OCCULTATION STUDIES WITH SMALL TELESCOPES

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ABSTRACT. Various types of occultations and eclipses offer individuals with access to small telescopes the opportunity to contribute significantly to modern solar system research. In fact, often it is only through the cooperation of several such observers that the desired scientific objectives can be realized. This review discusses three classes of occultations which are of high current interest and which are particularly suitable for investigation with small telescopes.

1. INTRODUCTION

When one considers the types of solar system research that a ground-based observer can productively undertake with a modest-aperture telescope, investigations based on observation of occultations immediately spring to mind. Within the last decade and a half, observations of occultations (and eclipses) have resulted in several important discoveries, in precise measurement of size and shape for a variety of objects, in accurate determinations of the temperature and density profiles of planetary ionospheres, and in marked refinement of the orbits of the Galilean and certain Saturnian satellites.

The high potential of occultations for solar system research results from a variety of factors. Not the least of these is the fact that occultations have not been observed for very long or very widely; hence the chance for unexpected discovery is relatively high. Additionally, in an occultation of a star, for example, we observe the solar system object in transmitted, refracted, or diffracted light rather than in scattered or reflected light, as is more usually the case. Since different physical processes are involved, in an occultation it is often possible to measure physical parameters that are extremely difficult or impossible to measure with more conventional Earthbased techniques. Occultations are also ideally suited for measuring dimensions and positions of solar system bodies primarily because the problem is converted from one of angular resolution to a simple matter of timing. Resolution in an occultation is limited by the Fresnel scale rather than the seeing, with the result that order-

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of-magnitude improvements in accuracy over conventional techniques can be achieved.

It is interesting to note that most occultation observations have been made with telescopes of 1-meter aperture or less. There are several reasons: First of all, certain types of occultations must be observed with a distributed network of telescopes if the maximum scientific return is to be achieved. Usually, it is only through the use of small, sometimes portable telescopes that an appropriate network can be put together. Secondly, the objects involved in occultations are often bright, giving an adequate signal-to-noise ratio with a very modest telescope. Finally, for many occultations completely satisfactory observations can be obtained with simple, even rudimentary photometric equipment at observing sites that are less than optimum. Moreover, a large time commitment is not required to prepare for and conduct the observations. In short, occultations offer the busy professor or student at a small college an ideal way to contribute meaningfully to astronomical research. Occultations by their very nature require wide cooperation and collaboration; many individuals isolated at out-of-the-way institutions have found this type of work to be an avenue to active involvement with colleagues at major observatories.

In this paper no effort will be made to review the entire spectrum of occultation studies. Rather, a few classes of occultations that seem to the author to be of greatest current interest and that are most amenable to observation with small telescopes will be highlighted. The intent here is to explain the scientific objectives to be achieved by observing these events and to outline the instrumental requirements. Readers seeking a broader treatment of the subject are directed to reviews by Elliot (1979) and Millis (1983).

2. ASTEROID OCCULTATIONS

When one considers the thousands of asteroids moving against the backdrop of distant stars, it is evident that occultations of stars by minor planets will occur with great frequency. Millis and Elliot (1979) have estimated that thirteen of the larger asteroids would alone produce more than 160 potentially observable occultations per year. In spite of the near-hourly occurrence of these events, all but the tiniest fraction of a percent pass unobserved. Most are not predicted; of those that are, many are rejected because of one unfavorable characteristic or another--they are observable only over the ocean, the asteroid is too close to the Sun, the star is too faint, the asteroid's angular diameter is too small to permit accurate prediction of the region of visibility, etc. Yet these events can tell us much about the asteroids that we can learn in no other way from Earth.

During an occultation the shadow cast by the asteroid in the light of the occulted star sweeps across the Earth, describing a ground track such as the one illustrated in Figure 1. Observers within the ground track will see the asteroid approach the star and momentarily block it from view, while those near the track will observe only a close appulse. Because the asteroid's shadow, when projected onto a plane perpendicular to a line connecting the star and asteroid, has the same size and shape as the asteroid's profile on the sky and because the velocity of the shadow is known, an observer has only to record the times of the star's disappearance and reappearance to determine the length of one chord across the minor planet. By combining observations from sites at various distances from the centerline of the track, the complete profile of the asteroid can be mapped. In principle the occultation technique can yield asteroid dimensions significantly more accurately than other presently existing techniques. A typical occultation lasts 10 to 20 seconds, though some fall well outside this range. If immersion and emersion are timed at a given site to within 0.1 second--a level of accuracy easily achievable with simple photoelectric equipment--then the length of the corresponding chord is known to about one percent. By combining an adequate number of equally accurate chords, the dimensions of the face of the asteroid seen at the time of occultation can be determined to a percent or two. The occultation method has the added virtue that it is direct, with no need for simplifying assumptions about limb darkening or shape.

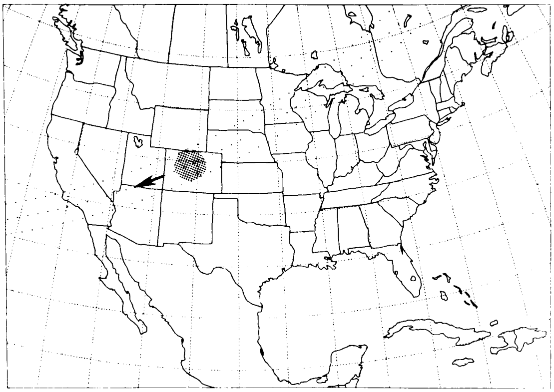

Figure 1. Schematic illustration of an asteroid shadow sweeping across the Earth during an occultation.

Why do we want to know precise sizes and shapes of asteroids? There are many reasons. In the cases of Ceres, Pallas, and Vesta, whose masses are known accurately (Schubart and Matson 1979), well-determined diameters permit calculation of the mean density, providing valuable clues to gross composition. This objective has been accomplished for Pallas (Wasserman **et al.** 1979; Millis and Elliot 1979) and Ceres (Millis **et al.** 1985a), but the density of Vesta remains to be learned.

Accurate diameters of asteroids spanning a broad range in size and taxonomic type are needed to permit the best possible calibration and refinement of the radiometric method of size determination (e.g., Morrison and Lebofsky 1979). This indirect, model-dependent technique has been applied widely not only to asteroids, but to other solar system objects ranging from cometary nuclei to planetary satellites. Significant improvement of the radiometric method has been accomplished already on the basis of occultation results (Brown **et al.** 1982; Lebofsky **et al.** 1986). Figure 2 shows a comparison of occultation and radiometric diameters. The agreement between the two methods is much improved compared with the situation five years ago, but it is important to extend the points in the diagram to cover smaller asteroids and to fill in more points at intermediate sizes. When developed to its full potential, infrared radiometry will provide a tool with which to measure with confidence size and albedo for large numbers of small solar system bodies and, perhaps, to identify those whose surfaces have unusual thermal properties.

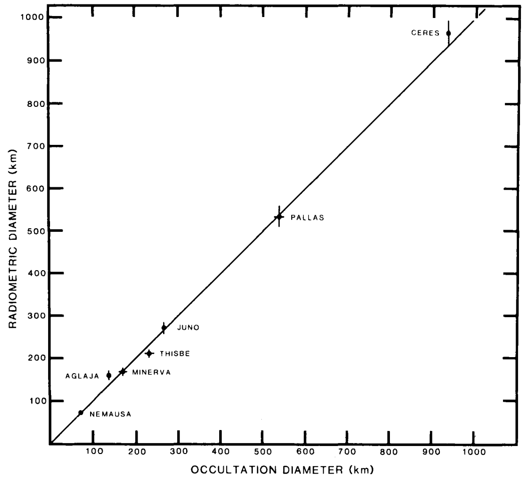

Figure 2. Radiometric diameters of asteroids plotted against their occultation diameters. The solid line corresponds to perfect agreement between the two methods.

Just as occultation observations complement infrared observations, they similarly enhance the potential of radar studies of minor planets. Radar has the unique capablity to probe the porosity, roughness (on the scale of centimeters to meters), and metal concentration of asteroidal regoliths. However, the radar observations can be interpreted fully only when size, shape, and spin vector of the target asteroid are known (Ostro 1985). Occultation observations can provide the first two parameters, while knowledge of the spin vector comes from rotational light curves recorded at many different aspects.

Knowledge of the shapes of asteroids, in addition to aiding interpretation of radar observations, is of interest for its own sake. Our understanding of the collisional history of the asteroid belt and the clear evidence provided by the complex and often large-amplitude rotational light curves of asteroids lead us to expect that many, if not most, small minor planets are irregular in shape. Asteroid occultations provide us with the only presently available means of accurately measuring the figure of an asteroid, short of a space mission. Observation of a single occultation gives us the shape of the asteroid's limb profile at one particular viewing aspect. For most well-observed occultations by minor planets of 200 km-diameter or larger, it has been possible to represent the limb reasonably well with an ellipse or a circle (e.g., Wasserman **et al.** 1979; Millis **et al.** 1981; Millis **et al.** 1984; Millis **et al.** 1985b; Dunham **et al.** 1984), but in all cases real limb irregularities having vertical scales of a few kilometers have been detected. A measure of the three-dimensional figure of an asteroid can be obtained by observing two or more occultations by the same minor planet occurring at different rotational phases and/or viewing aspects. To date this feat has been accomplished only for Pallas (Wasserman **et al.** 1979; Dunham **et al.** 1983), whose figure was found to be well represented by a triaxial ellipsoid (see Figure 3). When dealing with the larger asteroids such as Pallas and Ceres, departures from sphericity place useful constraints on the strength of the material of which these bodies are composed and on their internal structure (e.g., Dermott 1979).

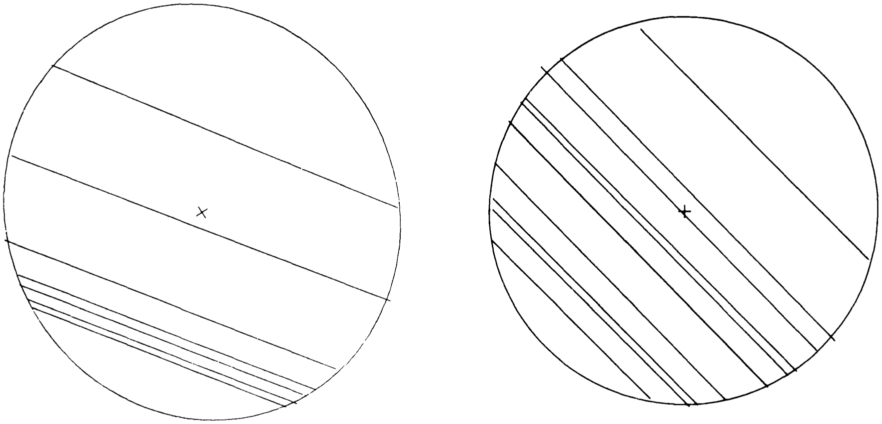

Figure 3. The figure of Pallas seen at two different aspects. The profile on the left is from a 1978 occultation (Wasserman **et al.** 1979); the one on the right is from the 1983 occultation of 1 Vulpeculae (Dunham **et al.** 1983).

An aspect of asteroid research that has been greatly stimulated by occultation observations concerns the possible existence of minor planet satellites. On occasion observers well outside of the primary asteroid occultation ground track have reported brief obscurations of the target star (Williamon 1980; Arlot **et al.** 1985). These reports have been interpreted in terms of minor planet satellites (e.g., Van Flandern **et al.** 1979), as have the binary-like light curves of certain asteroids and the higher-than-expected frequency of double craters on the Earth, Moon, and other cratered bodies (Hut and Weissman 1985). Some have found the occultation evidence for the existence of minor planet satellites to be less than convincing (Reitsema 1979). Certainly, reports of secondary occultation events, as the presumed satellite detections are called, have been less frequent in the last few years. Moreover, deep, coronographic CCD exposures covering the immediate vicinity of a few asteroids have failed to detect satellites (Gradie **et al.** 1985; Terrile and Smith 1985). These negative results at first glance seem surprising, since satellites have been claimed to be stable within a zone extending out to about 100 times the diameter of the asteroid (Van Flandern **et al.** 1979). Weidenschilling (1985), however, has recently shown that the only configurations likely to be stable are contact binaries whose mass ratio is near one or small satellites at large distances from the primary. It is of interest in this regard that a speckle search for duplicity among a sample of about 30 asteroids failed to find any close binaries (Franz 1985). If CCD searches continue to find no small satellites, we will be forced to conclude that minor planet satellites are rare, if they exist at all. In the meantime, it is possible that occultation observations will unequivocally turn up a satellite, but any such case must be extremely well documented.

Most observations of asteroid occultations have been attempted with the aim of surveying the occulting asteroid. However, these events, in principle, offer the opportunity to measure the angular diameter of the occulted star as well by recording the diffraction pattern which is present in the immersion and emersion light curves. All other things being equal, the limiting angular resolution achievable goes as $1/\sqrt{D}$, where D is the distance between the observer and the occulting body (Ridgway 1977). The asteroid belt is roughly 800 times farther from Earth than is the Moon, so one might expect by observing asteroid occultations to measure the angular diameters of stars which are 20 to 30 times smaller than the limit for lunar occultation measurements. This advantage is often largely offset by the fact that the diffraction pattern in an asteroid occultation typically sweeps across the telescope 10 to 20 times faster than in a lunar occultation. To date, efforts to derive stellar angular diameters from asteroid occultation data have not been successful (e.g., Reitsema **et al.** 1981), primarily because of inadequate signal-to-noise. The Fresnel diffraction pattern was clearly seen in observations of the 11 April 1985 occultation of AG+20°1138 by Antigone (see Figure 4), but unfortunately only a strip-chart tracing of the occultation was obtained. In any case, future observers should bear in mind the potential of asteroid occultations for measuring stellar angular diameters.

Additional help is badly needed in observing asteroid occultations. Table I lists the occultations that have been observed for which the author could find reasonably reliable reports in the scientific literature. Note that many of the events were observed only at one or two sites or were observed primarily by visual observers. In such cases, a diameter determination of useful accuracy is usually not possible. If more photoelectrically equipped observers were available, there is no question that the success rate in observing asteroid occultations could be markedly improved. Predictions are available on

TABLE I. SUMMARY OF OBSERVED OCCULTATIONS OF STARS BY ASTEROIDS

Date	Asteroid	No. of Chords*	Reference
19 Feb 58	3 Juno	1 v	J. Brit. Astron. Assoc. 72, 212, 1962.
2 Oct 61	2 Pallas	1 p	J. Brit. Astron. Assoc. 72, 212, 1962.
6 Feb 73	2 Pallas	2 p	J. Roy. Astron. Soc. Canada 67, 198, 1973.
24 Jan 75	433 Eros	8 v	Icarus 28, 133, 1976.
5 Mar 77	6 Hebe	2 v	Icarus 34, 89, 1978.
29 May 78	2 Pallas	7 p	Astron. J. 84, 259, 1979.
7 Jun 78	532 Herculina	1 p/2 v	Bull. Amer. Astron. Soc. 10, 594, 1978.
19 Jul 78	3 Juno	1 v	Occultation Newsletter 2, 12, 1979.
11 Dec 78	18 Melpomene	6 p/2 v	Astron. J. 85, 174, 1980.
17 Aug 79	51 Nemausa	2 p	Astron. Astrophys. Suppl. 44, 375, 1981.
17 Oct 79	65 Cybele	1 p/2 v	J. Brit. Astron. Assoc. 92, 1, 1981.
11 Dec 79	9 Metis	2 v	IAU Circular No. 3437.
11 Dec 79	3 Juno	15 p	Astron. J. 86, 306, 1981.
4 Sep 80	78 Diana	10 v	Occultation Newsletter, March 1981.
10 Oct 80	216 Kleopatra	9 v	Occultation Newsletter, March 1981.
24 Nov 80	134 Sophrosyne	5 v	Occultation Newsletter, March 1981.
8 Jan 81	44 Nysa	1 v	Occultation Newsletter, March 1981.
19 Mar 81	48 Doris	3 v	Occultation Newsletter, March 1982.
7 Aug 81	18 Melpomene	2 p	Sky and Telescope, January 1982.
5 Oct 81	105 Artemis	1 p	Sky and Telescope, January 1982.
7 Oct 81	88 Thisbe	3 p/9 v	Astron. J. 88, 229, 1983.
23 Mar 82	386 Siegena	1 p/1 v	Sky and Telescope, January 1983.
30 Mar 82	15 Eunomia	1 v	Sky and Telescope, January 1983.
18 Apr 82	146 Lucina	1 p/1 v	Icarus 61, 224, 1985.
17 Sep 82	19 Fortuna	1 p	Sky and Telescope, January 1983.
14 Nov 82	690 Wratislavia	2 v	IAU Circular No. 3747.
15 Nov 82	375 Ursula	2 p/3 v	Astron. J. 89, 592, 1984.
22 Nov 82	93 Minerva	5 p/5 v	Icarus 61, 124, 1985.
19 Jan 83	106 Dione	10 v	Astron. Nachr. 305, 207, 1984.
29 May 83	2 Pallas	~100 p&v	Bull. Amer. Astron. Soc. 15, 822, 1983.
11 Sep 83	51 Nemausa	6 p	Astron. J. 89, 1755, 1984.
16 Sep 84	47 Aglaja	3 p/7 v	Bull. Amer. Astron. Soc. 16, 1027, 1984.
13 Nov 84	1 Ceres	13 p	Bull. Amer. Astron. Soc. 17, 729, 1985.
11 Apr 85	129 Antigone	3 p/2 v	Occultation Newsletter, August 1985.
15 Apr 85	275 Sapientia	1 p/1 v	Occultation Newsletter, August 1985.

*p = photoelectric or video observations; v = visual observations.

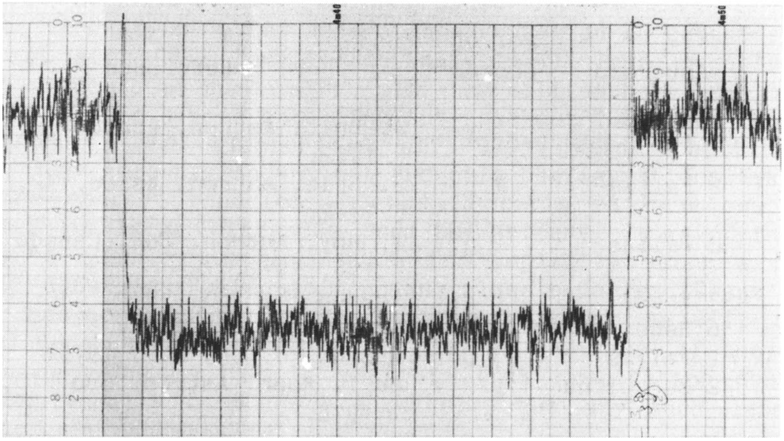

Figure 4. A light curve of the 11 April 1985 occultation of AG+20°1138 by Antigone. Note the diffraction pattern at immersion and emersion. Observations were made by O. G. Franz and R. Oliver of Lowell Observatory using a 0.35-meter portable telescope.

a worldwide basis (e.g., Wasserman **et al.** 1985), and the techniques of accurately refining the location of the ground track for any individual occultation are well developed. The only instrumental requirements for this work are a small telescope (instruments as small as 8-inches aperture have been used successfully), a simple photometer, and a data system capable of recording the signal from the photometer at a timing resolution of 0.1 second.

3. THE PLUTO-CHARON MUTUAL EVENTS

In 1978 Christy and Harrington (1978) discovered that Pluto possesses a relatively large satellite which is now commonly called Charon. Soon after the discovery, Andersson (1978) pointed out that the orientation of Charon's orbit was such that Pluto's orbital motion would soon cause the satellite's orbital plane to sweep across the Earth and Sun. Andersson noted that this process would extend over five or six years, during which time alternate transits of the satellite across Pluto and occultations of Charon by Pluto would occur.

Photometric observations of the Pluto-Charon mutual events can tell us much about the Pluto-Charon system. If a large number of the events are observed, it will be possible to measure the size of each object; their relative magnitudes, albedos, and colors; the precise parameters of Charon's orbit; and hence, the total mass and bulk density of the system. Low-resolution albedo maps of one face of each object may also be derived.

The first of this series of Pluto-Charon mutual events was detected in early 1985 (Binzel **et al.** 1985). Since the next series will not begin until about the year 2109, it is important that the best job possible be done this time. Tholen (1985) has published predictions for the events occurring during the 1985/1986 apparition. Eighty-one events will occur, each lasting between four and five hours, a time span which near the ends of the apparition exceeds the available observing interval at any given observatory. Presumably similar numbers of occultations and transits will occur during subsequent years of the present series.

Clearly, worldwide cooperation is needed to insure adequate observation of the Pluto-Charon events. Given the amount of telescope time that will be required, it seems certain that much of the observing must be done with meter-class or smaller telescopes. Pluto will be near 14^m in V so photometry accurate to 1% in V or B with a time resolution on the order of 5 minutes should be possible with a 1-meter telescope. For reasons of uniformity, observations in V or B are preferred, but individuals using telescopes of significantly less than 1-meter aperture may have to observe without a filter in order to achieve the maximum signal-to-noise ratio in their data.

A worldwide campaign is being organized to observe the Pluto-Charon mutual events. Individuals interested in participating should contact Dr. Edward Tedesco at the Jet Propulsion Laboratory, Pasadena, California 91109.

4. OCCULTATIONS BY COMETS

Because of their relatively rapid motion across the sky, comets, like asteroids, have frequent close appulses to moderately bright stars. The small size of cometary nuclei and the difficulty of doing very high-precision astrometry of comets cause the probability of observing an occultation of a star by the nucleus of a comet to be vanishingly small. However, valuable information about the solid grains in the inner coma of a comet can be learned from events where the starlight has passed within a few hundred kilometers of the nucleus (Bowell **et al.** 1984). At greater distances the coma is likely to be too tenuous to produce detectable diminution of the starlight.

The reflectance, R, of the coma at a given point is given by

$$R = N \sigma A , \qquad (1)$$

where N is the total number of grains in a column of unit cross-section extending completely through the coma, σ is the cross-section of a single grain, and A is the albedo of the grains as defined by A'Hearn **et al.** (1984). The optical thickness, τ, of the coma at that point is related to the filling factor, $N\sigma$, by

$$N\sigma = (1-e^{-\tau}) . \qquad (2)$$

Combining Eqs. (1) and (2), we get

$$R = (1-e^{-\tau})\,A. \tag{3}$$

Furthermore, the optical thickness of the coma is by definition

$$I/I_0 = e^{-\tau}, \tag{4}$$

where I is the apparent brightness of a star seen through the coma at the point in question, and I_0 is the unobscured brightness of the star. Hence, photometric observations of a close appulse of a star and a cometary nucleus will yield by Eq. (2) the distribution of grains in the coma along the apparent path of the star. When combined with measurements of the surface brightness of the coma along that path, the grain albedo can be found from Eq. (3).

Although predictions of comet occultations have been published during the past few years (e.g., Bowell and Wasserman 1985), very few events of this type have been observed, and those few have been recorded serendipitously rather than as a result of predictions. The best-documented observations are those by Larson and A'Hearn (1984), who observed the passage of the light from a 15th-magnitude star to within about 540 km of the nucleus of Comet Bowell. These investigators reported a maximum extinction of the star of 3% ± 1%. Obviously, more definitive results could be obtained with events involving dustier comets, closer appulses, and brighter stars; but events of that type are unlikely to be observed accidentally. Perhaps the best approach would be for large numbers of observers to attempt observations of all predicted comet occultations in their geographical region. While success cannot be guaranteed for any particular observer, over time the cooperative effort should produce good results. Here again, as with the two types of events discussed earlier, only small-telescope observers can achieve the necessary density and distribution of observing sites.

5. CONCLUDING REMARKS

This review has emphasized three particular classes of occultations: occultations of stars by asteroids, mutual phenomena of the Pluto-Charon system, and occultations of stars by comets. Other types of occultations sometimes also can be productively observed with small telescopes. The Uranian rings were discovered with telescopes of less than 1-meter aperture during an occultation of the 9th-magnitude star SAO 158687 (Elliot **et al.** 1977; Millis **et al.** 1977). Subsequent observations of similar events have made possible remarkably detailed kinematic models of the nine rings (e.g., French **et al.** 1985). Recently, observations of occultations by Neptune have shown exciting evidence for a fragmented ring around that planet (Brahic **et al.** 1985). The contributions of occultation observers to studies of the thermal and density structure of planetary atmospheres, to measurements of the oblateness of distant planets, and to the search for atmospheres of Pluto and outer planet satellites likewise should be mentioned. Clearly, continued observations of these kinds will be valuable. They have not been treated in detail in this review, primarily because few such events involving bright stars have been found in searches extending through the end of this decade (e.g., Mink and Klemola 1985; Killian and Dalton 1985). It appears that for the next several years stellar occultations involving the outer planets, their rings, and their satellites of necessity will be observed with large telescopes. Eventually, however, events within the grasp of small telescopes will occur, and observers should be alert for these opportunities.

Many predictions of occultations are published well in advance in widely circulated scientific journals. Most early predictions, however, are only approximate, requiring refinement a few weeks or days prior to the occultation. The refined predictions are disseminated through formal and informal networks of observers. Since it is usually only these last-minute predictions which are sufficiently accurate to serve as the basis for actual observing plans, individuals interested in observing occultations should seek to become a part of a network. The Working Group on Occultations of IAU Commission 20 operates one such network. Observers interested in receiving predictions from the Working Group are urged to contact the author.

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References

A'Hearn, M. F., Schleicher, D. G., Feldman, P. D., Millis, R. L., and Thompson, D. T. (1984). **Astron. J.** 89, 579-591.

Andersson, L. E. (1978). **Bull. Amer. Astron. Soc.** 10, 586.

Arlot, J. E., Lecachaux, J., Richardson, C. H., and Thuillot, W. (1985). **Icarus** 61, 224-231.

Binzel, R. P., Tholen, D. J., Tedesco, E. F., Buratti, B. J., and Nelson, R. M. (1985). **Science** 228, 1193-1195.

Bowell, E., and Wasserman, L. H. (1985). **International Halley Watch Newsletter** No. 7, 30-37.

Bowell, E., Wasserman, L. H., Baum, W. A., Millis, R. L., and Lumme, K. (1984). In **Cometary Astrometry** (D. K. Yeomans, R. M. West, R. S. Harrington, and B. G. Marsden, Eds.), pp. 105-122. Jet Propulsion Laboratory, Pasadena.

Brahic, A., Hubbard, W. B., Bouchet, P., Eliser, L.-R., Hafner, R., Manfroid, J., Roques, F., Sicardy, B., and Vilas, F. (1985). **Nature,** in press.

Brown, R. H., Morrison, D., Telesco, C. M., and Brunk, W. E. (1982). **Icarus** 52, 188-195.

Christy, J. W., and Harrington, R. S. (1978). **Astron. J.** 83, 1005-1008.

Dermott, S. F. (1979). **Icarus** 37, 575-586.
Dunham, D. W., Van Flandern, T. C., Millis, R. L., Chapman, C. R., Maley, P. D., and Povenmire, H. (1983). **Bull. Amer. Astron. Soc.** 15, 822.
Dunham, E. W., Baron, R. L., Conner, S., Dunham, D. W., Dunham, J. B., Schneider, G., Cohen, H. L., Helms, V. T., Croom, M., and Safko, J. (1984). **Astron. J.** 89, 1755-1758.
Elliot, J. L. (1979). In **Annual Reviews of Astronomy and Astrophysics** (G. Burbidge, D. Layzer, and J. G. Phillips, Eds.), Vol. 17, pp. 445-476. Annual Reviews, Inc., Palo Alto.
Elliot, J. L., Dunham, T., and Mink, D. (1977). **Nature** 267, 328-330.
Franz, O. G. (1985). Presented at the June 1985 meeting of the Astronomical Society of the Pacific.
French, R. G., Kangas, J. A., and Elliot, J. L. (1985). **Bull. Amer. Astron. Soc.** 17, 718.
Gradie, J., Hammel, H., and Pilcher, C. (1985). **Bull. Amer. Astron. Soc.** 17, 729.
Hut, P., and Weissman, P. R. (1985). **Bull. Amer. Astron. Soc.** 17, 690.
Killian,A. M., and Dalton, A. S. (1985). **Astron. J.** 90, 2372-2376.
Larson, S. M., and A'Hearn, M. F. (1984). **Icarus** 58, 446-450.
Lebofsky, L. A., Sykes, M. V., Veeder, G. J., Tedesco, E. F., Matson, D. L., Brown, R. H., Gradie, J. C., Feierberg, M. A., and Rudy, R. J. (1986). Submitted to **Icarus**.
Millis, R. L. (1983). In **Solar System Photometry Handbook** (R. M. Genet, Ed.), pp. 7-1 to 7-18. Willmann-Bell, Richmond.
Millis, R. L., and Elliot, J. L. (1979). In **Asteroids** (T. Gehrels, Ed.), pp. 98-118. University of Arizona Press, Tucson.
Millis, R. L., Wasserman, L. H., and Birch, P. V. (1977). **Nature** 267, 330-331.
Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., and Klemola, A. (1984). **Astron. J.** 89, 592-596.
Millis, R. L., Wasserman, L. H., Bowell, E., Franz, O. G., Nye, R., Osborn, W., and Klemola, A. (1985b). **Icarus** 61, 124-131.
Millis, R. L., and 37 other authors. (1981). **Astron. J.** 86, 306-313.
Millis, R., Wasserman, L., Franz, O., Nye, R., Oliver, R., Jones, S., Kreidl, T., A'Hearn, M., Schnurr, R., Osborn, W., and Klemola, A. (1985a). **Publ. Astron. Soc. Pacific,** in press.
Mink, D. J., and Klemola, A. (1985) **Astron. J.** 90, 1894-1899.
Morrison, D., and Lebofsky, L. A. (1979). In **Asteroids** (T. Gehrels, Ed.), pp. 184-205. University of Arizona Press, Tucson.
Ostro, S. J. (1985). **Publ. Astron. Soc. Pacific,** in press.
Reitsema, H. J. (1979). **Science** 205, 185-186.
Reitsema, H. J., Hubbard, W. B., Zellner, B. H., and Lebofsky, L. A. (1981). **Astron. J.** 86, 121-126.
Ridgway, S. T. (1977). **Astron. J.** 82, 511-515.
Schubart, J., and Matson, D. L. (1979). In **Asteroids** (T. Gehrels, Ed.), pp. 84-97. University of Arizona Press, Tucson.
Terrile, R. J., and Smith, B. A. (1985). **Bull. Amer. Astron. Soc.,** in press.
Tholen, D. J. (1985). **Astron. J.,** in press.
Van Flandern, T. C., Tedesco, E. F., and Binzel, R. P. (1979). In

Asteroids (T. Gehrels, Ed.), pp. 443-465. University of Arizona Press, Tucson.

Wasserman, L. H., Bowell, E., and Millis, R. L. (1985). **Astron. J.** 90, 2124-2129

Wasserman, L. H., and 17 other authors. (1979). **Astron. J.** 84, 259-268.

Weidenschilling, S. J. (1985). **Bull. Amer. Astron. Soc.** 17, 731.

Williamon, R. L. (1980). **Astron. J.** 85, 174-176.

DISCUSSION

Evans: I don't want to discourage anybody, but trying to do minor planet occultations from fixed observatories is very much of a gamble, since one must be within a shadow track only about as large as an asteroid. This may be fine for the larger ones but it is difficult for the smaller ones.

Millis: One needs to make a concerted effort using portable instruments. Fixed telescopes are a little more difficult, but many good observations have come from them.

Penhallow: The first international expedition to observe an asteroid occultation was successful and produced the first photograph of such an event. This involved Metis in South America in 1979. The photograph was reproduced in Sky & Telescope. The prediction was based on last minute astrometry from Lick, Lowell, R.G.O. and the Quonochontang Observatory.

Evans: Are timings of close approach worthwhile observations?

Millis: They have astrometric value, and any observation of a near miss makes it more unlikely that there are minor planet satellites. Speckle interferometry and deep CCD images have also failed to find any satellites.

Woodward: To compliment the occultation observations we have been imaging planets to try and detect rings and sattelites. We have recently resolved the rings of Uranus with the University of Rochester infrared array camera. Our 2.2μm broad-band image has appeared in Sky and Telescope (in the October 1985 issue). We are writing up our results currently, and will soon submit the manuscript for publication in the astronomical literature.

Millis: We see the ring structure all together. We are still doing some image processing to look for any finer structure in the rings.