Asteroids and comets

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The formation of the Sun and planets left remnants, such as the million objects larger than 1 km between the orbits of Mars and Jupiter, that give us a look at the original building blocks of the solar system.

Tom Gehrels

Asteroids that orbit the Sun in a belt between the orbits of Mars and Jupiter are well known. A few other asteroids cross Earth's orbit, and, from time to time, one collides with our planet, as figure 1 so clearly indicates. What are they made of? How did they originate? We suspect that material much like the asteroids played a part in the origin of the solar system—can we see similar forces at work elsewhere?

If you look at the Milky Way with the unaided eye on a clear, dark night, you see not only thousands of stars lighting up the galactic plane, but also vast dark clouds of gas and dust (figure 2). These opaque clouds are the material from which stars and planets form through a number of stages of accumulation, beginning with a local increase in density. Such a perturbation, which may be caused by density waves rippling through space, or by shock waves and radiation pressure from supernova explosions, initiates a process of coagulation. The gas condenses onto particles that may have originated in certain stars, forming grains with diameters up to about 0.3 microns. These grains then accumulate and form particles like the one shown in figure 3. Further accretion proceeds to make larger objects. When the mass is large enough, gravitational collapse causes much greater coagulation. The result of the next stage of accumulation we call planetesimals: objects with sizes up to kilometers or tens of kilometers. The planetesimals collide and crush together, forming planets and stars whose sizes depend on the amount of material locally available.[1]

We can observe planetesimals today, 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 only major changes that these objects have undergone in time have been due to mutual collisions, particularly within the asteroid belt between the orbits of Mars and Jupiter. This belt consists of some 10^6 objects larger than 1 km, and an increasing number of objects toward smaller meteoritical sizes.

In spite of the fact that there are trillions of cometary cores and asteroids in the solar system, readers probably know much more about the nine planets. One objective of this article, then, is to highlight the most significant features of comets and asteroids. After a look at the distribution of these objects in the solar system, I will discuss some of their physical and chemical characteristics, and how these are being measured with Earth-based instruments. Then I will turn to gravitational processes, which dominate the lives of asteroids. These processes are responsible for the ejection from orbit—or from the solar system—of asteroids with particular orbital periods, bringing some of them occasionally into the neighborhood of Earth. Impact with Earth is of obvious interest, and I will discuss it both in terms of past impacts, such as those that may be associated with extinctions, and future impacts, which we may be able to avoid. Finally, I will describe the Spacewatch Camera project, a ground-based effort in which I am involved and that promises to increase the rate of discovery of near-Earth asteroids and comets by an order of magnitude.

Asteroids and comets

Asteroids probably are rather loosely conglomerated rubble piles. Some of the larger ones may have been heated and melted; after such an asteroid breaks up in a collision the fragments are more dense and solid.

Cometary cores formed where it was cooler, farther from the Sun. At lower temperatures, gases, volatile substances and ices could be included in the dusty rubble. We therefore think

Barringer Meteorite Crater near Winslow, Arizona. An asteroid about 35 meters in diameter made this 1.2-km-diameter crater about 25 000 years ago. Fragments of the asteroid are called Canyon Diablo meteorites, after the canyon seen in this photograph. The volcanic area of the San Francisco Peaks, near Flagstaff, Arizona, is visible on the horizon at a distance of 70 km from the crater. (Photograph by David Roddy and Karl Zeller, US Geological Survey.) Figure 1

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Galactic nebula in Cygnus, named the North America nebula because of its shape. Photographed in red light at the Palomar 1.2-m Schmidt telescope. (Hale Observatories photograph.) Figure 2

Table 1. Various asteroids

Catalog number	Name	Perihelion (AU)	Aphelion (AU)	Inclination (degrees)	Diameter (km)	Type
1566	Icarus	0.2	2.0	23	2	Unclassifiable
1864	Daedalus	0.6	2.4	22	3	Silicaceous/Apollo
1862	Apollo	0.7	2.3	6	2	Apollo
2062	Aten	0.8	1.1	19	1	Silicaceous
1620	Geographos	0.8	1.7	13	2	Silicaceous
1627	Ivar	1.1	2.6	8	8	Silicaceous
1221	Amor	1.1	2.8	12	1	?
434	Hungaria	1.8	2.1	23	12	Enstatite
944	Hidalgo	2.0	9.7	42	29	Dark
4	Vesta	2.2	2.6	7	555	Vesta
29	Amphitrite	2.4	2.7	6	199	Silicaceous
1	Ceres	2.6	3.0	11	960	Subclass of carbonaceous
108	Hecuba	3.0	3.4	4	70	Silicaceous
153	Hilda	3.4	4.6	8	224	Pseudometal
279	Thule	4.1	4.4	2	131	Dark
624	Hektor	5.0	5.3	18	150×300	Dark
2060	Chiron	8.5	18.9	7	200?	Subclass of carbonaceous

The astronomical unit (AU) is the mean distance of the Earth from the Sun.

of these objects as dirty snowballs. There are an estimated 10^{13} of them with fairly stable, nearly circular orbits in cloudy rings at the outskirts of the solar system. These are usually referred to as the Oort Cloud, after the Dutch astronomer Jan Hendrik Oort of Leiden University, who first derived its existence. The orbits can be decircularized by an encounter with a massive object such as a molecular cloud or passing star. A proposed dark stellar companion of the Sun, called "Nemesis" by one of the groups that suggested it, also could decircularize orbits. In any case, cometary cores do come occasionally through the inner parts of the solar system. As they get closer to the Sun, the volatiles and ices are heated and come jetting out from the core, taking along some of the dust, so that we have what we call a comet displaying a cloudy coma and tails of dust and ionized gases.

Table 1 lists a variety of objects that are all called asteroids. The first column gives the international catalog number. The name, usually given by the discoverer, appears next. The asteroid's perihelion and aphelion are its closest and farthest distances from the Sun in its elliptical orbit. The inclination is the angle between the asteroid's orbital plane and the mean of the orbital planes of the major planets. The last column gives the asteroid's surface compositional types. Of the objects in the table, 1 Ceres, 4 Vesta and 29 Amphitrite move in the asteroid belt proper, which lies between about 2.2 and 3.3 AU, and contains objects with nearly circular orbits. Most of the "near-Earth asteroids," which occasionally cross or come close to Earth's orbit at 1 AU, still have aphelia in the asteroid belt.

There have been no missions as yet to asteroids, so that no pictures are available that show more than a speck of light: a starlike object. (The Greek word *aster* means star.) However, the Viking spacecraft obtained high resolution photographs of the surface of Mars's satellites Phobos and Deimos, whose appearance is believed to be similar to that of asteroids. The Phobos image of figure 4 may therefore give an accurate impression of an asteroid. The impacts of other planetesimals have left Phobos with a pockmarked surface similar to that of Earth's moon. The great impact crater visible at the top of the photograph must have been caused by a large object that nearly broke up Phobos. We see cracks or rills through the surface, emanating from the crater.

Earth-based measurements

Even though we cannot resolve asteroid surfaces from Earth, and even though asteroids are faint because of distance, it is possible to make measurements of color, brightness, polarization and their variations, and a few asteroids and comets come close enough for radar observations. A recent listing shows about 200 scientists involved in studies of asteroids: telescopic surveys, orbit determinations, occultation observations, photometry, radiometry, spectrometry, interferometry, polarimetry, mass determination, radar and radio observations, planning of missions and future mining, studies of interrelations with comets and meteorites, and studies of origin and evolution.

Particle collected at high altitude and believed to be cometary in origin. The diameter of this particle is about 6 microns. The typical extraterrestrial particle collected at high altitude is chondritic, containing elements in the same relative abundances as elements in the Sun. (Photograph courtesy of Donald Brownlee, University of Washington.) Figure 3

A relatively old technique is to do spectrophotometry with filters of ultraviolet, blue and visible light. When one plots the difference of logarithmic magnitudes of ultraviolet and visible light as a function of the reflectivity, the result is a diagram such as the one in figure 5.

The reflectivity is determined through a combination of observations in visible light and at longer wavelengths, near 10 or 20 microns. The radiometry at the longer wavelengths gives the thermal flux, which is a measure of the size of the radiating object because this flux depends on the cross section of the material. Comparison with the amount of visible radiation indicates the reflective power.

Figure 5 shows some distinct domains; many asteroids fall into the areas labeled carbonaceous and siliceous. We must be careful not to consider these types as having precisely defined compositions, but laboratory comparisons do indicate that the objects labeled carbonaceous have characteristics similar to materials containing carbon, while those labeled siliceous are more like sandy, ferromagnesian (containing iron and magnesium) silicates. The objects in the upper left are labeled on the basis of their similarities with the enstatite meteorites. 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—and perhaps the Moon or Mars—from which the meterorites fragmented.

Figure 6 shows characteristic reflectivity profiles for various asteroids. The abscissa gives the wavelengths of the photometer's filters, while the ordinate is again a measure of the reflectivity. Typical asteroids are indicated on the right with their names and catalog numbers. The enstatite-type asteroids, of which 44 Nysa is an example, are the brightest.

Table 2. Earth-approaching objects

Diameter (km)	Number of objects	Impact probability (impacts per year)	Impact energy ("Hiroshimas")
10	10	10^{-8}	10^{9}
1	1 000	10^{-6}	10^{6}
0.1	100 000	10^{-4}	10^{3}

The fact that individual asteroids have individual spectra is of fundamental importance. Apparently asteroids are not all covered with the same interplanetary dust. Instead, material liberated from an asteroid in a collision settles gravitationally upon the surface of that same asteroid. An explanation of the initial heterogeneity is, however, still needed. Either asteroids formed by heterogeneous accretion at early times, or they formed in larger differentiated bodies—differentiated like the Earth, with a metallic core—that were subsequently broken up in collision.

It has been known for some time that the silicaceous asteroids occur near the inner part of the asteroid belt and the carbonaceous ones toward the outer. This is of great significance, as it mirrors a change in composition from that of the rather silicaceous inner planets towards the more volatile, lighter elements found in the outer parts of the solar system. Was the asteroid belt formed with this zonation in compositions, or did asteroids move there subsequently, silicaceous types from the inner regions and carbonaceous types from the outer regions of the solar system? This is a fundamental question that has not as yet been answered.

Gravitational processes

According to Ed Tedesco of the Jet Propulsion Laboratory, the present mass in the asteroid belt is only 6×10^{-4} Earth masses. This is a small amount of material in the large space between Mars and Jupiter. Elsewhere in the solar system the mass density is much greater. Massive Jupiter—and other planets as well—appear to have gravitationally jostled, swept up or thrown out of the solar system many of the early planetesimals. Let us look at some of the gravitational processes.

The histogram in figure 7 shows the distribution of the 2436 numbered asteroids in the belt between Mars at 1.5 AU and Jupiter at 5.2 AU. The ratios at the top of the figure are commensurabilities with Jupiter's orbit. Asteroids at the distance from the Sun labeled $1/3$, for instance, circle the Sun exactly three times during one orbital period of Jupiter. The commensurabilities usually are regions of depletion, as are similar regions of resonance, where various orbital parameters other than the period match those of Jupiter. Beat phenomena are at work, with the massive planet repeatedly meeting the asteroid in the same configuration and

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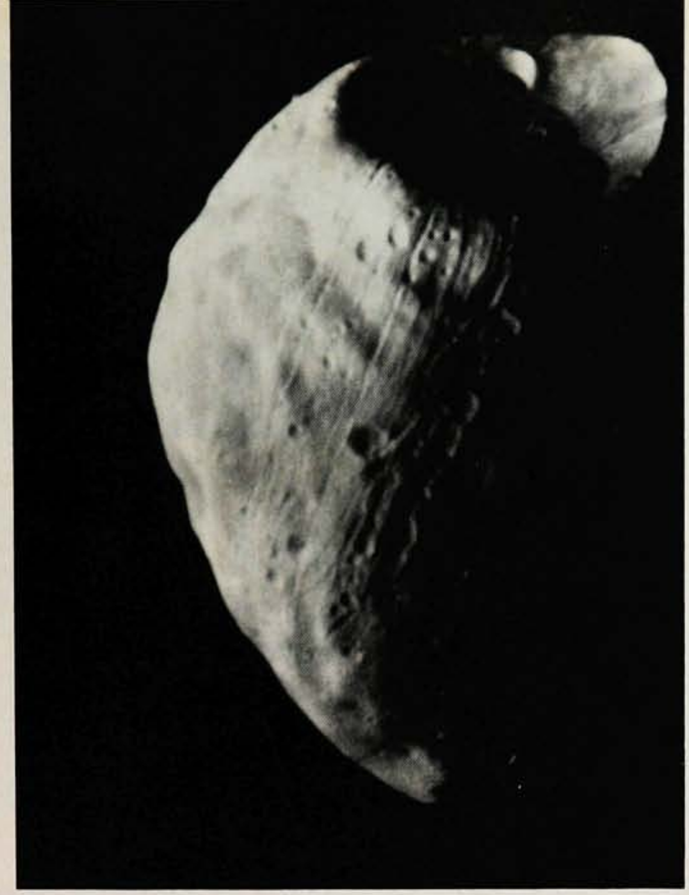
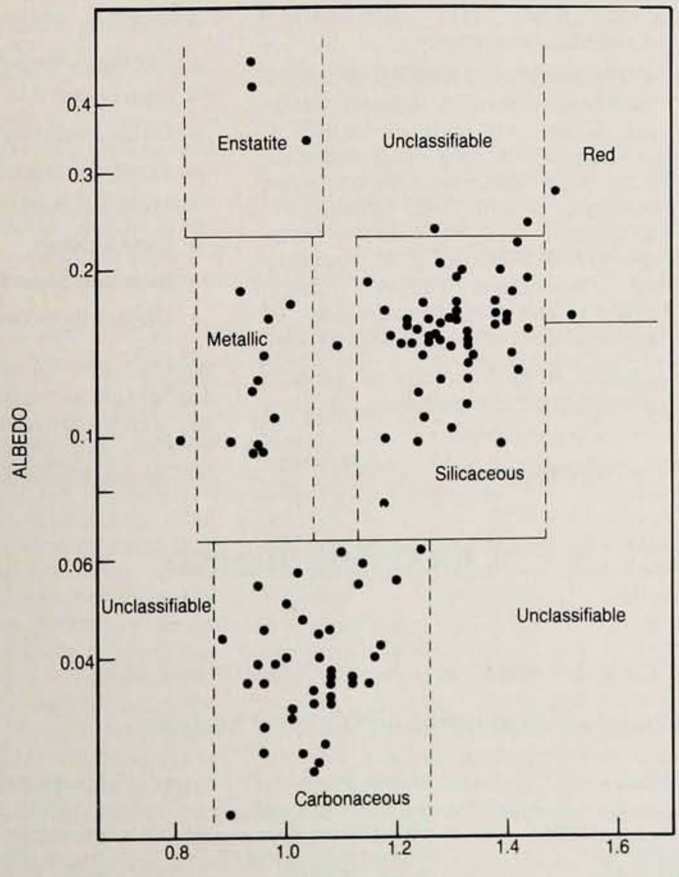


Phobos, satellite of Mars. The Viking spacecraft obtained this high-resolution image. (NASA photograph.) Figure 4

Albedo as a function of color for various asteroids. The asteroids are progressively redder than sunlight toward the right in the figure. (After a diagram by Ben Zellner, University of Arizona.) Figure 5



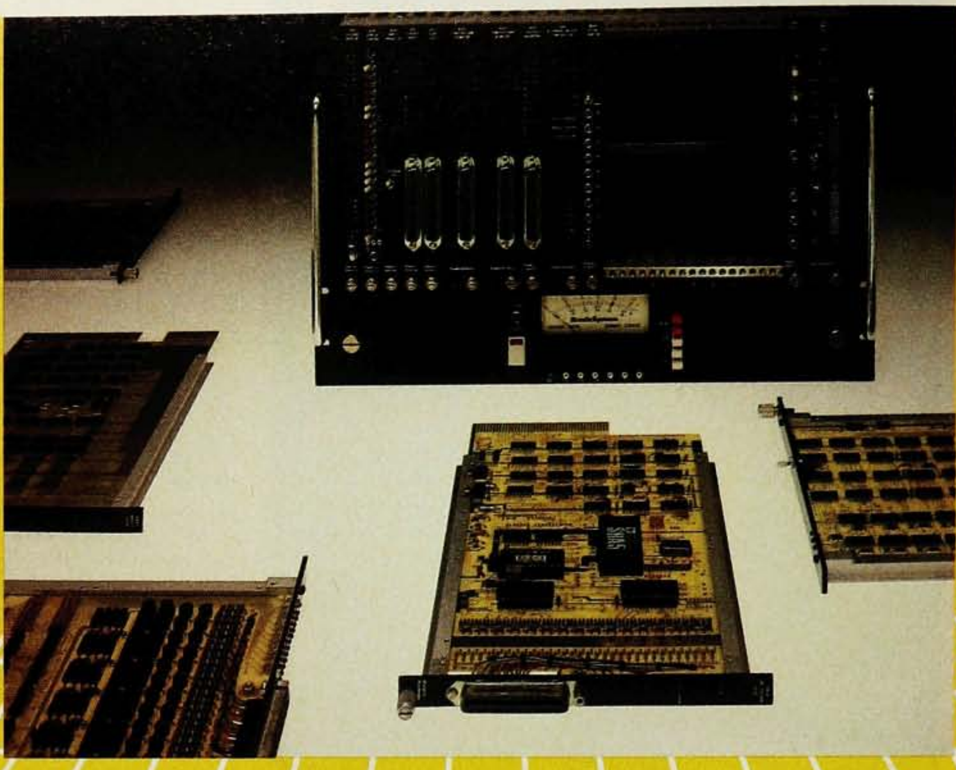
affecting the asteroid's orbit with its gravitation. With giant Jupiter stirring and removing material from its inner zone, a planet could not form there for lack of mass concentration, and we are left with some of the planetesimals.

What is the present state of asteroids outside and inside the orbit of Mars? The average velocity of the belt asteroids with respect to each other is substantial: 5 km/sec. This differential velocity implies a finite collision probability in the asteroid belt. Collisional fragments that go into resonance and commensurability regions will be thrown by Jupiter, either outwards to leave the solar system or inwards to come close to Mars, Earth, the Moon and Venus.

Figure 8 shows how, in four stages, collisional gravitational processes may produce asteroidal fragments of various compositions within the orbit of Mars. This sequence requires an asteroid that was heated sufficiently to be molten—by radionuclides perhaps—so that it differentiated by gravitation, with the heavier metallic substances towards the core, as indicated in part a. This was possibly the case for Vesta. Part b shows the situation after a giant collision with another asteroid, and c shows the result after further impacts. Such fragments have been studied with photometry as described above. Results indicate, for example, that asteroid 338 has a metallic composition, while 349 appears to consist of a lighter material. Finally, if the collisions send objects into orbits near any of the commensurabilities, such as the one indicated in d, then Jupiter's gravitation will cause the orbit to become more elliptical, and the objects will cross into other parts of the solar system. Gravitational interaction with Mars, Earth and Venus may further affect the orbits. The ultimate fate is a collision with a planet or ejection from the solar system.

Impact with Earth

Our knowledge of the statistics of the asteroids and comets that occasionally cross the Mars orbit comes from studies based on techniques such as telescopic searches and counts of craters on the Moon.[2] A precise determination with a telescopic survey of faint objects seems an important goal, and the Spacewatch Camera is to do this, as I will discuss below. There probably are at least 1000 asteroids larger than 1 kilometer in diameter that occasionally come close to Earth. This includes old cometary cores that have passed by the Sun



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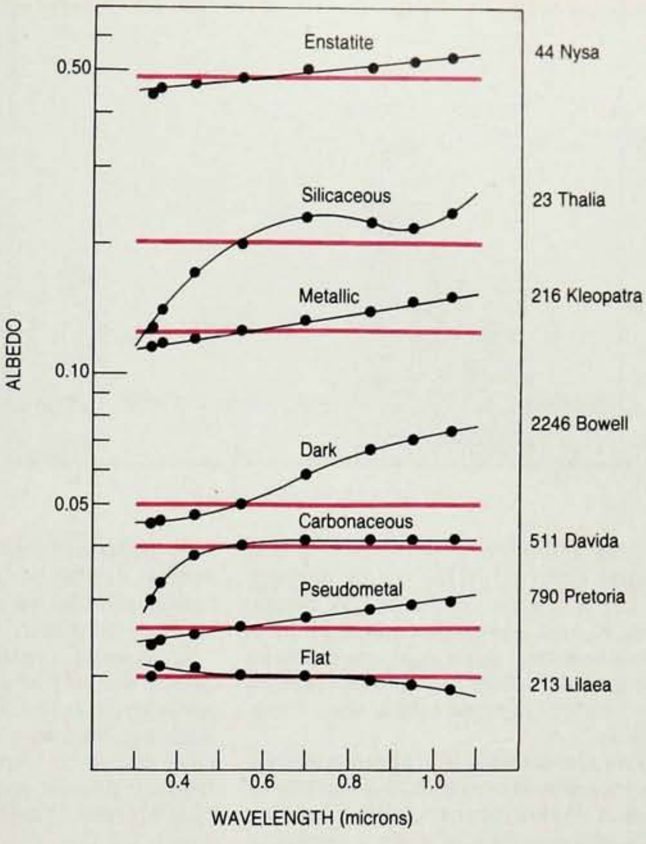
Reflectivity of asteroids plotted as a function of wavelength. (After a diagram by Ed Tedesco, JPL.) Figure 6



enough times to have had their volatiles exhausted, so that they are now indistinguishable from asteroids. According to Eugene M. Shoemaker of the US Geological Survey, interactions with Jupiter will eventually remove half of them from the solar system, about one-fourth will hit the Earth and about one-fourth will hit Venus. The orbits of the planet-crossing asteroids are unstable with lifetimes on the order of 10^7 years. Statistically, it is a steady-state situation, with the removals and impacts balanced by resupply from the asteroid belt and from the outer comet regions.

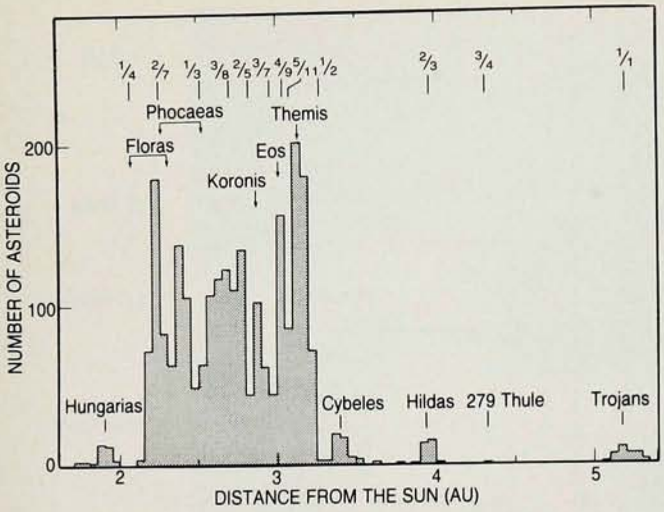
Table 2 gives an estimate of the statistics of Earth impact, with approximate numbers that are easy to remember. I assume here that with each factor of 10 decrease in size, the number of objects increases by a factor of 100. This is true in the asteroid belt, but for these Earth-approaching fragments the scaling is uncertain; it is among the parameters to be determined by the Spacewatch Camera. Various astronomers have estimated the impact probabilities. The kinetic energy of the impact follows from $\frac{1}{2}mv^2$, where typical differential velocities v between Earth and asteroids are 11 to 30 km/sec, while the mass m can be estimated from an assumed 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 6 August 1945. This is to show the enormous energies involved; it is not done callously, as we do not forget the suffering at Hiroshima. The energy of the Hiroshima explosion was equivalent to 13 000 tons of TNT, or 5×10^{20} ergs. While they have much larger energies, the asteroid impacts do not have nuclear-radiation effects.

Figure 1 demonstrates that the Earth has been bombarded by asteroids. The object in that case was metallic, with a diameter on the order of only 35 meters. The impact occurred about 25 000 years ago, releasing some 10^{23} ergs of kinetic energy, and the effect is seen today as a crater 1.2 km in diameter and 167 meters deep (below the crest of the rim, which rises about 50 meters above the surrounding plain).

Extinctions. More serious was the impact of a 10-km asteroid or cometary core, or of a group of smaller objects, that apparently caused the extinction of about 60% of the animal species, the so-called Cretaceous–Tertiary Extinction, which occurred between these two geological periods about 65 million years ago (PHYSICS TODAY, May 1982, page 19). Another asteroid of about 3-km diameter appears to have impacted some 34 million years ago and may have caused the Eocene–Oligocene Extinction of various species.[3]

There still is some debate about 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 cause major extinctions was already pointed out in 1973 by Harold 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 heavy elements, such as iridium, found in the 1- to 2-cm-thick boundary between the deposits of the Cretaceous and the Tertiary periods.[4] The abundances are similar to those of meteorites, and unlike those at the surface of the Earth. The large impact crater has not been found, but it may be in the oceans where it would have filled with mud and would no longer be recognizable. Even on the surface, a crater may disappear due to plate-tectonic movements. In any case, the cloud of asteroidal matter, surface soil or water ejected by the impact was so massive that it settled as a 1- to 2-cm clay layer over the whole Earth. It is estimated that most of the cloud was material from the Earth's surface, with about 7% asteroidal material of carbonaceous chondritic composition.

An impact on land may cause a dust cloud in the atmosphere thick enough to extinguish sunlight at the surface. This would have stopped weather patterns, which are caused by differences of the effects of solar radiation on land and oceans. For lack of photosynthesis, most green growth including that of certain algae, would have stopped, de-



Number distribution of asteroids in the solar system. The number of asteroids is shown as a function of distance from the Sun. Various groups and families of asteroids, defined by their orbital similarities, are indicated. The ratios are commensurabilities with the orbital period of Jupiter. (After a diagram by Ed Tedesco, JPL.) Figure 7

priving animals of green fodder. If this impact occurred in the ocean, perhaps in the northern Pacific or the Bering Sea, it may have been followed by a transient but significant increase in the global surface temperature due to the water injected into the atmosphere.[5]

It is also possible that there was not a single asteroid or comet, but a group or even a shower of them, either landing at the same time or over a period of time. This seems to be confirmed by recent findings of several craters that are about 65 million years old. It also can explain the variation over the Earth of the iridium abundance in the 1- to 2-cm layer, if the impacting objects differed in composition. It has been postulated that a stellar companion to the Sun, the "Nemesis" I mentioned above, brings in showers of comets with a periodicity of some 26 million years; this proposal is being debated critically. What seems established is that asteroidal or cometary impact caused some of the extinctions associated with the Cretaceous–Tertiary boundary.

We see in table 2 that impacts of large objects may occur again. This is not to be dismissed from our concern because of the low probabilities. One consequence of the impact of a 10-km asteroid, or even a 1-km asteroid, would be the elimination of human society. This appears certain on the basis of the studies made for the Cretaceous–Tertiary event.[6] We are fortunate that the orbits in the asteroid belt are stable and that we receive on Earth only collisional fragments, for the diameters of asteroids in the belt range up to almost 1000 km! With such large objects impacting, life might not have had a chance on Earth. As it is, the major impacts must have affected the evolution of our species. Some have speculated[7] that without the Cretaceous–Tertiary Extinction the most advanced species might now have looked like a dinosauroid—similar to us, but with more brains and less sex. What probably happened instead, was that the sudden demise of species by asteroid impact opened up evolutionary opportunities on Earth.

It appears possible to change the orbital velocity of a menacing asteroid sufficiently to avoid an impact. Preliminary studies of this problem indicate that with enough advance warning, the present technology of shuttle-type spacecraft and existing explosives could do the job. Years of careful astrometry would be required to determine the orbit precisely. One would want to do physical studies to determine the strength of the asteroid before using explosives, because breaking up a menacing object would aggravate its effects: like using buckshot instead of a single bullet. In any case, the menacing comets and asteroids have to be found first, and that is one of the goals of the Spacewatch Camera.

The Spacewatch Camera

The statistics I have cited of near-Earth asteroids come mainly from surveys by Eleanor F. Helin, Eugene M. Shoemaker and Carolyn Shoemaker, who use the photographic Schmidt telescopes at the Palomar Observatory. The rate of discovery of asteroids or cometary cores crossing Earth's orbit is about five per year, and the total number known at this time is near 70. A dedicated search instrument could increase the discovery rate to perhaps 50 faint ones per year. This is a design goal for the Spacewatch Camera.

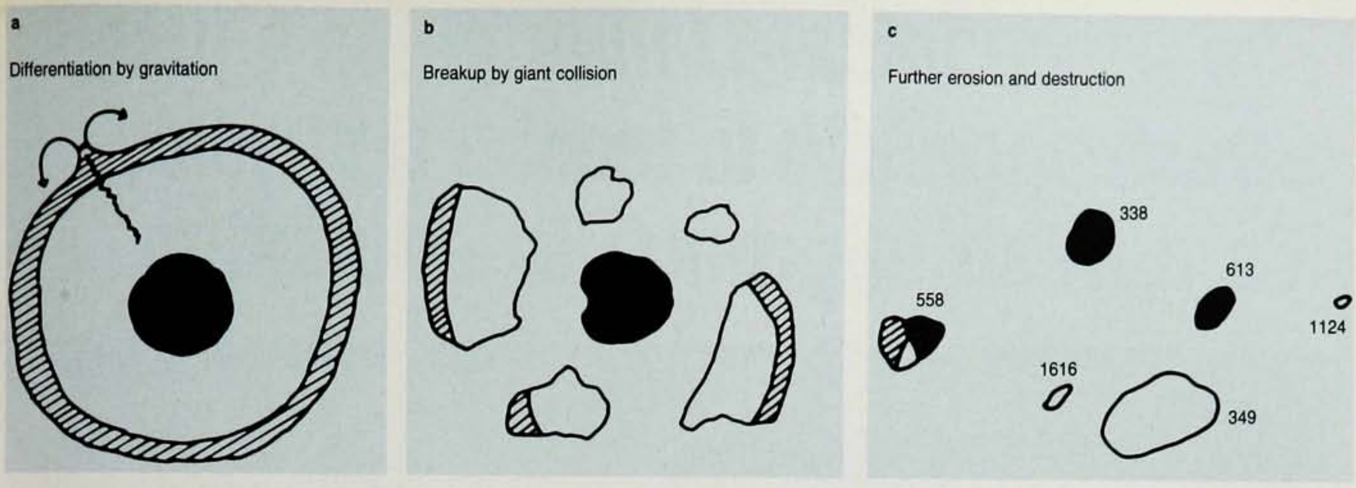
On Kitt Peak, about 70 km west of Tucson, Arizona, is located the Kitt Peak National Observatory and also a station of the University of Arizona Observatories. The university is letting us use one of its domes, including its 0.9-m Newtonian telescope, which we call the first Spacewatch Camera. The image quality at this site, at an altitude of 2076 meters, is excellent. A design is complete for a 1.82-m Spacewatch Camera to replace the 0.9-m Newtonian within a few years.

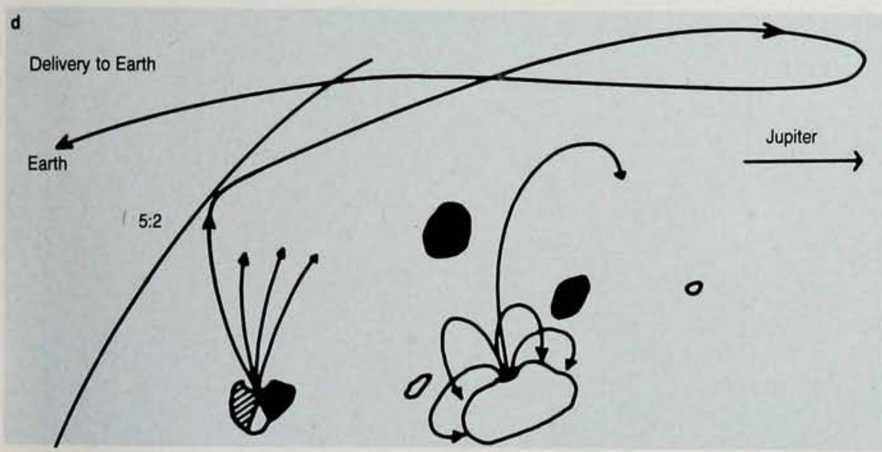
At the focus, we mount a charge-coupled device for observations during the dark half of the month, centered on the New Moon. The charge-coupled device that we are now using is manufactured by RCA and has 512 channels of 320 pixels each. The pixel is a light-sensitive metal-oxide-semiconductor capacitor, 30 microns square. Several astronomical observatories use this type of CCD detector in the "stare mode," in which the shutter remains open for a guided exposure. After the exposure, the charges accumulated in the pixels are transferred from channel to channel until they come to an output shift register, from which they enter a computer.

Our own use of the CCD is in the "scan mode," sometimes called the time-delay integration mode. We transfer the accumulating charge from channel to channel continuously, at a rate that exactly matches the rate at which the telescope scans the sky. The shutter is open during the scan, which for near-Earth asteroids may last typically 30 minutes. We then close the shutter, reset the telescope and repeat the scan. A computer superposes the two scans and subtracts them, canceling the images of stars that exactly superpose. The objects that moved during the 30-minute interval therefore remain and are discovered. It is essential in this procedure to have a fast computer because we are dealing with data rates near one million bits/second and storage requirements on the order of a billion bits.

The National Aeronautics and Space Administration and several private and corporate supporters are helping to fund the Spacewatch project. This is in addition to considerable support from the State of Arizona in the form of site, dome and a finished 1.82-m mirror.

During the moonlit half of the month, another group of astronomers replaces the CCDs with 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, that star is also attracted to the planet, and it therefore describes a small orbit about the system's center





Differentiation of asteroidal fragments. The sequence of sketches shows how collisional and gravitational processes can produce objects of various compositions and deliver them to Earth. (After a diagram by Clark R. Chapman, Planetary Science Institute.) Figure 8

of mass. The star may appear to us to be moving back and forth in space, sometimes radially away from us, and at other times toward us. A precise accelerometer can detect such radial velocities.

We use the Spacewatch Camera to learn more about asteroids than just their existence. We use it to determine their orbits and, through joint programs with other scientists, to study their physical properties. One fundamental problem is to find out how many exhausted nuclei of previously active comets occur among the Earth-approaching objects. 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, but the high quantum efficiency of the CCD should make it much easier to discover faint and fast-moving objects. Long exposures on photographic plates show a trail for moving objects, so that the effective exposure is actually short. Charge-coupled devices provide faster detection of moving objects. CCDs have a 70% quantum efficiency over a wide range of wavelengths, while the fastest of photographic plates have quantum efficiencies of only a few percent.

Many fundamental studies have yet to be made. The Infrared Astronomical Satellite has observed thousands of asteroids, but astronomers have only begun to determine the dielectric properties and surface textures of these objects with radio telescopes and polarimeters. Asteroidal bodies rotate with periods between 2 and 60 hours, but mostly near 8 hours, producing lightcurves due to the variation in reflected sunlight as various cross sections are presented. Are these rotations primordial, or caused by more recent collisions?

The Spacewatch Camera will make possible many future investigations. The study of the beautiful primordial objects is to us the most important use of the Camera, but there are other interests: concern for the hazards of future impacts; preparation for missions for flyby, rendezvous, docking and sample analysis; and the possibility of mining asteroids in the future. Landing on a near-Earth asteroid is in principle easier than landing on the Moon because of the negligible gravitation of the small body. Work on asteroid-mining technology is already underway in the form of research on how to separate platinum, for instance, from the other metals on the surface of an asteroid in space.

The time for the execution of flyby missions is coming closer. The United States has the International Comet Explorer flying by comet Jacobini–Zinner in late 1985. March of 1986 will be very exciting with five spacecraft—launched by space programs in Europe, the Soviet Union and Japan—flying by comet Halley. The Galileo probe to Jupiter will fly by asteroid 29 Amphitrite in December 1986, and the USSR may have a mission to 1627 Ivar in 1989.

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