CHAPTER ONE

The Minor Bodies of the Solar System

It is widely believed that about 4600 million years ago our solar system suffered a chain of disruptive events associated with condensation, intense heating, melting and eruptions, and that such events never occurred again with the same intensity. Throughout the remainder of cosmic history, the primary planetary and meteoric bodies are assumed to have cooled more or less homogeneously. Mutual collisions have increased their number and reduced their average size. On the other hand, through gravitational pull of the planets, a large number of the smaller bodies have already been eliminated in crater-producing events, while a few have been captured as satellites of the larger planets, Jupiter, Saturn, Uranus, Neptune and Mars.

It is now well known that the larger bodies of our solar system, Earth, Mars and Moon, are scarred to a considerable degree by craters which on Earth are called astroblemes (Dietz 1963). The fact that the smaller bodies are also severely damaged, or perhaps are themselves fragments, was proved when in November 1971, the U.S. spacecraft Mariner 9 succeeded in relaying the first detailed views of any natural satellites in the solar system except the Moon. Photographed from a distance of 5500 km, Mars' two satellites, Phobos and Deimos, were found to be irregular, angular objects. The roughly potato shaped Phobos is 26 km long and 21 km wide and displays at least a dozen impact craters. The biggest depression, about 6 km across, probably indicates where a large fragment broke off during an asteroidal collision. The morphology of these tiny satellites not only suggests that they are very old but also that they possess considerable structural strength.

On January 3, 1970, at 2014 local time, a fireball brighter then the full moon descended over Oklahoma and caused sonic booms that were heard over a 100 km long zone below the line of flight. The fireball was photographed by the Prairie Network and the analysis of the trajectory indicated that it had produced some sizable meteorites. A careful search resulted in the recovery of four fragments of a stone meteorite totaling 17 kg. The successful recovery was immediately followed by extensive studies of the mineralogy, chemistry, and isotope chemistry, with the result that the Lost City meteorite is today perhaps our best known from all points of view (McCrosky et al. 1971; Clarke et al. 1971b).

The entire range of basic problems in meteoritics may be divided into two main parts. One comprises the study of the circumstances of meteorite falls on the Earth and is closely associated with the astronomical interpretation of the orbits of meteoroids and minor planets of our solar system. The other is mainly concerned with the physical-chemical study of meteoritic matter itself and with the solution of the problem of the origin of meteorites and the size of the parent bodies. A start will be made by examining some basic aspects of the solar system. We will then turn to the physics of the meteorite fall and eventually examine the fallen meteorite. Finally, in the main part of the handbook, the individual iron meteorites will be described in alphabetical order.

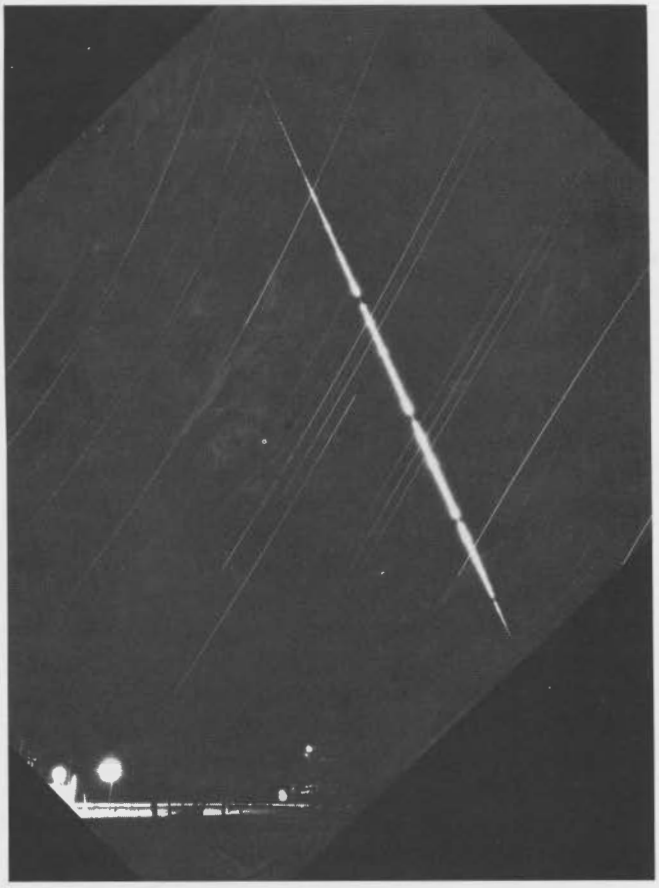

Figure 1A. The Lost City Fireball. A photograph taken at the Hominy, Oklahoma, camera station, operated by the Smithsonian Astrophysical Observatory, showing the spectacular meteor descending the eastern sky on January 3, 1970. It remained visible for nine seconds as may be deduced from the series of dashes into which the trail was automatically broken by a chopping shutter. Star trails of Taurus, Orion, and Canis Major cross the background. (Courtesy R.E. McCrosky.)

Figure 1B. Lost City (U.S.N.M. no. 4848). Reconstruction by Roy S. Clarke, Jr. of the mass. The 9.8 kg main mass was found on January 9th after analyzing the trail in Figure 1A; three other masses were found later. Lost City is an olivine-bronzite chondrite of a common type (H5), containing about 15% (by weight) kamacite, 1.5% taenite, 6% troilite and 0.5% chromite (Clarke et al. 1971b; S.I. neg. 1636c.) Scale bar 5 cm.

Asteroids

When comparing the orbits of the planets, there appears to be an exceptionally large gap separating Mars and Jupiter. At an early date Kepler suggested that a planet might be found in this region of the solar system, and in 1772 a German astronomer, J.E. Bode, publicized what has later become known as Bode's rule (Jaki 1972). According to this, the distances, in astronomical units (A.U.), of the successive planets from the Sun are obtained by adding 0.4 to each of the following numbers: 0, 0.3, 0.6, 1.2, 2.4, 4.8, etc.; see Table I. The discovery of Ceres, in 1801, appeared to fill the gap in the system, but by 1807 three other similar bodies (see Table 2) had been discovered with orbits in the same region. These also happened to be the largest of all asteroids and their orbital elements are typical for the majority of asteroids. Chladni (1819: 412) discussed the then known four asteroids as possible sources of meteorites, and he expected more asteroids to be found.

This assumption proved to be correct. By 1800, 280 had been discovered and subsequently, after the introduction of the systematic photography of the skies, the number increased sharply. Today, 1779 are numbered (Ephemerides, Chebotarev, 1971) and accurate orbits have been calculated. There are in addition, however, a large number of smaller asteroids which usually have only been seen and identified once, at the time of their discovery. According to the recent extensive photographic survey conducted at the Palomar and Leiden observatories, the total number of asteroids that become brighter than photographic magnitude 20.4 at mean opposition is about 40,000; see Figure 2. The steady growth in numbers as that magnitude limit is approached makes it very likely that the sequence continues down to bodies as small as meteorites and dust grains.

The great majority of the asteroids move in orbits which lie within the range of 2.1 to 3.5 A.U. from the Sun, so that the approximate average of 2.8 is in agreement with the requirement of Bode's rule. See Table 2. The orbital periods vary between 3.3 and 9 years, with an average of 4.5 years. Most eccentricities lie between 0.02 and 0.3, with an average of 0.15. The orbital inclinations range from 0° to 35° with an average of about 10°. They all move in their orbits in the same direction as the major planets, i.e., direct or counterclockwise.

The large asteroids, such as Ceres, Pallas and Vesta, are nearly spherical, but many others have irregular, angular shapes suggesting that they are secondary collision fragments. The angular shape is indicated by the large variation in brightness observed as the asteroid rotates and reflects sunlight from different regions on its surface. See Figure 3 or McCord et al. (1970). From the fluctuations in brightness of Eros, for example (table 3), it has been estimated that it measures about 24 x 8 x 8 km in three perpendicular directions. The masses of even the largest asteroids are too small to be determined by conventional methods. Rough estimates based upon the observed, not too precise dimensions, and on the assumption that the density is comparable

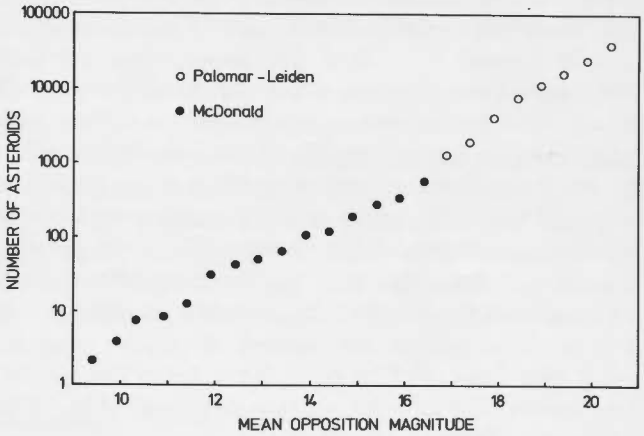

Figure 2. Each point represents the cumulative number of bodies in the entire asteroid ring. (Adapted from a diagram by C.J. van Houten in Astronomy and Astrophysics Supplement, Vol. 2, Springer Verlag, 1970.)

to that of the Moon, 3.3 g per cm^3, leads to a figure of 7.6×10^{17} tons for Ceres, or about one percent of the mass of the Moon. The total mass of all asteroids is estimated to be about 3×10^{18} tons (Putilin 1952).

Among the relatively few asteroids whose orbital characteristics are outside the range given above are a number which have attracted special attention; see Table 3. *Hidalgo* has the largest orbit known, almost touching the orbit of Saturn. It was possibly deflected into its present orbit relatively recently as the result of a collision with another minor planet (Marsden 1970). *Eros* was the first asteroid found to cross inside the orbit of Mars and use was made of this to calculate a much improved value for the Earth-Sun Distance, the astronomical unit. *Kepler* and *Amor* belong to a small family of asteroids with Mars-crossing orbits. *Apollo, Hermes, Ikarus* and *Geographos* are members of the *Apollo* family of eight asteroids with high eccentricities and Earth-crossing orbits. The Amor and Apollo asteroids are very probably former normal asteroids which were perturbed into their present orbits by Mars.

The known asteroids are no doubt accompanied by a huge number of smaller fragments not large enough to be observed from Earth. The 80 cm telescope on board Skylab may, however, have a chance to identify some of the smaller asteroids since the optical resolution is much improved outside our atmosphere. As the asteroidal orbits

Table 1 – The Planets

Planet and date of discovery	Bode's Rule 1771	Mean distance from Sun, A.U. a	Eccentricity e	Inclination to ecliptic i	Sidereal period, years T	Diameter km	Mass tons	Mean density g/cm^3
Mercury	0.4	0.39	0.21	7°	0.24	4 800	$0.32 \cdot 10^{21}$	5.4
Venus	0.7	0.72	0.007	3°24′	0.62	12 200	$4.87 \cdot 10^{21}$	5.1
Earth	1.0	1.00	0.017	0°	1.00	12 740	$5.98 \cdot 10^{21}$	5.52
Moon	–	–	0.055	5°9′	–	3 475	$0.074 \cdot 10^{21}$	3.34
Mars	1.6	1.52	0.093	1°51′	1.88	6 750	$0.64 \cdot 10^{21}$	4.1
Ceres 1801	2.8	2.77	0.076	10°37′	4.60	760	$0.76 \cdot 10^{18}$	3.3 ?
Jupiter	5.2	5.20	0.048	1°18′	11.86	138 000	$1.90 \cdot 10^{24}$	1.33
Saturn	10.0	9.54	0.056	2°29′	29.46	114 000	$0.57 \cdot 10^{24}$	0.71
Uranus 1781	19.6	19.18	0.047	0°46′	84.01	48 000	$87 \cdot 10^{21}$	1.55
Neptune 1846	38.6	30.06	0.009	1°46′	164.79	45 000	$103 \cdot 10^{21}$	2.47
Pluto 1930	76.6	39.5	0.247	17°8′	247.7	6 000	?	3 ?

All distances are in astronomical units, A.U. One A.U. equals the mean Sun-Earth distance, i.e., $149.6 \cdot 10^6$ km.

Table 2 – Some Normal Asteroids, or Minor Planets

Planet	Discovered	Mean distance from Sun, A.U. a	Eccentricity e	Inclination to ecliptic i	Sidereal period, years T	Mean opposition magnitude	Absolute magnitude	Estimated diameter km
1 Ceres	1801	2.77	0.076	10°37′	4.60	7.6	4.1	760
2 Pallas	1802	2.77	0.234	34°48′	4.60	8.6	5.2	490
3 Juno	1804	2.67	0.259	13°0′	4.34	9.7	6.4	190
4 Vesta	1807	2.36	0.089	7°8′	3.63	6.8	4.3	515*
5 Astraea	1845	2.58	0.185	5°20′	4.14	11.0	8.0	120
6 Hebe	1847	2.43	0.203	14°45′	3.78	9.4	6.7	230
41 Daphne	1856	2.76	0.270	15°52′	4.59	11.8	8.3	100
279 Thule	1888	4.28	0.032	2°20′	8.80	15.5	9.8	50

*Veverka (1971)

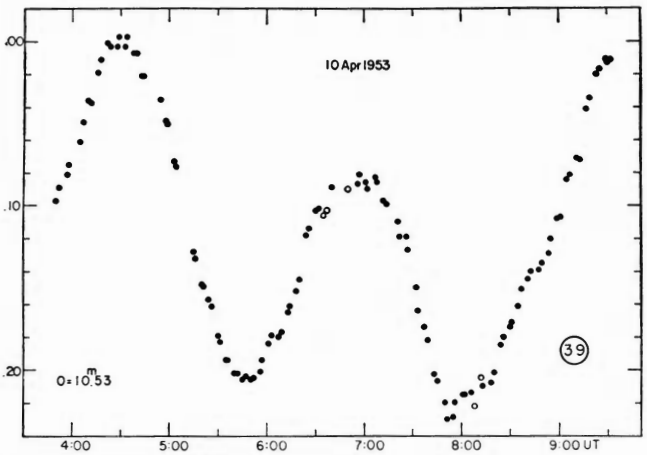

Figure 3. Photoelectric light curve of the asteroid Laetitia (No. 39). From observations like this a period of 5 hours 11 minutes was derived. (From Watson 1956.)

shift and fluctuate, due to collisions and gravitational pull from Mars and Jupiter, the fragments must from time to time come into a collision course with Earth (Anders 1965a; Hartmann & Hartmann 1968; McAdoo & Burns 1973). Such objects, if recovered after the collision, are meteorites by definition. It is now widely believed that a large percentage or perhaps all of the known meteorites are of asteroidal origin. Anders (1964; 1971a, b, c), in particular, has considered the various problems associated with this interpretation. He concluded that most meteorites come from a small number (6 to 11) of parent bodies, with radii mainly between 100 and 300 km. The most likely sources are believed to be seven asteroid families with semimajor axes between 1.9 and 2.8 A.U. and with eccentricities sufficiently high to permit their collision debris to cross the orbit of Mars.

Comets

While asteroids have only been known for a relatively short period and were dependent upon telescopes and, later, photography for their discovery, comets have been known from ancient times. Particularly good reports are to be found in Japanese and Chinese annals. In Europe it appears that the medieval astronomers were not interested because they believed comets to be phenomena in the atmosphere of the Earth. Tycho Brahe found, however, that the comet of 1577 had the same position among the stars when seen from Prague and from his observatory, Uranienborg, on the island of Hveen outside Copenhagen. He estimated the distance of the comet to be at least six times greater than the distance to the Moon and consequently concluded that comets were truly astronomical objects. Newton created the mathematical apparatus for determining the orbital elements. In 1705 Halley calculated that the comet from 1682 which was named after him had a sidereal period of about 76 years and predicted its reappearance in 1758. Later, archival studies have shown that the same comet had been observed and registered in European annals in 1531 and 1607, and in Asiatic annals as early as 240 B.C. Halley calculated orbits for 24 bright comets. Today the orbits of five or six hundred comets have been computed with reasonable accuracy but these constitute only an insignificant fraction of the whole population of comets.

The comets with well known orbital elements fall into two categories. In the larger one, comprising about eighty percent, the orbits are highly eccentric and the periods are long, many of them being several hundred and possibly up to a million years. These long-period comets have highly inclined orbits and roughly half of them revolve about the Sun in direct orbits, like the planets and asteroids, while the other half display retrograde orbits. Because of uncertainties in their orbits, – the eccentricities are very close to 1, and slight variations mean either elliptic ($e < 1$), parabolic ($e = 1$) or hyperbolic orbits ($e > 1$) – the periods of the long-period comets are not well known. However, it is believed that e is usually smaller than one, so that comets do belong to our solar system; for a major part of their life, though, they are in parts of their orbits well beyond Saturn and even Pluto.

The smaller category comprises ninety-four short-period comets, half of which have been seen more than

Table 3 – Some Anomalous Asteroids

Planet	Discovered	Mean distance from Sun A.U. a	Eccentricity e	Perihelion A.U. q	Aphelion A.U. Q	Inclination to ecliptic i	Sidereal period, years T	Mean opposition magnitude	Absolute magnitude	Estimated diameter km	Closest approach to Earth, A.U.
944 Hidalgo	1920	5.82	0.66	2.00	9.6	42°30′	13.9	19.3	12.0		1.0
433 Eros	1898	1.46	0.22	1.13	1.80	10°50′	1.76	11.5	12.4	24X8X8	0.17
1134 Kepler	1929	2.68	0.47	1.43	3.94	15°2′	4.40	18.7	15.4		
1221 Amor	1932	1.92	0.44	0.85	2.99	11°55′	2.66	20.4	19.2	5	0.11
– Apollo[1]	1932	1.47	0.57	0.65	2.3	6°20′	1.78	19	18	1-2	0.02
– Hermes[1]	1937	1.64	0.47	0.68	1.9	6°13′	2.10	20	19	1-2	0.005
1566 Icarus	1949	1.08	0.83	0.19	1.97	23°0′	1.12	12.4	17.1[2]	1.5[2]	0.04
1620 Geographos	1950	1.24	0.33	0.41	2.07	13°20′	1.38	13.4	16.0	3X1	

1) Apollo and Hermes were discovered when they approached Earth closely and were named because of their unusual orbits. They were not numbered because their orbital elements were not sufficiently accurate for a prediction of their movements. They have not been seen since their discovery.

2) Veverka & Liller 1969

once. These have definitely elliptical orbits about the Sun, and their orbital periods range from 3.3 to roughly 200 years. While most of them display direct orbits, seven have retrograde orbits, i.e., the inclination is above 90°. Halley's comet and the Tempel-Tuttle comet are two such cases; see Table 4.

As a comet approaches to within 1 or 2 A.U. of the Sun, it may develop an observable tail, which is directed away from the Sun (Wurm 1968; Wurm & Rahe 1969). Because of the rapid motion of the comet, the tail generally appears to be curved. Many comets are undoubtedly difficult to recognize or may even go unobserved if their perihelia lie further out than 2-3 A.U. There is a story that when Baade discovered Hidalgo in 1920 (Table 3), he could not decide whether to call it an asteroid or a comet and finally selected the former appellation mainly because he thought that in that case observers would be more likely to pay attention to it. Telescopic observations usually reveal the comets as nebulous luminosities which have an exterior fuzzy coma and an interior, more substantial, nucleus. The size of the nuclei is estimated to range from 1 to 25 km, with an average value of only a few kilometers.

The mass of even the heaviest comet is too small to produce a detectable perturbation in the orbit of any adjacent celestial body. Estimates indicate that the mass of an average comet is comparable to that of the smaller asteroids, i.e., roughly 10^{-9} of Earth's mass. The total number of comets, up to an including bodies with extremely eccentric orbits, with aphelia of 1200 A.U., is estimated to be about 10^{11} (Porter 1952). In spite of this enormous number, the total mass of the comets may only be of the order 10^2 that of Earth.

Whipple (1950; 1963) proposed a theory for the cometary structure which has been widely accepted and discussed (see e.g., Donn 1963). The nucleus is very cold and consists of a conglomeration of solidified methane, ammonia, carbon dioxide and water. Within these "ices" there are inclusions of particles of minerals, ranging from microscopic sizes to walnut-size or perhaps even meter-size. The total mass of the inclusions is perhaps one-fourth of the whole mass of the comet. As the comet approaches the Sun, the ices vaporize and the resulting gases produce the coma. At distances of 1 or 2 A.U., the pressure of solar radiation and the impact of the electrically charged particles in the solar wind blow part of the coma away to form the comet's tail. Calculations indicate that about 0.5% of the mass of a comet is lost by vaporization of the ices and dispersion of the mineral matter in the nucleus upon each approach to the Sun. A point is eventually reached when the comet disappears as a result of complete disruption, rather than of gradual attrition. In general, a comet may not be expected to survive more than a hundred or so passages through its perihelion (Sekanina 1969).

In Table 4, Biela's comet represents an example of a vanishing comet. It was first observed in 1772 and then reidentified in 1815, 1826, 1832 and 1845. About that time it split into two bodies which were observed in 1852

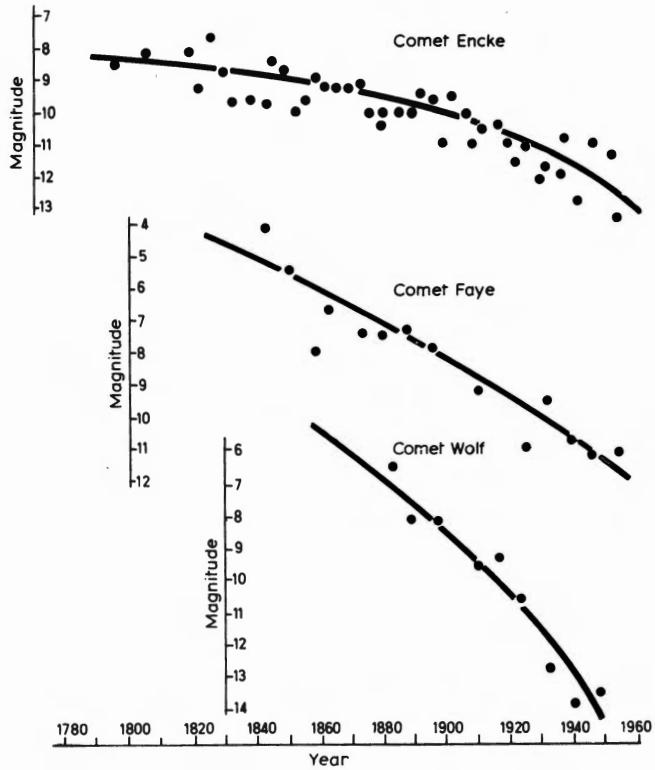

Figure 4. Estimates of the absolute magnitudes at each return of three periodic comets. Comet Encke seems to be a remarkably stable object, since most periodic comets fade as quickly as Faye or Wolf. (From Hindley 1971.)

and 1859. Renewed observations at the following oppositions failed to identify the comet; instead, in 1872 and 1885, eminent meteor showers appeared, and even an iron meteorite, Mazapil, page 808, was observed to fall. Unfortunately the records of the fall are insufficient to prove beyond doubt that Mazapil was originally part of Biela's comet, but the circumstantial evidence is in favour of it. Meteors which are probably remnants of Biela's comet have occasionally been observed and have been photographed and thoroughly discussed by Hawkins et al. (1959).

The famous Siberian explosion which occurred near Tunguska River (60°54′N, 101°57′E) on June 30, 1908, has puzzled the whole world for two generations. Up to the 1960s, it was generally assumed that an iron meteorite caused the explosion (see bibliography in Hey 1966: 493, 558), but the Russian scientists now favor the theory first proposed by F.J.W. Whipple (1930) that it was due to a comet. In numerous papers, mainly Russian, Kulik (1921; 1922), Vosnessenski (1925), Astapovich (1933), Krinov (1949), Levin (1954), Fesenkov (1964) and others have accumulated facts and ideas, based upon several difficult and costly expeditions to the remote area.

The phenomena associated with the explosion, such as the destruction of the forest within a radius of about 20 km, the luminescent night clouds over Northern Europe, the retrograde motion of the impacting body and the absence of craters and meteoritic material, indicate that the

Figure 5. Photograph from Aalborg, Denmark, towards north on the bright night of August 30, 1908. The rays from the Sun, which is below the northern horizon, are reflected from a particle cloud at an altitude of several hundred kilometers. (Photo by N.B. Buchwald, August 30, 1908, at 11:55 p.m. local time.)

explosion was caused by a rare and hitherto unrecorded phenomenon, namely the collision between a minor comet and the Earth. The cometary nucleus exploded at an altitude of about 5 km, while the cometary tail was decelerated at a very high altitude, probably 400-600 km. The detained dust particles of the tail reflected the direct solar rays at midnight and thus gave rise to the noctilucent sky. The phenomenon was only observed over Russia and Northern Europe, because the cometary tail extended in that direction, away from the Sun at the moment of impact. Only gases and insignificant iron-nickel spherules (< 0.1 mm in diameter) survived the impact; some of these particles have afterwards been isolated by a tedious separation of soil samples. The energy released by the impact has been estimated to be of the order of 10^{22}-10^{23} ergs (10^{15}-10^{16} Joule).

Summaries, with bibliographies, have been published by Astapovich (1940), Buchwald (1961a), Krinov (1966a), and Zotkin (1969). The Academy of Sciences in Moscow has prepared a 35 minute film, edited and translated in 1969 by the Smithsonian Institution; the film shows how the understanding of the event slowly developed towards a cometary interpretation as more and more data accumulated during systematic expeditions and laboratory experiments.

Meteors and Extraterrestrial Dust

A meteor is a light- and ionization-producing phenomenon caused by the interaction of a rapidly moving, small celestial body with the earth's atmosphere. When the streak of light has a luminosity which equals or exceeds that of the brightest planets it is called a fireball.

Cases are known when fireballs have been brilliant enough to illuminate briefly one hundred thousand square kilometers of the Earth's surface. By far the greatest part of the light of a meteor is concentrated around the vaporizing and disintegrating meteoroid, the head; and, as a result, the average bright meteor approximates a moving point of light when seen by an observer. Some luminosity, called the train, may extend behind the head. Train luminosity of short duration, lasting a small fraction of a second, has been called the wake; that lasting considerably more than a second is known as the persistent train. The term meteor trajectory defines the line of motion of a meteor in a three-dimensional coordinate system referred to the Earth. The meteor path is the trajectory as seen by the observer projected on the celestial sphere. The meteor radiant is the point where the meteor trajectory intersects the celestial sphere (Millmann 1963).

Meteors which occur randomly and singly in various parts of the sky are called sporadic. Meteors which recur annually or periodically at the same date(s) and come from the same parts of the sky – i.e., have the same radiant – are called showers. They are named after the constellation from which they seem to radiate. It is well established that several of the best known showers display orbital elements

Table 4 – Some Short-period Comets, or Periodic Comets (P/), and Their Associated Meteor Streams

	Apparitions N	Mean distance from Sun A.U. a	Eccentricity e	Perihelion A.U. q	Aphelion A.U. Q	Inclination to ecliptic i	Sidereal period years T	Associated Meteor Shower: Name	Radiant α	Radiant δ	Max. Day Month	Average Velocity V_∞ km/sec
P/Encke[1]	46	2.22	0.85	0.34	4.1	12°24′	3.30	Taurids	64°	+22°	7.XI	30
P/Pons-Winnecke[2]	16 { 1819 / 1886 / 1951	3.36	{ 0.76 / 0.73 / 0.65	{ 0.77 / 0.89 / 1.16	5.56	{ 10° / 14°30′ / 21°42′	{ 5.6 / 5.8 / 6.1	Draconids	220°	+55°	28.VI	20
P/Giacobini-Zinner	7	3.46	0.73	0.94	5.97	31°	6.42	Draconids	266°	+53°	10.X	23
P/Biela	6	3.53	0.76	0.86	6.19	13°	6.62	Andromedids	25°	+43°	22.XI	16
P/Oterma	4	3.96	0.14	3.39	4.53	4°	7.88	–			–	–
P/Neujmin[1]	3	6.86	0.77	1.55	12.17	15°	17.97	–			–	–
P/Tempel-Tuttle[3]	2	10.33	0.91	0.98	19.7	163°	33.2	Leonids	152°	+22°	15.XI	72
P/Halley[4]	29	17.95	0.97	0.59	35.3	162°	76.0	{ Eta-Aquarids / Orionids	334° / 92°	- 2° / +15°	5.V / 20.X	60 / 66

1) Estimated to transform to an Apollo-like object in the next few hundred years (Marsden 1970).
2) Orbital variations due to Jupiter's influence.
3) Associated with the Leonid showers 1799, 1833, 1866 etc.
4) The first identified periodic comet.

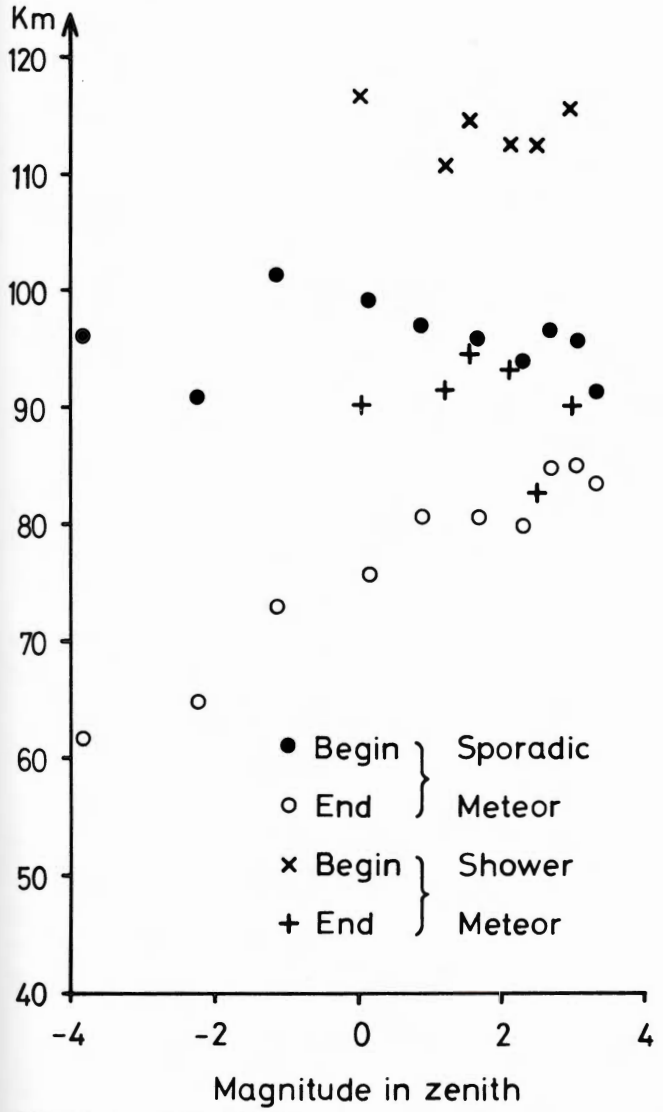

Figure 6. Systematic observations of the first and last appearance of typical meteors. The clear Arizona night sky favored the visual observations made by trained observers. (From Watson 1956.)

similar to some of the short-period comets. Typical examples are given in Table 4. It is commonly inferred that all meteors – including the sporadic – are fragments of comets, released by vaporization of the ices and thereafter occasionally or periodically caught when crossing the orbit of Earth. Apparently about 10% of observed meteors have asteroidal orbits.

Both photographic and radio-echo methods (Sekanina 1970) – based upon the reflection of radio waves from the ionized trail – indicate that meteors begin to appear at heights of 60 to 130 km and that they are visible down to between 40 and 90 km. Bright meteors penetrate much lower than do faint ones, and shower meteors seem to begin and end somewhat higher than do sporadic meteors; see Figure 6. On the average, something like ten meteors per hour can be seen by a single observer (Olivier 1960).

The hourly rate of visual meteors is, however, found to vary during the night by a factor of about two. As early as 1866, Schiaparelli qualitatively explained the higher rate of appearance in the hours after midnight by pointing out that, if meteors are distributed randomly in the solar system, there will be a noteworthy increase of encounters in the direction in which the Earth moves in its orbit. The morning side of the Earth is the side which faces the direction of the Earth's motion and, therefore, it receives a larger number of encounters than does the evening side.

The largest variation in the rate of meteor encounters occurs during the periods of meteor showers. Typical major showers will at their maximum display rates of 50 to 100 per hour. Occasionally, showers have reached for a brief period of time the phenomenal rate of 12,000 per hour, such as was the case for the Leonids in 1833 (Watson 1956: 95).

Calculations by Öpik (1923) and Watson (1956) indicate that perhaps 24 x 10^6 particles, producing visible trails, enter Earth's atmosphere each day. While estimates as to the total mass vary widely, it is generally accepted that the individual meteor particles weigh no more than 1-10 grams (Whipple 1952; 1959; Levin 1956; Öpik 1958b; Millman 1970b; Dohnanyi 1972). The specific gravity is probably between 0.1 and 1, suggesting that the particles are either porous, or loosely compacted aggregates of somewhat heavier minerals.

In addition to the meteor particles, a significant influx comes as invisible dust particles, or micrometeoroids. Various estimates indicate that the Earth thereby daily

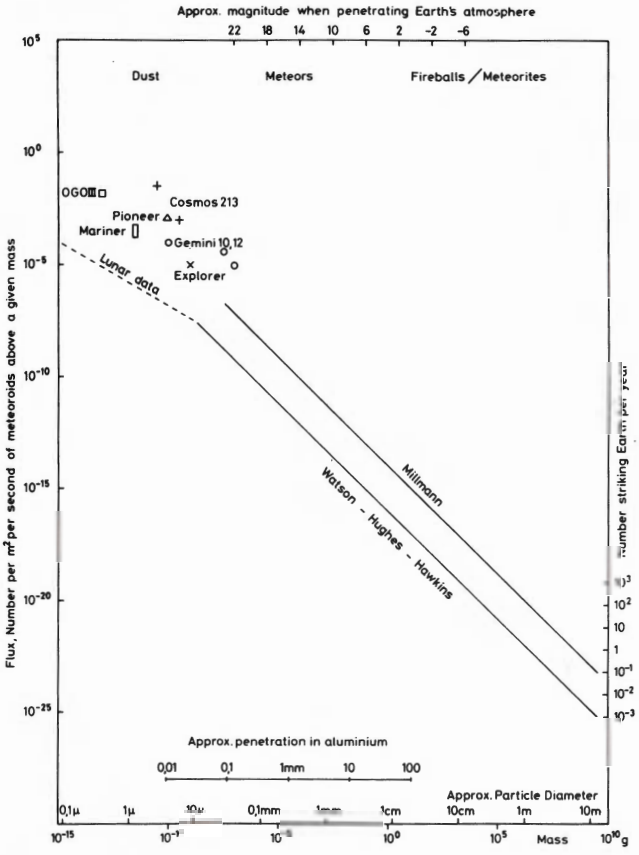

Figure 7. A graph which indicates the approximate particle flux in the solar system near Earth. Data from various sources as indicated.

acquires about 10^6 kg (Millman & McKinley 1963, Table 8; Hawkins 1963; Singer 1969). However, the collection, identification and interpretation of these very small particles pose extraordinary problems, and it has turned out that it may be extremely difficult to arrive at final conclusions as to their origin, see, e.g., the discussion by Bigg et al. (1972).

In an attempt to measure the flux directly, numerous satellites have been equipped with micrometeoroid detectors. Early detectors based on piezoelectric microphones have provided data that were interpreted as if the Earth was surrounded by a rather voluminous dust cloud, comprising particles of masses between 10^{-7} and 10^{-13} g. These results could, however, not be reconciled with the significantly lower (10^{2}) fluxes deduced from photometric measurements of zodiacal light, and Nilsson (1966) has shown that the satellite data probably were in error because the piezoelectric sensors were oversensitive to intrinsic temperature changes on the skin of the satellite.

Qualitative knowledge of the composition of the meteors is derived from the photographic study of meteor spectra from bright meteors above magnitude −1. From the examination of about 250 spectroscopical plates, Millman (1962) concluded that iron was the most common element and was identified in practically every case. In addition, spectra from meteor showers almost always contained sodium, calcium and magnesium as prominent elements. Other elements identified were silicon, aluminum, nickel, chromium, manganese, hydrogen, oxygen and nitrogen. The last three elements may either be due to ionization of the upper atmosphere, or they may derive from decomposition of the organic compounds of carbonaceous chondrites, or they may derive from the "ices" of any cometary particles. The first mentioned nine elements are known to occur abundantly in both stony and iron meteorites, but manganese and, sometimes, chromium are less abundant and, perhaps are associated with bodies which are so frail that they rarely penetrate our atmosphere but completely disintegrate as meteors.

Orbital Velocities and Temperatures

It is probably not altogether out of place to put in a few words here about the celestial mechanics, since it will help in understanding the velocities and temperatures to which the various bodies of the solar system may be exposed. We will also need the velocities when we discuss the meteorite fall – i.e., the collision of a small celestial body with our Earth.

Kepler translated Tycho Brahe's magnificent tables of data into a simple and comprehensive system of curves and rules. Kepler's three laws may be expressed thus; compare Figure 8:

I. Each planet moves in an elliptical path with the Sun at one focus, F (1609).

II. As a satellite moves in its orbit, radius vector, R, joining the satellite's center, m, to the focal point, sweeps out equal areas in equal periods of time (1609).

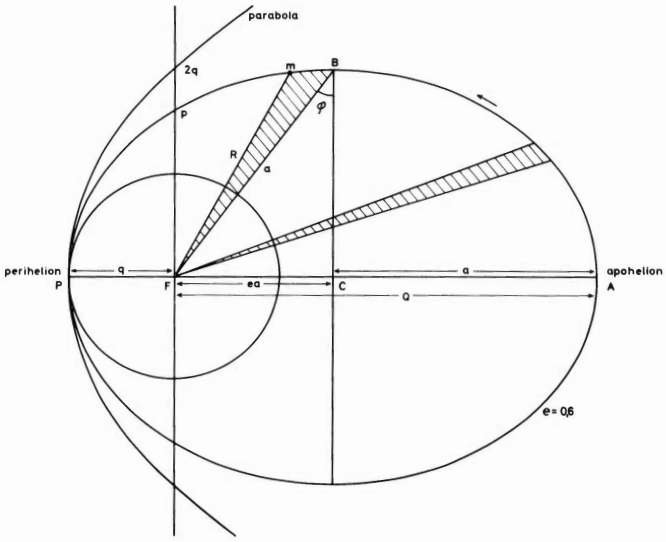

Figure 8. A schematic illustration of a circular, elliptic and parabolic orbit around the Sun which is situated at F. For symbols see text.

III. The square of the sidereal period, T, is proportional to the cube of the semimajor axis, a, of the elliptical orbit, or a^3/T^2 = constant (1618).

The elements of the elliptical orbits are presented in Figure 8. The eccentricity is defined as

$$e = \frac{FC}{PC} = \sin\phi = \frac{p}{q} - 1 \;;$$

also

$$e = \frac{a - q}{a} = \frac{Q - q}{Q + q} \;.$$

The derivation of an expression giving the velocity of a planet – or a meteoroid – at any point in its elliptical orbit is based on the law of gravitation. The mathematical treatment is fairly complicated but the result is relatively simple. If M represents the mass of the Sun in the focal point F, and m is that of a small celestial body in an elliptical orbit, ABP, then the velocity of m is given by the so called *vis viva* integral

$$v^2 = G(M + m)\left(\frac{2}{|R|} - \frac{1}{a}\right),$$

where G is the universal gravitational constant. If m is small compared to M, the equation becomes:

$$v = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)}$$

and v is then independent of the mass of the orbiting particle and varies solely with the orbital parameters. The maximum velocity of m is reached in perihelion P, where R is minimum and equals the focal distance q:

$$v_P = \sqrt{GM\left(\frac{2}{q} - \frac{1}{a}\right)} = 29.8\sqrt{\frac{2}{q} - \frac{1}{a}} \text{ km/sec.}$$

Similarly, the minimum velocity is reached at aphelion A, where R is maximum and equals Q:

$$v_A = \sqrt{GM\left(\frac{2}{Q} - \frac{1}{a}\right)} .$$

Comparing the expressions for v_P and v_A, it is noted that

$$\frac{v_P}{v_A} = \frac{2a - q}{q} = \frac{Q}{q} .$$

The perihelion and aphelion velocities are thus inversely related to their respective radius vectors. Thus, for example, the asteroid Icarus, Table 3, moves ten times faster at perihelion, and Halley's comet, Table 4, moves 60 times faster at perihelion than at aphelion. The time spent in the high-temperature regime near the perihelion is thus a relatively small fraction of the object's total sidereal period.

For bodies that move in near circular orbits, q approaches a and Q, and $e \rightarrow 0$. The maximum velocity approaches circular velocity and becomes constant at

$$v_C = \sqrt{\frac{GM}{a}} = \sqrt{\frac{GM}{q}} ,$$

when the orbit is a mathematical circle.

At the other extreme, when $Q >> q$, e approaches unity, and in the limit we have the parabolic case, where Q and a are infinite. A body in a parabolic orbit will have a velocity at perihelion

$$v_{par} = \sqrt{\frac{2GM}{q}} .$$

It follows, therefore, that at a given distance from Earth's center, i.e. at a specified altitude of, for instance, 200 km, a particle approaching Earth in a parabolic orbit moves at a velocity that is $\sqrt{2}$ times that of a similar particle in a circular orbit. Particles in hyperbolic orbits move at velocities above $\sqrt{2}$ times the circular velocity. Particles in parabolic and hyperbolic orbits cannot continue to reside within our Solar system, except if they are perturbed by gravitational pull from some major planet into an elliptical orbit.

In many of the descriptions in the book we shall be concerned with the temperatures to which the meteorites may have been exposed when orbiting in space as relatively small bodies, meteoroids. If the source of heat is assumed to be the Sun, and other possible internal heat sources are neglected, a heat balance will be attained in which the infrared emission from the body (according to Stefan-Boltzmann's law, proportional to the surface area and to T^4) accurately equals the Sun's irradiation. It can then be shown that the average temperature at a given solar distance can be approximated by the equation

$$T(^\circ\mathrm{K}) = 277/\sqrt{R}$$

where the distance R is expressed in astronomical units (Jones 1923; Wylie 1934; Watson 1956: 181; Peebles & Dicke 1962).

If the body is small and rotating and with a good heat conductivity, it will have a fairly uniform temperature throughout; for example, at Earth's distance from the Sun, 277° K or 4° C. If, on the other hand, the body is large or has one side exposed to the Sun for long intervals, as the Moon has, the temperature of the illuminated side may rise to 120° C and that of the dark side decrease to about -180° C (Saari 1964; Allen & Ney 1969).

Bodies in elliptical orbits move through cyclical reheating and cooling. An asteroid, like Apollo (Table 3), will pass a maximum temperature of about 70° C and a minimum temperature of -90° C at aphelion, while Icarus will correspondingly suffer extremes of 365° C and -75° C. Evidently, if small meteoroids – the parent bodies for meteorites – are assumed to have orbits similar to those of these asteroids, they may in some cases arrive at Earth thoroughly heat-treated. Most iron alloys would recover fully and, perhaps in extreme cases, have a chance of recrystallizing through the cyclical reheating in eccentric orbits, provided they were first cold-worked or shock-deformed.