DISCOVERY AND OBSERVATION OF CLOSE-APPROACH ASTEROIDS

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Close-approach asteroids, members of the so-called Apollo and Amor groups, are of considerable current interest as potential targets for probes and also in connection with the question of identification of the parent bodies of the meteorites. The possibility that some of these asteroids may be surviving comet nuclei has been suggested earlier. (See, e.g., Öpik, 1963.) Relatively few objects of this type are known; all are small bodies found accidentally in the course of work not always related to investigations of minor planets. The known Apollo and Amor asteroids, and notes as to their present observational status, are listed in table I. (See also table II of Marsden.[1]) Except when they are relatively close to Earth (many can approach within 0.10 AU), these objects are faint and often in very awkward positions as well, low in the evening or morning sky at twilight. When they are close, the rate of apparent motion is very great–Icarus was 12 mag and moving 1 deg/hr at its closest approach (to 0.04 AU) in June 1968. Thus even a favorable and accurately predicted apparition presents a share of observational difficulties. Sometimes years go by without a reasonable opportunity for observation–definitely a problem in determination of reliable orbits. Only when these small asteroids are relatively close to Earth, with fast apparent motion, are they bright enough for investigation of physical characteristics. Under such circumstances, if the prediction of position is within a few minutes of arc, the fast motion may be an asset in the sense that it quickly attracts the eye and aids in identification ("bird-in-the-bush effect").

It obviously would be extremely interesting to know more of the population statistics of this class of objects and to extend the list of individual members for which any sort of physical information is available. Proposals have been made for search programs to these ends. The practical execution of a useful search entails massive work, however, and is fraught with problems, some of very recent origin.[2]

The critical considerations in planning a search are (1) where and how to observe so as to maximize the chances of photographing an interesting object

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[1]See p. 419.
[2]See p. 649.

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TABLE I.—*Current Observational Status of Apollo and Amor Objects* ($q \leqslant 1.15$ *AU*)[a]

Object	Discoverer, observatory	Status	Date observed	Next search opportunity
1953 EA	A. Wilson, Palomar	Recoverable?	Mar. 9 to June 17, 1953	1973
887 Alinda	Wolf, Heidelberg	Secure	–	–
1948 EA	Wirtanen, Lick	Recoverable?	Mar. 5 to Sept. 28, 1948	Oct. 1971 to Dec. 1972
1960 UA	Giclas, Lowell	Recoverable	Oct. 22, 1960, to Feb. 6, 1961	1977
1936 CA Adonis	Delporte, Uccle	Recoverable?	Feb. 12 to Apr. 11, 1936	1977
1580 Betulia	Johnson, Johannesburg	Secure	–	–
1968 AA	Cesco and Samuel, Observatorio Austral Yale-Columbia	Secure	Jan. 1 to Feb. 9, 1968; June 1, 1970, to Jan. 24, 1971	–
1221 Amor	Delporte, Uccle	Secure	–	–
1937 UB Hermes	Reinmuth, Heidelberg	Lost	Oct. 25-29, 1937	–
1627 Ivar	Hertzsprung, Johannesburg, and Hoffmeister, Boyden	Secure	–	–
1950 DA	Wirtanen, Lick	Lost?	Feb. 23 to Mar. 12, 1950	1974
1971 FA	Gehrels, Palomar	Secure?	Mar. 24 to May 26, 1971	Oct. 1971 to Mar. 1972
1932 HA Apollo	Reinmuth, Heidelberg	Recoverable?	Apr. 27 to May 15, 1932	Oct. to Dec. 1971
1950 LA	Wilson and Wallenquist, Palomar	Lost?	June 19 to Sept. 16, 1950	–
1566 Icarus	Baade, Palomar	Secure	–	–
1685 Toro	Wirtanen, Lick	Secure	–	–
1959 LM	Hoffmeister, Boyden	Lost	June 5-11, 1959	–
433 Eros	Witt, Berlin	Secure	–	–
1620 Geographos	Wilson and Minkowski, Palomar	Secure	–	–
1947 XC	Giclas, Lowell	Lost	Dec. 12, 14, 1947	–

[a]The order in which objects are listed is that of decreasing aphelion distance, making this table directly comparable with table II of Marsden, p. 419, in which orbital elements q, Q, e, i, and P and the absolute magnitude $B(1,0)$ may be found. The object 1947 XC, of which the orbital elements are very uncertain, has been added. B. G. Marsden has very kindly supplied information regarding future search opportunities in advance of publication.

and (2) how to manage examination of the plates to maximize the chance of the object being promptly recognized. Whether or not objects are found, one would like at least to be able to specify what volume of space was searched, its location with respect to Earth and Sun, and the brightness (size) limit to which discovery should have been complete. Because trailing of images decreases the brightness limit of detection, some interpretable decision needs to be made as to how to compensate for apparent motion of possible objects in any particular field.

Very fast, wide-field optical systems are now available that make rapid coverage of vast areas of the sky entirely feasible. Even rapid, unknown rates of apparent motion (which depend on the character of the heliocentric orbit, but more critically on the geocentric distance) are a less serious problem than they were formerly with slower optical systems. But when and how should the second plate be taken for best detection of a moving object?

The most critical difficulty comes in examination of the photographic records. Blink examination of rich star fields can take days and even weeks per field, without necessarily reaching to the plate limit. Objects displaced by considerable amounts between exposures can still be missed unless the motion during a single exposure is enough to attract attention. Examination should be carried out at the same rate at which observational material is obtained if there is to be feedback into the observational program to secure continuing observations of any interesting objects that might be found. Without possibility of following up on discoveries, much of the value of the search effort is lost.

In fact, no more sophisticated examination than a reasonably careful survey of the plate with a hand magnifier was involved in discovery of some of the known objects of the Apollo class. Others were evident on the most cursory naked-eye inspection. The critical point is that whatever information is to be obtained from the plates must be abstracted promptly (i.e., the day after observation), and further observations must be obtained immediately (within a night or two, depending on the rate of motion and on the equipment available for followup).

Full details of the discovery of Icarus and of the struggle to keep it under observation during the first critical weeks have been published by Richardson (1965). Similar sagas can be related regarding the difficult and critical first weeks of observation of most of those objects of table I for which reasonably reliable orbits have eventually been determined. In each success story, and in some failures, someone gave close support with computations of orbits and ephemerides, and someone was in a position to continue with observations and measurements of position as the new objects faded beyond the reach of the instruments with which they were discovered. Names that recur repeatedly are L. E. Cunningham, H. M. Jeffers, Seth B. Nicholson, Paul Herget, and in recent years B. G. Marsden.[3] It is this immediate effort, and not so much the care that

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[3] And E. Roemer [editor's footnote].

goes into calculation of the definitive orbit, months or years after the discovery, that really determines whether the new object can be reobserved at future apparitions.

Even though Apollo and Adonis have usually been considered lost, very considerable effort was expended in keeping Apollo under observation for nearly 3 weeks in 1932 and Adonis for 2 months in 1936. The situation with Hermes in 1937 was so extreme that every observation save one (14 in all, obtained at four observatories) was made quite accidentally with small patrol cameras. At its closest approach to Earth, to about 0.005 AU on October 30, 1937, Hermes was 8 mag and moving 5 deg/hr. Many attempts were made to obtain observations, but, because of the very rapid motion, only one was successful. A number of plates are known to cover the proper fields, but Hermes was traveling too fast to leave a trace. In 9 days it had traveled completely across the sky–comparison with the problems of meteor photography may not be entirely out of order. The orbit, from a 4 day arc, was determined essentially by the geocentric parallax, to which the Johannesburg observations were critically important, as, indeed, they have been for many other, more ordinary asteroids.

In relation to current proposals to conduct a planned search for close-approach asteroids, it may be worthwhile to mention the survey conducted under the direction of C. W. Tombaugh (1961; Tombaugh et al., 1959) from December 1953 to October 1958 for small natural satellites of Earth. Tombaugh's project was, in fact, inspired by his experiences, together with H. L. Giclas, at the Lowell Observatory in 1943 in the attempt to recover the lost asteroid Adonis during a close approach to Earth.

In the course of the satellite search, Tombaugh and his coworkers took and examined more than 15 000 photographs. Various cameras, including a 22 cm *f*/1.6 Schmidt, were employed to search systematically, with appropriate telescope driving rates, for Earth satellites in near-circular orbits ranging through periods from 2 to 24 hr and to limits of 12 to 14 mag. Several promising, but faint, objects were found. Vigorous efforts to reobserve them, however, failed in every case. Although it was felt that most of these objects, originally recognized from weak images near the plate limit, probably were spurious, the possibility remains that some were objects in highly eccentric geocentric orbits, or small asteroids passing close by Earth in heliocentric orbit. In either case it would have been extremely difficult to know in what position to search, and for what rate of motion to compensate. It would be very discouraging indeed to conduct a comparable search at the present time, with the abundance of space "junk" to identify and discount.

It would seem that the most productive avenues open at the present time toward discovery and observation of close-approach asteroids are likely to lie in two directions: (1) encouragement of observers who take wide-field plates for various astronomical purposes to look for and report potentially interesting objects to a center at which both observing and computing resources are available for immediate, but probably somewhat selective, followup and (2) devotion of adequate efforts toward reobservation of those known Apollo and Amor objects, unseen since their discovery apparitions, for which a reasonable search prediction can be made.

Wide-field plates taken with fast cameras show so many asteroid trails that some basis for selection must be applied by even the most enthusiastic asteroid hunter. It has been said that for an asteroid to attract the attention of a Palomar Schmidt observer, the trail "must be an inch long, or must be directed the wrong way" (Struve, 1952; the quotation is apparently attributed to Jesse Greenstein). Any object found far from the ecliptic must either have a high inclination or be relatively close to Earth. If there are other asteroids in the field, distinctly different motion will identify potentially interesting objects. The typical minor planet near opposition has a daily motion, in the retrograde direction, in the range from 5′ to 15′. Near quadrature the motion will be of comparable magnitude, but in the direct sense. At discovery 1960 UA was between 11 and 12 mag and had a direct motion of about 2 deg/day, exemplifying the fact that an object close to Earth may have large direct motion even at opposition.

On occasion it may be necessary to infer the direction of motion from characteristics of the trail on a single plate. This was, in fact, the situation at the discovery of Icarus. The usual rule is, in the absence of complicating effects such as variable transparency because of clouds or changing altitude, that the *beginning* of the trail is denser than the end (Miller, 1965). In estimating the magnitude, necessary for the guidance of other observers, correction should be applied for any appreciable trailing.

Marsden (1969) has recently redetermined the orbits of several of the known Apollo and Amor asteroids and provided search ephemerides for several for which he considers recovery efforts reasonable. Included are Apollo and Adonis, as well as 1948 EA and 1953 EA. Even though bands as long as 75° across the sky may need to be searched, every encouragement should be given to the effort, at the appropriate times, to reobserve these objects. It seems clear that search efforts in these cases would have a much better chance of contributing useful information than would a comparable amount of time spent in a general effort to discover new objects.

While observing with the 122 cm Schmidt on Palomar Mountain late in March in a survey of the western equilateral point for faint Trojans, Tom Gehrels discovered several asteroids that, by their motion, seemed sufficiently interesting to warrant further observation. One of these, of about 16 mag, and with opposition motion of about 40 arcmin/day in the retrograde direction, has turned out to be a new Apollo asteroid (Gehrels, Roemer, and Marsden, 1971). This motion is some two to three times that of a typical asteroid, but by no means sufficiently extreme to make the asteroid an immediate Apollo suspect. The object was, in fact, at a distance of about 0.9 AU from Earth at the time of discovery. The high orbital inclination (22°) and present orientation of the line of nodes preclude approaches to Earth closer than about 0.3 AU, the first Apollo asteroid to which a comparable statement presently applies. The new Apollo, designated 1971 FA, was kept under observation through May 26. There is an extended favorable opportunity for observation in late 1971, and it seems that this new close-approach asteroid will be put in secure status with little additional effort.

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