Asteroids: A Key to Understand the Evolution of the Solar System

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1. Introduction

Asteroids are believed to be remnant planetesimals from the crucial period of planetary formation and are mostly located in the transition region, separating the terrestrial planets from the jovian ones. There the planetary formation process was interrupted at an intermediate stage owing to an unknown mechanism, probably associated with the gravitational influence of the massive proto-Jupiter.

Asteroid eccentricities and inclinations were pumped up, thereby increasing collision velocities, and transforming...
the accretion among planetesimals into collisional destruction and erosion. Impacts have altered asteroid sizes, physical structures and rotation rates over the course of solar system history; however, the magnitude of these changes is not yet well understood. Collisional comminution among the asteroids continues to the present.

Asteroids comprise a great diversity of objects, with wide variations in mineralogy, in size (sub-km to 950 km in diameter), in spin rate (a few hours to two months), in shape (spherical to elongated or even binary), and in solar system location. Most of them should be constituted of essentially unaltered primitive material in which is preserved important information about the chemical composition and the environmental conditions of the protoplanetary nebula and the processes that produced the planetary bodies: asteroids would represent the last remnant of the swarm of planetesimals which formed the terrestrial planets.

Even though asteroids remain points of light through ground-based telescopes, the knowledge of these small bodies has considerably improved over the last twenty years, but the asteroid population is still poorly known with respect to the other bodies of the solar system which have been explored by spacecraft. Ground-based observations provide the only available information.

Most of the current knowledge on asteroid rotational properties (rotation period and pole direction) and on their shapes is deduced by analysing the amplitude and the behaviour of the light-curves obtained by photoelectric and CCD photometry. Surface albedo homogeneity is estimated on the basis of three- or eight-colour photometry; chemical composition of the surface materials is deduced comparing the IR reflectance spectra of asteroids with those of different materials (meteorites, lunar and terrestrial rocks, etc.) obtained in the laboratory, while significant contributions to the knowledge of the physical properties of these materials have been obtained by radiometry and polarimetry and on the basis of the few available radar observations. Star occultations and speckle interferometry give better data on asteroid shapes and pole orientation, but these measurements are difficult and only few data are presently available.

2. Current Knowledge

2.1 Rotation

Asteroid magnitudes vary periodically as they spin, mostly because of changes in cross section for nonspherical bodies but also because of surface albedo variations and scattering anomalies. Amplitudes are typically 0.1 to 0.3 mag but can exceed 1 mag. To date, there are about 4500 numbered minor planets, and we know the rotation periods of about 600 objects, but the rotation data set for the smaller objects is very incomplete when compared with the rotation periods available for asteroids larger than 100 km. In fact, only less than 10% of objects with diameter smaller than 50 km have been observed and have a well-determined rotation period, while the percentage is 30–40% for objects of about 100 km, and close to 100% for asteroids larger than 200 km. It follows that special efforts should be made to enlarge the available set for the smaller asteroids.

The first lightcurve of a minor planet was obtained in 1901 of 433 Eros, and in the next years light variations were observed for several other asteroids, at first by unreliable photographic photometry which was replaced in the 1950s by photoelectric photometry. In general, we can assert that asteroids are irregular bodies, partially spotted by albedo variegations it is possible to have ambi-

Editor's note: This paper is published in response to a request from the ESO Observing Programmes Committee, whose members suggested that an overview of current theories of asteroid formation, etc. should be prepared. We are thankful that Drs. Di Martino, Barucci and Fulchignoni have taken on this task and feel sure that many readers of the Messenger will appreciate this concise summary of minor planet work.
guity in determining the rotation period (Zappala et al., 1983). A few asteroid lightcurve amplitudes are too small to reveal reliable rotation periods.

Plotting the available asteroid rotation rates versus their diameter by a so-called “running box” technique that was first used for asteroid rotation rates by Dermott et al. (1984), there appears to be an increase in the rotation rates for very large objects, relative to the smaller ones (see Fig. 2). It is as if the marked change in the rotation-diameter distribution at sizes of about 100 km may separate primordial asteroids (right) from their collisional products (left). A possible trend towards more rapid rotation rates is present among the very small asteroids, but there is also an excess of slowly rotating objects below a size of about 50 km (this is evident in the figure from the increase in the dispersion for the lower size range), and the distribution of rotation rates among the smallest asteroids is distinctly bimodal. Unfortunately, for these objects the results are only indicative because, as already noted, they are affected by the incompleteness of the data set.

2.2 Shape

We have some indications on asteroid silhouettes that can be derived from star occultations, which give the cross-sections of asteroids in the plane perpendicular to the line of sight. Although this result is aspect dependent, star occultations (Millis and Dunham, 1989) indicate that larger asteroids have either a spherical or an ellipsoidal shape, while radar delay-Doppler images of small asteroids (Ostro, 1989) show more irregular shapes. On the hypothesis that the asteroids evolved collisionally from planetesimal swarms, these observations can be easily interpreted: the largest bodies (D > 200 km) are the remnants of the original population characterized by equilibrium figures, while decreasing the size increases the number of irregularly shaped asteroids, affected or produced by disruptive collisions. This interpretation is confirmed by the most recent results from experimental studies of catastrophic fragmentation processes (Fujiiwara et al., 1989, Capaccioni et al., 1986).

The images of the smaller bodies of the solar system (satellites of Mars and minimoons of Jupiter, Saturn and Uranus), obtained during space missions, show that elongated shapes are common in the size range 20 to 200 km. For this reason, bi- and triaxial ellipsoids seem to be a realistic approximation of the shape of most asteroids.

The lightcurve of an asteroid constitutes the primary observational data needed to determine its shape and pole direction. Much work has been carried out to determine these parameters from the observed light variations, also by comparing the observations with laboratory simulations that help in understanding how each parameter (shape, orientation and surface morphology) influences the lightcurve (Ostro and Connelly, 1984; Barucci et al., 1989).

Barucci et al. (1989) analyzed asteroids with known rotation periods by means of Fourier analysis of all lightcurves published before 1985. They used a sample of about one hundred “best observed” objects to discuss their shape distribution. The sample was subdivided in four categories: 32% of the selected asteroids have been classified as more or less elongated ellipsoids, 25% irregular, 23% spheroids and 20% as objects probably characterized by albedo features.

2.3 Pole Direction

The methods for pole determination can be summarized as follows: photometric astrometry (Taylor, 1979), amplitude-aspect and/or magnitude-aspect relation (Zappala et al., 1985), speckle interferometry (Drummond et al., 1985), methods combining epochs of extrema and amplitude-aspect relations (Magnusson, 1983; for a review of pole determination methods, see Magnusson, 1989). The method based on the lightcurve amplitude as a function of the position of the asteroid in its orbit (amplitude-magnitude method) has already given spin axis directions for about 30 asteroids with a good accuracy. The amplitude-magnitude (AM) method can be applied when complete lightcurves, obtained during at least 3 different oppositions, are available. In this way we can obtain a rough estimate of the pole direction: the larger the number of lightcurves at different ecliptic longitudes, the more accurate is the determination. Astrometric and speckle interferometry methods are in principle more accurate, but are also more difficult to apply and have resulted in about ten additional determinations up to now.

The number of asteroids with known pole directions is too small to perform conclusive statistical studies, but from a preliminary analysis there seems to be a distinct bimodality in the pole direction distribution (Fig. 3).

The determination of the pole direction of asteroids should lead to a better understanding of the role of the coll-

Figure 2: Plot of rotational frequency versus log diameter for all asteroids with known rotational period, excluding the planet-crossing objects and members of the major dynamical families. The “running-box” contained n = N/10 asteroids (N is the total number of objects in the sample) and was stepped through the population of asteroids at a time over the entire diameter range. One-sigma uncertainties are shown above and below the mean (dashed lines).
Terrestrial processes in shaping the physical characters of the population: a distribution with a preferential orientation would record the initial state of the axis inclinations, while a random distribution would indicate a complete reorientation of the spin axes due to the prevalence of collisions.

2.4 Taxonomy and Composition

The chemical composition of asteroids is of great interest because the different mineralogical assemblages may give interesting clues to the understanding of the primordial processes that took place in the solar nebula and during the early stages of the accretion. The principle source of information about composition comes from spectral analysis of reflected sunlight, although other techniques like polarimetry, radiometry and radar have yielded important contributions.

Many taxonomic classifications have been developed in the last decade (for a review, see Tholen, 1989), aiming at understanding some of the physical and compositional properties of the asteroid population. Two recent works are based on multivariate statistical analysis of asteroids for which a homogeneous set of spectrophotometric data, from ultraviolet to infrared, are available (Tholen, 1984; Barucci et al., 1987, which complete the data set with IRAS albedos). Barucci et al. analysed 442 asteroids and in this sample identified nine major taxonomic types, namely B, E, G, C, M, D, S, V, A and interpreted the links between the classes in terms of genetic trends. To understand better their possible evolution, they compared the asteroid classes with some meteorite samples.

In Figure 4 the classes are reported in a diagram where four trends are distinguished by the arrows that leave from D asteroids (dark objects with very red spectra suggesting the presence of low-temperature organic compounds and typical of the Trojan group) supposed to be primitive objects which have undergone little or no heating. Each arrow goes towards an “end class” and its direction generally indicates a decrease in heliocentric distance.

The first trend links together the D cluster with the B one, including the C class (probably similar in composition to carbonaceous chondritic meteorites). This trend might be interpreted in terms of volatile content reduction. According to this interpretation, the class D samples are richer in volatiles, while the B’s are the poorest due to higher formation temperature.

The second trend, connecting the D to the E class through G and M, may be interpreted as a progressive evolution of the solar nebula condensates (D) towards the enstatite achondrites (E) through an ultraprimitive, high-carbon, low-metamorphic-grade C-type mineral assemblage (G) and a reduction (transition metal free) silicate similar to the enstatite chondrites (M). The E asteroids may be composed by the silicates formed when enstatite chondritic bodies (M) were differentiated.

The third and fourth trends ending at V and A classes, respectively, seem to represent lines of increasing differentiation, starting from the undifferentiated material D. The third trend connects the D class (through a subunit of S asteroids) to the V class whose members are covered by basaltic material (4 Vesta) and olivine/pyroxene rich materials (349 Dembowska and 192 Nausikaa). The fourth trend connects the primitive D cluster to the A unit and contains most of the S asteroids, whose spectra show bands due to silicates. The A asteroids show in their spectrum an olivine absorption band that may represent the signature of mantle material of a differentiated body.

In the asteroid population a great diversity of albedos is present. Accounting for the observational biases, about 75% of the asteroids are found to be very dark, with average albedo of about 0.3 (D, C, and B types), another group of objects presents an albedo of about 0.15 (S, E, M, and V types), few asteroids lie in between, while some bright bodies have albedos up to 0.40 or more.

Very interesting is the fact that, in general, different taxonomic types are located at different heliocentric distances. This compositional gradient is interpreted as a “portrait” of the solar nebula matter, which condensed into

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Figure 3: Distribution of pole ecliptic latitudes (ßo) for 27 main-belt asteroids whose pole direction has been determined with good accuracy. Shaded boxes indicate objects larger than 200 km.

Figure 4: Diagram showing the evolutionary compositional trends of asteroids. The arrows leave from D-type objects supposed to be primitive objects which have undergone little or no heating.
The outcome of collisions are strongly influenced by the elements: semi-major axis (a), eccentricity (e), and inclination (i). In this case, the resulting objects may be described as differentiated bodies that have been jumbled up, thus forming a group of bodies that make up more than half of Trojans, Graciel, and Veverka (1980) suggested that the spectrum of D-type material can be reproduced by a mixture of silicates with carbonaceous compounds, even more primitive than those found in the carbonaceous chondrites. This is in agreement with current condensation theories about the formation of the solar system and is supported by the spectral studies of Vilas and Smith (1985), who observed an increasing reddening of asteroid spectra with heliocentric distance among the Cybele, Hilda, and Trojan groups of asteroids. Eight-colour photometry of the outer jovian satellites, at the same heliocentric distance as the Trojans, shows however that these objects are probably mostly C-type. This “mixing” of C and D types – D in the Trojan groups and C in the jovian system – poses a complication for the standard formation model of direct correlation between asteroid composition and heliocentric distance. The identification of D material in the saturnian satellite system and the similarity between the continuum spectra of some old comets to those of D objects suggest that the Trojans may not have formed at their present location, but further out, and could be related to comets.

For the above-mentioned reasons, observations of distant groups of asteroids (a > 3.25 AU) should be considered highly important, offering the possibility to collect data on objects quite different from the main-belt population.

5. Conclusions

Space missions devoted to the exploration of small bodies of the solar system, such as Vesta, CERES, and Rosetta,
or including asteroid fly-by, as Galileo and Cassini, will give a wealth of high-quality data on the asteroid population. Not a single close-up picture of a minor planet is yet available, but more information on asteroid rotations, shapes, poles and compositional types would provide interesting clues in understanding the role of collisions in producing the observed asteroid belt and more in general in the evolution of the solar system. Moreover, the data coming from in situ measurements will be detailed enough to clarify the nature and the interrelations between small bodies populations, if any. Are some of the Earth-crossing asteroids nuclei of dead comets? Are the meteorites fragments of asteroids disrupted by mutual collisions, or are they the smallest size tail of the asteroidal size distribution? Are double or multiple systems present among asteroids?

In order to give an answer to these and other questions, while we wait for the results of the space missions, it is necessary to improve the number and quality of data on asteroids: unbiased and detailed Earth-based surveys, ISO orbiting observatory results and Space Telescope inputs will be the main sources of the future data. Embedded in the asteroid belt may be the clues that will help us to unravel the structure of the early solar system, to learn about the planetesimals and their evolution, and to fathom the mechanism by which planet-building was halted in this part of our planetary system.

Thanks to the ESO facilities, especially in the last five years, a lot of data, both physical and astrometric, were obtained on asteroids. Nevertheless, many unsolved problems still remain open and among these the most intriguing are:

(i) the knowledge of physical characteristics and origin of outer main belt and A&A asteroids, (ii) the collisional evolution of main belt objects and the related origin of dynamical families.

So far ESO has provided to the European asteroidal community small telescopes only (ESO 50-cm and 1-m, Bochum 61-cm, Danish 1.52-m and GPO). But in order to deepen our knowledge on asteroids and to solve, at least partially, the above-mentioned problems, the availability of larger instruments will be necessary, in particular, for photometric, polarimetric and spectroscopic observations.

Asteroids may be "small" and "near", nevertheless they deserve being investigated by means of large telescopes!

References


The Dust Tail of Comet Wilson 1987 VII

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1. Introduction

Several photographic plates, both in red and blue light, were obtained by means of the ESO Schmidt camera to study the dust and plasma tails of Comet Wilson 1987 VII. All these plates were calibrated by means of calibration wedges and therefore are suitable for a quantitative analysis of the dust and ion tails. The pass-band of the emulsion (630 to 700 nm, close to the R photometric system. We used plates 6810, 6829 and 6842 to study the dust environment of C/1987 VII before perihelion by means of the inverse numerical method which was successfully tested on C/1973 XII and C/1982 III (Fulle, 1989).

This model considers \( N_t \times N_a \times N_s \) sample dust grains, where \( N_t \) is the number of samples in the time interval of dust ejection, \( N_a \) is the number of samples in the sizes, and \( N_s \) is the number of grains of a fixed size uniformly distributed on a dust shell. It considers different ejection geometries for each of which the ejection of dust is restricted to a cone of half width \( w \) with its symmetry axis pointing toward the Sun. The position of each grain at the observation is derived from its keplerian motion, then projected into the photographic plane coordinate system, so as to obtain the model distribution of the scattered light with the related kernel matrix \( A \). The solutions are given by the minimization of the functional \( \| A F - I \|^2 + \| B F \|^2 \), where \( A \) is the kernel matrix, \( I \) is the data vector containing the dust tail

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