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# Fundamental studies of asteroids

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**Abstract.** Planetesimals are intermediate stages, in the kilometer size range, between interstellar matter and large bodies such as planets and stars. Planetesimals can still be studied in the form of asteroids although they have been modified by mutual collisions since their formation. The collisional fragments are gravitationally perturbed by Jupiter into the inner part of the solar system where they are observed as near-earth asteroids.

*Key words*: asteroids—planetesimals—comets—CCD

## 1. Introduction

Surveying of near-earth asteroids is done photographically on Palomar mountain, and with charge-coupled devices (CCD) on the spacewatch camera in Arizona. Newly discovered objects are followed up with physical studies such as spectrophotometry. Future perspectives are in flyby and rendezvous missions to comets, near-earth asteroids and the asteroid belt, in analysis of samples either on spacecraft or after return to earth, and in prospecting and mining of asteroid surfaces.

A simple visual observation can be made by everyone during a dark and clear night by looking carefully at the Milky Way. One sees dark clouds in between the thousands of stars that make up the Milky Way; these irregular features occur in the same place from night to night. The irregularities are caused by interstellar clouds of gas and dust so that in some places we do not see as many stars as in others because of obscuration of the starlight. Interstellar dust particles appear to have been captured by high-altitude aircraft and balloons; a photograph of one of them is shown in figure 1. These particles are so small that if you held one in your hand you could not see it; the obscuration of starlight is due to their large number.

The interstellar clouds of gas and dust are the formation sources for the stars and the planets. A local increase of density may be needed to initiate the process of coagulation of the dust and gas; such an increase may be provided by density waves rippling through space and/or by shock waves from supernova explosions. In any case, interstellar dust and gas coagulates into objects called planetesimals,

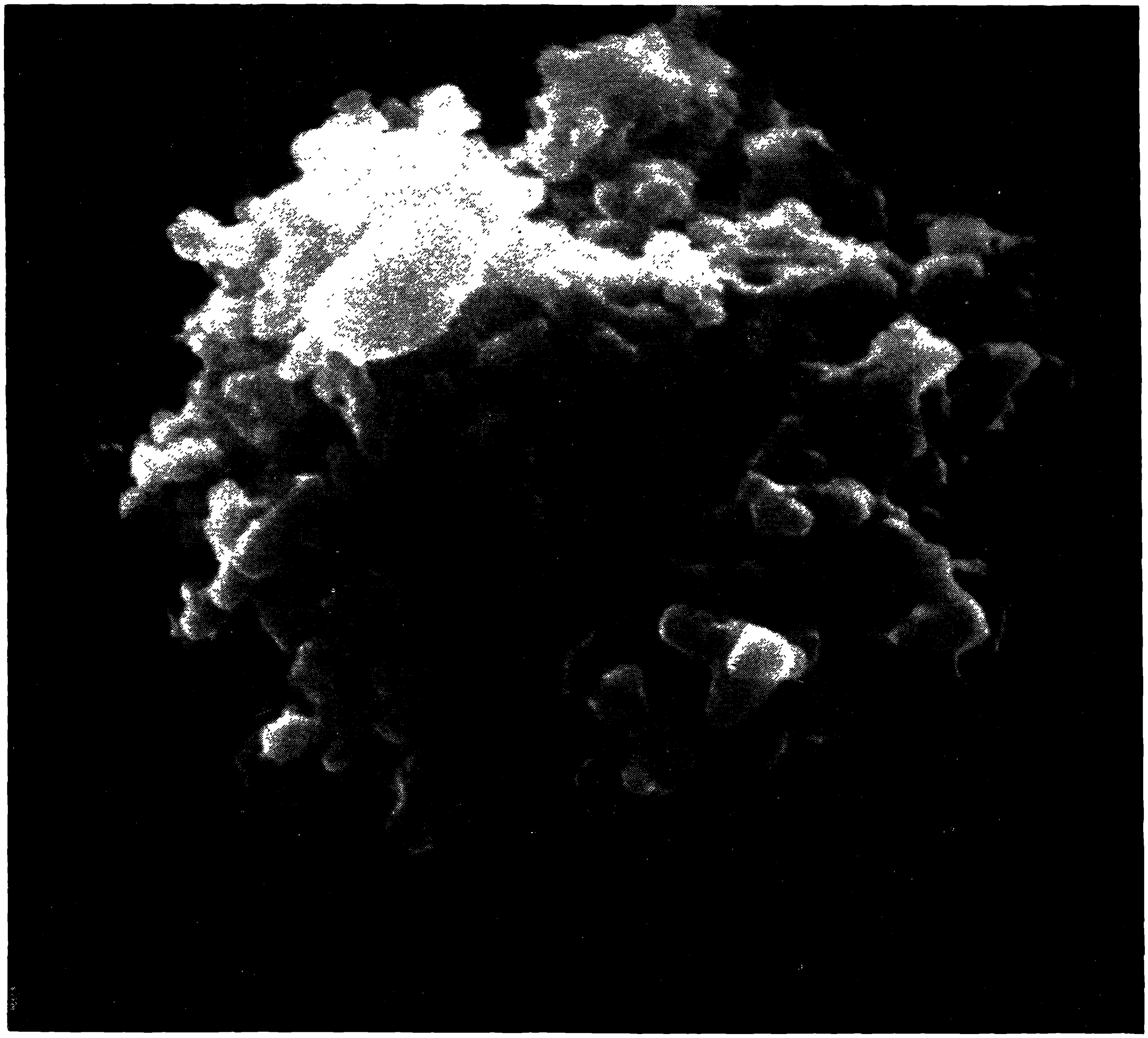

**Figure 1.** A particle collected at high altitude and believed to be cometary or interstellar. The diameter of this particle is about 6 microns. (Photograph courtesy of D. E. Brownlee, University of Washington.)

with sizes of the order of kilometers. The planetesimals further collide with and crush each other, forming larger masses whose size depend on the amount of material available in the original interstellar cloud. In this manner the formation of planets and stars is belived to take place; the theories are described in books edited by Gehrels (1978) and Black & Matthews (1984)

The planetesimals can still be observed now in the form of comets and asteroids. Such observations allow us to look back in time upon the original building blocks of the solar system. The major changes they underwent in time were in mutual collisions, particularly within the asteroid belt. Asteroids probably are rather loosely conglomerated rubble piles. Some of the larger ones may have been heated and melted; after break up by collision, their fragments are more dense and solid.

## 2. The asteroid belt

Tables 1 lists a variety of objects that are all called asteroids. The first column shows their number in the international catalogue (Ephemerides 1983), and the name, usually given by the discoverer, is in the second column; perihelion and aphelion are the closest and the farthest distance from the sun in the elliptical orbit, respectively. Also listed is the inclination, which is the angle between the orbital plane of the asteroid and that of the major planets. The last column gives an indication of the compositional types such as S for siliceous, C for carbonaceous, while U stands for uncertain or unclassified. Of the objects in the table only 1 Ceres and 4 Vesta are in the asteroid belt proper, which lies mostly between about 2.2 and 3.3 A.U., having objects with nearly circular orbits.

**Table 1.** Various asteroids

| No. in catalogue | Name | Perihelion (A. U.) | Aphelion (A. U.) | Inclination | Diameter (km) | Type |
|---|---|---|---|---|---|---|
| 1566 | Icarus | 0.2 | 2.0 | 23° | 2 | U |
| 1864 | Daedalus | 0.6 | 2.4 | 22 | 3 | SU |
| 1862 | Apollo | 0.7 | 2.3 | 6 | 2 | U |
| 2062 | Aten | 0.8 | 1.1 | 19 | 1 | S |
| 1620 | Geographos | 0.8 | 1.7 | 13 | 2 | S |
| 1221 | Amor | 1.1 | 2.8 | 12 | 1 | ? |
| 434 | Hungaria | 1.8 | 2.1 | 23 | 12 | E |
| 4 | Vesta | 2.2 | 2.6 | 7 | 555 | E |
| 1 | Ceres | 2.6 | 3.0 | 11 | 1025 | C |
| 108 | Hecuba | 3.0 | 3.4 | 4 | 70 | S |
| 153 | Hilda | 3.4 | 4.6 | 8 | 224 | P |
| 279 | Thule | 4.1 | 4.4 | 2 | 131 | D |
| 624 | Hektor | 5.0 | 5.3 | 18 | 150 × 300 | D |
| 944 | Hidalgo | 2.0 | 9.7 | 42 | 29 | D? |
| 2060 | Chiron | 8.5 | 18.9 | 7 | 200? | C or F? |

There have been no missions as yet to the distant asteroids and no pictures are available that show more than a speck of light, a star-like object. Viking spacecraft obtained resolution of the surfaces of Martian satellites Phobos and Deimos and the appearance of these objects is believed to be similar to that of asteroids; figures 2 and 3 may therefore give an impression of asteroidal surfaces. Collisions with other objects have left a pockmarked surface similar to that of the earth's moon. The great impact crater must have been caused by a large object that nearly broke Phobos up; cracks through the surface are clearly seen.

Figure 4 is an artist's concept of the surface of 4 Vesta painted by planetary scientist W. K. Hartmann; the dark basaltic patch had been suggested by M. J. Gaffey. In the case of Vesta it is presumed that the coagulated dust and gas were heated and that at some time the body was melted; various heating mechanisms have been suggested such as radioactivity and electromagnetic effects (these effects and other overview chapters of the asteroids may be found in the book edited by Gehrels 1979).

Even though the surfaces cannot be resolved from the earth and most asteroids are faint because of their distance, it is possible to make measurements of colour and brightness. A rather old technique was to use ultraviolet, blue and visual filters (*UBV*) which are about 0.07 microns wide centred on wavelengths 0.37, 0.44

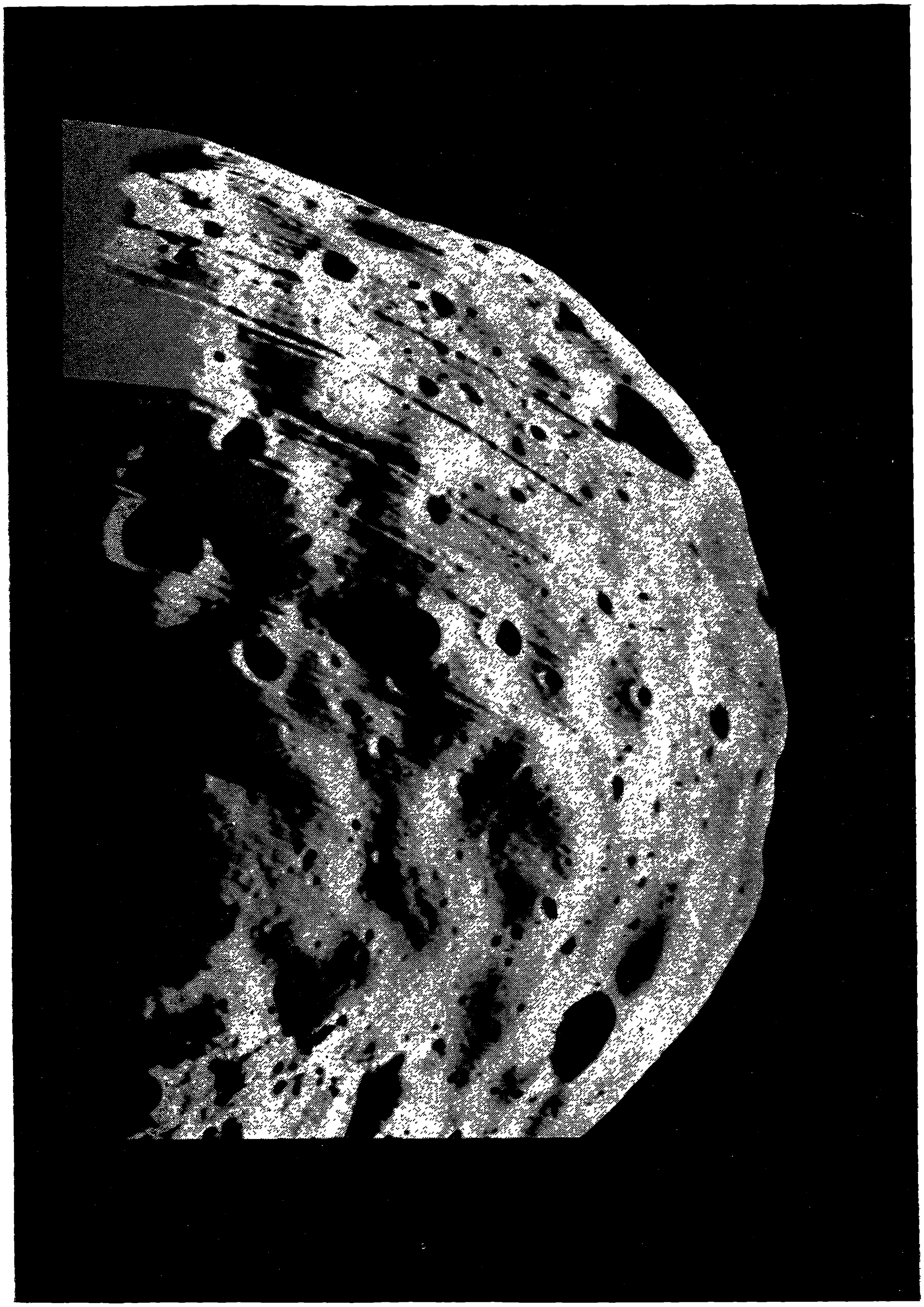

**Figure 2.** The surface of Phobos (NASA photograph).

and 0.55 microns. When the logarithmic magnitude difference is taken between the signals in $U$ and $B$ as a function of those in $B$ and $V$ one obtains a diagram such as figure 5. The sun would occur about where asteroid 785 is plotted so in its case we speak of a neutral object; most other asteroids are redder in both colour

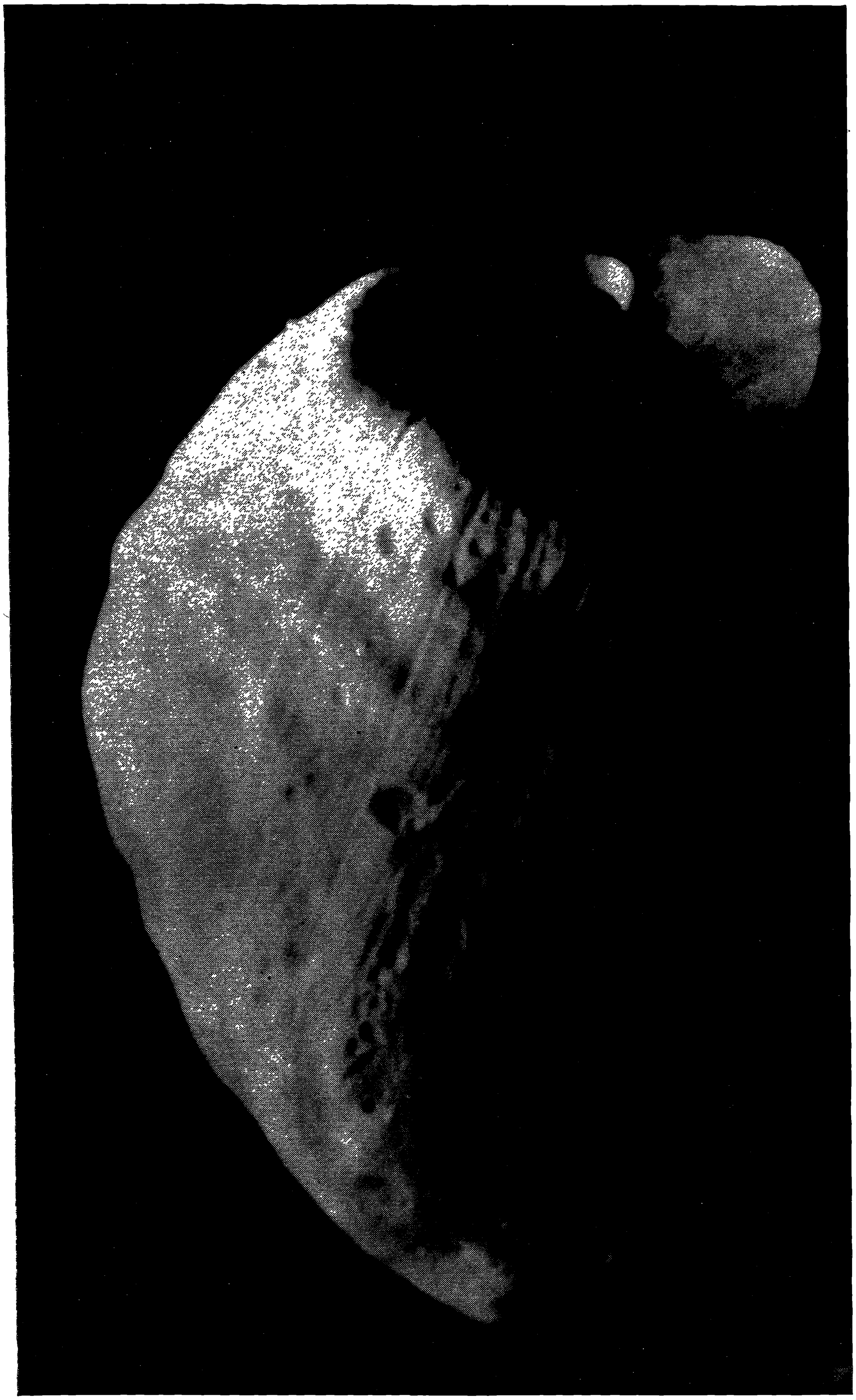

**Figure 3.** Phobos (NASA photograph).

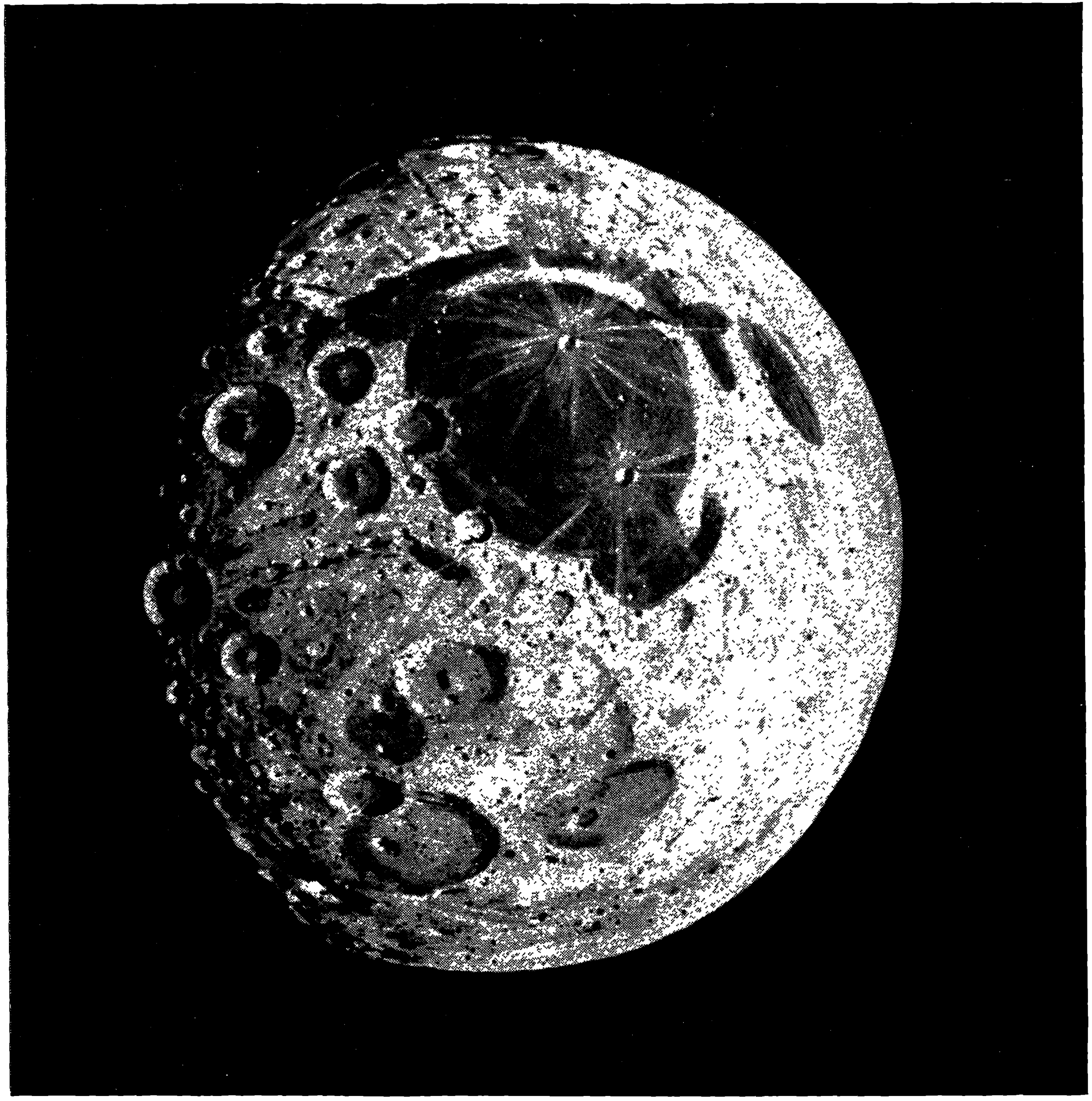

**Figure 4.** Vesta (painting by W. K. Hartmann).

indices $B - V$ and $U - B$, that is with greater output through the $V$ filter than in $B$, and in $B$ than in $U$.

There are some distinct domains in figure 5; there are many asteroids occurring in the hatched area indicated by the letter C while there are also many S-type asteroids. We have to be careful not to consider the C and S types as precisely defined compositions, but it is known from laboratory comparisons that the characteristics of the C objects are similar to those of carbonaceous meteorites, while S-types are more like sandy silicates. Such comparisons were initiated in 1969 by T. C. McCord and have been made extensively by McCord, Gaffey and others. Around the C and S zones is an area of uncertainty which is indicated with the letter U. Other regions in figure 5 are M for metallic asteroids and E for objects showing similarities with the enstatite meteorites, while very red objects occur in the upper right. Individual asteroids are also seen, the prime example being 4 Vesta, a planet by itself.

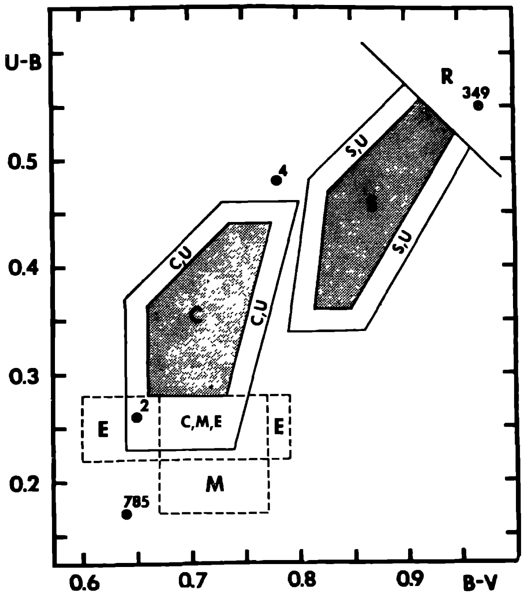

**Figure 5.** Colour plot of asteroids (Zellner 1978).

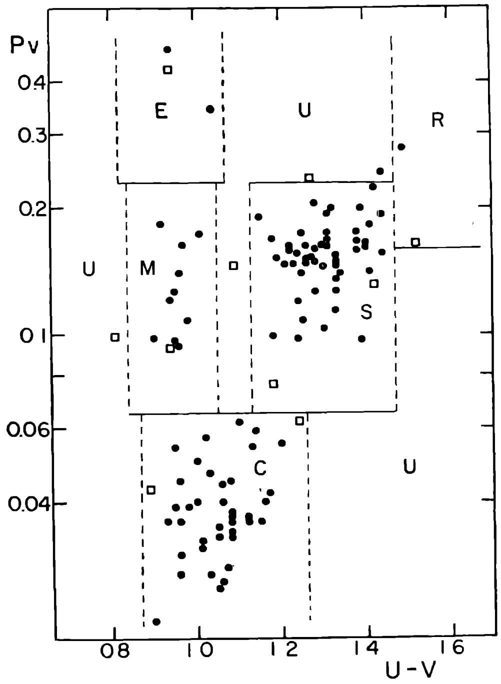

**Figure 6.** Reflectivity as a function of colour for various asteroids (Zellner 1978).

Figure 6 gives similar domains for the combined colour index of ultraviolet minus visual, $U-V$ in magnitudes, in the abscissa, while the ordinate shows a measure of the reflectivity. Geometric albedo, $p_V$, is the ratio of observed flux with that expected if the object were perfectly reflecting directly back to the source, without shadowing. C objects are dark, with reflectivities of only a few per cent, while the E-type asteroids are bright. Square symbols in figure 6 indicate asteroids that cannot be classified.

The determination of reflectivity is made through a combination of observations in visible light with those at longer wavelengths, near 10 and/or 20 microns. The measurements at the longer wavelengths give the thermal flux, which is a measure of the size of the radiating object, because thermal flux depends on the cross-section of the radiating material. The amount of visible radiation is derived from the visible light, so that the comparison indicates the reflective power.

The laboratory comparisons are made with samples of meteoritic material. A search is on to find the parent bodies of the meteorites, to identify specific asteroids from which the meteorites fragmented (McFadden 1983). It has been suggested at various times that some meteorites may have come from the moon, or even Mars (French 1983).

Surveying with an 8-filter photometer is done by B. H. Zellner, E. F. Tedesco and D. J. Tholen. Some of their plots are shown in figure 7; the abscissa has the wavelengths of the filters while the ordinate is again a measure of the reflectivity. Typical asteroids are indicated on the right with their name and catalogue number. The vertical range over which the various types may scatter is delineated by square brackets. The E-type asteroids are the brightest; one of their examples, 44 Nysa is displayed in detail. There are new types such as D (for dark), P (for pseudo-M), and F (for flat) that show distinct profiles.

The asteroid types of figure 7 are shown in spatial distribution in figure 8 where the abscissa has their distance from the sun in astronomical units. The ordinate

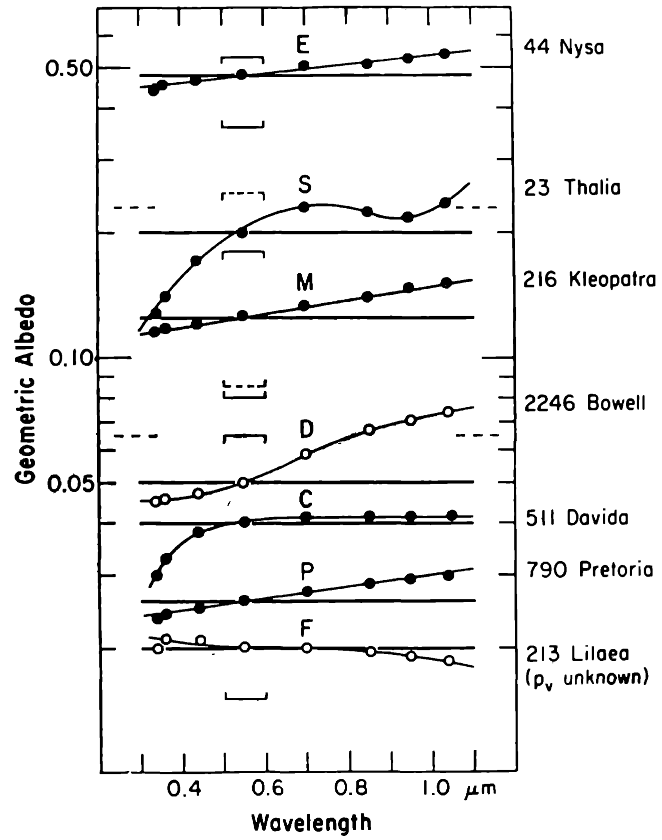

**Figure 7.** Reflectivity as a function of wavelength of the observation (Tedesco 1982, personal communication).

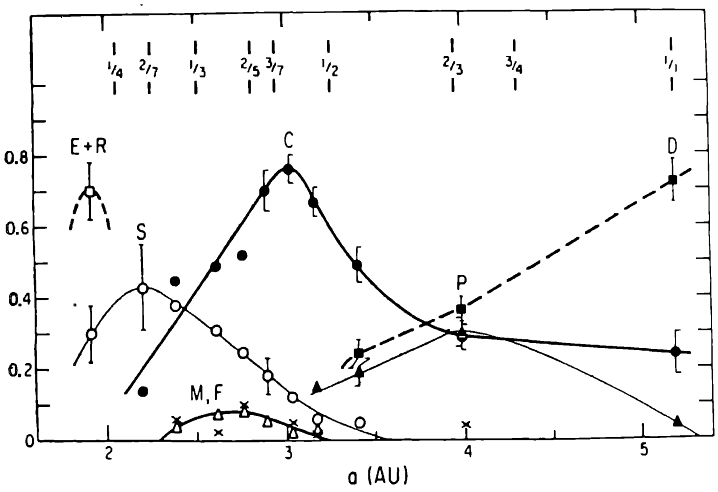

**Figure 8.** For each type, its fraction of the total number of asteroids as a function of distance from the sun (Tedesco 1982, personal communication).

gives for the indicated type its fraction of the total population at that distance. It has been known for some time that the siliceous type of asteroids occur near the inner part of the asteroid belt and the carbonaceous ones towards the outer. This is of great significance as it demonstrates a change in the composition, apparently occurring in the asteroid belt, from that of the rather siliceous inner planets towards the more volatile, lighter, elements such as in carbonaceous material in the outer parts of the solar system.

Was the asteroid belt formed with this zonation in composition, or have asteroids been moved there subsequently, S-types from the inner and C-types from the outer regions of the solar system ? The present mass in the asteroid belt is only $6 \times 10^{-4}$ earth masses (see Tedesco 1983 for a recent determination). This is a small amount of material in a large space, between Mars at 1.5 A.U. and Jupiter at 5.2 A.U.; elsewhere in the solar system the mass density is much greater. Massive Jupiter, and other planets too, appear to have gravitationally jostled around, and thrown out of the solar system, many of the early planetesimals. Let us look at some of these gravitational processes.

At the top of figure 8 are indicated commensurabilities with Jupiter's orbit; for instance at 1/3 there is, at that distance from the sun, exactly one orbital period of Jupiter in the time of exactly three orbital periods of the asteroids. The M asteroids occur near the 1/3 commensurability. This observation is better understood when we consider the asteroid populations at various distances from the sun; in figure 9; the commensurability regions usually are regions of depletion, and

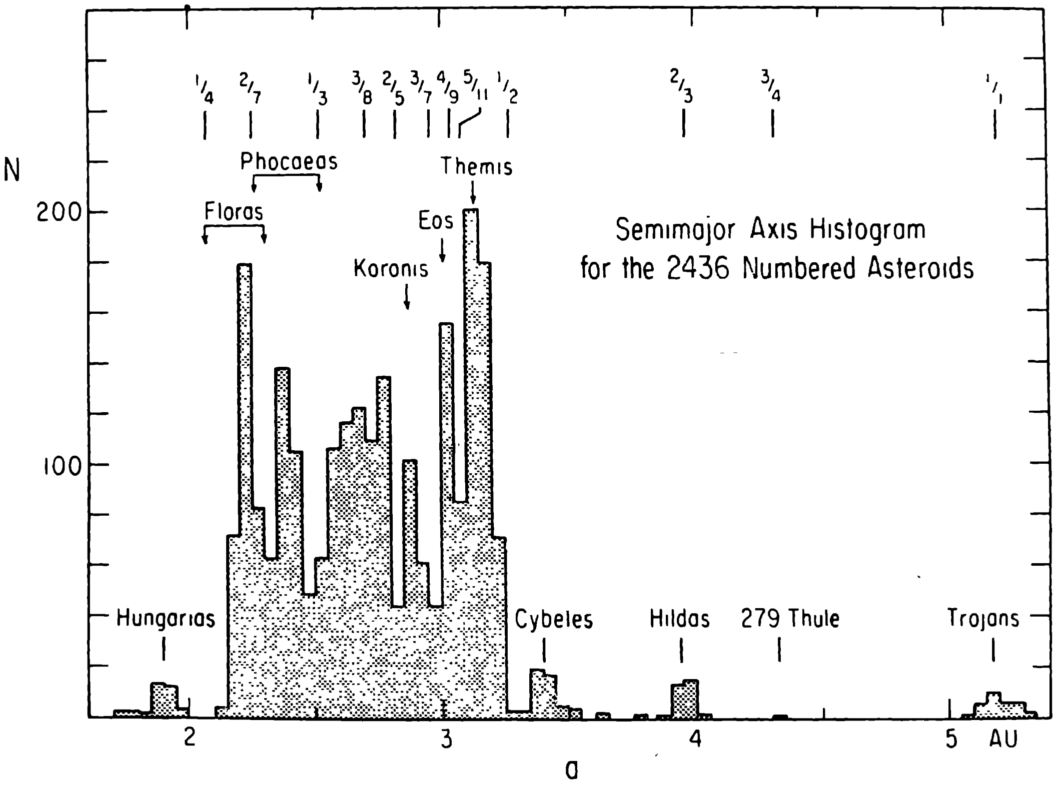

**Figure 9.** The number of asteroids as a function of distance from the sun. Various groups and asteroid families, that have orbital similarities, are indicated. Commensurabilities with the orbital period of Jupiter are marked (Tedesco 1982, personal communication).

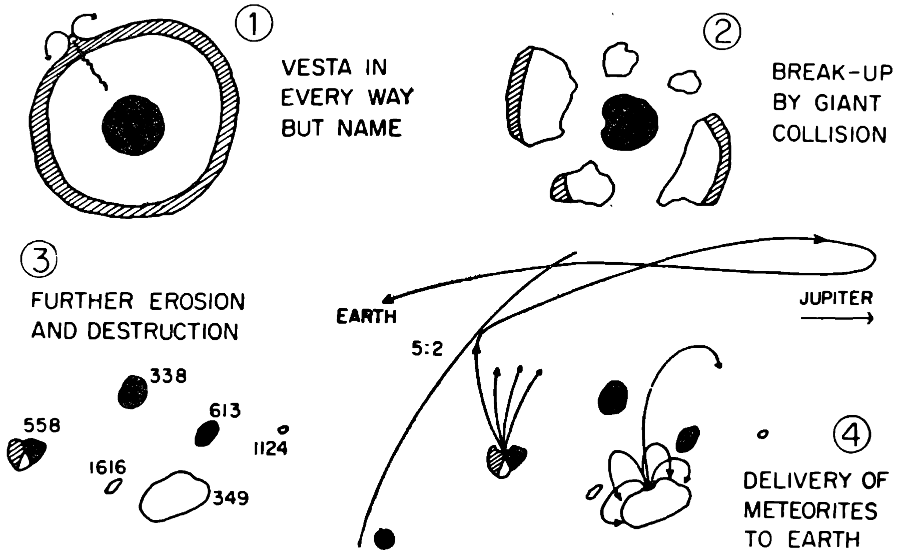

**Figure. 10.** Four cartoons of a differentiated asteroid after collisions and resonance effects by Jupiter. (A figure by C. R. Chapman in Gehrels 1979.)

there are similar regions where resonance of orbital parameters of the asteroids compared with the Jupiter orbit occurs. There are beat phenomena at work, with massive Jupiter repeatedly meeting the asteroid in the same configuration and with its gravitation affecting the asteroid's orbit. The next step we understand is mutual collisions among the asteroids, feeding fragments into the regions of commensurability and resonance. The average velocity of the belt asteroids with respect to each other is about 5 km $s^{-1}$; this dispersion itself appears to be evidence that some large object(s) travelled and stirred the asteroid belt, possibly in an early stage of its formation too close to and therefore severely perturbed by Jupiter. The four cartoons in figure 10 further show the process of producing certain types of asteroids and the mechanism of their becoming objects which can occasionally come close to the earth.

## 3. Near-earth asteroids

Figure 10 shows in four stages how we might obtain asteroidal fragments of various compositions within the orbit of Mars. To begin with, the interpretation requires as asteroid that was heated sufficiently to be molten so that it differentiated by gravitation with the heavier metallic substances towards the core; this was the case for the earth and possibly for Vesta (see the discussion with figure 4). Next, in the second cartoon, we see what may have been the situation after a giant collision with another asteroid. The third cartoon gives the result after further impacts; such fragments have been studied with photometry as described above. For instance asteroid 338 has a metallic composition, whereas 349 appears to consist of a lighter material. Finally, if the collisions occur near any of the resonances or commensurabilities, then Jupiter's gravitation may cause the orbit to be decircularized, to become more elliptical, and the objects cross into other parts of the solar system. Gravitational interaction with Mars, the earth and Venus may further affect the orbits. The ultimate fate is a collision with a planet or ejection from the solar system.

The statistics of the near-earth asteroids have been studied by several colleagues such as E. Anders, Ľ. Kresák, E. Öpik, E. M. Shoemaker and G. Wetherill; they used various techniques like searches for asteroids and counts of craters on the moon (see Shoemaker *et al.* 1979). A precise determination with a thorough telescopic survey seems an important goal; the spacewatch camera is to do this as will be discussed below. Shoemaker (1982, personal communication) believes there may be as many as 2,000 asteroids, larger than 1 km in diameter, that occasionally come close to the earth; half of them will eventually be removed from the solar system by Jupiter interactions, about one-fourth will impact the earth and about one-fourth Venus. The orbits of the planet-crossing asteroids are unstable, called "chaotic" by astronomer E. Everhart, with lifetimes on the order of $10^7$ yr. Statistically, it is a steady situation, with the removals and impacts balanced by the supply illustrated in figure 10.

Table 2 displays an estimate of the statistics, with approximate numbers that are easy to remember; I assume conservatively that the total number of the near-earth asteroids larger than 1 km is only 1,000. With each step of 10 in size, the number of objects changes by a factor of 100; this is a fundamental property in the asteroid belt. The largest ones have an impact probability of about once in $10^8$ yr as has been estimated by various colleagues. The impact energy follows from $\frac{1}{2}\,mv^2$ where v is 11–30 km $s^{-1}$, typical differential velocities between the earth and asteroids, while $m$ is estimated on the assumption of a density of 3 gm $cm^{-3}$, which is typical for meteorites. The impact energy in the last column is expressed in terms of the Hiroshima A-bomb of 1945 August 6. This is for comparison and to show the enormous energies involved; it is not done callously as we know of the suffering at Hiroshima. The asteroid impacts do not have nuclear radiation effects. The energy of the A-bomb explosion in Hiroshima was 13,000 tons TNT or $5 \times 10^{20}$erg.

**Table 2.** Approximate statistics for earth-approaching objects

| Diameter (km) | No. of objects | Impact probability (once per number of years) | Impact energy (in "Hiroshimas") |
|---|---|---|---|
| 10 | 10 | $10^{-8}$ | $10^9$ |
| 1 | 1,000 | $10^{-6}$ | $10^6$ |
| 0.1 | 100,000 | $10^{-4}$ | $10^3$ |

Figure 11 demonstrates that the earth is being bombarded by near-earth asteroids. The asteroid of figure 11 was a metallic object with a diameter of about 35m; the impact occurred about 25,000 yr ago and the effect is seen as a crater 1.2 km in diameter and 167 m deep below the crest of the rim which rises about 50 m above the surrounding plain. Even more serious was the impact of a 10 km asteroid that caused the extinction of about 60% of the animal species, the so-called cretaceous-tertiary extinction occurring between these two geological periods about 65 Myr ago. Another asteriod of about 3 km diameter appears to have impacted some 34 Myr ago (Ganapathy 1982; Alvarez *et al.* 1982) and to have caused the Eocene-Oligocene extinction of various species.

There still is some debate whether or not the dinosaurs were eliminated by the cretaceous-tertiary impact. Were they already on their way out due to other causes? That collisions with asteroids and comets have to cause major extinctions occasionally was already pointed out in 1973 by H. C. Urey. The fact that there was a meteoritic impact at the time of the cretaceous-tertiary extinction seems proven by the high content of the heavy elements iridium, osmium, etc. in the 1–2 cm thick boundary between the deep sea deposits of the cretaceous and the tertiary periods (Alvarez *et al.* 1980; Ganapathy 1980). The abundances are similar to those of meteorites and unlike those at the surface of the earth from which the heavy metals settled gravitationally towards the centre during early, mostly molten stage of the earth's formation. The impact crater has not been found, but it may have occurred in the oceans and the crater would have filled with mud and not be recognizable any more. Even on the surface, a crater may disappear due to plate-tectonic movements. In any case, the cloud of asteroidal matter, surface soil and water due to the impact was so massive that it settled as a 1–2 cm clay layer rather uniformly over the whole earth; it is estimated that most of it was thrown out from the earth's surface, with about 7% asteroidal material of carbonaceous chondritic composition. An impact on land may have caused a dust cloud in the atmosphere so thick that sunlight was extinguished; the weather patterns stopped since they are caused by differential solar radiation on land and oceans; and, for lack of photosynthesis, most green growth stopped so that certain algae, for instance, could no longer grow resulting in a lack of green fodder for the large animals. Actually, it appears more likely that this impact occurred in the ocean, perhaps in the northern Pacific-Bering sea area, and that it was followed by a transient but significant, increase in the global surface temperature due to the water injected into the atmosphere; this scenario is described by Emiliani *et al.* (1981).

We see in table 2 that an impact of a 10 km asteroid may occur again. This is not to be dismissed from our concern because of the low probability of the event, once in $10^8$ years. The consequences of such an impact would be enormous; it would eliminate human society (L. W. Alvarez 1983, personal communication). We are fortunate that the orbits in the asteroid belt are stable and that we receive on the earth only collisional fragments, for the diameters in the belt range up to 1000 km! Otherwise, advanced forms of life might not have had a chance on the earth. Even so, the major asteroidal impacts must have affected the evolution of our species. But for the cretaceous-tertiary extinction "we", the most advanced species, might have looked like a dinosauroid (Russell & Séguin 1982).

When a menacing asteroid has been identified, it may be possible to change its orbital velocity sufficiently so that an impact does not occur. Preliminary studies of this problem indicate that such changes could be accomplished, if there is enough advance warning, with the present technique of Shuttle-type spacecraft and existing explosives (Shoemarker 1983). Years of careful astrometry are required to determine the precise orbit. Physical studies need to determine the strength of the asteroid if explosive forces are to be used. In any case, the menacing asteroids have to be identified first, and that is one of the goals of the spacewatch camera.

## 4. The spacewatch camera

The above statistics of the near-earth asteroids are based on the surveying by E. F. Helin, and E. M. and C. Shoemaker with photographic Schmidt telescopes at the Palomar observatory (Helin 1983). The rate of discovery is about four earth crossers per year, including the findings at other observatories. The total number known at this time is near 70. With faster electronic detectors and with a dedicated search instrument the discovery rate may be increased to perhaps 100 per year; this is the aim for the spacewatch camera.

Figure 12 shows a photograph of Kitt Peak taken from an airplane. The telescopes are associated with the Kitt Peak national observatiory, except the second and third (a small dome) from the right and next the aluminum-coloured dome which belongs to the Steward observatory of the University of Arizona. The latter dome along with its 0.9-m Newtonian telescope were made available to us and it is now the first spacewatch camera. The site has excellent image quality at an altitude of 2091m; increasing light pollution, however, may affect the lifetime of Kitt Peak for faint work. Figure 13 has the design of the 1.82-m spacewatch camera which is to replace the 0.9-m Newtonian within a few years. At the Newtonian or prime focus we mount a charge-coupled device (CCD) during the dark half of the month.

During the other half of the month when the moon is up, the CCD is replaced by a fiber-optics head to lead the light into a radial-velocity spectrometer for the detection of planets of other stars. As a planet orbits a star, the star also is attracted to the planet and it therefore describes a small orbit about the centre of mass of the system. The star may look to us as moving back and forth in space, radially away sometimes and towards us at other times. Such radial velocities are detected with a precise spectrometer (see McMillan *et al.* 1982; Merline 1982; Smith 1982).

Our CCDs are of type RCA SID 53612 which have 512 channels of 320 pixels each. The pixel is a silicon light-sensitive metal-oxide-semiconductor capacitor, 29.5 micrometers square. This type of CCD detector is used at several observatories in the "stare mode" which is to set on an object, for instance a galaxy, opening the shutter for a guided exposure, closing the shutter, and transferring the charges from channel to channel until, on the right in figure 14, they come to the output shift-register where the charges are transferred into a computer.

Our application of the CCD is in the "scan mode" (sometimes called time delay integration, TDI) whereby the transfer from channel to channel occurs continuously at a rate exactly matched to the scanning rate of the telescope on the sky. The shutter is open during the scan, which for near-earth asteroids may last typically 10 min, after which the shutter is closed, the telescope reset, and the scan is repeated. The two scans are compared in the computer by superposition of the two starfields by subtracting, or cancelling, the images that exactly superpose. The objects that moved during the 10 min interval therefore remain and are discovered. It is essential in this procedure to have a fast computer; we use a Perkin-Elmer 3241 that eventually will be expanded to a 3244. We are dealing with data rates near one million bits per second and storage capacity on the order of a billion bits, for the comparison of the scans and for orbit computations. Details of the operation are given by Gehrels *et al.* (1984). Details of the performance of our CCD are shown in figure 15.

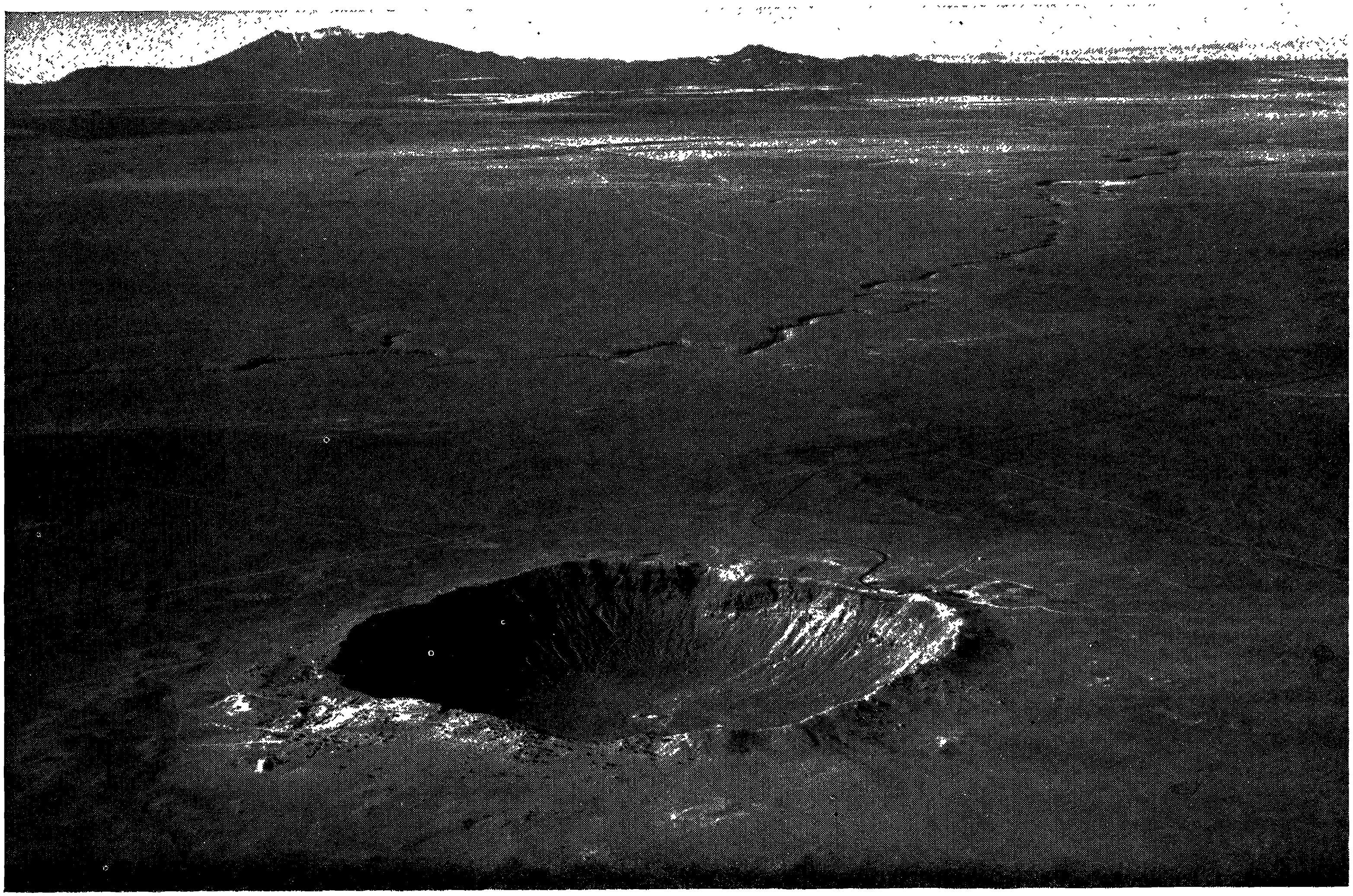

**Figure 11.** Barringer meteorite crater near Winslow, Arizona. Its fragments are called Canyon Diablo meteorites named after the canyon seen in this photograph. The volcanic area of the San Francisco peaks, near Flagstaff, Arizona, is seen on the horizon. (Photograph by D. J. Roddy & K. Zeller, U. S. Geological Survey.)

Figure 12. Kitt Peak, about 80 km west of Tucson, Arizona.

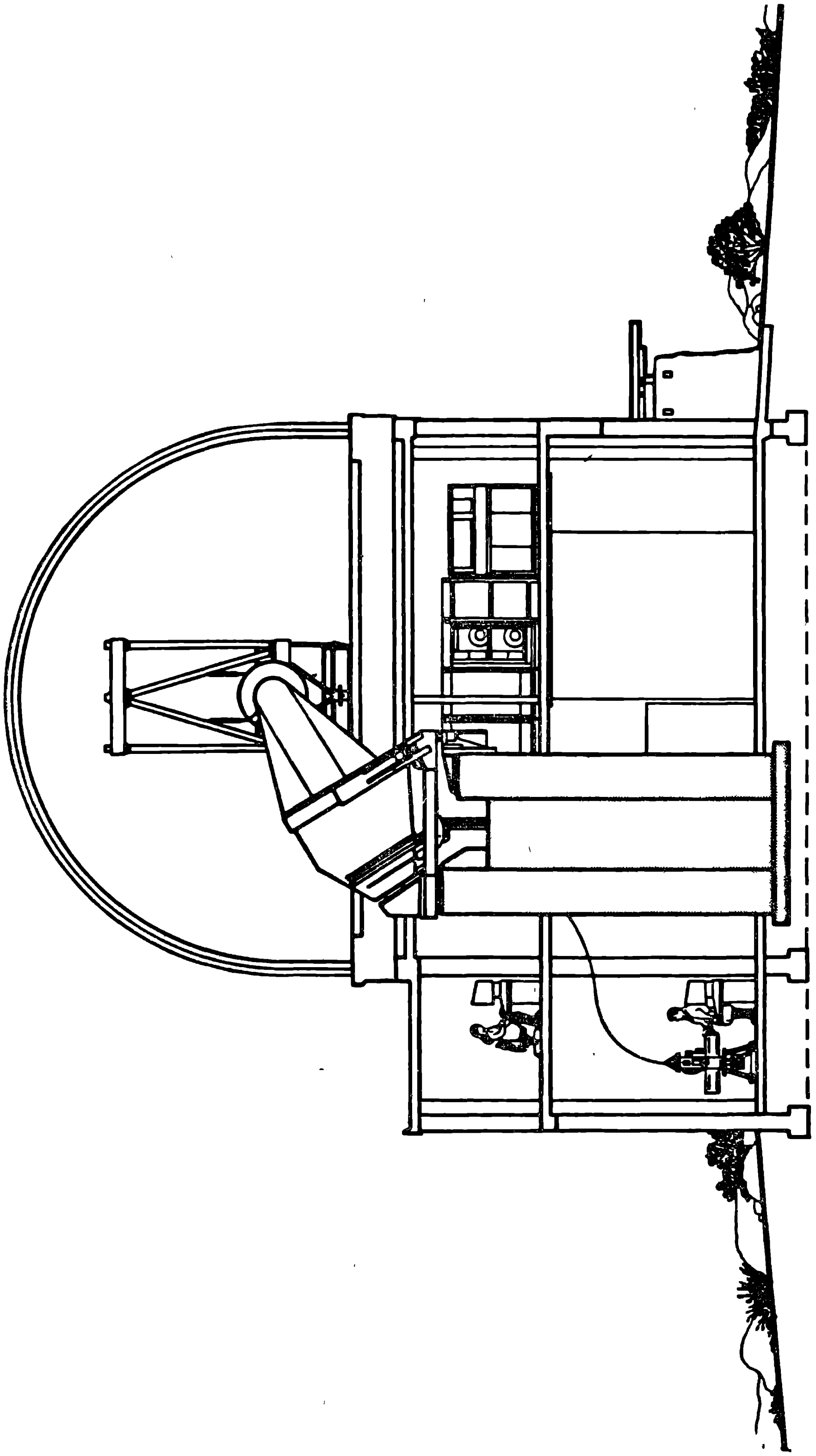

**Figure 13.** Design by H. Boesgaard of the 1.82-m spacewatch camera in its dome. The radial velocity spectrometer is shown downstairs.

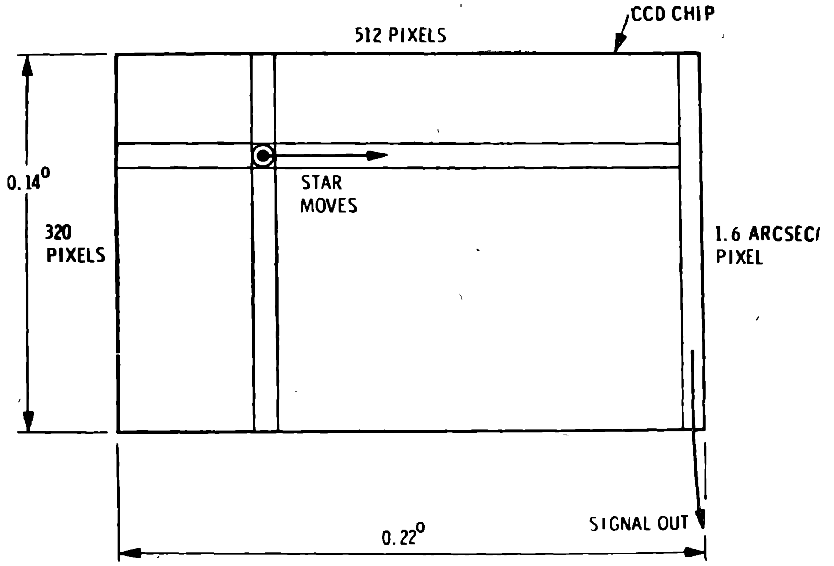

**Figure 14.** Principle of a charge-coupled device (CCD) on the 1.82-m spacewatch camera.

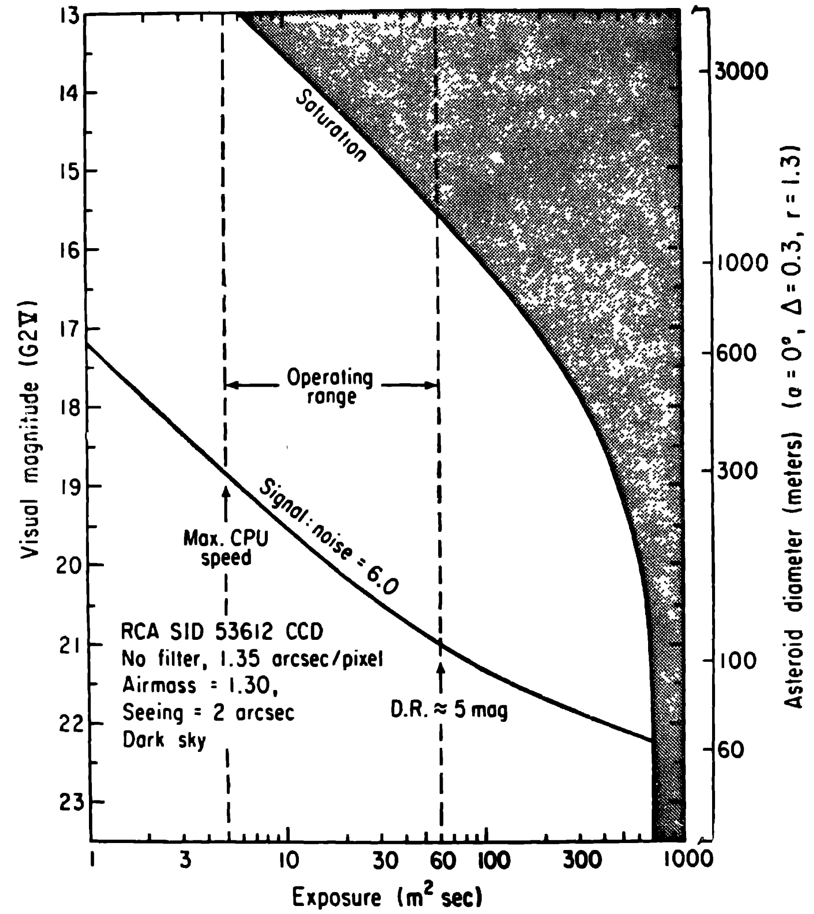

**Figure 15.** Operating range of RCA 53612 CCD. CPU = central processing unit; RCA = Radio Corporation of America; SID = silicon imaging device; DR = dynamic range; Δ = distance from the earth: $r$ = distance from the sun; G2V is the spectral type of the sun (McMillan & Stoll 1982).

The spacewatch camera project is supported by the National Aeronautics and Space Administration. To accelerate the program we seek additional funding, and several private supporters, corporate, and governmental funding organizations have already helped. This is in addition to the considerable support from the State of Arizona in the form of site, dome, and a finished 1.82-m mirror, F/2.7.

In addition to the surveying and discovery observations, the spacewatch camera follows the objects and computes their orbits with help from other observatories. As joint programs with other scientists we also work on physical studies of newly discovered asteroids. One of the fundamental problems is to find out how many cometary cores, the exhausted nuclei of previously active comets, there are among the earth-approaching asteroids. The distinction between such a cometary core and an original asteroid is still elusive in physical observations. The detection of active comets also is incomplete; with the high quantum efficiency of the CCD many new comets can be discovered. The situation is described by Gehrels (1981). Long exposures photographic plates show a trail for moving objects so that the effective exposure time is actually short. Therefore, the comet populations fainter than about magnitude 19 are currently incompletely surveyed. Faster detection of moving objects is provided by the CCD which has 70% quantum efficiency over a wide range of wavelengths, versus about 1% for the fastest of photographic plates.

Table 3 gives a list of various asteroid programs at this time. The listing is incomplete; I apologize for errors and omissions and I would like to receive improvements for a future listing. Particularly in the fields of astrometry and orbit determination there are many more participating astronomers. I also tried to avoid repeating names, while several colleagues are involved in more than one program. The purpose of table 3 is to show the great interest in studies of minor planets.

**Table 3.** Asteroid studies

| Investigations | Investigators | Institutions |
|---|---|---|
| Studies of asteroid origin and evolution | H. Alfvén | Royal Inst. Tech. Stockholm |
| | G. Arrhenius | Univ. Cal. San Diego |
| | M. Blander | Argonne National Lab. |
| | A. G. W. Cameron | Centre for Astrophys. |
| | D. J. Clayton | Rice Univ. |
| | M. J. Cintala | Brown Univ. |
| | D. R. Davis | PSI |
| | L. Grossman | Univ. of Chicago |
| | J. W. Larimer | Arizona State Univ. |
| | G. Morfill | MPI Garching |
| | R. T. Reynolds | NASA-Ames Res. Centre. |
| | V. S. Safronov | Schmidt Inst. Moscow |
| | D. N. Schramm | Univ. of Chicago |
| | R. Smoluchowski | Univ. of Texas |
| | C. P. Sonett | Univ. of Arizona |
| | J. T. Wasson | Univ. Cal. Los Angeles |
| | S. J. Weidenschilling | PSI |
| | G. W. Wetherill | Carnegie Inst. of Washington |
| | I. P. Williams | Queen Mary College |
| Surveying | N. S. Chernykh | Crimean Astrophys. Obs. |
| | T. Gehrels and<br>R. S. McMillan | Univ. of Arizona |

*Continued*

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**Table 3**—*Continued*

| Investigations | Investigators | Institutions |
|---|---|---|
| | E. F. Helin, S. J. Bus and colleagues | JPL |
| | C. T. Kowal | Calif. Inst. of Tech. |
| | T. Seki and colleagues | Geisei Obs. |
| | E. and C. Shoemaker | JPL and U. S. Geol. Survey |
| | L. G. Taff | Lincoln Lab. |
| | C. J. and I. van Houten | Leiden Obs. |
| Orbit determinations | D. F. Bender | JPL |
| | E. G. Bowell | Lowell Obs. |
| | O. V. Dobrovolsky | Dushanbe Inst. of Astrophys. |
| | W. Landgraf | Univ. of Göttingen |
| | S. S. Lavrov and other colleagues | Inst. of Theo. Ast. Leningrad |
| | B. G. Marsden and C. M. Bardwell | Smithsonian Astrophys. Obs. |
| | D. K. Yeomans | JPL |
| Magnitudes | E. F. Tedesco | JPL |
| Dynamical studies | R. S. Bogart | Stanford Univ. |
| | A. Carusi | Istituto Astrofisica Spaziale |
| | S. F. Dermott | Cornell Univ. |
| | E. Everhart | Univ. of Denver |
| | C. Froeschlé | Obs. de Nice |
| | R. J. Greenberg | PSI |
| | W.-H. Ip | MPI Lindau |
| | Y. Kozai | Tokyo Astr. Obs. |
| | L. Kresák | Astr. Inst. Bratislava |
| | E. J. Öpik | Armagh Obs. |
| | S. J. Peale | Univ. Cal. Santa Barbara |
| | H. J. Scholl | Astr. Rechen-Inst. |
| | G. B. Valsecchi | Istituto Astrofisica Spaziale |
| | W. Ward | JPL |
| | J. G. Williams | JPL |
| | C. F. Yoder | JPL |
| Mass determinations | J Schubart | Astr. Rechen-Institut |
| Photometry, radiometry and spectroscopy for classification | J. B. Adams | Univ. of Washington |
| | R. H. Brown | Univ. of Hawaii |
| | C. R. Chapman | PSI |
| | J. Degewij | Emmen, the Netherlands |
| | M. J. Gaffey | Hawaii Inst. of Geophys. |
| | J. C. Gradie | Cornell University |
| | T. V. Johnson | JPL |
| | L. A. Lebofsky | Univ. of Arizona |
| | T. B. McCord | Hawaii Inst. of Geophys. |
| | L. A. McFadden | NASA Goddard S. F. C. |
| | D. Morrison | Univ. of Hawaii |
| | E. F. Tedesco | JPL |
| | D. J. Tholen | Univ. of Arizona |
| | G. J. Veeder | JPL |
| | J. Veverka | Cornell Univ. |
| | B. H. Zellner | Univ. of Arizona |
| Phase relations | E. G. Bowell | Lowell Obs. |
| | B. W. Hapke | Univ. of Pittsburgh |
| | K. A. Lumme | Univ. of Helsinki |
| | M. Wolff | Long Beach, CA |
| Usage of the Infrared Astron. Satellite (IRAS) for asteroid observations | A. J. Meadows and colleagues | Univ. of Leicester |
| | D. L. Matson and colleagues | JPL |
| Lightcurves | R. P. Binzel | Univ. of Texas |
| | J. A. Burns | Cornell Univ. |
| | P. Birch | Perth Obs. |
| | D. P. Cruikshank | Univ. of Hawaii |

*Continued*

Table 3—*Continued*

| Investigations | Investigators | Institutions |
|---|---|---|
| | H. Debehogne | Obs. Royal de Belgique |
| | P. Farinella | Univ. of Pisa |
| | J. R. Greenberg and colleagues | PSI |
| | A. W. Harris | JPL |
| | W. K. Hartmann | PSI |
| | C.-I. Lagerkvist | Obs. of Uppsala |
| | P. Paolicchi | Osservatorio Astr. Merate |
| | F. Pilcher | Illinois College |
| | H. Rickman | Obs. of Uppsala |
| | F. Scaltriti | Torino Obs. |
| | H. J. Schober | Univ. of Graz |
| | A Schroll | Univ. of Graz |
| | A. and J. Surdej | Inst. of Astrophys., Liège |
| | R. C. Taylor | Univ. of Arizona |
| | E. F. Tedesco | JPL |
| | Zhou Xing-hai | Purple Mountain Obs. |
| | Yang Xiu-ui | Purple Mountain Obs. |
| | V. Zappalà | Torino Obs. |
| Polarimetry | A. Dollfus | Obs. de Paris |
| Fourier transform spectrometry | H. P. Larson | University of Arizona |
| | M. A. Feierberg | NASA-Ames Res. Centre |
| Speckle interferometry | J. D. Drummond | Univ. of Arizona |
| Radar observations | D. B. Campbell | Arecibo Obs. |
| | R. F. Jurgens | JPL |
| | S. J. Ostro | Cornell Univ. |
| | G. H. Pettengill | Massachusetts Inst. Tech |
| Radio observations | J. R. Dickel | Univ. of Illinois |
| Asteroid occultations | M. F. A'Hearn | Univ. of Maryland |
| | J. L. Elliot | Massachusetts Inst. Tech |
| | W. B. Hubbard | Univ. of Arizona |
| | R. L. Millis | Lowell Observatory |
| | G. E. Taylor and colleagues | Royal Greenwich Obs. |
| Planning of asteroid missions | N. D. Hulkower | JPL |
| | J. C. Niehoff | Science Applications, Inc. |
| | E. Stuhlinger | Huntsville, Alabama |
| Mining of asteroids | J. S. Lewis | Univ. of Arizona |
| | J. R. Arnold | Univ. of Calif. San Diego |
| | S. D. Nozette | Univ. of Calif. San Diego |
| | L. Haskin | Washington Univ. |
| Effects due to asteroid impacts | L. W Alvarez and colleagues | Univ. of Cal. Berkeley |
| | S. V. M. Clube and W. M. Napier | Royal Obs. Edinburgh |
| | C. Emiliani | Univ. of Miami |
| | R. Ganapathy | Res. Lab., J. T. Baker Chem. Co. |
| | R. A. F. Grieve and colleagues | Dept. of Energy, Ottawa |
| | J. Hertogen | Fysico-Chem. Geology, Belgium |
| | E. B. Kraus | Univ. of Colorado |
| | F. Kyte | Cal. Inst. of Tech. |
| | H. J. Melosh | Univ. of Arizona |
| | E. M. Shoemaker | U. S. Geological Survey |
| | J. Smit | Geological Inst , Amsterdam |
| Interrelations with meteorites | E. Anders | Univ. of Chicago |
| | W. Boynton | Univ. of Arizona |
| | T. E. Bunch | NASA-Ames. Res. Centre |
| | D. Burnett | Cal. Inst. of Tech. |
| | R. N. Clayton | Univ. of Chicago |
| | M. J. Drake | Univ. of Arizona |
| | W. V. Engelhardt | Univ. of Tübingen |
| | J. E. Geake | Univ. of Manchester |
| | K. Keil | Univ. New Mexico |
| | J. F. Kerridge | Univ. Cal. Los Angeles |

*Continued*

**Table 3**—*Continued*

| Investigations | Investigators | Institutions |
|---|---|---|
| | D. Lal and colleagues | Phys. Res. Lab. Ahmedabad |
| | C. B. Moore | Arizona State University |
| | J. A. O'Keefe | NASA-Goddard Space Flight Cen. |
| | P. Pellas | Lab. Mineralogie, Paris |
| | R. Pepin | Univ. of Minnesota |
| | C. T. Pillinger | Univ. of Cambridge |
| | J. H. Reynolds | Univ. Cal. Berkeley |
| | E. R. D Scott | Univ. of New Mexico |
| | R. M. Walker | Washington Univ. |
| | H. Wanke | MPI, Mainz |
| | G. J. Wasserburg | Calif. Inst. of Tech. |
| | L. L. Wilkening | Univ. of Arizona |
| | J. A. Wood. | Centre for Astrophys. |
| Interrelations with Comets | J. A. Fernandez | Obs. Astronomico, Madrid |
| | J. G. Hills | Los Alamos Nat. Lab |
| | B. J. Levin | Astr. Council, Moscow |
| | J. H. Oort | Leiden Obs. |
| | E. Roemer | Univ. of Arizona |
| | S. van den Bergh | Dominion Astr. Obs., Victoria |
| | P. R. Weissman | JPL |
| | F. L. Whipple | Centre for Astrophys. |

PSI = Planetary Science Institute; JPL = Jet Propulsion Laboratory; MPI = Max-Planck Institut.

The infrared astronomical satellite (IRAS) has the capabilityto observe hundreds of asteroids. At the time of completing this article, about half a year after IRAS launch, no asteroid data have yet been released, but will be forthcoming.

Only a beginning has been made to determine the dielectric properties and surface texture, with radio telescopes and polarimeters. The asteroidal bodies rotate with periods between 2 and 60 hours, but mostly near 8 hours, due to variation in reflected sunlight as various reflectivities and cross sections are presented. Are these rotations primordial, or caused by more recent collisions ? So many fundamental studies are yet to be made !

The spacewatch camera opens future investigations and it is therefore strongly supported by colleagues. Various people have various interests in it : studies of the original planetesimals; curiosity about the asteroids that impacted the earth in the past; concern for the hazards of future impacts; preparation of missions for flyby, rendezvous, docking and sample analysis, and the possibility of mining the asteroids in the future. Landing on a near-earth asteroid is in principle easier than on the moon because of the negligible gravitation of the small body. Missions to asteroids have been proposed for instance by Stuhlinger *et al.* (1972), and their merit has been debated (see Anders 1971); the mining was mentioned by Wernher von Braun and others (von Braun & Ordway 1979; Freitas & Gilbreath 1982).

The time for the execution of asteroid missions is coming closer. A start is being made with engineering technology on how to separate platinum, for instance, from the other metals on the surface of an asteroid in space. Figure 16 is an artists' concept of ventures that may happen before long.

## 5. Concluding remarks

This article is based on lectures given in India, Japan, the Netherlands, Germany and Alabama; it gained from discussions with several colleagues. I am especially

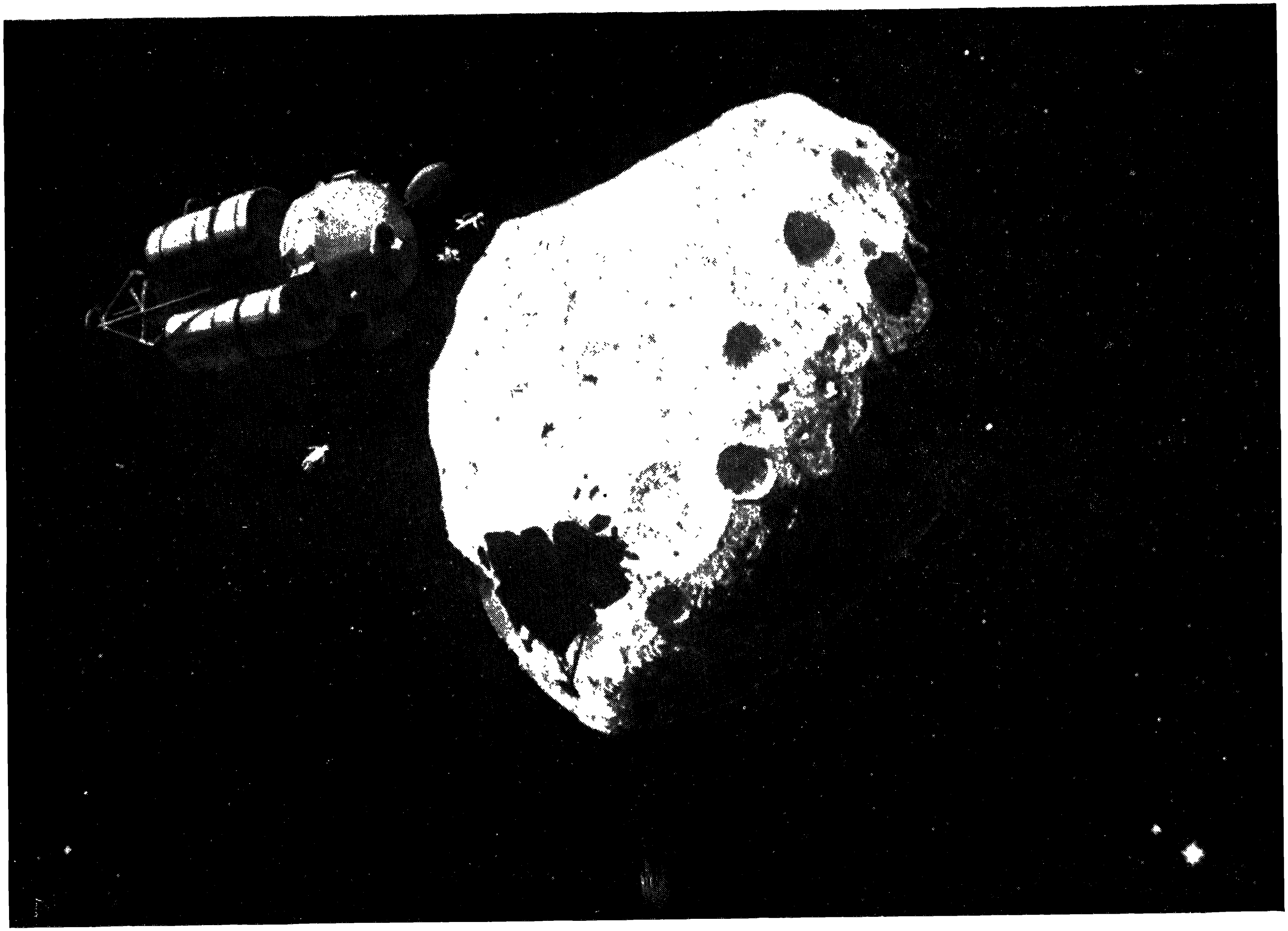

**Figure 16.** A future asteroid mission as an extravehicular excursion from a spacecraft in rendezvous with the asteroid. The earth and the moon are in the lower right-hand corner (painting by W. K. Hartmann).

indebted to M. J. Drake, E. F. Tedesco and D. J. Tholen for improvements. The presentation in Huntsville, Alabama was the von Braun Lecture which ended with the following remarks.

In the invitation lettter, Ernst Stuhlinger wrote : "Wernher von Braun would have felt deeply honoured and gratified by your acceptance." I trust this is so, and I have the same feelings, especially because Wernher and I had backgrounds that were violently opposite.

As considerate people and especially as scientists we try to be free of bias and prejudice. But none of us is truly free. We all start with our education and inheritance as background. Mine was in the Netherlands in World War II; I grew up in Resistance, escaped from the German occupation, was trained in England as a saboteur, and parachuted back into Holland. I have had close encounters with the Peenemünde rockets which have been described, for instance, by von Braun & Ordway (1975; see page 108). Friends and family suffered terribly, and some of them perished. My brother died in one of the Nordhausen camps. How then could I speak in memory of one of the leaders of Peenemünde ? Deep emotions had to be overcome.

But I did overcome. And I could speak in memory of Wernher von Braun, because he was a dedicated pioneer and laid foundations for our space programs. For instance, President Kennedy's speech "...before the end of the decade we will land on the moon..." was originated by von Braun (Stuhlinger 1983, personal communication). It is our inheritance to stand on his shoulders as we continue to build a future of space exploration.

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