ASTEROIDS

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ABSTRACT. Using a number of different conventional observing methods of astronomy like spectrophotometry, polarimetry, IR-radiometry and UBV-photometry, physical properties of asteroids can be derived, such as diameters, spectral reflectivity and albedo. Based on observable parameters a classification in terms of taxonomic types can be made and the mineralogy of the surface can be determined and compared with meteoritic analogues. UBV-photometry at different phase angles can reveal something about surface properties and diameters, whereas from accurate photometry during different phases of the rotational cycles we are able to derive rotation periods, geometric irregularities of the asteroid-body and topographic features on the surface. If observations of lightcurves are obtained during several oppositions at different ecliptic positions, the orientation of the spin axis in space and sometimes the sense of rotation can be derived. Observations of asteroids are especially well suited to small and medium-sized telescopes, as most of the programmes need long telescope runs. In addition there is a definite need for a large number of observations of asteroids in the magnitude range 12-15 mag.

1. INTRODUCTION

At the present stage of solar system space research we must state that we have had different space missions to nearly all the objects in the planetary system, which include the investigations of the moon, the sun, the planets and their satellites and of course interplanetary space. With the reappearance of Comet Halley a space mission to such an object has been undertaken. We must wonder why there has so far been no fly-by of a specific selected object in the asteroid belt. It would be logical to explore asteroids directly at a fly-by by means of in situ investigations of asteroids whose orbits are more or less between the planets Mars and Jupiter.

Projects for such flights were presented and proposed to ESA in missions like ASTEREX in 1979 or AGORA in 1983. A fly-by of an asteroid is planned by NASA in the CRAF mission between 1990 and 2000. Looking

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into the future it seems at least possible to talk about possible mining and exploiting such relatively small rock-like objects. Of special interest are nearby asteroids with earth-crossing orbits and it would be of special interest to know the mineralogy of a small asteroid (with a diameter of about a kilometer). Also the property of the surface would be of interest and could tell us something about the impact history.

The interesting physical parameters of asteroids are especially their masses, volumes and densities, as well as the geometry of the body, its rotation and surface properties. As far as masses and densities are concerned, it is extremely difficult to obtain precise values. Schubart and Matson (1979) have collected and presented results for the asteroids 1 Ceres, 2 Pallas and 4 Vesta and get for example, 2.3 ± 1.1 g/cm^3 for 1 Ceres and 3.3 ± 1.5 g/cm^3 for 4 Vesta, which give a rough indication that there probably are density differences for different types of asteroids - but the precision is only about ± 50%. Masses are usually derived from perturbation computations, but it also should be mentioned that it is difficult to obtain accurate diameters. The best diameters are based on occultation measurements - until now obtained only for a few asteroids with larger diameters, and they represent only diameters at certain rotational phases. Asteroids up until now have been resolved directly, the largest asteroid, 1 Ceres with a listed diameter of 1025 km has only 0.7 arcsec apparent diameter at most, and many asteroids are much smaller, or farther out. From earth there is no chance of getting direct images of the surface, though speckle interferometry is used to get elliptical images of asteroids.

2. COLLISIONAL EVOLUTION OF ASTEROIDS

Today we believe that the study of asteroids contributes a lot to our understanding of the origin and evolution of the solar system. There are other objects, too, but we think that asteroids are small enough that they have not undergone the complicated chemical evolution like the larger planets, and on the other hand they are large enough, when compared to comets, that their orbits have not been perturbed too much. In addition, masses should be higher than for comets, since asteroid orbits are not too close to the sun, so that little disintegration has taken place. We believe that in general asteroids are still found in those regions where they were formed.

Wilkening (1979) has given a schematic diagram of the possible formation and evolution of asteroids. It is assumed that out of the primitive solar nebula in the asteroid zone a number of primordial asteroids were formed, roughly with diameters of a few hundred kilometers, by condensation or by accretion of material. If no chemical evolution takes place, such an asteroid should go only through the process of impact cratering, produced by smaller objects. It should end up as a typical C-type asteroid with surface structures due to impacts. As indicated by Paolicchi et al. (1981) there could occur a kind of catastrophic impact which would produce a number of smaller objects, depending on the size, on the kinetic energy involved and on the solid-

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state forces. The smaller parts could, under the influence of self-gravitation, form a kind of loose pile of rubble, or binary and multiple asteroids, or the asteroid could be disintegrated and the resulting product could probably be a more physically defined asteroid family than those defined only by orbital characteristics.

If the temperatures are higher an asteroid would go through melting processes and would be heated up and cooled down. Through the repeated process of fractional differentiation, layers of different densities would be formed around the central core. If again we have impacts or catastrophic collisions, deep cratering or fragmentation would occur. The asteroid, e.g. an S-type asteroid with a dense core, would exhibit deeper layers with different properties, and if observed from earth in reflected sunlight - that is the only information we get - it would show variations on the surface during its rotation.

3. SPECTROPHOTOMETRY

The number of asteroids with known orbital characteristics (in order to identify and recover any given object) has increased during the last few years. In the Ephemerides of Minor Planets for 1979 we find 2050 numbered asteroids. In 1985 we have 2958, which means an increase of roughly 900 asteroids in six years, and for the year 1986 we find 3143 asteroids listed which is 200 more than last year. Though most of the newly discovered asteroids are fainter objects, we would estimate that in the magnitude range V = 8 to 15 there are about 600 to 700 observable asteroids, depending on the distances between the sun, the earth and the asteroid. These are within easy reach of any telescope of 0.5 m up to 1.5 m aperture. Doing simple photometry even V = 17 can be reached. Modern detectors can also enhance the finding and identification of asteroids.

Bobrovnikoff (1929) stated that 2 Pallas was bluer than other asteroids - that was a kind of qualitative spectrophotometry and was a first indication of possible surface composition differences. Only a few years ago detailed studies of the brighter asteroids were made by Gaffey and McCord (1979), using a 25-filter spectrophotometer, covering the optical wavelength range from 0.3 to 1.1 μm. From a comparison with reflectance spectra of meteorites and artificial mixed powders of olivine, pyroxene and nickel-iron containing material, analogues for asteroids were derived. Quantitative spectral curves were measured for about 300 brighter asteroids by Chapman and Gaffey (1979) and average spectra were found for the major asteroid compositional type. C-types, which show low reflectivity and a flat spectrum, are silicates and opaque carbons, similar to carbonaceous meteorites. S-type asteroids have higher reflectivity, typically 15-20%, and consist of metallic silicates. Their spectral curve is deep and not flat and exhibits an absorption near 0.95 μm in the olivine-pyroxene band. The third and major class is named M (medium, metallic) with high reflectivity. They generally rotate faster and might have higher densities. Chapman and Gaffey (1979) tried to group the reflectance spectra due to the composition of the material with C : S ranging from 1 : 6 to 6 : 1, but the resulting classes were far too complicated and had only laboratory importance. Among all asteroids 4 Vesta turned out to be a unique case, classified as U (unknown) and showing a deep olivine-pyroxene absorption band.

It should be noted, that this type of specrophotometry has not been continued. Zellner et al (1985) used an eight-colour asteroid survey system for nearly 600 asteroids, and derived a new classification system. Recently there are reports of using IDS systems for continuous spectral-scanning with about 1 to 2 nm resolution over the optical wavelength range. There is a need to continue this type of work and to extend it to about magnitude 15, which will require a lot of observing time.

4. POLARIMETRY AND IR-RADIOMETRY

In order to study the surface texture and the broadband reflectivity, Dollfus and Zellner (1979) measured the scattered partly polarized light of asteroids. The polarization curve is characterized by the minimum negative polarization at small phase angles and the width of the negative part up to the inversion angle, where polarization becomes positive. These are also the parameters which describe the surfaces in terms of roughness and porosity. Additionally, the linear slope of the polarization curve, if polarization is measured over a longer phase angle range, is linked to the albedo (in the visual spectral range p_V) and in consequence with the diameter. The albedo of about 300 asteroids has been measured and an interesting bimodality due to surface reflectivity was found for the C-type asteroids with p_V from 0.065 down to a peak between 0.035 and 0.04, and for the S-type objects with p_V between roughly 0.065 to 0.23 and a peak at about 0.14 (Zellner and Gradie (1976) and Morrison (1977)).

In addition Morrison and Lebovsky (1979) derived radiometric albedos and diameters for about 200 asteroids, measuring the thermal emission of asteroids at infrared wavelengths (10 and 20 μm), combined with simultaneous B and V measurements. They assumed a standard thermal model of high thermal inertia,caused by an insulating and poor conducting regolith, which was responsible for the fact that both the illuminated and non-illuminated sides of an asteroid have no temperature difference. In general, the diameters and albedos, derived from infrared methods do not differ much from those derived from polarimetry, and they usually agree within 10% which is within the accuracy limits of diameters derived from modern occultation measurements. It must be noted, that this type of work has not been extended to a larger sample of fainter asteroids to enhance the statistics.

5. UBV-PHOTOMETRY

The most complete list of UBV data for asteroids was created (and is still maintained) by Bowell et al. (1979). This list contains not only colours, but types, diameters and magnitudes. This type of work is still going on and UBV photometry has the advantage that measurements can be made quickly and that a large number of asteroids, including fainter ones down to 17-18 mag, can be analyzed. For the taxonomy of asteroids the albedo, polarization, spectroscopic parameters and colour indices B-V and U-B were used. For a total of 750 asteroids with reported UBV measurements the following results were obtained: about 75% are dark C-type asteroids, 15% bright S-asteroids, the rest, 10% are of type M (metallic), E (enstatic achondrites), R (reddish) or U (unknown). Asteroid classification will become more complicated, since Gradie and Tedesco (1982) announced new categories based on the new eight-filter system. Using this system Zellner et al. (1985) find an interesting clustering of asteroids within a given class if analysed for various distances from the sun.

The mean brightness of an asteroid depends on the geometry and on the scattering properties of the asteroid surface. If the magnitude is measured over a larger phase angle range, reduced for a defined absolute distance, we obtain a phase curve, called the magnitude-phase relation. It consists of a (nearly) linear part for phase angles larger than 10 degrees (which gives the phase coefficient) and the non-linear part at smaller phase angles, called the opposition effect, where asteroids become brighter than they should. Scaltriti and Zappalá (1980) showed that the opposition effect is similar for all asteroids, i.e. it is not affected by type or albedo.

The opposition effect in the phase curve is mainly controlled by the volume density or porosity whereas the linear part in the phase curve is determined by the roughness of the surface. From more than 1500 UBV observations and based on a multiple scattering theory of the surface of atmosphereless bodies, Bowell and Lumme (1979) found that asteroid surfaces are similar in texture, moderately porous, purely as a consequence of the similarity of the opposition effect. From different slopes of the magnitude-phase relation they concluded that asteroids are moderately rough and that the surface roughness varies with types. It also should be noted that just recently at the IAU General Assembly at New Delhi this theory was adopted by Commission 20 of IAU for the future prediction of the magnitudes of asteroids, which will finally provide a system which is based upon photometric observations.

6. PHOTOMETRY AND SURFACE VARIEGATION OBSERVED DURING THE ROTATION

A large research field during the last few years - and also in the future - is the study of asteroid rotation rates. All asteroids rotate somehow, with spinrates from only hours up to days. Most of the asteroids have rotation rates of between 8 and 15 hours, but very long rotation rates of up to 50 days have been found. Light variations of 0.01 to 1.5 mag. are measured and expressed in terms of the variation of the cross-section. Light curves turn out to be generally double-wave and very symmetric. Therefore with respect to surface geometry properties this would give a direct determination of the geometry of an asteroid. That is also the easiest method to get an idea about the shape of an asteroid. Nearly all observed asteroids do show such variations during rotation, but for some it might be at the limit of detectability.

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In order to get information about details on the surface itself, e.g. the possible variation in composition on different sides of an asteroid, one needs to carry out spectrophotometry during one rotation which is time consuming and not applicable for a large number of asteroids at smaller telescopes. But to find any kind of colour-patches or albedo spots, a mixture of E-type and S-type material, on the surface, or even topographic features like mountains or the shadowing effects of such features, the best method to be applied would be polarization and/or colour measurements during rotation. Lists presented by Degewij et al. (1979) and by Schober and Schroll (1981) could show that there is evidence for about 20% of investigated asteroids to exhibit such variations - but only to the order of a few hundredths of a magnitude. Among them 3 Juno and 4 Vesta seem to be especially good candidates.

Simple photometry is still one of the best means to investigate the surface and the rotational properties of asteroids but lightcurves of asteroids sometimes turned out to be more complicated. Frequently rotation rates have to be revised after repeated observations, mostly by a factor two and often there are features in the lightcurves which are caused by surface properties and result in triple or even quadruple lightcurves with triple extrema. Interpretation is difficult and sometimes repeated observations could give completely different results. Also there is the possible existence of satellites or binary asteroids (with lightcurves quite similar to eclipsing binary stars) which must be considered. Evidence for such binary lightcurve objects may be found, from: triple or quadruple extrema, colour variations during rotation, different apparitions which show different lightcurves, very slowly spinning asteroids showing tidal effects and nonperiodic irregular lightcurve features within the lightcurves of an asteroid. It must be mentioned that there is still a lot of speculation and that until now no real proof has been found for any binary object or satellite.

7. POLE DETERMINATION OF ASTEROIDS

One of the most important parameters of asteroid physics is certainly the knowledge of the orientation of the spin axis - or pole coordinates with respect to the plane of the ecliptic. For the study of the collisional evolution of asteroids the distribution of spin axis orientation is important. Also for future studies, including possible space research projects, knowledge of the pole orientation and if available the sense of rotation is important. During the last years an increasing effort has been made to improve our knowledge of pole positions, mainly due to the effort of Zappalà et al. (1983) and Magnusson (1983).

In principle, the lightcurve of an asteroid depends on the aspect of the asteroid, which means that an asteroid, if observed at different earth-sun-asteroid geometry, shows changing lightcurve amplitudes, changing timings of the extrema, and changing appearance of the lightcurve. That is, it depends on the line of sight of the observer towards the surface of the asteroid. The most extreme possibilities are pole-on and equator-on views with the respective result that there is either no light variation or maximum light variation.

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If we do not consider the most direct method of using speckle interferometry to derive pole orientations, there are in principle four different methods to determine pole positions: graphic pole determination (using amplitudes and ecliptic longitudes) as given by Vesely (1971), semianalytic methods (using amplitudes, ecliptic longitudes and the V magnitude at lightcurve maximum) as given by Zappalà (1981), astrometric photometry as introduced by Gehrels and reviewed by Taylor (1979) and combined methods by Magnusson (1983). Until now only about 30 asteroids have been successfully observed and analysed, with good accuracy for pole orientations - a program which definitely merits future attention and telescope time. But again it must be noted that it is time consuming as every two or three years, depending on the asteroid, observations are necessary including observations for a large phase angle range. On the other hand this project is very well suited for smaller telescopes, as many of the brighter asteroids from V = 8 to 13 are still to be observed.

7. CONCLUSION

Although I know that this review is far from covering all the different aspects of asteroid research (I completely omitted the still necessary astrometric work for improving orbits and for positions and discoveries, and I did not even mention the modern CCD-imaging and automatic discovering of moving targets), I hope that a few topics were mentioned, which makes it clear that observing asteroids is a useful project. I also should mention that there are a number of groups working in asteroid physics, and that there is a number of publications, which must and should be mentioned. The last official asteroid meeting was held in 1979 at Tucson and a book "Asteroid" edited by T. Gehrels (1979) came out of that meeting. That book is unique and it will be hard to make a better one in the future. Every potential observer is certainly recommended to look at that book. The next asteroid conference will again be held at Tucson in 1987. There are two other Asteroid-related books available, both the result of conferences: "Asteroids, Comets, Meteors" I and II, both edited by Lagerkvist and Rickman (1983) and part II is just in print, in 1985 or 1986. They contain the current programs in a more detailed form. I have tried to concentrate on modern observing techniques, mostly based on photometry or related methods, but I should not forget to mention the "Minor Planet Bulletin" now edited by Binzel and appearing several times per year. I would also like to make reference to Binzel's (1983) article on the Photometry of Asteroids in the Solar System Photometry Handbook, edited by Genet.

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REFERENCES

Books:

Asteroids, ed. T. Gehrels, Univ. of Arizona Press, Tucson, Arizona,1979.

Asteroids, Comets, Meteors, eds. C.I. Lagerkvist and H. Rickman, Uppsala universitet, Uppsala, 1983.

Asteroids, Comets, Meteors II, eds. C. I. Lagerkvist and H. Rickman, Uppsala universitet, Uppsala, 1986.

Solar System Photometry Handbook, ed. R. M. Genet, Willmann-Bell Inc., Richmond, 1983.

Articles:

Binzel, R.P.: 1983, *Solar Photometry Handbook*, Chapter 1.

Bobrovnikoff, N.T.: 1929, *Lick Obs. Bull.*, 14, 18.

Bowell, E., Gehrels, T., Zellner, B.: 1979, in *Asteroids*, p.1108.

Bowell, E., Lumme, K.: 1979, in *Asteroids*, p.132.

Degewij, J., Tedesco, E., Zellner, B.: 1979, *Icarus*, 40, 346.

Gaffey, M.J., McCord, T.B.: 1979, in *Asteroids*, p.688.

Gradie, J., Tedesco, E.F.: 1982, *Science*, 216, 1405.

Morrison, D.: 1977, in *Comets, Asteroids, Meteorites: Interrelation, Evolution Origin*, ed. Delsemme, A.H., Univ.of Toledo Press, Toledo, p.177.

Morrison, D., Lebovsky, L.A.: 1979, in *Asteroids*, p.184.

Magnusson, P.: 1983, in *Asteroids, Comets, Meteors*, p.75.

Paolicchi, P., Farinella, P., Zappalà, V.: 1982, in *Sun and Planetary System*, eds. W. Fricke, G. Teleki, Reidel, Dordrecht, p.295.

Scaltriti, F., Zappalà, V.: 1980, *Astron. Astrophys.*, 83, 249.

Schober, H.J., Schroll, A.: 1982, in *Sun and Planetary System*, eds. W. Fricke, G. Teleki, Reidel, Dordrecht, p.285.

Schubart, J., Matson, D.L.: 1979, in *Asteroids*, p.84.

Taylor, R.C.: 1979, in *Asteroids*, p.480.

Vesely, C.D.: 1971, in *Physical Studies of Minor Planets*, ed.T.Gehrels, NASA SP-267, Washington, p.133.

Wilkening, L.L.: 1979, in *Asteroids*, p.61.

Zappalà, V.: 1981, *Moon and Planets*, 24, 319.

Zappalà, V., M. di Martino, Farinella, P., Paolicchi, P.: 1983, in *Asteroids, Comets, Meteors*, p.73.

Zellner, B., Gradie, J.: 1976, *Astron. Journ.*, 81, 262.

Zellner, B., Tholen, D.J., Tedesco, E.F.: 1985, *Icarus*, 61, 443.

DISCUSSION

Millis: The diameters quoted by Schubart and Matson (1979) for Ceres and Vesta are not occultation diameters. We still don't know the diameter of Vesta, but the diameter and density of Ceres are now known and they are significantly different from the values given by Schubart and Matson.

Graham: What type of asteroid observations, using small telescopes, are required at present?

Schober: Probably polarisation measurements.

Rowe: In your bimodal distribution, which asteroids are on the inner parts of the solar system?

Schober: The darker ones (C-type) should be more on the inside.

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