	20 Jun	9:50	0.76s	16.5	134	15 07 29.799	-1 06 14.65	15.1	Central Pacific
P13[a]	5 Sep	14:49	0.58s	21.4	64	15 07 16.221	-1 48 20.30	15.4	India
	1991								
P14[a]	15 Sep	15:10	0.55n	24.1	57	15 17 03.742	-2 55 30.75	15.2	W.India
	1992								
P15[ab]	30 Jan	12:49	0.72s	14.6	78	15 34 05.532	-4 01 14.78	15.5	W. N.America
P16[a]	1 Mar	16:16	0.35n	7.1	108	15 34 59.050	-3 50 14.79	15.2	W. Pacific
P17[a]	21 May	6:19	0.20s	23.2	162	15 29 06.351	-3 11 38.97	14.3	N.+S.America, Hawaii
P18[a]	13 Sep	14:26	0.62n	22.6	61	15 25 56.817	-3 52 58.86	14.9	India
	1993								
P20	3 Oct	9:17	0.36n	28.5s	45	15 36 50.527	-5 06 50.77	12.4	E.Australia, Japan
	1995								
P23	5 Jan	13:58	0.69n	27.6	47	15 58 53.032	-6 53 58.54	14.8	W. N.America
P24[a]	8 Jan	3:37	0.27s	26.7	49	15 59 11.331	-6 54 16.65	13.7	Africa, Middle East
P25[c]	13 Mar	8:03	0.85n	7.2	111	16 02 40.652	-6 41 25.66	15.0	E. N.America, S.America
P26	7 May	2:05	0.46n	22.6	161	15 59 04.826	-6 17 16.59	14.7	Europe, Africa, S.America
P27[d]	14 Jun	14:36	0.54n	21.1	152	15 55 03.783	-6 09 06.26	14.7	W. Pacific
P28[a]	6 Jul	3:26	0.25n	15.7	133	15 53 13.669	-6 10 46.87	15.7	E. Americas
	1996								
P29[a]	27 Feb	17:02	0.75n	6.6	95	16 11 53.104	-7 43 24.09	16.3	W. Pacific
P30[a]	17 Apr	3:44	0.16n	18.2	143	16 10 16.559	-7 23 12.39	16.4	Europe, Africa, S.America
P31[a]	28 Jul	2:32	0.86s	9.5	114	16 01 20.764	-7 15 35.67	14.5	E. N.America, S.America
P33	6 Sep	22:55	0.81s	15.5	76	16 01 41.582	-7 37 44.39	16.1	E. S.America
P34[a]	19 Sep	14:44	0.05s	20.7	65	16 02 31.159	-7 46 22.72	15.3	India
	1997								
P35	10 Jan	23:35	0.57n	27.2	47	16 17 32.029	-8 44 14.17	15.6	India
P36	22 Feb	11:33	0.84n	8.9	88	16 20 55.933	-8 40 00.42	15.6	W. N.America
P37	9 May	4:21	0.78s	22.3	159	16 17 43.528	-8 12 14.12	15.7	E. Americas
	1998								
P40	28 Feb	14:03	0.48n	7.4	92	16 30 15.914	-9 32 28.49	15.6	New Zealand, Hawaii
P42[a]	9 Jul	22:00	0.06s	16.8	137	16 21 01.635	-9 03 30.47	14.7	Africa, Europe
P44	21 Sep	15:19	0.45n	19.1	68	16 20 40.094	-9 36 36.84	15.7	India
	1999								
P45[a]	1 Feb	18:52	0.57s	0.4	63	16 37 43.506	-10 29 39.10	14.7	Australia
P46[a]	27 Feb	23:32	0.07s	8.5	89	16 39 22.097	-10 25 27.11	15.1	India, Central Asia
P47	25 May	1:06	0.33s	23.4	167	16 34 58.401	-9 59 31.00	15.2	Europe, Africa, S.America
P48[a]	11 Jul	22:49	0.57s	17.0	138	16 30 13.718	-9 58 51.54	15.6	Europe, Africa, S.America
P49[a]	26 Sep	1:01	0.25s	19.7	66	16 29 58.316	-10 32 05.73	12.7	W. S.America, Carribean

[a] possible occultation by Charon
[b] Extremely weak image with uncertain position.
[c] Star not seen on Palomar Sky Survey plates. Despite stellar appearance on the Lick astrograph plate, it could be a film defect or previously unknown variable star.
[d] Palomar Sky Survey plates show faint companion several arcseconds to the southeast.

TABLE 2. Possible Occultations by Charon 1990-1999

Number	Closest Approach Date	U.T.	Distance	Velocity (km/sec)	Sun Angle	α_{1950}	δ_{1950}	Mv	Region of Observability
	1990								
C10[a]	9 Jan	23:53	0.84s	21.2	63	15 14 25.440	-2 06 07.31	13.1	India
C11[a]	31 May	2:46	0.58n	21.3	152	15 09 16.333	-1 06 32.66	15.9	S.America, E. N.America
C12[a]	20 Jun	9:51	0.05n	16.5	134	15 07 29.799	-1 06 14.65	15.1	Australia, New Zealand, Hawaii
C13[a]	5 Sep	14:37	0.06n	21.4	64	15 07 16.221	-1 48 20.30	15.4	India
	1991								
C14[a]	15 Sep	15:10	0.33n	24.2	57	15 17 03.742	-2 55 30.75	15.2	India
	1992								
C15[ab]	30 Jan	12:53	0.21s	14.5	78	15 34 05.532	-4 01 14.78	15.5	W. N.America, Hawaii
C16[a]	1 Mar	17:02	0.43n	7.2	108	15 34 59.050	-3 50 14.79	15.2	W. Pacific
C17[a]	21 May	6:18	0.80s	23.1	162	15 29 06.351	-3 11 38.97	14.3	N.America, S.America, Hawaii
C18[a]	13 Sep	14:28	0.34n	22.7	61	15 25 56.817	-3 52 58.86	14.9	India
C19	27 Sep	19:39	0.60s	27.7	48	15 27 18.130	-4 04 48.34	15.3	W. Africa
	1994								
C21	15 May	10:53	0.35s	23.5	165	15 48 42.805	-5 14 52.89	14.9	Pacific Ocean
C22	18 May	16:08	0.86n	23.4	166	15 48 22.272	-5 13 52.03	14.8	W. Pacific, India
	1995								
C24[a]	8 Jan	3:41	0.23s	26.7	49	15 59 11.331	-6 54 16.65	13.7	Africa, Middle East
C28[a]	6 Jul	3:20	0.10n	15.7	133	15 53 13.669	-6 10 46.87	15.7	S.America, E. N.America
	1996								
C29[a]	27 Feb	17:02	0.27n	6.8	95	16 11 53.104	-7 43 24.09	16.3	W. Pacific
C30[a]	17 Apr	3:51	0.97n	18.3	143	16 10 16.559	-7 23 12.39	16.4	Atlantic, S.America
C31[a]	28 Jul	2:16	0.04s	9.6	114	16 01 20.764	-7 15 35.67	14.5	S.America, E. N.America
C32[c]	28 Jul	8:20	0.76s	9.5	114	16 01 20.270	-7 15 42.13	14.6	Hawaii, New Zealand, Australia
C34[a]	19 Sep	14:55	0.48s	20.6	65	16 02 31.159	-7 46 22.72	15.3	India
	1997								
C38	4 Jun	22:23	0.88s	23.1	163	16 14 53.687	-8 06 11.42	16.1	Europe, Africa, Asia, Atlantic
	1998								
C39	25 Jan	13:41	0.27n	22.6	59	16 28 04.590	-9 37 52.53	15.3	W. N.America
C41	27 Jun	4:17	0.82n	20.1	148	16 22 06.146	-9 01 55.79	15.7	S.America, E. N.America
C42[a]	9 Jul	21:58	0.97s	16.7	137	16 21 01.635	-9 03 30.47	14.7	Europe, Africa, E. S.America
C43[a]	7 Aug	12:25	0.67s	8.2	110	16 19 33.762	-9 12 05.77	15.7	W. Pacific
	1999								
C45[a]	1 Feb	18:45	0.05s	20.4	63	16 37 43.506	-10 29 39.10	14.7	Australia
C46[a]	27 Feb	23:36	0.82n	8.4	89	16 39 22.097	-10 25 27.11	15.1	India, Central Asia
C48[a]	11 Jul	22:53	0.28n	17.1	138	16 30 13.718	-9 58 51.54	15.6	Europe, Africa, S.America
C49[a]	26 Sep	0:51	0.04s	19.7	66	16 29 58.316	-10 32 05.73	12.7	S.America, E. N.America

[a] possible occultation by Pluto
[b] Extremely weak image with uncertain position.
[c] This is southwest component of close pair of equal brightness.

TABLE 3. Photometry of Occultation Candidate Stars

Pluto Number	Closest Approach Date	U.T.	Guide Star Region	Guide Star Number	U	B	V	R	I	K
P/C10	1990 9 Jan	23:53	5006	309	13.83	13.78	13.13	12.72	12.32	11.4
galaxy	1990 26 Jan	13:20	5006	365	—	—	—	—	—	13.3
P/C12	1990 20 Jun	9:50	5001	764	15.56	15.70	15.13	14.78	14.43	13.4
galaxy	1991 16 Sep	13:58	5006	320	—	—	—	—	—	14.6
P/C17	1992 21 May	6:19	5020	294	14.26	14.16	13.47	13.03	12.59	11.6
P20	1993 3 Oct	9:16	5025	552	13.90	13.31	12.31	11.76	11.24	9.9
P/C24	1995 8 Jan	3:37	5044	934	15.90	15.37	14.41	13.88	13.31	12.0
P27	1995 14 Jun	14:36	5031	434	15.65	15.50	14.74	14.39	14.09	12.7
[a]	1995 6 Sep	6:00	5031	160	11.05	10.84	10.15	9.73	9.34	8.5

[a] Plate position missed Pluto by almost 2 arcsec, dropped from prediction table
$\alpha = 16\ 01\ 52.331$, $\delta =$ -7d 37 44.39

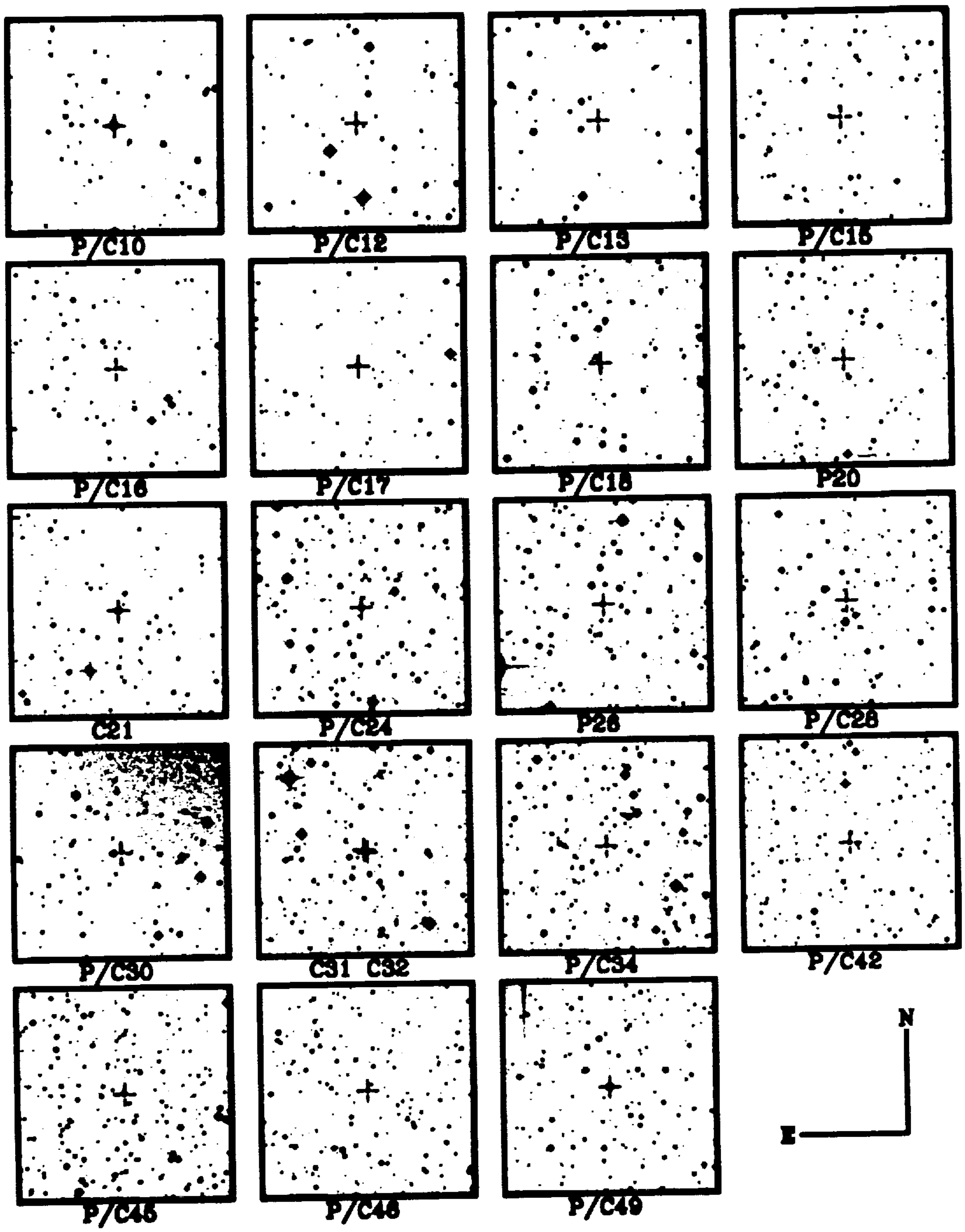

FIGURE 1. Finder charts for some stars which may be occulted by Pluto and Charon.

The numbers are the event numbers in Tables 1 and 2. Note that the star occulted by Charon in event C32 is on the lower right of the star labelled C31.

APPENDIX 2

OCCULTATIONS BY URANUS AND NEPTUNE: 1991-1999

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Abstract

The results of a photographic plate search for stars as faint as V=14 which may be occulted by Uranus or Neptune or their rings between 1 January 1991 and 31 December 1999 are presented. Circumstances for the closest approach of Uranus to 76 stars and Neptune to 18 stars are presented. Occultations by Neptune's ring "arcs" are predicted in 1992, 1997, and 1999.

1. Introduction

Observations of planetary occultations of the outer planets have led to the discovery of rings around Uranus (Elliot *et al.* 1977) and the discovery of ring "arcs" around Neptune (Reitsema *et al.* 1982; Hubbard 1986), as well as knowledge about the shape of the planets (Baron *et al.* 1989, Hubbard *et al.* 1987). The Voyager 2 imaging, photopolarimeter and radio occultation experiments provided snapshot views of Uranus in 1986 (Gresh *et al.* 1989; Colwell *et al.* 1990) and Neptune in 1989 (Smith *et al.* 1989; Lane *et al.* 1989; Tyler *et al.* 1989). However, future occultation measurements can play an important part in an ongoing program to monitor these complex systems.

A model of the orbits of the Uranian rings was developed from occultation observations (French *et al.* 1982), and further improvements were made as more occultations, including those from Voyager 2, were observed (French *et al.* 1988). Now that Voyager 2 has passed Uranus, additional occultations can be used to further refine the time-dependent parameters of the ring model. This search provides a variety of events from which observers can select those which will provide the most information.

Voyager 2's confirmation of the existence of Neptune's rings ended the speculation that had been going on since the discovery of the Uranian rings. Many occultation observations have shown no trace of ring material (Elliot *et al.* 1981 and 1985; Sicardy *et al.* 1983; Hubbard *et al.* 1985). Others (Sicardy *et al.* 1985; Brahic *et al.* 1986; Covault *et al.* 1986; Brahic *et al.* 1987) observed part of what we now know to be a ring system around Neptune. Sicardy *et al.* (1990) summarize positive and negative observations of the Neptune ring arcs. Nicholson *et al.* (1990) combine Voyager 2's observations of a ring system containing regions of denser material with the ring arcs observed from the ground. Additional occultation observations will aid in characterizing the nature and extent of those parts of Neptune's ring system which are opaque enough to occult stars.

Earlier plate searches for occultations by Uranus covered the intervals 1977-1980 (Klemola & Marsden 1977), 1981-1984 (Klemola *et al.* 1981), and 1985-1990 (Mink & Klemola 1985a). Taylor (1978) searched for occultations by Uranus of stars in the SAO Star Catalog through 1989. For Neptune, previous searches covered the years 1978-1980 (Klemola *et al.* 1978), 1981-1984 (Mink *et al.* 1981), and 1985-1990 (Mink & Klemola 1985a). Nicholson *et al.* (1988) searched for Uranus and Neptune events in the near-infrared. Searches for occultations by satellites of Uranus and Neptune were undertaken for the period 1983-1985, based on plate catalogs made for the 1981-84 survey (Mink & Klemola 1982), and for the period 1985-1990, based on the plate catalogs made for the 1985-1990 survey (Mink & Klemola 1985b).

The catalogs of stars near which Uranus and Neptune will pass provide astrometric standards for other occultation searches which may go to fainter or redder limits. Nicholson *et al.* (1988) used the stars from the 1985-1990 survey in that way. These stars may also be used as standards for high resolution astrometric or photometric observations of the outer planets or their satellites.

This paper carries the occultation search through 31 December 1999, past Neptune's resumption of its title of eighth planet from the Sun on 15 February of that year.

2. Astrometric and Photometric Observations: Coarse Selection

Photographic observations were made with the yellow lens of the Lick 51-cm Carnegie astrograph, using 17x17-in (6x6 deg) yellow-sensitive Kodak 103aG plates with GG 14 filter. All exposures were 30 minutes in length, permitting stars somewhat beyond yellow magnitude 15 to be measured. The nine photographic plates, overlapping up to one degree in right ascension, were taken on three nights for which the mean epoch is 1989.5. The trajectory of Uranus spans 46 deg. for the 10-year interval (1990-1999) surveyed here. The results for 1990, which are not included in this paper, were distributed earlier to some interested observers. During this decade Neptune remains about one degree north of the trajectory of Uranus. Consequently, the same set of photographs is used for the survey reported here, where Neptune is measured on six of the nine plates. Currently, both planets are leaving the Milky Way from Sagittarius to Capricornus, with progressively fewer useful occultations during the course of the coming decade and beyond.

The search for occultation candidate stars was made in a way similar to our previous work (Mink & Klemola 1985) and the concurrent Pluto survey (Mink *et al.* 1990). For the present survey the 10-day ephemerides of Uranus and Neptune were computed using the JPL DE-130 ephemeris (Standish 1987) and used to identify candidate stars on the photographic plates visually scanned with the Lick Gaertner survey machine (see Part IV in Klemola *et al.* 1987). As an aid to identifying stars on the photographs, these ephemerides were subdivided into one-day steps, using a simple interpolation scheme.

For Uranus the coarse survey includes most stars almost to the plate limit in a band of half-width 50 arcsec in declination and the same range in right ascension near the turn-around points of the trajectories. This band encloses the extreme ranges in declination for the four Uranian satellites Ariel (14"), Umbriel (20"), Titania (34"), and Oberon (45"). For Neptune the surveyed band has a half-width of about 22 arcsec in declination, adequate to enclose the motion of Triton (16"). Although no effort was made to enclose the motion of the faint satellite Nereid (252"), the chosen band should yield some useful occultation candidate stars from an extension of our survey. Moreover, the catalog of stars from the present survey may be useful as position reference objects for small-field astrometry associated with these planets and their satellites and may yield some useful occultation candidate stars for a future extension of our survey.

The reduction for equatorial coordinates for equinox 1950 was carried out in a way similar to that employed in our earlier survey (Mink & Klemola 1985) and the concurrent Pluto survey (Mink *et al.* 1990). Reference stars from the PERTH 70 catalog (Hog & von der Heide 1976) define the reference frame. Because of the weakness of images in the last magnitude interval above the plate limit (near V= 15), the derived coordinates for those stars are less certain.

Photometer readings, derived from the two-dimensional Reticon of the Lick Gaertner automatic measuring machine (Klemola *et al.* 1987), were converted to approximate V-magnitudes, using stars from the Guide Star Photometric Catalog (Lasker *et al.* 1988) for the Hubble Space Telescope. Since these standard stars occupy only one or two relatively small areas on Lick astrograph plates, the needed position-dependent terms could not be included in the photometric reduction model. Moreover, the absence of adequate standard stars for the last magnitude above the plate limit required an extrapolation for the photometric transformation. There is indication that our magnitudes may be unreliable by 0.5 mag., or more, despite a measurement precision that is some small fraction of this. Consequently, our magnitudes must be regarded only as an approximate guide.

3. The Occultation Survey

The first results of the survey were catalogs of coordinates (B1950) and magnitudes for 11780 stars for Uranus and 4818 stars for Neptune from the separately reduced plates. These initial catalogs were then merged with the catalogs generated in our earlier surveys, combining measurements from multiple scans and overlapping plates. Stars with coordinates within 1.0 arcsec from overlapping plates and within 0.3 arcsec from multiple measurements of the same plate were regarded as identical and the separate coordinates averaged. A catalog of 8469 stars was searched for possible occultations by Uranus and its rings, and a catalog of 3631 stars was searched for possible occultations by Neptune over the years 1990 through 1999.

The resulting catalogs were sorted by right ascension and put into a database format designed for rapid random access. Searches were conducted in two stages. Coarse searches for stars within 10 arcsec of the paths of Uranus and Neptune associated specific stars with specific dates. Those stars passed by Uranus and Neptune when they are within 45 degrees of the Sun iwere dropped at this stage. Exact occultation circumstances were computed for the remaining candidates, and those stars further than 5 arcsec from the path of Uranus or 2 arcsec from the paths of Neptune were dropped. For consistency with our previous work, we eliminated all stars with V magnitudes fainter than 14 for Uranus and 14.25 for Neptune. We also dropped all stars occulted before 1 January 1991, to avoid overlap with our previous paper. This left 76 stars which might be occulted by Uranus and its rings and 18 stars which might be occulted by Neptune.

Each candidate star was examined visually under high magnification on both the Lick astrograph plates and Palomar Sky Survey blue prints to verify the reality of the measured images and to note possible nearby faint stars. If there are stars within about 10" of the candidate star on POSS, these are noted in Tables 1 and 2 with a letter "a" after the event number. Unless otherwise noted, such stars are too faint to be seen on astrograph plates and, consequently, should have no adverse influence on our measured coordinates. Any future deep CCD photometry or astrometry of such stars may need to be treated with care. Normally if a faint companion star lies over 4-5" away, the position measurements of faint target stars at the magnitude range of this study are not affected on yellow astrograph plates. Virtually all of our selected candidate stars lie well above the astrograph plate limit and have well-exposed images.

Tables 1 and 2 give the results of these searches. The events are numbered sequentially in time, continuing from our previous papers (Mink & Klemola 1985). Chanover and French (1990) have computed the positions of Neptune's ring arcs for the events in Table 2, and those stars for which ring arc occultations are predicted are noted.

Explanation of Tables 1 and 2

- Number is the event number continuing from our previous surveys. Events are numbered sequentially and preceded by a "N" for Neptune and and a "U" for Uranus.
- Distance is the closest approach of the planet to the star in arcsec. "s" indicates that the star will appear to pass south of the planet and "n" that the star will pass north of the planet.
- Velocity is that of the planet relative to the star on the sky plane in km/sec.
- Sun Angle is the angular distance in degrees between the planet and the Sun as seen from Earth. Small numbers mean that the region on the Earth where the planet is above the horizon and the Sun is below the horizon is small.
- Right ascension and declination are given for the equinox B1950 and epoch of observation 1989.5.
- Mv is an approximate visual magnitude determined from the plate.
- Region of Observability is a brief description of that part of the earth where the planet is more than 20 degrees above the horizon and the Sun is more than 10 degrees below the horizon.

4. Recommendations

Uranus is still moving across a star-dense region of the Milky Way at the start of our survey, so that there are many events from which to choose. The brightest stars are U137 (SAO 189232) on 16 March 1996 and U138 (SAO 163583) on 10 April 1996. The areas of visibility for these events are small, but cover major observatories. The occultation of U138, an M0 star, should be an especially good event in the infrared. In addition to these events, widely visible, near-central occultations occur on 8 July 1992 (U102), 13 July 1994 (U126), and 27 August 1998 (U148).

Neptune is emerging from the galactic plane into a much less dense region of stars, so there are few events in the 1990's. Those Neptune events occurring on 18 July 1993 (N66) and 6 September 1996 (N72) stand out as the best planet occultations, with the best observability and the most central events. U74 (SAO 188797), on 29 November 1997, is the brightest star occulted, but the occultation is only visible from Western Australia and Southeast Asia. On 11 July 1992 (N61), 6 November 1997 (N73), and 22 March 1999 (N75), occultations by Neptune's ring arcs are possible. A further effort will be made to search for ring arc occultations by the fainter stars in our plate catalogs. Additional photometry of the candidate stars, as was done for stars in our previous paper by Covault and French (1986), French *et al.* (1986), and Vilas and Mink (1986), is encouraged.

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TABLE 1. Possible Occultations by Uranus 1991-1999

Number	Closest Approach Date	U.T.	Distance	Velocity	Sun Angle	α_{1950}	δ_{1950}	Mv	Region of Observability
	1991		"	km s^{-1}	°	h m s	° ' "		
U77[a]	18 Feb	10:44:01	2.44n	27.54	47	18 51 31.283	-23 14 37.03	12.9	C.America,Carribean
U78[b]	18 Feb	19:23:18	3.98s	27.40	47	18 51 35.564	-23 14 38.66	12.8	Australia
U79[a]	23 Feb	13:08:32	4.86n	25.59	52	18 52 29.399	-23 13 29.03	13.9	Mexico,E.Pacific
U80	24 Feb	01:32:20	0.97s	25.38	52	18 52 35.089	-23 13 28.43	13.0	W.Africa
U81	10 Mar	01:27:44	0.27n	19.39	66	18 54 50.760	-23 10 52.83	11.9	W.Africa
U82[c]	03 Jun	14:41:33	1.50s	18.50	150	18 54 04.264	-23 14 02.38	13.3	Australia,Hawaii,New Zealand
U83[a]	25 Jun	13:12:17	2.37s	22.25	171	18 50 33.027	-23 18 46.74	12.8	Australia,Hawaii,New Zealand
U84[a]	28 Jun	10:36:43	3.25s	22.44	174	18 50 02.886	-23 19 25.64	12.7	Australia,Hawaii,N.Z.,W.U.S.
U85	6 Aug	13:40:04	1.35n	17.80	147	18 43 36.120	-23 26 40.82	13.8	Australia,E.Asia,New Zealand
U86	13 Aug	14:17:23	4.31n	15.64	140	18 42 41.651	-23 27 32.18	13.7	Australia,E.Asia,New Zealand
U87[d]	16 Aug	10:38:10	3.77s	14.66	137	18 42 21.773	-23 27 59.49	13.8	Australia,Hawaii,New Zealand
U88[e]	16 Aug	13:43:00	3.70s	14.62	137	18 42 20.906	-23 28 00.25	13.7	Australia,E.Asia
U89	13 Sep	04:47:47	1.43n	2.96	110	18 40 25.849	-23 29 34.24	13.8	W.N.America,S.America
U90	17 Oct	23:44:20	2.52s	14.37	76	18 41 52.756	-23 27 49.42	13.7	E.N.America,S.America
U91[f]	21 Oct	16:14:59	1.81s	16.14	73	18 42 17.346	-23 27 21.73	13.7	Arabia,E.Africa
U92[g]	27 Oct	04:01:55	1.62n	18.72	67	18 42 59.018	-23 26 32.72	13.8	E.Pacific
U93	29 Oct	10:49:23	2.29s	19.77	65	18 43 18.111	-23 26 15.74	12.8	Australia,E.Asia
	1992								
U94	28 Feb	20:17:10	1.16n	25.24	53	19 10 46.505	-22 49 39.07	13.6	W.Australia
U95	2 Mar	07:23:26	0.48n	24.25	55	19 11 12.488	-22 48 59.32	13.2	E.S.America
U96	12 May	08:53:31	3.37n	9.53	124	19 14 59.745	-22 44 19.11	12.6	E.N.America,W.S.America
U97[h]	27 May	17:06:45	2.82s	15.38	139	19 13 32.673	-22 47 22.17	13.6	E.Asia,Australia,New Zealand
U98	28 May	03:25:31	1.81n	15.52	140	19 13 29.607	-22 47 23.46	13.3	W.Africa,S.America
U99[i]	4 Jun	10:59:59	1.52n	17.78	147	19 12 33.949	-22 49 10.14	14.0	W.N.America,Hawaii,New Zealand
U100[j]	4 Jun	13:20:56	3.75n	17.81	147	19 12 33.131	-22 49 09.42	13.8	Hawaii,Australia,New Zealand
U101	8 Jul	00:54:43	1.37n	22.62	180	19 07 09.370	-22 58 39.42	13.7	Africa,S.Europe,S.America
U102	8 Jul	10:07:28	0.27n	22.62	179	19 07 05.365	-22 58 47.10	13.0	W.N.America,Hawaii,New Zealand
U103	11 Jul	08:17:56	2.80n	22.56	177	19 06 34.794	-22 59 34.43	13.5	W.N.America,W.S.America,Hawaii
U104	14 Jul	05:11:12	3.93n	22.43	174	19 06 04.917	-23 00 21.47	12.0	N.America,S.America
U105[a]	19 Jul	12:41:26	1.66s	22.01	168	19 05 10.325	-23 01 53.71	13.7	E.Asia,Australia,N.Z.,Hawaii
U106	29 Jul	22:55:30	4.26n	20.48	158	19 03 27.556	-23 04 25.83	14.0	Africa,S.Europe,E.S.America
U107[k]	21 Oct	11:08:48	1.53s	14.33	76	19 00 04.932	-23 08 35.46	13.8	Australia,E.Asia
U108[l]	11 Nov	21:49:41	0.52n	24.11	55	19 03 03.493	-23 03 56.48	14.0	E.S.America
U109	17 Nov	18:44:19	2.73n	26.45	50	19 04 06.682	-23 02 15.42	14.0	W.Africa
	1993								
U110	26 Feb	19:43:03	3.64s	27.29	47	19 27 40.520	-22 20 32.97	12.7	Australia
U111	14 Apr	09:34:09	0.26n	5.94	92	19 33 20.213	-22 09 37.23	12.6	E.N.America,W.S.America
U112[a]	27 May	13:30:01	3.94n	13.75	134	19 31 55.825	-22 13 56.03	13.3	E.Australia,New Zealand,Hawaii
U113	3 Jun	15:29:09	3.90s	16.15	141	19 31 08.287	-22 15 57.85	12.6	Australia,New Zealand,Japan
U114	24 Jul	05:24:38	3.85s	22.03	168	19 23 06.684	-22 33 15.90	12.3	N.America,S.America
U115	27 Jul	21:43:10	0.91s	21.58	165	19 22 29.945	-22 34 25.52	10.4	Africa,Europe,E.S.America
U116	8 Aug	22:17:02	4.55n	19.34	153	19 20 37.034	-22 37 57.39	14.0	Africa,Europe,E.S.America
U117[a]	21 Oct	14:07:47	3.78n	12.20	80	19 17 39.967	-22 42 30.21	13.4	Indonesia,India,W.Australia
U118	21 Oct	22:57:04	1.15s	12.38	80	19 17 41.965	-22 42 31.13	13.7	E.S.America,NE.U.S.
U119	4 Nov	13:46:50	0.27s	18.94	67	19 19 13.499	-22 39 26.69	13.1	India,Indonesia
U120[m]	9 Nov	14:15:56	4.27s	21.22	62	19 19 56.405	-22 38 05.29	13.7	India
U121	23 Nov	16:06:27	2.13s	27.02	48	19 22 20.169	-22 33 15.62	13.6	E.Africa

TABLE 1 *(continued)*. Possible Occultations by Uranus 1991-1999

Number	Closest Approach Date	U.T.	Distance	Velocity	Sun Angle	α_{1950}	δ_{1950}	Mv	Region of Observability
	1994		"	km s^{-1}	°	h m s	° ' "		
U122	15 Mar	16:13:02	0.42s	22.28	59	19 47 29.519	-21 37 33.46	11.7	New Zealand,Hawaii
U123	16 Mar	00:31:25	3.92s	22.13	60	19 47 32.777	-21 37 29.30	13.4	Indian Ocean
U124[a]	27 Mar	12:18:48	0.93s	16.93	71	19 49 07.192	-21 33 44.01	13.7	Mexico,SW.U.S.
U125	19 Apr	12:38:44	1.61n	5.57	93	19 50 58.090	-21 29 36.50	14.0	E.Asia,Australia,New Zealand
U126	13 Jul	01:41:41	0.27s	22.60	176	19 43 29.727	-21 50 46.33	13.8	S.America,Africa,SW.Europe
U127	27 Jul	15:34:38	4.77s	22.16	170	19 41 01.373	-21 56 55.54	13.9	Asia,Australia,New Zealand
U128	1 Aug	06:02:15	2.81s	21.65	165	19 40 15.760	-21 58 42.68	14.0	N.America,S.America,Hawaii
U129	13 Aug	23:15:29	0.84s	19.24	152	19 38 17.715	-22 03 16.10	14.0	S.America,Africa,SW.Europe
U130	20 Aug	09:18:15	4.33s	17.54	146	19 37 24.560	-22 05 20.04	13.9	Australia,New Zealand,Hawaii
U131	13 Nov	11:49:08	0.81n	21.00	62	19 37 36.239	-22 03 19.21	13.0	Australia,S.E.Asia
U132[n]	19 Nov	08:34:55	3.65n	23.53	57	19 38 30.884	-22 01 03.75	13.4	New Zealand
U133[a]	25 Nov	19:47:48	1.83n	26.15	50	19 39 37.862	-21 58 22.75	13.5	W.Africa
	1995								
U134	9 Sep	18:44:34	1.55n	12.10	130	19 53 09.707	-21 28 17.46	11.2	Africa,S.E.Europe,S.W.Asia
U135	13 Nov	23:26:24	1.88n	19.20	66	19 54 32.976	-21 23 09.49	14.0	E.S.America,E.N.America
U136[a]	18 Nov	15:39:59	1.51s	21.33	61	19 55 12.314	-21 21 20.60	13.1	Middle East
	1996								
U137[o]	16 Mar	15:21:55	0.74s	25.06	53	20 20 53.603	-20 04 07.63	9.0	Hawaii
U138[p]	10 Apr	11:39:46	1.07s	13.96	77	20 24 13.557	-19 53 44.00	9.9	Mexico,SW.U.S.
U139	25 Jul	02:57:22	0.97s	22.70	179	20 17 25.692	-20 19 14.55	13.6	S.America,Africa,E.N.America
U140	25 Nov	10:36:03	0.39n	22.82	58	20 12 56.343	-20 31 26.63	13.6	E.Australia,China
	1997								
U141	15 Mar	06:01:08	2.39n	27.20	47	20 36 44.402	-19 10 36.28	13.5	W.Africa
U142	5 Apr	09:43:32	3.86n	18.42	68	20 39 59.319	-18 59 09.97	14.0	W.S.America
U143	8 Sep	16:37:28	0.85s	15.48	139	20 28 18.251	-19 44 38.72	13.6	Africa,Asia,Australia
U144	30 Sep	22:37:42	2.35n	6.48	117	20 26 31.178	-19 50 17.48	12.8	E.S.America,Africa
	1998								
U145	27 Mar	19:08:36	2.23s	24.02	55	20 54 41.985	-18 03 16.03	13.0	Australia
U146	14 Apr	23:52:53	2.49s	15.95	73	20 57 07.192	-17 53 58.06	13.3	India
U147	30 Jun	04:38:34	4.14s	17.76	146	20 55 58.772	-18 01 26.05	13.7	S.America,Africa,E.N.America
U148	27 Aug	01:19:01	0.09n	20.25	156	20 47 10.863	-18 37 04.42	10.5	S.America,Africa,E.N.America
U149	6 Nov	04:30:42	0.99n	9.41	85	20 43 29.618	-18 49 35.17	11.5	Hawaii,W.N.America
	1999								
U150	4 Aug	05:33:28	4.48s	22.75	176	21 07 46.603	-17 13 57.20	12.9	Hawaii,Australia,New Zealand
U151	31 Aug	10:25:18	3.80s	20.29	156	21 03 33.624	-17 32 02.01	13.7	Hawaii
U152	27 Nov	00:21:11	3.39s	17.61	69	21 01 22.583	-17 38 54.07	13.4	E.N.America, S.America

Notes to TABLE 1. Possible Occultations by Uranus 1991-1999

[a] denotes faint stars seen within about 10" of candidate star on Palomar Sky Survey (POSS) O (blue) print

[b] U78: Slight contamination wit the grating image of nearby bright star, so that measure position could be slightly affected. Very faint stars seen to SW an SE on POSS.

[c] U82: Fainter star about 10" to N seen on astrograp (an POSS) plate.

[d] U87: E component of two stars (W component = U88).

[e] U88: W component of two stars (E component = U87).

[f] U91: Slight contamination wit the grating image of nearby bright object, so that measure position could be slightly affected.

[g] U92: Faint star seen 2-3" to S, so that measure position must be mean of partially blende images.

[h] U97: NE component of two stars.

[i] U99: E component of pair (W component = U100).

[j] U100: W component of pair (E component = U99).

[k] U107: Faint star about 10" to N seen on astrograp (an POSS) plate.

[l] U108: Faint star about 2-3" to NE seen on astrograp plate (elongate on POSS).

[m] U120: Faint star seen about 8-10" to W on astrograp (an POSS) plate.

[n] U132: SE component of two stars of same brightness. Faint star to SW of candidate star seen on POSS.

[o] U137 is SAO 189232 (G0, M_v=8.5)

[p] U138 is SAO 16358 (M0, M_v=9.2)

TABLE 2. Possible Occultations by Neptune 1991-1999

Number	Closest Approach Date	U.T.	Distance	Velocity	Sun Angle	α_{1950}	δ_{1950}	Mv	Region of Observability
	1991		"	km s^{-1}	°	h m s	° ′ "		
N58	19 Mar	12:49:08	0.62n	15.14	72	19 08 43.689	-21 41 57.51	14.0	SW.N.America
N59[a]	22 Jun	01:00:08	1.27s	22.78	164	19 05 39.317	-21 45 48.95	12.7	Africa,Europe,S.America
N60[a]	19 Nov	12:59:37	0.19n	25.80	48	19 01 17.874	-21 56 29.58	13.8	India
	1992								
N61[b]	11 Jul	18:21:38	1.43n	23.85	178	19 12 55.148	-21 37 37.97	14.0	Australia,Asia,E.Africa
N62	24 Aug	18:49:06	1.88s	15.05	135	19 08 31.289	-21 46 03.65	14.1	Hawaii,New Zealand,E.Australia
N63	18 Nov	08:00:08	0.63s	24.78	51	19 10 20.833	-21 45 46.50	13.8	Central Pacific
	1993								
N64	8 May	08:02:48	1.51s	7.45	117	19 28 08.744	-21 12 15.20	12.9	S.America,E.N.America
N65	21 Jun	03:02:46	1.68n	22.00	159	19 24 51.015	-21 18 48.14	13.0	S.America,Africa,SE.Europe
N66[a]	18 Jul	12:20:54	0.27s	23.71	174	19 21 45.925	-21 25 12.20	12.7	Australia,New Zealand,Hawaii
N67	25 Oct	13:49:51	1.68n	12.94	76	19 17 22.995	-21 36 12.93	13.7	India,SE.Asia,W.Australia
	1995								
N68	26 May	08:47:06	1.07n	12.97	129	19 46 04.300	-20 38 20.63	12.4	S.America,N.America
N69	2 Jun	05:16:58	1.85n	15.53	136	19 45 36.549	-20 39 28.59	12.0	S.America
	1996								
N70	8 Aug	23:53:37	1.94s	21.93	159	19 48 01.129	-20 37 58.12	14.2	Africa,SE.Europe,S.Americaa
N71[a]	14 Aug	09:01:45	1.72n	20.83	154	19 47 28.271	-20 39 24.73	11.4	Hawaii,New Zealand,E.Australia
N72	6 Sep	22:44:14	0.24s	13.49	131	19 45 31.511	-20 44 53.87	13.2	Africa,SE.Europe,S.Ameria
	1997								
N73[c]	6 Nov	11:38:12	0.18s	14.48	73	19 54 46.590	-20 26 04.70	13.7	Australia,SE.Asia
N74[d]	29 Nov	11:11:16	1.01n	24.82	51	19 56 50.689	-20 20 51.68	8.9	Australia,SE.Asia
	1999								
N75[e]	22 Mar	09:12:06	0.80n	21.89	57	20 21 24.769	-19 10 37.92	14.1	W.S.America

[a] denotes faint stars seen within about 10" of candidate star on Palomar Sky Survey O (blue) print

[b] N61 may be occulted by the leading ring arc after Neptune emersion

[c] N73 may be occulted by the middle ring arc before Neptune immersion

[d] N74 is SAO 188797 (K0 M_v=9.1); SAO catalog has erroneous proper motion

[e] N75 may be occulted by the trailing ring arc before Neptune immersion

APPENDIX 3

Abstracts of Conference Presentations

American Astronomical Society, Division on Dynamical Astronomy 28-30 August 1989, Pasadena, California

Automated Occultation Prediction using the Space Telescope Guide Star Catalog

D. J. Mink (CfA) and M. W. Buie (STScI)

An automated system for predicting occultations of stars by planets and satellites has been developed based on rapid star catalog access, JPL planetary ephemerides, and additional satellite orbit computations. The Space Telescope Guide Star project has developed an all-sky catalog covering sources almost as faint as previous photographic occultation plate searches have gone. A search was undertaken using the Space Telescope Guide Star catalog for occultations by Uranus, Neptune, and Pluto from 1989 to 1999. In addition to finding possible occultations, a comparison of Guide Star Catalog positions with astrometric plate positions for stars from V=9 to V=15 was made.

American Astronomical Society, Division for Planetary Science 31 October-3 November 1989, Providence, Rhode Island

Occultations by Uranus, Neptune, and Pluto: 1990-1999

D.J. Mink (CfA) and A.R. Klemola (Lick Obs.)

Photographic plates were taken along the projected paths of Uranus, Neptune, Pluto from 1990 to 1999. Star positions were measured in wide bands around each planet's path and catalogued. The results of a search for occultations of stars to the measurement limit of V=16 by the planets and their satellites are presented.

American Astronomical Society, Division for Planetary Science
22-26 October 1990, Charlottesville, Virginia

Occultations of Space Telescope Guide Stars by 2060 Chiron: 1990-1995

D.J. Mink (CfA) and S.A. Stern (U. Colorado/LASP)

The minor planet 2060 Chiron appears to exhibit an extended atmosphere or coma. Stellar occultations can be used to probe the region around Chiron as they have the atmospheres of the planets. In addition to coma studies, the nucleus, ~0.1 arc-sec in diameter, might be occulted, setting a lower limit for Chiron's size and, thus, an upper limit on it's albedo. Good astrometry of near-misses would also help (potentially) by contraining the diameter and albedo.

A search of the Space Telescope Guide Star Catalog was conducted along the projected path of 2060 Chiron from 1 January 1990 to 31 December 1995. and 69 stars were found within 5 arcseconds of Chiron's path, after those less than 45 degrees from the sun at the time of Chiron's closest approach were eliminated.

Stars which Chiron approaches within 1 arcsecond include GSC 776.0612 (V=13.4) on 16 February 1991, GSC 800.0307 (V=14.69) on 9 January 1992, GSC 241.0175 (V=10.45) on 6 January 1993, and GSC 4930.0473 (V=13.87) on 13 February 1995. Further refinement of the ephemeris of 2060 Chiron is needed to improve the accuracy of these predictions. Observers are encouraged to try to observe these events, as well as others on the complete list, which is available from the authors.

APPENDIX 4

Saturn to Occult a Bright Star

David W. Dunham
International Occultation Timing Association

Carolyn C. Porco
Lunar and Planetary Laboratory, University of Arizona

Doug Mink
Harvard-Smithsonian Center for Astrophysics

Sky & Telescope June 1989
Volume 77, pages 638-641

Saturn To Occult a Bright Star

A ONCE-IN-A-LIFETIME event will happen early next month, one that nobody with a telescope will want to miss.

Saturn and its rings will occult the 5.4-magnitude star 28 Sagittarii on July 2-3, Sunday night-Monday morning, for viewers throughout the Americas. The occultation will also be visible over the Pacific and, in part, New Zealand and eastern Australia. The whole extraordinary series of events will last some 3½ hours — from about 6:00 to 9:30 Universal time July 3rd.

This is by far the brightest star yet predicted to be occulted by Saturn. Major observatories in the zone of visibility have already made plans to record the sequence of events with CCD's. As the rings slide in front of the star, moment-to-moment variations in the star's brightness will reveal very fine structure within the rings — far finer than can be resolved any other way from Earth.

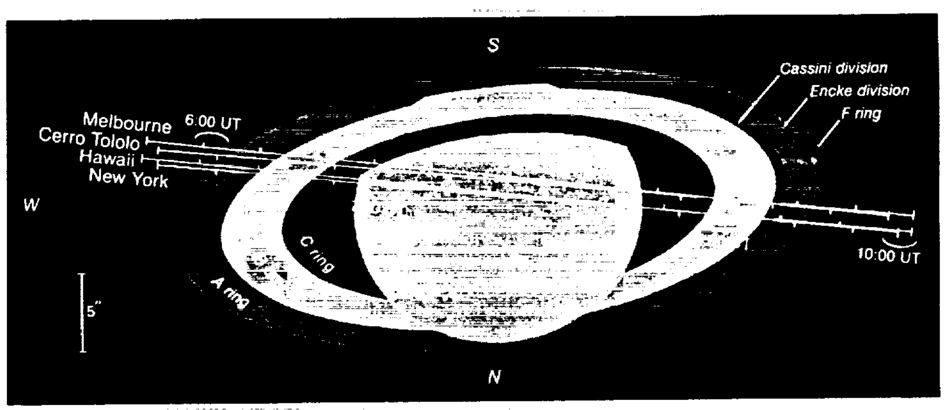
Such observations will be an invaluable complement to data gathered by the Voyager spacecraft at Saturn nearly a decade ago. Indeed, if the star's ring passage is observed from many sites, we can construct a detailed two-dimensional map of the rings' fine structure — something that was not possible even from the Voyagers.

We urge *Sky & Telescope* readers to join in this campaign. If possible, you should record the star's variations with a CCD, photometer, or videocamera. If you are not so equipped, we encourage simple visual timing of events.

WHAT TO EXPECT

The charts on these pages show the predicted path of the star behind the rings and ball of Saturn as seen from New York, Hawaii, the Cerro Tololo Inter-American Observatory in Chile, and Melbourne, Australia. As the charts show, the star's apparent path will be quite similar from these widely separated sites, since the Earth is small compared to Saturn. Therefore the four paths can serve as guides for observers anywhere.

Throughout the continental United States, for example, the star will cross the outer edge of the A ring between 5:58 and



The white lines show the apparent path of the 5th-magnitude star 28 Sagittarii as seen from four locations on Earth. The lines begin at 5:40 UT July 3rd; ticks mark every 20 minutes. South is up. During this very long and remarkable occultation, which was discovered by Gordon Taylor several years ago, amateur telescopes may show the star flashing in and out of tiny gaps in the rings — revealing fine detail not seen since the Voyager spacecraft flybys. All diagrams courtesy Douglas Mink.

6:03 UT, preceded by a possible dimming by the tiny F ring about 2½ minutes earlier. The star should shine through the Encke division in the A ring about 2 minutes later. Timetables of predicted events are provided on page 641 for various sites.

In North America, Saturn will be best placed for observing in the southwestern states, where it will be near the local meridian for much of the 3½-hour occultation. New England gets a good view of the show's first half, the events leading up to the star's disappearance behind the ball of Saturn. But when the star reappears, Saturn will be less than 10° above the horizon and dawn will be under way. Saturn will set and the Sun will rise while the star is still involved in the rings.

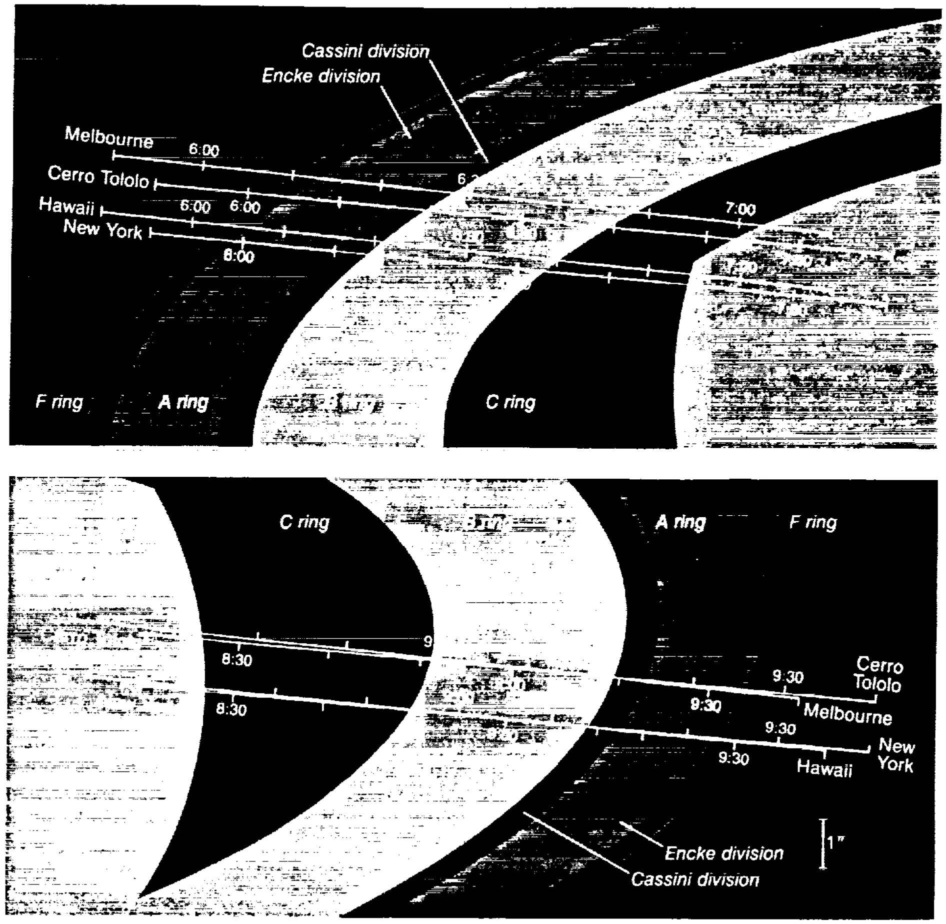
Observers in Canada and northern and eastern states should be careful to select sites with unobstructed south and southwest views. To see where Saturn will be at any time during the occultation, go out and look on a previous night at a time 4 minutes later for each day you are early. (If you need high precision, such as if Saturn will be nearing a tree at a crucial moment, look at 28 Sagittarii instead of the planet and add 3.93 minutes per day instead of 4.)

Observatories needing detailed local predictions may contact coauthor Mink at the Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, Mass. 02138, or phone 617-495-7408.

Saturn will be moving between 20 and 21 kilometers per second relative to our line of sight to the star. The star's angular diameter is about 0″.0014, which corresponds to about 9 km at Saturn's distance. Therefore, even a sharp-edged ring feature will produce a gradual occultation lasting about half a second.

This 9-km resolution is not nearly as fine as that obtained by Voyager 2 when it recorded Delta Scorpii passing behind the rings during its Saturn flyby in August, 1981. However, that observation provided only a single, one-dimensional slice through the rings. We can expect to learn much new information from two-dimensional data if many stations make good recordings on July 3rd. In addition, comparisons with the Voyager data may show that ring details have changed in eight years.

When the star finally disappears behind Saturn's atmosphere, still more information can be gleaned. Recordings of this event may yield improved information about the density, temperature, and composition of Saturn's atmosphere as a function of height. There may be sudden brightenings from thermal layers — Saturnian mirages. Widespread observations of such brightenings might trace out the horizontal extent of these layers.



Closeup views of the star's path into and out of the rings and behind Saturn itself. The ticks are 10 minutes apart. The A ring is partially transparent, so at least some starlight should shine through more or less continuously. Parts of the B ring are quite opaque. The C ring is very transparent; dimmings here will be the exception rather than the rule.

At mid-occultation, the star passes almost behind Saturn's center. The planet's atmosphere will refract the starlight into a ring of light around Saturn's limb at this time, but this "central flash" will be most intense just north of the Earth as best we can predict. Refined predictions from new astrometric measurements should be ready by the time you read this. If so they will be on the recorded occultation hotline, 301-474-4945. In any case it is unlikely that the exact center of the star's refracted light will cross the Earth's surface.

In fact, because Saturn is flattened at the poles, the central-flash light will be distorted into a cross-shape beam hundreds of miles wide. So observers may notice one or two brightenings at different places around Saturn's limb. These brightenings will probably be detectable only by CCD or photoelectric observations in the infrared.

HOW TO WATCH

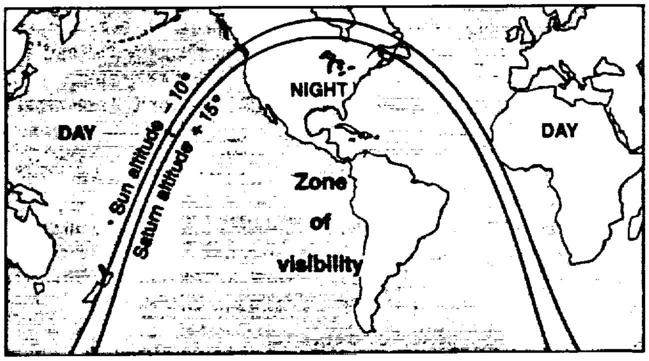
How easy will the occultation be to observe? Saturn is 140 times brighter than the star, which might seem daunting. But more to the point, an average square arc second of Saturn and its rings is only magnitude 6.9, four times dimmer than the star. An area of Saturn two seconds on a side will equal the star's light. Two seconds is roughly the size of a star image in mediocre atmospheric seeing. Clearly, the quality of the seeing will play a major role.

The denser parts of the rings are brighter than average and will also dim the star the most. So here the star may be hard or impossible to follow for some lengths of time.

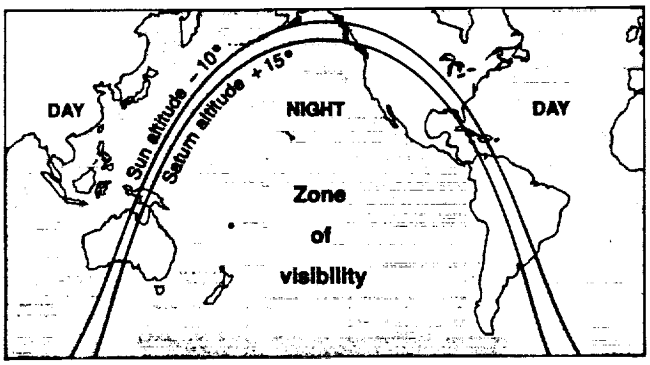
Past events give plenty of reason for optimism. In 1917, two English observers using 5- and 9-inch telescopes easily followed a 7th-magnitude star almost continuously as the A ring passed across it. In 1962, amateurs using 6- to 12½-inch telescopes followed an 8.6-magnitude star off and on as the rings occulted it. By comparison, July's event with a 5.4-magnitude star should be easy — perhaps even spectacular.

A CCD will probably be the best detector for recording the events, especially if infrared wavelengths can be used. (The star, type *K*2, is brighter in the infrared and Saturn is fainter.) Photometers and videocameras subject to blooming, such as the common surveillance cameras that use vidicons, will have to contend with the

Start of Occultation



End of Occultation



Saturn will be higher than 15° above the horizon in a dark sky for observers who are located below the arches on each map. The top map is for 6:00 UT July 3rd, the bottom is for 9:30 UT. Because Saturn is very near opposition, it will be up wherever the sky is dark. Its altitude above the horizon is almost exactly the Sun's depression below the horizon.

bright background light of the rings. A long effective focal length to decrease Saturn's surface brightness, plus excellent tracking, may be required for success by these means. A copy of any such recording of the star's brightness variations should be sent to coauthor Porco at the Lunar and Planetary Laboratory, University of Arizona, Tucson, Ariz. 85726.

Visual observers should use the highest power consistent with the quality of the seeing and ease of tracking. An aluminum-foil occulting bar in the eyepiece, such as was described in last September's issue, page 280, may prove helpful in reducing eyestrain and loss of contrast from Saturn's overall glare.

Get set up well in advance, and arrange a chair so you will be comfortable gazing steadily into the eyepiece for many minutes without a break. Tune a shortwave radio to a time-signal station such as WWV, and set up a tape machine to record the station along with your running comments on the star's brightness variations. Have enough tape for the nearly hour-long passage of the star inbound through the rings. A second cassette should be used to record the reappearance and outbound ring passage.

While watching, describe any dimmings or brightenings of the star's light that you see, giving estimates of the change either in terms of magnitude or percent brightness. If you react slowly to an event, give an estimate of your delay.

If you take a break even momentarily, announce its beginning and end into the tape. To reduce fatigue and still get continuous coverage, two or more observers can set up telescopes next to each other and overlap each others' breaks.

All reports of visual observations should be sent to coauthor Dunham at 7006 Megan Lane, Greenbelt, Md. 20770. The longitude and latitude of your observing site must be provided to an accuracy of 0'.1 (500 feet), and the height above sea level to 300 feet. These can be carefully measured from a U. S. Geological Survey topographic map, available in libraries and camping-equipment stores.

The report itself can simply be a transcript of your taped commentary with each comment's time noted. Also include a full report of the observing conditions, your telescope aperture and power, and all other relevant details.

TITAN TOO?!

Incredibly, Saturn's moon Titan is also likely to occult the star. Following a suggestion by John Westfall, Larry Wasserman at Lowell Observatory has calculated that Titan and 28 Sagittarii will have a minimum geocentric separation of 1".2 at 22:42 UT July 3rd. His prediction implies that an occultation will be visible from Europe. But the uncertainties are such that Titan's shadow could miss the Earth entirely or produce an occultation anywhere Saturn is above the horizon at that time — including Africa, southwest Asia, and much of South America.

An updated prediction for this event will also be available on the occultation hotline noted above. Any occultation will be *very* easy to observe; the star outshines Titan by 3.1 magnitudes! Recordings of its dimming as it "sets" through Titan's atmosphere could yield the same kind of new information as for Saturn's atmosphere.

A central occultation would last 4.3 minutes. Since Titan is nearly a perfect sphere, it could produce an intense central flash that would probe very deep layers of its atmosphere. Any observations of a Titan occultation would be valuable for planning the Cassini mission that will drop a probe into the satellite's dense atmosphere early in the next century.

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International Occultation Timing Assn.
CAROLYN C. PORCO
Lunar and Planetary Laboratory
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Harvard-Smithsonian Center
for Astrophysics

MAJOR OCCULTATION EVENTS (UT TIMES JULY 3rd)

Feature	*New York* *75° 00'W* *41° 00'N*	*Cerro Tololo* *70° 49'W* *30° 10'S*	*Los Angeles* *118° 00'W* *34° 00'N*	*Hawaii* *155° 28'W* *19° 50'N*	*Melbourne* *145° 00'E* *37° 00'S*
F ring (approx.)	5:56:29	6:02:02	5:59:43	6:03:42	—
A ring, outer edge	5:59:03	6:04:38	6:02:15	6:06:15	—
Encke division	6:01:19	6:06:55	6:04:31	6:08:31	—
Cassini div., outer edge	6:10:06	6:15:51	6:13:15	6:17:18	—
Cassini div., inner edge	6:13:27	6:19:17	6:16:36	6:20:39	—
B ring, inner edge	6:32:43	6:39:05	6:35:44	6:39:54	—
C ring, inner edge	6:45:59	6:49:30	6:48:53	6:53:08	—
Saturn (1 microbar)	6:48:23	6:52:57	6:51:20	6:54:25	—
Saturn mid-occultation	7:37:24	7:37:17	7:40:09	7:43:14	7:44:54
Saturn (1 microbar)	8:26:52	8:25:56	8:29:18	8:32:19	8:33:52
C ring, inner edge	8:36:09	8:37:04	8:38:15	8:41:36	8:45:12
B ring, inner edge	8:49:31	8:51:03	8:51:27	8:54:47	8:59:19
Cassini div., inner edge	9:08:58	9:11:04	9:10:39	9:13:56	9:19:22
Cassini div., outer edge	9:12:22	9:14:33	9:14:01	9:17:17	9:22:50
Encke division	9:21:15	9:23:37	9:22:47	9:26:00	9:31:51
A ring, outer edge	9:23:33	9:25:57	9:25:03	9:28:16	9:34:10
F ring (approx.)	9:26:08	9:28:35	9:27:37	9:30:48	9:36:47

APPENDIX 5

Notes on the 3 July 1989 Saturn Occultation

By Doug Mink
Harvard-Smithsonian Center for Astrophysics
30 January 1989

Where is 28 Sagittarii?

In order to give the best forecast for the circumstances of the occultation of 28 Sgr by Saturn and its rings on 3 July 1989, a literature search returned the following published positions:

Catalog No.	$RA_{1950.0}$	$Dec_{1950.0}$	Epoch	μ_{RA}	μ_{Dec}
Boss 25687	$18^h43^m19^s.667$	$-22^\circ26'47''.10$	1906.7	$+.0021^s$	-.002"
SAO 187255	$18^h43^m19^s.678$	$-22^\circ26'46''.86$	1950.0	$+.0022^s$	.000"
Perth70 44003	$18^h43^m19^s.730$	$-22^\circ26'46''.95$	1970.62	$+.0021^s$	-.002"

Arnold Klemola of Lick Observatory will be taking plates in April to get a better position, but until then he recommends the use of the Perth 70 position and the Boss proper motion (which turns out to be the same as the Perth 70 proper motion). At epoch 1989.50, this gives a position of $18^h43^m19^s.770$ $-22^\circ26'46''.91$, 0.05 arcseconds from the SAO position in declination and 0.075 arcseconds away in right ascension.

It's Double!

First catalogued as double star See 360 by the US Naval Observatory, 28 Sgr is also 11652 in Aitken's catalog (1932). The *Lick Index Catalog of Visual Double Stars* (1963) gives the secondary a V magnitude of 13.5 and a separation of 12.5 arcseconds at position angle 214 at epoch 2000.0. Using this as an approximation of the actual position (a better one will come from Arnold Klemola's plates), we get a star at 10.36" south and 6.99" west of the primary at $18^h43^m19^s.304$ $-22^\circ26'57''.27$.

Saturn System Parameters

The following parameters, supplied by Carolyn Porco, were used in the 28 Sgr Saturn system occultation predictions:

Saturn		**Ring feature**	**Radius**
Equatorial radius (1 μbar)	60,968 km	Inner C ring edge	74,493 km
Polar radius (1 μbar)	55,064 km	Outer 'Titan' gap	77,925 km
Pole right ascension	38.4107 degrees	Mid C ring feature	82,046 km
Pole declination	83.32352 degrees	Outer Maxwell gap	87,614 km
		Inner B ring edge	92,006 km
		Outer B ring feature	117,118 km
		Outer B ring edge	117,577 km
		Inner Cass 4th outer ring edge	118,975 km
		Inner Cass outer ring edge	120,048 km
		Inner A ring edge	122,056 km
		Outer Encke gap edge	133,754 km
		Outer Keeler gap edge	136,531 km
		Outer A ring edge	136,773 km
		F ring (approx.)	140,185 km