1
The grand tour

> The planets are no longer wandering lights in the evening sky. For centuries man lived in a universe which seemed safe and cozy – even tidy. The Earth was the cynosure of creation and Man the pinnacle of mortal life. But these quaint and comforting notions have not stood the test of time. … No longer does "the World" mean the Universe. We live on one world among an immensity of others.
>
> Carl Sagan (1970)

From the seventeenth to the middle of the nineteenth century it was customary for the scions of affluent British families to make a long tour of all the capitals of Europe to acquaint them with the architecture and culture of their larger world. In the twentieth century NASA planned a "grand tour" of our Solar System that would visit every planet outside the orbit of Mars. That tour never happened. Nevertheless, we have just about accomplished its goals, with the final New Horizons encounter with Pluto scheduled for 2015.

Scientific exploration of the Solar System can be said to have started around 1610, when Galileo Galilei (1564–1642) applied the newly invented telescope to investigate the world beyond the Earth. Telescopes have increased greatly in both size and sophistication since the days of Galileo, but even the best ground-based telescopes are unequal to the task of detailed exploration of the planets. The beginning of the Space Age, opening with the launch of Sputnik 1 in 1957, was the next leap forward in planetary exploration. Spacecraft, carrying instruments and humans, have greatly expanded our knowledge of the planets and moons around us.

The usual course of exploration of a planetary body, after remote astronomical observations, has been, first, flyby spacecraft, followed by orbiters, then landers and finally sample returns and human *in situ* visitation. The majority of bodies discussed in this book are still in the orbiter or flyby stage of exploration: Humans have returned multiple large samples only from our Moon, so far. In addition, very small amounts of material from comet Wild 2 and asteroid 25143 Itokawa have been returned by NASA's Stardust and Japan's Hayabusa missions, respectively. Nevertheless, a great deal has been learned about the other bodies orbiting our Sun. As this is written, the astronomical exploration of the planetary systems around other stars has been underway for about a decade.

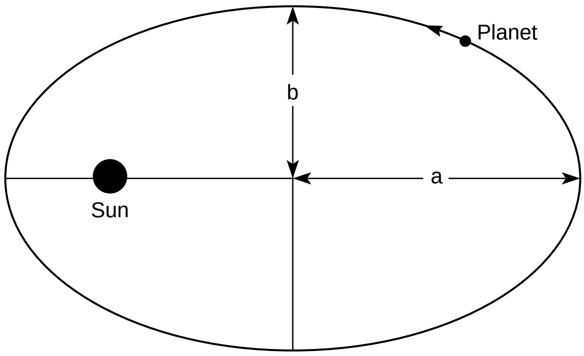

Figure 1.1 Planets orbit about the Sun in elliptical orbits that lie in a plane. The Sun lies at one focus of the ellipse. The size of the ellipse is defined by the semimajor axis *a* and the semiminor axis *b*.

1.1 Structure of the Solar System

Planets move around the Sun along paths that are, to a very good first approximation, elliptical (Figure 1.1). Johannes Kepler (1571–1630), using tables of planetary positions, deduced that the Sun lies at one focus of each planet's ellipse and that the square of the period P of each planet's orbit is proportional to the cube of its semimajor axis a, a relation now known as Kepler's third law (the first law is that the planets move in elliptical orbits with the Sun at one focus and the second is that, in moving along its orbit, planets sweep out equal areas in equal times). Isaac Newton (1642–1727) extended Kepler's empirical observations with his law of universal gravitation, writing that the period of a small body moving around a much larger body of mass M is given by:

$$P^2 = \frac{4\pi^2}{GM} a^3 \tag{1.1}$$

where G is Newton's gravitational constant, equal to $(6.67259 \pm 0.00085) \times 10^{-11}$ m^3/(kg s^2). The detailed position of a planet in its orbit is defined by six numbers, of which we shall be concerned with only three. The first is the semimajor axis a, which is conventionally expressed in Astronomical Units (AU), equal to the semimajor axis of the Earth's orbit around the Sun. One AU is approximately equal to 1.496×10^8 km. The second is the eccentricity e, defined by the ratio between the semimajor axis and semiminor axis b of the ellipse:

$$e = \sqrt{\frac{a^2 - b^2}{a^2}}. \tag{1.2}$$

The eccentricity is zero for a circular orbit and equal to one for a parabolic orbit. Eccentricities larger than one describe unbound, hyperbolic orbits. The last orbital parameter of interest to us is the inclination of the ellipse to a reference plane, conventionally chosen to be the plane of the Earth's orbit around the Sun, the ecliptic plane (another often-used reference plane is the invariable plane of the Solar System, which is mostly defined by Jupiter's orbit). The other three orbital parameters describe the orientation of the ellipse's axis in space (two numbers, the longitude of the ascending node and the argument of the perihelion) and the location of the planet in its orbit (the true anomaly).

1.1.1 Major facts of the Solar System

There are a number of important facts about the Solar System, not all of which are yet explained by models of Solar System formation, although most are at least consistent with the current solar nebula model of Solar System formation. Table 1.1 lists the orbital characteristics of the major planetary objects.

Planets and asteroids all formed at the same time. To the best of our ability to date them, the Earth, Moon, Mars, and the most ancient meteorites all have the same formation age, about 4.57 Gyr before the present. To less precision, the age of the Sun is also the same.

Planetary orbits are nearly coplanar. The planetary objects with the largest inclinations to the ecliptic plane are Mercury, inclined at 7.0°, Venus, inclined at 3.4°, and Saturn, inclined at 2.5°. Pluto, which is inclined at 17.1° is now believed to be a member of a family of similar *Trans-Neptunian Objects* or TNOs with similarly large inclinations (Eris, the largest TNO, is somewhat larger than Pluto and is inclined at 44° to the ecliptic).

Planetary orbits lie near the plane of the Sun's equator. The Sun's equator is inclined to the ecliptic at about 7.5°, so that its orbital momentum vector is similar in direction to those of the planets.

Planetary orbits are nearly circular. The three most eccentric planetary orbits are those of Mercury, $e = 0.2065$, Mars, $e = 0.0934$, and Saturn, $e = 0.0560$. Pluto, with $e = 0.2482$, seemed less like the other planets, until the discovery of many other similar TNO objects confirmed that it belongs to a different population of objects than the inner planets (Eris' eccentricity is 0.44, larger than Pluto's).

The planets all revolve around the Sun in the same direction. There are no exceptions to this rule, although many long-period comets do travel on retrograde orbits.

The rotation direction of most *planets is direct*. The obliquity (the inclination of the axis of rotation to the orbital plane) of most planets is small, with the following major exceptions: Venus, whose rotation is retrograde, is inclined at an angle of 177.3° to its orbital plane. Uranus is also retrograde, although with an obliquity of 97.86° it nearly lies on its side with respect to its orbit. Neptune is prograde, with an obliquity of 29.6°.

The spacing of planetary orbits follows a rough logarithmic series. Called the *Titus–Bode* law, this relation states that the semimajor axis of the nth planet, a_n, is given by:

$$a_n = c_1 + c_2\, 2^n. \tag{1.3}$$

Table 1.1 *Planetary orbits*

Planet	Period (years)	Semimajor axis, *a* (AU)	Semimajor axis *a* by Titus–Bode	Eccentricity, *e*	Orbital inclination, *i* (degrees)
Mercury	0.241	0.387	0.55	0.2056	7.004
Venus	0.615	0.723	0.7	0.0068	3.394
Earth	1.000	1.000	1.0	0.0167	0.000
Mars	1.881	1.524	1.6	0.0934	1.850
Ceres	4.60	2.766	2.8	0.0739	10.585
Jupiter	11.862	5.203	5.2	0.0483	1.038
Saturn	29.458	9.539	10	0.0560	2.488
Uranus	84.01	19.191	19.6	0.0461	0.774
Neptune	164.79	30.061	*	0.0097	1.774
Pluto	248.54	39.529	38.8	0.2482	17.148
Eris	557	67.67	77.2	0.4418	44.187

* Advocates of the validity of this *law* frequently skip Neptune and list Pluto in its place, noting that the "agreement is better." Readers are encouraged to judge for themselves.

If the constants c_1 and c_2 are chosen to be 1 for Earth ($n = 3$) and 5.2 for Jupiter ($n = 6$), this rule states:

$$a_n = \frac{2}{5} + \left(\frac{3}{40}\right) 2^n. \tag{1.4}$$

Table 1.1 lists the predictions of this "law" and shows that it does agree roughly with observation. So far, there is no fundamental understanding of why this relation should be true.

1.1.2 Varieties of objects in the Solar System

Besides the major planets, many different types of object make up the Solar System. In order of decreasing size, these comprise the satellites of major planets: The larger ones in the Solar System include Ganymede and Callisto (satellites of Jupiter, 5262 and 4800 km diameter, respectively), Titan (satellite of Saturn, 5150 km diameter), Triton (satellite of Neptune, 2700 km diameter) and our Moon (3476 km diameter). Ganymede and Titan are larger than Mercury and, as bodies in themselves, can be classed as planetary objects. For the purposes of this book, we shall discuss these large satellites as varieties of planetary object and make no distinction between objects that orbit the Sun and those that orbit other planets.

In addition to satellites, we recognize asteroids, the largest of which is Ceres (diameter 950 km), but whose sizes range downward to a few kilometers, grading into objects that would be classed as meteoroids (there is no universally recognized size that divides asteroids from meteoroids: current authors set the dividing line anywhere between 1 km and a few meters). The total mass of all the asteroids is small, only about 4% of the Moon's mass, most of which resides in the largest asteroids, Ceres, Vesta, and Pallas. By definition an asteroid orbits the Sun and appears "star-like" in a telescopic image: That is, it does not display a "coma" or regularly emit gas and dust like a comet. Unfortunately for classifications, there are a few objects that do not possess comas but in every other respect are comet-like, while other objects long recognized as asteroids have suddenly acquired comas.

Comets are objects that, upon approaching the Sun, emit gas and dust to produce a *coma* (literally, "hair" in Latin: Comets are "hairy stars"). The diameters of cometary nuclei range from about a kilometer up to several tens of kilometers. They contain ices that, upon warming near the Sun, create their characteristic tails of gas and dust as the ices evaporate. There are several classes of cometary orbit, ranging from low inclination orbits typical of short-period comets to long-period comets that approach the Sun from the depths of the *Oort cloud* (which ranges out to a large fraction of the distance from the Sun to the nearest star).

In addition to these macroscopic objects, the Solar System also contains dust particles, whose diameter ranges down to submicron sizes, as well as individual atoms in the form of plasma and cosmic rays, most of which are emitted by the Sun, although a small component comes from interstellar space, as do some tiny dust particles.

1.2 Classification of the planets

The planetary-scale objects in our Solar System can be grouped into three general classes, with a number of important subclasses.

Terrestrial planets. Planets similar to the Earth are of most direct interest to us as inhabitants of such a planet. The main mass of these planets is composed of silicate minerals, although most have a metallic core rich in iron and nickel. Their densities range from 3000 to 6000 kg/m^3 and they all have well-defined surfaces. Members of this class may or may not possess atmospheres. This class includes many satellites and asteroids as well as major planets. Examples are Mercury, Venus, Earth, our Moon, Mars, Io, and Ceres.

Icy satellites. Confined to the outer Solar System, this class consists of bodies mainly composed of water ice, with a possible component of other ices such as carbon dioxide, ammonia or, in the extreme outer Solar System, methane and nitrogen. These objects may have cores of silicate minerals that include hydrated silicates and, possibly, metallic inner cores. Densities of these objects range from 1000 to more than 2000 kg/m^3.

Jovian (gas giant) planets. Jupiter and Saturn are composed of nearly the same materials as the Sun, mainly hydrogen plus helium and an admixture of heavier elements such as carbon and oxygen typical of "ices." These objects do not possess definite surfaces although they may have dense rocky or metallic cores. Their densities fall in the range of 700 to 2000 kg/m^3. These planets are often divided into Jovian Planets (Jupiter and Saturn) and ice-rich Neptunian Planets (Uranus and Neptune), which contain a higher proportion of carbon and oxygen than the Sun.

1.2.1 Retention of planetary atmospheres

All of the large planets and the largest moons possess atmospheres. Planetary atmospheres are of great interest in themselves, but this book lacks space to discuss them: References to good sources of information on them are given in the *Further reading* section at the end of the chapter. However, the presence of an atmosphere strongly affects surface temperatures and, when present, permits a wide variety of surface processes to operate that would not be possible in its absence.

Whether or not a planetary object possesses a substantial atmosphere is dependent upon two main factors: The planet's escape velocity and the temperature of its exosphere. The escape velocity is the minimum speed required for a body initially on the surface to escape to infinity. If the mass of a planet is M and its radius is R, the escape velocity is given by:

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM}{R}} = \sqrt{2gR} \tag{1.5}$$

where g is the surface acceleration of gravity. The second form of this relation can be used to compute the escape velocity of the objects listed in Table 1.2. The escape velocity of the Earth is 11.2 km/s, faster than almost any molecule near its surface (except hydrogen and helium) and so it retains a substantial atmosphere. The Moon, on the other hand, has an escape velocity of only 2.4 km/s and it has no permanent atmosphere.

The other factor in atmospheric escape is the temperature of the atmospheric gases. Kinetic theory tells us that the most probable velocity of a gas molecule of mass m at temperature T is given by:

$$v_T = \sqrt{\frac{2kT}{m}} \tag{1.6}$$

where k is Boltzmann's constant. Note the dependence on the inverse molecular mass: Light molecules escape more easily than heavy ones, which accounts for the near absence of hydrogen and helium in the atmospheres of the terrestrial planets. There are two subtleties of this relation. The first is that, although Equation (1.6) is the most probable velocity, the velocity distribution has an exponential tail at high velocities and so a small fraction of gas molecules moves many times faster than v_T. Over geologic time a large fraction of the atmosphere may slowly leak away even though the most probable velocity is several times smaller than the escape velocity. The other subtlety is that the relevant temperature is not the surface temperature but the temperature high in the atmosphere, where the atmospheric gases are so thin that a molecule moving upward has a good chance of escaping into interplanetary space without colliding with another molecule. This portion of a planetary atmosphere is called the exosphere. Solar UV radiation tends to heat the upper reaches of planetary atmospheres to temperatures much higher than the surface, so that gases that might seem to be stable on the basis of the surface temperature can, in fact, leave the planet.

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Table 1.2 *Physical data on terrestrial planets and major moons*

Planet or moon	Rotation period (days)	Equatorial radius (km)	Mean density (kg/m^3)	Surface gravity (m/s^2)	Inclination of equator to orbit (degrees)	Maximum surface temperature (K)
Mercury	58.6	2439	5430	2.78	2	700
Venus	243	6051	5250	8.60	177.3	735
Earth	1.00	6378	5520	9.78	23.45	311
Moon	28	1738	3340	1.62	6.68	396
Mars	1.03	3393	3950	3.72	25.19	293
Ceres	0.38	487	2080	0.27	~3	~239
Io	1.77	1821	3530	1.80	2.2	130
Europa	3.55	1569	3010	1.31	0.1	125
Ganymede	7.15	2634	1936	1.43	0–0.33	152
Callisto	16.69	2410	1834	1.24	0	165
Titan	15.95	2576	1880	1.35	0	94
Triton	5.88	1353	2061	0.78	0	38
Pluto	6.4	1153	2030	0.66	119.6	55
Eris	> 0.33 ?	1300	2250	~0.8	?	55

In addition to this thermal escape mechanism, other erosion processes such as impingement of the solar wind on atmospheres that are not defended by a planetary magnetic field, or ejection of atmospheric gases by impacts, may play important roles. One or both of these mechanisms may have depleted the Martian atmosphere over time. An early phase of strong UV emission by the newborn Sun may have ejected atmospheric gases from the early planets in a process known as hydrodynamic escape.

1.2.2 Geologic processes on the terrestrial planets and moons

The gamut of geologic processes that act on the surface of a planet or moon is the principal subject of this book. In subsequent chapters each process is considered in some detail. The chapters are arranged in approximate order of the universality of each process, ranging from processes that act on all planetary objects to processes that may affect only a few special bodies. Different processes act on different bodies, but if there is any overall organization to how different processes affect different planets (and there are many exceptions to any rule one might try to make), it is that planetary complexity increases with planetary size. Small bodies are home to only a limited variety of processes, while large planets are much more diverse.

Figure 1.2 is an attempt to capture this progression in a simple diagram that lists process as a function of planetary diameter, with a few examples added for definiteness.

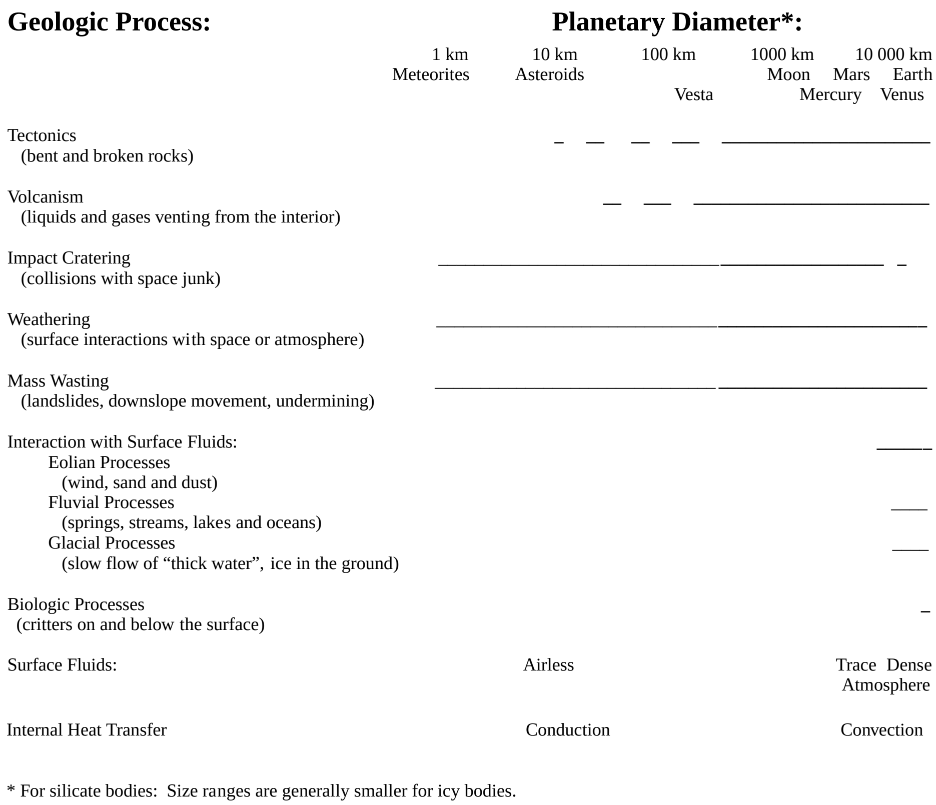

Figure 1.2 The activity of different geological processes is a function mainly of the size of the planetary body. The horizontal lines in this figure indicate the importance of each of the processes listed along the left side of the figure.

Impact cratering is probably the most universal process, although it is less important on large bodies than on small ones, mainly because other, more rapid, processes are more effective. Mass movement and surface modification of various kinds are similarly universal, although for small bodies both are strongly coupled with impact cratering. Tectonics, the process of rock deformation and fracture, is also important across the entire scale of sizes, but it is somewhat more effective on larger bodies where stresses can more easily approach the limit of rock strength. Volcanism might seem to be a mostly large-body process, yet evidence of melting has been found on even the smallest objects in the Solar System, remnants of an early era in which radioactive heat sources were more effective than now.

The cluster of processes that require active fluids on the surface of planets, including "wind" (the movement of any atmospheric gas), flowing "water" (which could be any liquid, such as methane on Titan), and "ice" (again, any highly viscous material near its melting point) are exclusively large-planet processes, because it requires a large body to hold an atmosphere. Finally, biologic processes are, so far as we know, confined to the largest and most diverse planet in the Solar System, Earth.

1.3 Planetary surfaces and history

Not all of the planets in the Solar System have well-defined surfaces. By surface, I mean a thin zone (thickness under a centimeter or less) across which physical and mechanical properties such as density, strength, sound speed, etc., show an abrupt change. The gas giant planets Jupiter, Saturn, Uranus, and Neptune probably do not show such abrupt changes and so can be considered to be without surfaces in this sense.

In this book we are mostly concerned with the surfaces of the terrestrial planets, silicate and icy moons. Much of what we will learn can also be applied to the surfaces of asteroids and comets. The surfaces of silicate-rich bodies are mostly composed of the refractory oxides of Si, Mg, Fe, Al, and Ca. These minerals have melting points far above ambient temperatures and so the physical state of the terrestrial planet's surfaces is solid: For most purposes we can treat the crust of these planets as a brittle elastic solid (something we loosely call *rock*). Because rocks do not deform until applied stresses exceed some yield point, it is difficult to remove all traces of past events that may have acted upon them. Rocks can record many aspects of the history of their planets. This fortunate aspect also makes planetary surfaces complex. A given planetary surface not only shows the effects of forces acting on it at the present time, but its structure also carries traces of forces that may have long ceased to exist. Similar considerations apply to the icy moons, so long as they remain well below the melting point of their ices. In the outer Solar System, beyond the orbit of Jupiter, temperatures are far below the melting point of water ice, and so water ice behaves in most respects like rock.

The gas giant planets are different in this respect from the solid planets: Although the atmospheres of the giant planets show complex structures, these structures are the consequence of presently acting forces: History is not a major player in their form. Even though the Great Red Spot on Jupiter has been visible for centuries, it would dissipate within hours if the vortex maintaining it were to die out.

The Earth's surface presents a minor exception to our emphasis on solid surfaces: Roughly ¾ of the Earth's surface is underlain by liquid water. The sea surface cannot maintain a record of the forces acting upon it for more than a few hours or days. The study of the sea surface is thus one of current or very recent forces acting upon the liquid: There is no paleontological aspect to sea surfaces. Of course, beneath the sea we find rocks that do maintain a record (although still of limited length due to plate tectonic recycling), so that we can learn much about the Earth's history by studying the sea floor.

Our emphasis in this book will be more on the response of rocky silicate or ice surfaces to applied forces than on the historical goal of using planetary surfaces to unravel the history of the planet. A clear understanding of these physical processes is a prerequisite to the interpretation of some particular surface. Moreover, we do not yet have sufficient data about most planets to make unambiguous statements about their history. Thus, at the present time, the most fruitful approach is the study of physical processes.

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We begin our study of planetary surfaces with a review of the gross properties of the terrestrial planets and moons, and undertake a brief description of their present surfaces and what is known of their past. Table 1.2 lists some of the basic physical properties of a selection of Solar System objects with solid surfaces.

1.3.1 The Moon

Two easily recognizable terrain types dominate the surface of the Moon: The maria and the terrae (or highlands). The *maria* are dark (with a normal albedo of about 0.08), smooth plains that are found predominantly on the Moon's nearside. They are lightly cratered and are mantled with a layer of comminuted rock (the regolith) to a depth of a few meters. Lava flow fronts are observed in them, with scarps up to 100 m high (many times higher than typical for terrestrial lava flows). Samples returned by the Apollo astronauts show that they are composed of fine-grained basalt. The maria are volcanic plains formed by the extrusion of large volumes of highly fluid basalt. These flows may be equivalent to terrestrial flood basalts such as those that form the Columbia Plateau or the Deccan Traps. The mare basalts sampled so far were extruded over a ca. 700 Myr interval from about 3.2 to 3.9 Gyr ago. Some small central volcanic features are also observed, although there is little indication of silica-rich explosive volcanism.

The *terrae* represent an older surface than the mare. The typical terra is a rugged-looking hilly surface in which many circular, rimmed pits (impact craters) form at many different size scales. The terrae surfaces are typically bright (normal albedo about 0.16) and are best developed in the Moon's southern latitudes on the nearside. They are the predominant terrain type on the farside. The terrae are covered with a layer of broken rock tens of meters thick that may itself overlie a *megaregolith* of broken rock ten or more kilometers thick. All lunar samples that have been returned from terrae are breccias (that is, composed of broken angular rock fragments that may have been cemented by heat and pressure from impacts). The terrae may represent areas where the original crust of the Moon is exposed: They have, however, been subjected to such intense meteoritic bombardment that crater has obliterated crater to the point that no remnant of the original surface remains. The entire surface is in a "saturated" or "equilibrium" condition with respect to cratering. Although the terrae were also once composed of igneous rock, they are richer in Al than mare basalts. The composition of the terrae is often described as "anorthositic gabbro" (70% plagioclase, 20% orthopyroxene, 9% olivine, 1% ilmenite). Anorthositic gabbro is mafic (Fe and Mg rich and poor in SiO_2) compared to terrestrial granite.

Because the terrae all formed since the crust of the moon crystallized at about 4.6 Gyr, their high crater density, compared to that on the more lightly cratered mare, implies that an era with an especially high cratering rate must have occurred in the interval between 4.6 and 3.9 Gyr. A controversy is currently raging about whether this era of heavy bombardment was the tail end of a high cratering flux extending from the time of the Solar System's origin, about 4.6 Gyr ago, or whether it was part of a relatively short spike in the cratering rate, the "Late Heavy Bombardment." Current models of Solar System formation relate