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THE ROLE OF EARTH-BASED OBSERVATIONS OF ASTEROIDS DURING THE NEXT DECADE

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During the past decade, Earth-based observations have led us from ignorance to considerable understanding about the physical properties of asteroids. Candidate targets for space missions can now be chosen using criteria that will not prove trivial in the future; intensive ground-based studies of targets can refine the choices. Present reconnaissance studies of asteroids are now reaching maturity. Ground-based programs are shifting to more specialized, intensive studies of selected individual bodies and special classes (*e.g.*, Hirayama families). Two powerful techniques--radar and mid-IR spectroscopy--have yet to be widely applied to asteroids; high priority should be given to these programs in the future and to (a) search programs with a large Schmidt telescope (especially for Mars- and Earth-approaching bodies), (b) a moderate resolution visible and near-IR spectrophotometric survey of at least half the asteroids, (c) high resolution spectrophotometry and radiometry of unusual objects, (d) radar studies of representative main belt asteroids, and (e) application of the full complement of astrophysical techniques (including polarimetry and intensive lightcurve studies) to objects of high scientific interest and to potential space mission targets. The infrared astronomical satellite (IRAS) also has high potential for contributing to asteroid science. Laboratory and theoretical programs complement observational programs by enabling data interpretation and synthesis. Ground-based programs should continue even in a future era of asteroid space missions in order to extend ground-truth to the diverse and widely dispersed population.

INTRODUCTION

Our present knowledge of the asteroids rests entirely on Earth-based astronomical measurements, bolstered of course by observational and experimental studies of other bodies thought to be related to asteroids. The long history of asteroid discovery, orbit determination, and photographic photometry had yielded by 1970 nearly 2000 known asteroids and a wealth of speculations about their statistical distributions and orbital evolution. But substantial understanding of the physical properties of asteroids awaited the application of modern remote-sensing techniques, using efficient detectors at large telescopes, beginning about 1970.

During the 1970's, reconnaissance measurements of parameters known to be related to surface composition have been made for over one-quarter of the numbered asteroids, although the full range of available techniques has been applied to few objects. We will address in this paper the question of what observations can be made in the near future. We will also attempt to treat the more speculative question of how much return may be expected from continued ground-based observations and whether such data have the potential for ultimately resolving the questions that have been raised in the past decade.

GROUND-BASED TECHNIQUES

The techniques discussed in this section have already been successfully applied to asteroids. It is not our purpose to describe the techniques here; the reader may consult other pertinent references (see papers in Session II of this volume). We will indicate what asteroid properties they reveal (or suggest) without delving into the methodologies and the caveats that always accompany interpretation of observations. The history of each technique is sketched to provide a frame of reference for our guesses about the future application of the technique. Of course, any application of ground-based techniques depends not only on theoretical capabilities of state-of-the-art instrumentation, but also on availability of facilities, funds, and interested observers. The growth in number of asteroids measured by several important techniques is illustrated roughly in Figure 1.

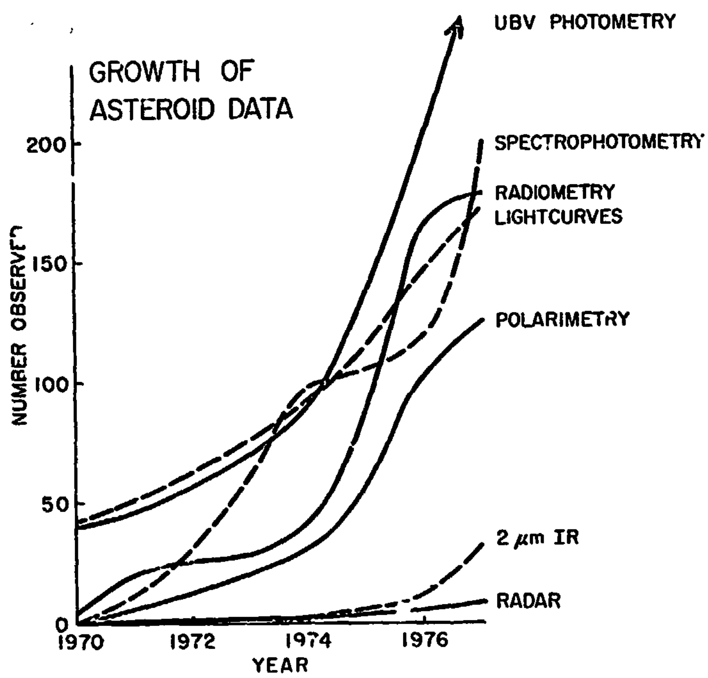

Fig. 1. Approximate growth in the number of asteroids observed using several techniques during the 1970's.

Asteroid Searches and Photographic Surveys

There have been two major photographic surveys of asteroids: the McDonald survey of all brighter asteroids, nearly complete to photographic magnitude 15 or 16, and the Palomar-Leiden survey, which sampled asteroids down to magnitude 20. The sheer number of fainter asteroids and time-consuming nature of photographic surveys prohibits extension of completeness much beyond the current limits. But sampling of the population of much fainter and smaller asteroids could lead to improved understanding of asteroid collisional processes, Hirayama families, and other important problems. Better sampling of asteroids in high inclination orbits and other unusual orbits is particularly important. Current search efforts by E. Shoemaker and E. Helin and by C. Kowal have slowly but substantially improved our knowledge about Mars-crossing and Earth-approaching asteroids. Application of a larger, dedicated instrument could increase the discovery rate by an order of magnitude and help to establish the relationship between Earth-approaching asteroids, the main belt asteroids, comets, and meteorites as well as to establish cratering rates and thus chronologies on the inner planets.

Visible Photometry of Asteroids

The measurement of the apparent brightness of an asteroid as a function of time provides a crude estimate of an asteroid's size; combined with radiometry or polarimetry, the size is much more precisely determined. Asteroid photometry as a function of phase angle yields some information concerning surface texture; but the measurements are time-consuming and not of primary importance. Relatively simple photometry over the course of a night (lightcurve photometry) can yield a fundamental property, rotation period, and some indication of asteroid shape. With great difficulty, photometry can yield more precise knowledge about asteroid spin, including pole direction and sense (prograde or retrograde) and better knowledge of asteroid shape. Some photographic photometry has been done for all asteroids; but for many of the fainter objects, the best available magnitudes are highly provisional. Photoelectric magnitudes are known for a quarter of all the numbered asteroids and could be extended to nearly all numbered asteroids within a few years by a single dedicated observer. Lightcurve photometry is a time-consuming program initiated in the 1950's and yielding rotation periods for several dozen bodies by 1970. Expanding interest during the 1970's, especially by foreign observers and some amateurs, has increased the number of known rotation periods to more than 150. The present sample only hints at some possibly very interesting correlations between lightcurve properties and diameter, orbit, and compositional type; yet it is difficult to imagine that the number of accurately known amplitudes and rotation periods will more than double in the next decade. Photoelectric photometry with sufficient aspect coverage to yield reliable pole positions is likely to be limited to a handful of objects for the foreseeable future. Nevertheless it is important to realize that, given time and sufficient motivation such as a planned space mission, the shape, pole, and spin rate can be obtained by ground-based techniques for almost any asteroid.

UBV Photometry

UBV photometry provides reconnaissance data that can be related to asteroid surface composition. While insufficient by itself to specify asteroid surface mineralogy, it does reliably imply membership in a few of the major compositional classes and is a useful tool for identifying anomalous asteroids. The technique was applied to several dozen asteroids in the 1950's and 1960's and has been applied recently to about [illegible]00 asteroids, mainly by E. Bowell at Lowell Observatory and by Degewij, Gradie and Zellner at the University of Arizona. The survey could be extended to virtually all known asteroids within a decade, given a dedicated observer and a telescope in the 2 m class. Color variation with rotation is potentially very important, but color variations discernable in Earth-based disk-integrated data seem quite rare among the handful of objects measured.

Polarimetry

Polarimetry provides information primarily on the texture and opacity of particulates on asteroid surfaces. Measurements as a function of rotational phase for a handful of asteroids suggest, as with UBV measurements, that most asteroid surfaces are homogeneous on a hemispheric scale. More useful in the past have been measurements (mainly by B. Zellner) of polarization as a function of solar phase angle, over the generally available range of 0° to 30°. Individual values at small phase angles are correlated with albedo and more extensive observations at larger phases yield precise albedos, except for the blackest asteroids. Since radiometry (discussed below) is more readily accomplished and yields the same information, the number of polarimetrically-determined albedos and diameters is not likely to increase much in the future. Future application of polarimetry will likely be for special-purpose studies; the technique can be applied, often with difficulty, to perhaps half the numbered population.

Radiometry

Measurement of the thermal radiation from an asteroid at wavelengths near 10 and 20 microns, when combined with visible photometry, yields a determination of asteroid diameter and albedo that is only slightly model-dependent (Matson *et al.*, 1978). The technique was developed less than a decade ago, but by 1976 had yielded more than 150 asteroid diameters. There has been a recent lull in the measurements since the two regular observing programs (those of D. Morrison and O. Hansen) have been discontinued. Work on special objects is continuing at the University of Arizona. The technique is not much more difficult than UBV photometry, at least for main belt objects, although it requires instrumentation that is less readily available. More than half of the numbered asteroids could be measured within a decade. More refined radiometry (as a function of asteroid rotation and phase angle) is correspondingly more time-consuming, but can yield better determinations of asteroid thermal properties and the sense of rotation. Thermal emission spectra are potentially indicative of composition, but so far no spectral features have been found.

Spectrophotometry

Spectrophotometry of asteroids can be accomplished from Earth in several different passbands and with a variety of instruments yielding different spectral resolutions. Such data are, to varying degrees, indicative of asteroid surface mineralogy (see McCord's paper elsewhere in this volume). Most spectral features of interest from 1000 Å to beyond 10 microns are relatively broad and can be detected with spectral resolutions ($\Delta\lambda/\lambda$) of about 0.1; absorption band position measurements made with 10 times better spectral resolution can define certain compositional characteristics reliably but still higher spectral resolution is not demonstrably useful. Filter spectrophotometry in the visible and near-IR (0.3 to 1.1 microns) has been published by McCord and Chapman for 100 asteroids and is available (in varying stages of reduction) for about 150 more. The technique can be applied, with difficulty, to more than half of the numbered asteroids; use of a multiplexing instrument would increase observing efficiency, but it is doubtful that the technique will be applied to more than a quarter of the numbered asteroids within the next decade. Broad-band filter photometry in the JHK region of the infrared has been done for several dozen asteroids, primarily by JPL scientists, and complements the visible spectrophotometry; because of low detector efficiency the technique cannot be applied to the fainter asteroids. Higher resolution studies in the 1-4 micron region, using quantum-efficient interferometric techniques, have been made of several asteroids and--with considerable effort and allocation of major facilities and resources--can be applied to the hundred brightest asteroids; a major effort is underway by H. Larson. This infrared region is rich with diagnostic spectral features, but observations are somewhat hindered by absorptions in the Earth's atmosphere. Spectral features exist in the UV, below 1500 A, that differ for various rocky and metallic materials; it is unknown if such features will prove to be as compositionally diagnostic as infrared features, but in any case, exploitation of this spectral region can be accomplished only from above the Earth's atmosphere and with exceptionally sensitive detectors because of the near-absence of short wavelength sunlight.

Radar

Radar is the one ground based astronomical technique that is known to be powerful but has yet to be widely applied to asteroids. Many Earth-approaching asteroids, and some of the larger main belt asteroids (especially those in the inner edge of the belt) are potentially within the range of the Goldstone and Arecibo observatory facilities. Radar detection provides information on asteroid bulk properties (especially presence or absence of a major metallic component), size, shape, and roughness; more refined observations, potentially applicable to only a few asteroids, could be much more revealing. It is doubtful that radar observations will be made of more than a few dozen asteroids during the next decade. Passive detection of microwave radiation from a few asteroids has been done, but the technique is difficult and unlikely to provide fundamental information.

There are several other techniques, or refinements of the above techniques, that have been, or could be, applied to asteroids. For instance, direct measurement of asteroid diameters by speckle interferometry, lunar occultations, or asteroidal occultations of stars could help calibrate, and give us greater confidence in, the radiometric technique. A combination of highly refined photometry, radiometry, polarimetry, spectrophotometry, and radar measurements of a single asteroid over a range of phase angles and rotational phase can uniquely specify geometric, physical, and compositional parameters that would be indeterminate or less certain from less complete data. Such a coordinated study of 433 Eros in 1975 illustrated the possibilities of essentially all the ground-based techniques in current use (see the May 1976 issue of *Icarus*). Mass determinations are available for three asteroids and estimates may be made of the masses of several more asteroids within a few years.

In combination with known orbital parameters (*e.g.*, membership in a Hirayama family), physical parameters may be statistically treated for all asteroids, or subsets; thereby we may speculate about some asteroid properties not directly measurable (*e.g.*, internal composition, strength, mode of origin). But, fundamentally, ground-based observations are restricted to telling us about the size, shape, and spin of an asteroid and something about the mineralogy and texture of the surface layer as resolved on a global scale. Basic data on sizes and surface properties are now available for several hundred asteroids, could be extended to any known asteroid, and probably will be extended to most known asteroids during the next decade. Basic data on spins and shapes exist for half as many asteroids, could be extended to most, but probably will not be done for more than a few hundred in the foreseeable future. Highly refined measurements of asteroid properties, employing most of the available techniques, have been done for only a few asteroids, could be done for a few Earth-approaching asteroids and perhaps 100 main belt asteroids, but probably will not be done for more than a handful.

OBSERVATIONS FROM EARTH ORBIT

Observations from Earth orbit permit the full resolving power of the telescope to be utilized over the full spectral range, unhindered by atmospheric absorptions. It remains to be seen how helpful such advantages may be. Extended spectral ranges in the UV and IR may provide important constraints on some types of asteroid mineralogical assemblages, but it seems unlikely that our understanding will be dramatically affected. The resolving power of the Space Telescope is probably insufficient to make useful maps of even the largest asteroids.

Observations from Earth orbit may also be made with much greater efficiency than from the ground. For instance, the Infrared Astronomical Satellite (IRAS), a project currently in preliminary stages, would have the capability for doing radiometry of all known asteroids; in fact it will measure such asteroids and thousands of as-yet-unknown asteroids unavoidably in the process of making a catalog of infrared sources. It remains to be established that the IRAS asteroid observations will be made and reduced in ways maximizing the scientific return.

While advantages to asteroid science by the allocation of a major fraction of observing time from Earth-orbiting satellites and observatories would be great, the facilities provide even greater benefits to other astronomical disciplines and are thus unlikely to be allocated for asteroid work except in rare instances. The best prospects are cases such as IRAS in which asteroid observations are made unavoidably in the process of carrying out another program.

THE FUTURE OF GROUND-BASED OBSERVATIONS OF ASTEROIDS

It is not easy to speculate about the future. Certainly during the next decade, new techniques--or at least important variations of present ones--will be developed that may be applied to a sample of asteroids. But any ground-based remote-sensing technique is fundamentally limited to telling us about reflected or emitted radiation from the hemispherically averaged *surface* of the body in question. New ground-based techniques are unlikely to address complementary aspects of asteroids (*e.g.*, concerning asteroid interiors) needed for complete understanding of these bodies.

In the previous section, we guessed at the likely application of present techniques during the next decade, assuming rough maintenance of present resources and priorities. Currently asteroids receive a substantial fraction of NASA-supported ground-based astronomical attention; vastly greater allocation of funds or major telescope time is unlikely. But modest increases are possible if continued asteroid observations are deemed to be important. Asteroids (unlike cometary nuclei, for example) are very profitably studied from the ground. In terms of maximum return from minimum effort, however, it is probably true that we will have soon skimmed the cream from the top of the ground-based asteroid observations. Certainly the less powerful techniques are approaching their limits. At this point, therefore, the critical questions are two-fold: (1) Is the present understanding of the asteroid population adequate for technical planning of space missions and intelligent choice of targets, or is the next decade likely to hold such surprises that any present mission strategy will ultimately seem ill-conceived? (2) What are the most profitable avenues for future ground-based work, both in support of space missions and in pursuit of questions (such as population statistics) that can be addressed only from the ground?

Anders (1971), in the context of the first question, argued as follows: "Ground-based research on asteroids and meteorites is nowhere near exhaustion; on the contrary, it is moving at an impressive pace. If we maintain this pace for another decade or two, we will not only have answered most of the questions posed for an early mission, but will be able to come up with a more worthwhile, more informative mission...Some crucial questions will undoubtedly remain when all ground-based studies have been pushed to their limit, and at that stage, perhaps ten years from now, further progress will require space missions. We do not know what sort of a target will have the highest scientific interest at that time: a Trojan, a Hilda group asteroid, a few nearly spherical asteroids (small or large) in the near or far parts of the belt, a few highly irregular objects, a Hirayama family, etc. Any choice we make now is likely to seem trivial or uninformative a decade hence."

We submit that the ground-based observers have done their homework since Anders' statement was drafted almost a decade ago. Whereas we were then largely ignorant about asteroids and their significance, we now have learned enough about them to formulate some fundamental cosmogonical and planetological questions that exploration of asteroids may answer. Compositional classifications are now adequate for the planning of quite a few multi-asteroid rendezvous missions, each including a variety of important types. To a substantial degree we know which asteroids are likely to be related to known meteorites (by avuncular, if not parental, association) and thus are interesting for *in situ* studies of the meteorite parent bodies. We also know of objects that are not represented in our meteorite collections, and are especially significant on that account. We can characterize asteroids sufficiently to assert that available techniques will likely prove practical for the determination of critical physical and engineering parameters--size, shape, spin, surface type, etc.--for almost any known asteroid. It no longer seems possible that target choices made on the basis of current knowledge will prove trivial. Of course, our understanding will be better when (and if) final target selection is required; a ground-based program dedicated to observing candidate targets could further upgrade target selection.

The second important question concerns the most productive directions for future ground-based programs. Clearly, several of the productive past reconnaissance programs are approaching their limits. As we learn more about the asteroids, there will be an inevitable shift toward more specialized programs addressing problems of high scientific interest. They may involve application of proven techniques (*e.g.*, radiometry) to special classes of bodies (*e.g.*, Hirayama families) or application of past or developing techniques to intensive studies (*e.g.*, lightcurve pole-determination, detailed measurement of absorption bands, or thermal IR studies of rotational and phase effects) of a modest sample of asteroids of exceptional interest. Thus we may expect a diminishing number of new asteroids measured but an increasing sophistication in techniques and results for sampled asteroids. Future programs will increasingly be directed toward well-formulated questions of cosmogony or interrelationships. A concomittant requirement of the ground-based program is that increased attention be given to interpretation and synthesis of data already obtained and to associated theoretical and laboratory research programs. For example, it is important to investigate the role of metal on and within asteroids: how metal reddens asteroid spectra, how metal responds to hypervelocity impact at asteroidal temperatures, and how metal affects thermal properties and interpretation of radiometry.

The progress of science is unpredictable. Nevertheless we can identify the following ground-based programs for high priority during the next few years:

1. A substantially expanded search for Earth-approaching objects, by broadfield photographic techniques, particularly in conjunction with the IRAS survey. A new large Schmidt telescope appears to be needed; the cost will be substantial but the benefits will be great for all of astronomy.

2. A spectrophotometric survey of roughly a thousand minor planets, at resolution comparable to UBV or somewhat higher, but extended to longer wavelength. Detectors now exist for adequate photon count out to wavelength 1.10 microns for the majority of the numbered asteroids. The survey is otherwise routine, using fully proven facilities and techniques.

3. Continued thermal-radiometric studies, especially of newly discovered Apollo/Amors and main belt objects that are found to be spectroscopically interesting. The techniques are fully proven, requiring only dedicated observers.

4. Continued and expanded high-resolution spectroscopy and narrow-band spectrophotometry in the visible and infrared of asteroids found to be especially interesting in the low resolution survey. The 0.8-3.5 micron spectral region is especially important for more sophisticated characterization of the mineralogy. Improved detectors are appearing. Additional laboratory and theoretical work on interpretation of reflection spectra is needed.

5. Radar studies of a small representative sample of main belt asteroids.

6. Application of the full complement of astrophysical techniques, including polarimetry intensive lightcurve studies, for the objects of greatest scientific interest, for those objects (such as Vesta) which are certain to be high on the list for space missions, and for all objects which emerge as good candidates for space missions on dynamical grounds.

We now seem to be passing from the stage of total ignorance about the ground-based observable properties of asteroid surfaces to a state of considerable knowledge. One may imagine that after another few years devoted to the remaining important observations and synthesizing the available data, the broad ground-based perspective on the nature of the asteroids will be largely complete. The scientific approach must ultimately shift from the observational characterization of asteroid surfaces to developing hypotheses concerning how asteroids got to be the way they are.

Beyond those problems that can be tackled from the ground, many fundamental questions about small bodies and implications for solar system history require close-up analysis of their chemical, physical, and geological traits (*e.g.*, minor minerals, trace elements, isotopic compositions, surface topography, compositional heterogeneities, internal structure, etc.). Space missions are required to measure such properties. Since asteroids are so numerous and so widely dispersed in space, missions will necessarily be restricted to only a few bodies. Thus we must ultimately rely on remote-sensing data from the vicinity of Earth to extend insights gleaned from missions to the entire asteroid population.

In conclusion, ground-based asteroid science has made sufficient progress so that we can be confident in designing a space mission exploration strategy that will not seem unintelligent a decade hence. At the same time, there remains high potential for further understanding of asteroids from Earth-based programs that apply state-of-the-art techniques to special subsets of the population and address fundamental problems raised by the early reconnaissance data.

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DISCUSSION

FANALE: About the variations in polarimetric measurements--if nature made asteroids very nonuniform, you wouldn't know which variables are varying, because you're looking at a composite of a thousand variables. But nature makes them quite uniform, so polarimetry is a wonderful technique for spotting something really wild.

MORRISON: Does α_0, the angle of zero polarization, contain much information about regoliths and dusty surfaces, or are these observations difficult or impossible to interpret?

CHAPMAN: It's my view that polarization is telling us something about surface properties, but not enough. It's telling us that there are interesting differences between the asteroids, but there is not enough information in polarization or even polarization combined with photometry and other techniques to specify what these differences are. Once again, perhaps some insight may come with more observations or with better laboratory data which would enable us to understand these differences.

VEVERKA: Let me come back to Fanale's point. Polarization is a useful technique. It can tell you which asteroids are different. It does not necessarily have to tell you why and one shouldn't make the assumption that a lot of people have made, that somehow if you're clever the information is there and you should be able to sort it out uniquely. The parameter α_0 may not have a unique interpretation in terms of regolith properties, yet it may still be useful to know that two particular asteroids do or do not have the same α_0.

FANALE: And it gets you around the problems that come from not knowing the shape of the asteroid.

MATSON: It seems to me that the differences that can be detected with polarimetry are at a smaller scale than the differences that can be detected with radiometry.

CHAPMAN: I think you're right. This is another reason why polarimetry is important.

MORRISON: You mentioned that masses are known for three asteroids, but only two are precise enough to tell us something. I expect we will not get many more with a precision like 10%.

MATSON: With current radar technology, we can get ranges to the larger asteroids, and once you have a record of ranging data to Ceres or Vesta over a period of five years or more, you can start to pull out asteroid masses.

VEVERKA: I think you have a problem there with time scales. It's certainly true that over a long period of time, say 100 years, you could get those asteroid masses.

MATSON: Yes, that's true for the large amplitudes that one must use with ground-based astrometry. But with radar you don't have to go for the maximum amplitudes. You can take some little wiggle.

GROSSMAN: Is the ground-based observational activity leveling off due to money?

CHAPMAN: Yes, it's leveling off due to saturation of several things, including the number of known asteroids, the funding, the available instrumentation, and the available manpower.

MATSON: From the data that are available now we are seeing the main themes, we are seeing the large-scale story. Once one delineates the main themes, then the exceptions to the themes become absolutely crucial. Maybe 10 years from now we may find a peculiar asteroid that really alters our perceptions.

CHAPMAN: We have come a long way and we have a considerable distance further to go with the present techniques, but we are not going to learn everything using only current techniques.