INTRODUCTION

TOM GEHRELS
University of Arizona

and

JOCELYN R. GILL AND JOSEPH W. HAUGHEY
NASA, Office of Space Science and Applications

HISTORICAL NOTES

Kepler, in his *Mysterium Cosmographicum,* probably was the first to point out that a planet was missing between the orbits of Mars and Jupiter. The Titius-Bode expression of planetary distances from the Sun ($r = 0.4 + 0.3 \times 2^n$) was formulated in 1772. That expression and the discovery of Uranus in 1781 stimulated plans to search for the missing planet at 2.8 AU, and at a congress in 1796 a group of astronomers undertook to search, each an assigned part of the sky, for the missing planet. Ceres was not found by any of that group, but by Piazzi at Palermo, rather by chance, on January 1, 1801.

In the early literature there occurred some mention that the orbits of Ceres, Pallas, Juno, and Vesta nearly intersect, and the possibility of a common origin was raised. At our request, Herget looked into this matter and table I gives for various pairs of asteroids the closest distance and the eccentric anomalies at which the closest approach occurs. The surmise of intersecting orbits appears without basis.

Asteroids were observed visually in the telescope by checking positions noted on star maps to detect motion among the stars. The asteroid work in the middle of the 19th century stimulated the making of the first stellar atlas, the *Bonner Durchmusterung.* The brightness of the asteroids was determined by comparison with the *Bonner Durchmusterung,* and because it has serious errors in the faint end of the magnitude scale, the asteroids were assigned magnitudes that were systematically off by as much as 1 or 2 mag.

One hundred asteroids had been found by 1868 and that number trebled by 1890. In 1892, Max Wolf of Heidelberg adopted a photographic method. The magnitude error, however, was propagated also to the photographic determinations. The asteroid magnitudes became reliable, to about ±0.1 mag, in 1958 when the IAU adopted a new magnitude system for the asteroids.

The observations of minor planets are still being conducted at several observatories, but mostly for astrometric purposes. Historical notes on

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TABLE I.—*Closest Distance Between Asteroids and Eccentric Anomalies of Closest Approach*

[Herget, 1971, personal communication]

Planet pair	Closest distance, AU	$E(1)$	$E(2)$
Ceres-Pallas	0.17	35°	58°
	.06	218	260
Ceres-Juno	.63	0	81
	.85	142	256
Ceres-Vesta	.40	44	310
	.51	222	113
Pallas-Vesta	.08	49	293
	.45	265	114
Juno-Vesta	.38	295	78
	.45	85	267
Pallas-Juno	.50	30	88
	.79	268	327

(disappointments experienced in) the use of asteroids to determine fundamental astronomical constants are found in the paper by Rabe,[1] whereas Vesely[2] discusses the history of pole determinations in photometry. The procedures at the telescope are described by Roemer.[3] Sometimes an additional plate is taken, guided on stars in a known magnitude sequence for calibration of the asteroid magnitude (photometric procedures were described by Gehrels, 1970).

The advent of fast electronic computers has improved and accelerated the process of orbit computation drastically. In the 1971 *Ephemeris* volume there are 1748 numbered asteroids. In addition, there are several thousand that have not been observed in subsequent apparitions, or that have for other reasons only a preliminary designation.

NAMES AND CATALOGS

A preliminary designation, at least after 1925, is made as follows: The year is followed by a letter indicating in which half of the month the finding occurred and the second letter gives the order of the discovery within that half month; for instance, the first asteroid discovered in the second half of March 1971 was 1971 FA. A preliminary orbit is computed from at least three observations within that first apparition. If the object is found during another apparition, a permanent number is assigned and the discoverer may name the planet. An effort is made to give all asteroids a name; originally the custom was to put all asteroid names into feminine form, but that convention is no longer followed.

[1]See p. 13. [2]See p. 133. [3]See p. 3.

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The cataloging of asteroids was done at the Rechen Institut in Germany; the yearly ephemerides volumes *Kleine Planeten* were published until 1944 and the ones from the Institute of Theoretical Astronomy in Leningrad started in 1947. From 1949 through 1952, the Minor Planet Center in Cincinnati also published ephemerides, but by international agreement in 1952 this was discontinued. Since then Cincinnati publishes the *Minor Planet Circulars* for observations, new orbits, and ephemerides, while Leningrad issues the yearly *Ephemeris* for numbered planets including their orbital elements. (See Herget.[4]) The *Astronomical Circular*, published by the Kazan or Englehart Observatory, and other scattered observatory publications list asteroid observations and calculations. New findings that are of urgent importance are transmitted to the IAU bureau at the Smithsonian Astrophysical Observatory in Cambridge, Mass., which in turn transmits this information to other observatories. A complication of searches for new objects is that many rockets or rocket parts are in orbit around Earth. (See Aksnes.[5])

The aim of this book and of the colloquium is to concentrate on physical studies, and we will not dwell on the applications of asteroid work in celestial mechanics. The work of precise orbit determination is crucial for determination of individual masses of asteroids, and this is discussed by Schubart.[6]

PHYSICAL CHARACTERISTICS

Hapke[7] opened his paper with these words: "The picture that most of us have in our minds of a typical asteroid is probably of a large, irregularly shaped chunk of iron, unrusted by exposure to oxygen or water, and with a surface kept clean and dust free by the sandblasting effect of repeated micrometeorite impacts." We wonder just how many people would think of asteroid surfaces that way, rather than of a dusty, rubbled regolith as the artist made for Geographos in the frontispiece. Hapke himself and others in this book endorse that artist's concept; in fact, at the colloquium there was some discussion of the possible materials and texture for the dusty surface.

The apparent diameters of Ceres, Pallas, Juno, and Vesta during oppositions when they are favorably near perihelion are about 0″.6, 0″.6, 0″.2, and 0″.4, respectively. Only these four and Eros have been measured directly. (See the paper by Dollfus[8] and the ensuing discussion.) Eros' apparent diameter was about 0″.18 when van den Bos and Finsen (1931) observed it, and this is considered too small for reliable size determination. The reflectivity is determined from size and brightness measurements; both are needed. New techniques of infrared observations to determine diameters are discussed by Allen,[9] and by Matson[10] who makes an interesting comparison of size and reflectivity.

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[4]See p. 9.
[5]See p. 649.
[6]See p. 33.
[7]See p. 67.
[8]See p. 25.
[9]See p. 41.
[10]See p. 45.

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Spectrophotometry is reviewed by Chapman et al.,[11] who also describe their own discovery of a spectral feature near 0.92 μm for Vesta and a few other asteroids; they give an interpretation in terms of absorption by Fe^{2+}. The integrated colors of asteroids vary but generally resemble the Moon and Mercury in showing a brownish-gray hue.[12] The photometric properties may resemble the Moon's, but this could be a misleading statement as there are considerable differences, as yet poorly determined. The nature of the surface can be studied with detailed photometry[13] and polarimetry.[14] Radar measurements may be used for a few asteroids, but only the largest radio telescopes have enough signal-to-noise ratio.[15]

When a photometric lightcurve has two nearly identical maxima and minima, it is concluded that the lightcurve is caused by effects of shape rather than by reflectivity differences over the surface.[16] The fact that lightcurves of the asteroids repeat over many periods is an indication that they do not wobble in space like spinning tops, but rather rotate about one axis only. Rotation periods are generally found between 3 and 19 hr; they are listed in table I of Taylor.[17] Geographos is known to be highly elongated because of its large amplitude of the light variation.[18] After the colloquium, a new Apollo asteroid was found[19] and its lightcurve was observed; this object also has a steep lightcurve, which is more irregular than that of Geographos, suggesting a more irregular shape for the object. Trojan asteroid Hektor also has a large amplitude of the lightcurve, but this object is so large that it may not be able to sustain itself gravitationally as a single elongated body; it may be a double object as suggested by Cook.[20] However, Hartmann (1972) derives for gravitational crushing and collapse to spherical shape a critical diameter of 680 km for rocks and 120 km for meteoritic material; Hektor is 110 km long and 40 km wide and therefore is a marginal case. The fact that asteroids can have exceptional shapes was noticed early in the 20th century for Eros.[21] The determination of the shapes, orientation of axes, and the analysis of lightcurve observations are discussed by Lacis and Fix,[22] and by three of the six high-school teachers working on a NASA-sponsored photometric program in Tucson: Dunlap,[23] Taylor,[24] and Vesely.[25]

STATISTICS AND GROUPS

Asteroids travel in prograde orbits defined by elements: the semimajor axis *a*, eccentricity *e*, and inclination to the ecliptic plane *i*. There is some preference for the direction of the semimajor axes to occur more frequently in the same direction as that of Jupiter. (This is seen in figure 2 of Lindblad and

[11]See p. 51.
[12]See p. 67.
[13]See, however, p. 79.
[14]See pp. 91 and 95.
[15]See p. 165.
[16]See p. 257.
[17]See p. 123.
[18]See p. 153.
[19]See p. 647.
[20]See pp. 155 and 162.
[21]See p. 133.
[22]See p. 141.
[23]See p. 147.
[24]See p. 117.
[25]See p. 133.

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Southworth.[26]) Like stars, asteroids may be listed according to their apparent magnitudes, ranging from 7 mag to the faintest seen in a reasonably large telescope, viz., 16 to 17 mag for the 154 cm Catalina reflector and 21 mag, the faintest photographed to date. These apparent magnitudes may be converted to absolute magnitudes, converted to zero phase angle and 1 AU distances to Sun and Earth, in order to give a representation of size.

A systematic photographic survey of the asteroid belt was made in the Yerkes-McDonald survey (MDS) to 16 mag. The Palomar-Leiden survey (PLS) gave a spot check, rather than a systematic survey around the ecliptic, and the corrections to completion are uncertain. The PLS does, however, give statistics to the 20th apparent magnitude for about 2000 asteroids and orbital characteristics for 1800. Valuable additions and clarification of MDS and PLS data occur in the papers–and in the ensuing debates–of van Houten,[27] Kiang,[28] Kresák,[29] Dohnanyi,[30] and Lindblad and Southworth.[31] In summary, it appears to us that there are no systematic errors in the PLS but that, because only a 12° by 18° area was photographed, there are selection effects and the corrections to completion are uncertain.

The total number of asteroids brighter than $B(a, 0) = 21.2$ (1.6 km in diameter), derived from the PLS, is $4.8\ (\pm 0.3) \times 10^5$ (Gehrels, 1971). Collisions continually occur to cause a steep frequency-size relation. The total mass in the asteroid ring is not so easily derived because the mass density and reflectivity of all but a few are unknown, but it appears to be about twice the mass of Ceres, or 2.4×10^{24} g, or 0.4×10^{-3} the mass of Earth. (See Schubart.[32]) The comparison with the masses of planets is qualitatively shown in figure 1 of Arrhenius and Alfvén.[33]

Whereas the asteroids on the inner side of the belt are concentrated toward the plane of the ecliptic, with $\bar{i} \sim 4°$, this concentration gradually diminishes, $\bar{i} \sim 11°$ near $a = 3.2$ AU, and the concentration toward the ecliptic plane is generally less for larger objects. (See van Houten[34] and Kiang.[35]) The outer boundary of the asteroid belt is not well defined but the inner one is rather sharply limited,[36] except for the Mars-crossing asteroids. When they can come close to Earth they are called "Amor-type asteroids"; they are defined to have aphelion distance between 1.00 and 1.38 AU (Gehrels, 1972). When the orbit of Earth is also crossed, the object is called an "Apollo asteroid" after one of these objects. Table II of Marsden[37] and table I of Roemer[38] give characteristics of these groups. Alfvén and Arrhenius[39] select from these a subgroup of asteroids having lower eccentricities as candidates for space missions.

R. B. Hunter (1967) predicted the possibility that asteroids would occur between Jupiter and Saturn. Rabe (personal communication) believes these

[26]See p. 351.
[27]See p. 183.
[28]See p. 187.
[29]See p. 197.
[30]See p. 263.
[31]See p. 337.
[32]See p. 33.
[33]See p. 214.
[34]See p. 183.
[35]See p. 187.
[36]See p. 177.
[37]See p. 419.
[38]See p. 644.
[39]See p. 473.

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regions to be rather unstable, although perhaps asteroid orbits roughly half-way between Jupiter and Saturn, if they are of small or moderate eccentricity, may be able to avoid approaches to both major planets and thus remain stable. No asteroids between Jupiter and Saturn have been found in the PLS down to 20.5 mag.[40]

The orbital periods of the asteroids are mostly between 2 and 6 yr, which is to be compared with 11.86 yr for Jupiter. Gaps and/or groups occur at certain commensurabilities. Three asteroid distributions are especially noted, separated by gaps called Kirkwood gaps after their discoverer. The principal gaps occur at 5.9, 4.8, and 4.0 yr (i.e., at 2:1, 5:2, and 3:1 ratios to Jupiter's mean motion), but objects are present, in resonance with Jupiter. Groupings[41] and families of asteroids are generally named after representative asteroids. Their mean motion as seen from the Sun is often considered; for instance, at the above 2:1, 5:2, and 3:1 commensurabilities, we have, respectively, Hecuba near 600, Minerva near 750, and Hestia near 900 arcsecs/day. Table II shows characteristics of a few representative asteroids.

The present eccentricities and inclinations of the asteroids have been affected by Jupiter's perturbations, but values of these may be computed such that they are free of most long-range perturbations. The three-dimensional distribution of these unperturbed elements (called "proper" elements) shows groupings of the minor planets against a general background. These groupings are referred to as Hirayama families; Hirayama found 10 of them and Brouwer extended the number to 458 out of 1537, or 30 percent of known asteroids. Presumably the members of each family are fragments of a collisional breakup; the chance of collision is estimated by Hills[42] and

TABLE II.—*Orbital Characteristics of Representative Asteroids*

Asteroid	*q*, AU	*Q*, AU	*e*	*i*	Mean motion, arcsec/day
1932 HA Apollo	0.65	2.31	0.56	6°	1959
1221 Amor	1.08	2.76	.44	12	1333
434 Hungaria	1.80	2.08	.07	23	1309
46 Hestia	2.09	2.95	.17	2	885
719 Albert	1.19	3.98	.54	11	854
93 Minerva	2.36	3.14	.14	9	776
1 Ceres	2.55	2.99	.08	11	771
108 Hecuba	2.96	3.49	.08	4	614
153 Hilda	3.38	4.58	.15	8	448
279 Thule	4.15	4.41	.03	2	400
624 Hektor	5.02	5.22	.02	18	306
944 Hidalgo	1.98	9.66	.66	43	253

[40]See p. xvii. [41]See p. 173. [42]See p. 225.

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Burns.[43] Some of these families are rather tightly packed, others are loose and may not even constitute real groups. (See the paper by Lindblad and Southworth.[44]) The consideration of nongravitational forces, in this case the ones by collision, are important. Collisions tend to diminish e and i, but more sharply the collisions may form jetstreams characterized by high space density and low relative velocity of members. Now we have arrived at a rather complex situation where inelastic collisions may cause accretion as well as dissipation; the new theoretical developments are introduced by Alfvén[45] and the degree of elasticity is studied by Trulsen.[46]

TROJAN ASTEROIDS

There are also accumulations at 1:1 and these are referred to as the Trojans. Sixteen members of the Trojans are definitely known and many others are suspected. The large number of Trojans and their asteroidlike size distribution suggests that they have a similar origin; e.g., that they were formed at their present location by condensation from the solar nebula.

The Trojans occur near points of equilateral triangles with the Sun and Jupiter in the plane of Jupiter's orbit. These lagrangian points L_4, preceding Jupiter, and L_5, west of Jupiter, are fairly stable points and permit large librations of the Trojans about these points. Rabe[47] discusses the possible Trojan origin of the Jupiter family of comets.

ORIGIN AND EVOLUTION OF THE ASTEROIDS

Asteroids and comets should be studied intensively because they are made of primeval matter of the solar system and are less affected by later action as is the case on the Moon, Mercury, etc. The comets, certain satellites, Trojans, ordinary asteroids, Mars-orbit crossers, meteorites, and meteors should be studied simultaneously because they are records for various parts of the solar system. A basic separation of cosmic material is generally recognized to be as follows: (1) earthy materials, solid at temperatures up to 2000 K, (2) the ices, vaporizing at about 300 K, and (3) the gases. This separation should be kept in mind for the study of the relative importance of asteroids, comets, and planets.

The three largest asteroids do not fit the normal frequency-size distribution. This has been explained by Hartmann (1968) as due to their having reached a range of sizes where the gravitational cross section was larger than the geometric one. The theory of Hills[48] considers the terrestrial planets similarly to be large asteroids. The number-size distribution[49] of the asteroid ring shows a discontinuity near about 20 km diameter. This may be due to two modes of asteroid formation: the asteroids brighter than about the 12th apparent

[43]See p. 257.
[44]See p. 337.
[45]See p. 315.
[46]See p. 327.
[47]See p. 407.
[48]See p. 225.
[49]See pp. 294 and 297.

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magnitude may be original condensations whereas the ones fainter than about 16 mag may be fragments of subsequent collisions. Alfvén has suggested that the present rotation rates, which have been observed only for the larger asteroids, are remnants of the original rotations obtained during formation, but this was debated by Whipple.[50] (Also see Burns.[51]) Dohnanyi[52] finds that the number-size distribution for the brighter asteroids $[B(1,0) < 11]$ may be compatible with a collision mechanism; this is a surprising conclusion.

Arrhenius and Alfvén[53] make introductory remarks on jetstream theory (also see Alfvén[54]) and on the application of studies of the Moon and meteorites to those of asteroids. Sustained jetstream accretion is discussed by Giuli[55] and the formation of comets by Vanýsek.[56] A mechanism for chondrule accumulation is proposed by Whipple.[57]

INTERRELATIONS WITH COMETS

The distinction between asteroids and comets is made, at the telescope, on the basis of visibility of a coma. Marsden[58] concluded that asteroid 944 Hidalgo may be an extinct cometary nucleus. The same has been surmised for 1566 Icarus. Nongravitational forces, in this case the ones that are presumably caused by the outgassing of the cometary nucleus, and the interrelations of comets and asteroids, are discussed by Marsden and by Sekanina.[59]

Some of the Mars-orbit crossers may be extinct nuclei of short-period comets, Icarus is an example, whereas a more asteroidal group has Geographos as the example. Characteristics of asteroids with $q \leqslant 1.15$ AU are shown in table II of Marsden and their observational status is given in table I of Roemer.[60] The orbits of the Apollo asteroids may not be stable whereas the ones crossing the Mars orbit but not that of Earth appear to be stable in terms of the age of the solar system. (See Williams.[61]) Their dynamical lifetime is limited by collision with and close approach to Earth, Mercury, Venus, and Mars. Their lifetime as live comets, wherein they emit gases to form envelopes and tails, is determined by solar radiation. The rate of evaporation and the dimensions of the nuclei are also factors in this lifetime, which is estimated to be less than 10^4 yr. Dynamically, however, the lifetime may be 10^4 times longer. This could mean that the space inside Jupiter's orbit is filled with the remnants of 10^4 to 10^5 extinct comets for every live comet.

A basic question, debated at the colloquium, is to what extent the meteorites originate from the common asteroids, from Apollo asteroids, or from the comets.[62] Anders[63] argues that only 10 percent of the asteroids can be parent bodies of the meteorites and that these are the ones with high

[50]See p. 249.
[51]See p. 257.
[52]See p. 263.
[53]See p. 213.
[54]See p. 315.
[55]See p. 247.
[56]See p. 465.
[57]See p. 251.
[58]See p. 413.
[59]See p. 423.
[60]See p. 644.
[61]See p. 177.
[62]See p. 447.
[63]See p. 429.

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eccentricity. In connection with this problem, the origin and properties of meteors were also discussed.[64]

SMALL PARTICLES

The mass range of small particles at distances between 0.1 and 30 AU is estimated to be from 10^{-12} to 10^2 g. Whipple (1967) has estimated that the total mass of the interplanetary dust is about 2.5×10^{19} g (for comparison, Ceres' mass[65] is 1.2×10^{24} g); the dust cloud is completely replenished on a time scale of about 1.7×10^5 yr, and this requires that about 2×10^{14} g/yr has to be added. We get into the problem of the origin of the zodiacal cloud where the main question is whether these particles come from the comets or from the asteroids, or both. Previous knowledge of small particles, their occurrence and physical properties, is based primarily on Earth observations of meteoroids, comets, asteroids, and the zodiacal and counterglow light. (The word gegenschein, incidentally, has been replaced by counterglow throughout this book.) The counterglow measures have been taken to derive an upper limit to the debris in the asteroid region. The measures of meteoroid flux (number of particles per unit time) have been made by visual, photographic, and radar observations from the ground and by experiments in sounding rockets, satellites, and space probes. None of these observations measure meteoroid flux as a function of mass directly. Light intensity is the usual parameter observed from the ground. It is interpreted through empirical relations from other data and by theory to determine meteoroid mass and velocity distribution. The best information to date comes from photographic observations. The meteor population so determined is subject to error because of several limitations in the data: Only Earth-crossing meteoroids are observed, a restricted range of masses is covered, conversion of luminosity to mass is uncertain, and the meteoroid composition is not well defined. The estimated mass range of the photographic meteors is 10^{-3} g or larger. The velocity of meteoroids can be obtained by reflecting a radar beam from ionized meteor trails. Interpretation of these data requires a theoretical relation between meteor ionization and mass. Because of selection effects, however, radar observations are considered less reliable than photographic measures. The estimated mass range for the radar measures is 10^{-6} to 10^{-2} g.

Acoustic impact and penetration sensors[66] on space-borne missions measure some product of mass and velocity. Penetration sensors probably give a more accurate description of meteoroid flux than either photography or radar. But the interpretation of physical damage to the sensors is subject to errors in the conversion from sensor thickness to meteoroid mass. There remain unresolved problems in the interpretation of the acoustic impacts also.

Surface brightness of the zodiacal light[67] is measured as a function of the angular distance from the Sun. The size distribution deduced from these data is

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[64]See p. 395.
[65]See p. 33.
[66]See pp. 366 and 607.
[67]See pp. 377 and 363.

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usually in vast disagreement with distributions determined by other techniques because different assumptions have been made. Nevertheless, recent spatial densities from penetration satellites, when extrapolated, are consistent with the zodiacal light results.

The large meteoroids ranging in mass from a few kilograms to 10^6 kg may be of asteroidal origin. It is difficult to derive the meteoroid flux from "falls." The flux value depends on the probability of seeing the "fall" and establishing the relation between the mass found and the original mass. Both cometary and asteroidal meteoroid orbits contain selection effects. The photographic measures show two peaks in a typical distribution relative to Earth. The second peak is attributed to meteoroids in retrograde orbits because their higher rate of entry is more easily detected than the slower moving, direct orbits. This selection effect distorts meteor numbers in both distance and velocity and is inherent in the photographic technique. Among the average velocities so determined are 20 km/s by Dohnanyi (1966), 17 km/s by Kessler (1969) for a gravitational Earth and 15 km/s for a nongravitational one, 19 km/s by Dalton (1965), 22 km/s by Whipple (1963), and 30 km/s by Burbank et al. (1965). Radar measurements do not exhibit the bimodal shape of the velocity distribution of the photographic measures. The high-velocity peak is not attained because the more numerous small meteors have a diffuse, ionized wake. Before removing selection effects, the investigators at the Smithsonian Astrophysical Observatory get a higher average velocity from radar measurements.

Kessler computes the probability of finding an asteroid at a given distance from the Sun. He has also flux levels for calculating the hazard to interplanetary flight; he gives the flux for interplanetary missions as 10^{-16} g/cm^2/s. Near Earth, protection from 0.02 g particles is required, although encounters with particles as large as 200 g are possible. Kessler has used the counterglow to place an upper limit on the spatial density of the asteroidal debris and he gives the flux measured by Pegasus and Explorer satellite penetration experiments as reported by Naumann as the best estimate. The density of debris may be enhanced in the asteroid belt, but at 2.5 AU the lower velocity causes the penetration flux to be comparable to that at Earth. (See also the paper by Whipple.[68])

According to Öpik (1968), the origin of those centimeter- to meter-size stony and nickel-iron fragments of interplanetary stray bodies, which have survived the passage through Earth's atmosphere and are now preserved in museums, is at present most commonly ascribed to the asteroid belt. The Lost City meteorite (McCrosky, 1970), whose orbit was calculated from photographic observations to have an aphelion of 2.35 AU, supports this assumption. If indeed the collision probability in the asteroid belt is high enough, a large number of fragments of all sizes result. With an orbital change, presumably obtained in the collision, these might be diverted to Earth's space.

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[68]See p. 389; Kessler's paper is on p. 595.

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Öpik (1968) discussed the statistics of inclination and eccentricity for several classes of small bodies. The statistics of true meteorite orbits are very incomplete because of the difficulty of obtaining satisfactory observations. The existing evidence shows that when the meteorite orbits are compared to belt asteroids and the ones that cross Mars' orbit, they have inclinations too small for their high eccentricities. The Mars and belt asteroids, on the other hand, have average eccentricities that are too small for their corresponding inclinations. Absence of dilution (equipartition) among the Mars-orbit-crossing asteroids implies insignificant perturbations during the age of the solar system.

The periodic comets set a lower limit to meteorite debris input. Their orbital elements have remarkable similarity and their repeated revolutions in a short period must make a considerable contribution to the debris in the solar system. This may even exceed that from the "almost parabolic" members of the cometary cloud that are not periodic; these surround the solar system. For meteoroids it is worth noting that because of their ablation and breakup in the atmosphere, the low-velocity objects are strongly favored by the selection process. But, for the fireballs this selection effect does not work and their low relative velocities cannot be explained solely by this means; they may form a real, physically unique population.[69]

LAUNCH VEHICLE AND PROPULSION REQUIREMENTS FOR ASTEROID MISSIONS

A program for exploration of an asteroid may be as important as exploration of the planets in order to study a primitive stage in the development of the solar system. As an aside, the satellites of Mars, Phobos and Deimos, comparable in size to asteroids, also are interesting objects in their own right;[70] Hills[71] made the prediction that few impact craters will be found on the satellites of Jupiter. A great debate[72] ensued over the timing of asteroid missions as there are so many preparatory ground-based studies still to be performed.

A flight to a near asteroid might be a flyby,[73] a rendezvous,[74] an orbiter, or a sample-return[75] mission. The mission might involve a man[76] or it might be completely automated. The precise launch vehicle and propulsion requirements will vary as a function of the mission objectives and the weight of the scientific package required to obtain the objectives. Some of the planning aspects for an asteroid mission are reviewed[77] and a specific mission is described.[78] A few examples of scientific experiments in the Pioneer program are reviewed[79] and a beginning with specific suggestions was made.[80]

The difficulty with all ground-based observations of the asteroids is the lack of resolution on the surface so that the need is obvious for flyby missions to

[69]See p. 447.
[70]See p. 399.
[71]See p. 225.
[72]See pp. 473 and 479.
[73]See p. 527.
[74]See p. 503.
[75]See p. 513.
[76]See p. 539.
[77]See pp. 489 and 561.
[78]See p. 543.
[79]See pp. 607, 617, and 633.
[80]See p. 561.

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take detailed pictures and to make photometric and polarimetric measurements over a wide spectral range. The range of phase angle attained during a flyby is much greater than that from Earth. A space-probe landing should be instrumented to study the surface in detail and collect samples that give precise information on the structure and composition of the asteroid.

An unmanned flyby of a near asteroid would be the least demanding of the various asteroid missions and could be accomplished with presently available launch vehicles (e.g., Atlas/Centaur) and a Pioneer-type spacecraft[81] weighing approximately 200 kg. The flight time for this mission would be approximately 100 days and the communication distance at encounter would be about 0.5 AU. This flyby mission would have a 40 day launch window and would be a relatively inexpensive space mission.

The unmanned rendezvous and/or orbiter mission[82] would require additional propulsion capability beyond that indicated for a flyby. This increased propulsion capability could be supplied by either a high-performance chemical-propulsion stage or a solar electric-propulsion[83] system utilized as the final stage for the Atlas/Centaur, Titan IIIC, or Titan IIID/Centaur launch vehicle. An asteroid rendezvous mission to Icarus or Geographos could be accomplished using a solar electric-propulsion system optimized for use with a Titan IIID/Centaur launch vehicle. The net spacecraft mass for a rendezvous with Geographos would be 1800 kg. The departure date for this Geographos rendezvous could be in August 1977 and the related flight time would be about 650 days. The reference power for the solar electric-propulsion system would be 40 kW and rendezvous would take place at about 1.1 AU. The departure date for an Icarus rendezvous could be in September 1978 with a flight time of some 670 days.

An asteroid rendezvous mission[84] is a relatively high-energy mission and would cost an order of magnitude more than a simple flyby of either Icarus or Geographos. An unmanned sample-return mission[85] would require a launch vehicle of even higher performance than for the rendezvous mission (e.g., Saturn V with appropriate upper stage). The amount of scientific information that could be collected from such a mission would, of course, be considerably greater in kind and quantity of data obtained.

A manned expedition[86] to a near asteroid would undoubtedly benefit from the availability of a space nuclear-power capability. A nuclear electric capability could be used to provide the power needed to propel an electric-propulsion spacecraft and/or to meet the onboard power requirements for the astronauts and their scientific instruments. Thermal nuclear rocket propulsion, when available, should provide an increase in performance over that presently obtainable from a comparable chemical stage. This increased performance would be most useful in accomplishing a manned exploration mission to an asteroid.

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[81]See p. 612.
[82]See p. 503.
[83]See p. 489.
[84]See p. 503.
[85]See p. 513.
[86]See p. 539.

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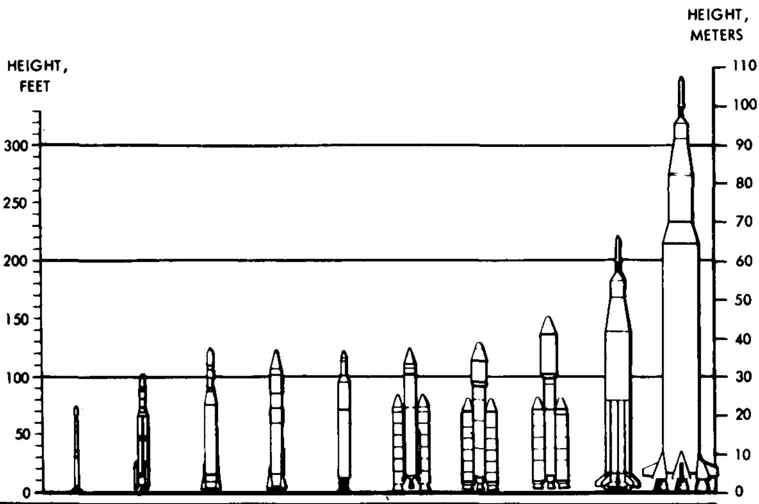
Any mission to an asteroid in this decade will probably use the current U.S. space transportation system. (See fig. 1.) At the end of this decade, however, if an operational space shuttle is available, missions to selected asteroids could be accomplished in part using this potentially cost-effective mode of transportation. When the space shuttle mode of transportation is used, appropriate upper stages will be required to operate in conjunction with the shuttle to accomplish an asteroid mission. These upper stages might be presently available ones (e.g., Centaur, Agena, Transtage, etc.), or entirely new stages designed to be used with the space shuttle (e.g., space tug, versatile upper stage, etc.). Mission requirements and the availability of an operational shuttle will dictate the appropriate transportation system to be used in accomplishing a mission to an asteroid.

In summary, it is seen that the initial mission to an asteroid might be a flyby of Eros or Geographos. This flyby could be followed by an automated orbiter or rendezvous mission making television or spin-scan imaging and photopolarimetric reconnaissance of the asteroidal surface. The orbiter could be appropriately followed by an automated sampling and return to Earth of selected asteroidal rocks. This automated mission could be followed by a manned mission to a suitable asteroid. Such a mission approach would represent a logical step-by-step sequence of exploration.



VEHICLE	SCOUT	LONG TANK TAT DELTA	ATLAS-AGENA D	ATLAS-CENTAUR	TITAN IIIB* AGENA	TITAN IIIC	TITAN IIID	TITAN IIID CENTAUR	SATURN IB	SATURN V
PAYLOAD-KG (185 KILOMETERS)	180	1130	3810	5100	4100	12 200	13 600	15 900**	18 600	118 000
PAYLOAD-KG (MARS-VENUS)	-	230	320	730	410	1270	-	3860	-	36 300

PAYLOAD VALUES ARE FOR EAST LAUNCH FROM ETR EXCEPT FOR SCOUT WHICH IS FROM WALLOPS
*NO LAUNCH FACILITIES AVAILABLE FOR TITAN IIIB AT ETR
**CENTAUR STAGE REQUIRES STRUCTURAL MODIFICATION FOR 15 900 KG PAYLOAD
PRESENT CAPABILITY DUE TO STRUCTURAL LIMIT IS 6360 KG

Figure 1.–Current U.S. space transportation system.

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Toward the end of the book, the topics return to the ones with which it started—ephemerides[87] and telescopic observation[88]—but this time more specifically having the future needs of the space program in mind. Finally there is a summary of the colloquium in terms of what appears urgent and interesting to do in the future.[89]

SOURCE BOOKS ON ASTEROIDS

Astronomical textbooks generally have only a few pages on minor planets; the asteroids are treated somewhat as "vermin of the sky." To a stellar astronomer who gets trails made by moving asteroids on his long-exposure plate they, indeed, must be a nuisance. Incidentally, space junk is also becoming an increasing problem;[90] an extension of the *National Geographic-Palomar Atlas* to the Southern Hemisphere, for instance, will be seriously hampered by long trails.

The new book by Hartmann (1972) has a good review chapter on asteroids. Krinov (1956), Watson (1962), and Roth (1962) have written brief semipopular reviews; Roth's historical section is a delight. There are articles written by Harwood (1924) and Arend (1945), but they are out of date. As inaccessible to readers in the United States as Arend's writing is the book by Putilin (1953), which is not too serious because it is mostly a review of certain procedures in positional work.

A semipopular introduction to the Trojan planets has been made by Wyse (1938) and Nicholson (1961). Short articles on asteroids have been written by Nicholson (1941), Porter (1950), Struve (1952), Miller (1956), and Ashbrook (1957). A splendid article on asteroids was written by Richardson (1965). The literature on asteroids and comets was reviewed recently (Gehrels, 1971). Summary reports of this colloquium have been made by Matthews (1971) and Hartmann (1971).

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[87]See p. 639.
[88]See p. 643.
[89]See p. 653.
[90]See p. 649.

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