Chapter 2
The Origin of the Sun and the Early Evolution of the Solar System

> *The direct investigation of such inner regions around protostars and young stars will also provide us with knowledge about the physics and evolution of circumstellar disks. It is within such disks that planetary systems are believed to be formed. We now have reason to believe that, as we progress toward a greater understanding of star formation, we will also begin to unlock the secrets of the origin of planetary bodies.*
> From Lada and Shu (1990, p. 572).

The origin of the Solar System has intrigued scientists for centuries. As recently as five decades ago the models were still very general (e. g., Cameron 1962) and were concerned mainly with the collapse of a cloud of stellar dust and gas of roughly solar composition and the transformation of that cloud into a rapidly rotating disk-shaped mass around a proto-sun. The next few decades were dominated by calculations of equilibrium chemical condensation models from a cooling nebula of solar composition (e. g., Lewis 1972, 1974; Grossman 1972) based mainly on the temperature and pressure conditions for the solar nebula from Cameron and Pine (1973). Identification of high-temperature condensates [calcium-aluminum inclusions (CAIs)] in the Allende meteorite was a critical event in the development of more sophisticated models for the evolution of the Solar System. After the discovery of CAIs it was important to develop models to explain (a) the origin of chondrules (the main constituent of chondritic meteorites), (b) the origin of CAIs, as well as (c) the origin of the very fine-grained matrix of the chondritic meteorites.

In the decades of the 1980s and 1990s, groups of astrophysicists presented the results of simulations of the dynamics of the early history of the Sun in an attempt to relate the rapidly rotating disk stage of Solar System evolution to observations of T-Tauri stars of roughly solar mass. For example, Lada and Shu (1990) and Shu et al. (1994) published the results of simulations of the dynamic interaction between the material infalling along the nebular midplane and the strong magnetic fields associated with a very hot, rapidly rotating nascent Sun. Major features of the magnetic field action were the formation, breaking, and reconnection of the magnetic flux lines. The breaking (snapping) and reconnection of the flux lines is associated with very high temperature pulses that may relate to the thermally generated features recorded in the various types of CAIs (summaries of the types of CAIs are in Taylor 2001). Shu et al. (1997) attempted to explain the origin of both CAIs and chondrules

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via the X-Wind model (the name of the model refers to the 2-D cross-sectional geometry of the intersection of magnetic flux lines and the midplane disk). After critical consideration of the merits of the X-Wind model, Taylor (2001) and Wood (2004) proposed that something like the X-Wind model can be used to explain many of the features of CAIs but that the X-Wind model does *not* relate to the environmental conditions for chondrule formation. Although the X-Wind model has its critics (e. g., Desch et al. 2010), it is generally accepted as a reasonable explanation for the origin of CAIs.

The origin of chondrules (the main features of chondritic meteorites and spherical particles that are much simpler in composition and structure than CAIs) is another story with a long history dating back to Henry Sorby and the petrographic microscope about 1870 (McSween 1999). Although chondrules appear to have less complex features, their origin appears to be more difficult to explain. Most investigators agree that a "flash-melting" process as well as rapid cooling are involved. The rapid heating melts whatever clumps of dust that are in the environment at that time and the resulting features are glass beads (some with crystallites and crystals of identifiable minerals). These chondrules, plus or minus a few CAIs, are the main megascopic components of chrondritic meteorites. These components of chondritic meteorites are bound together by a matrix material. Most investigators agree that the fine-grained material of the matrix is composed of a combination of fine-grained silicate-rich material which contains various quantities of chondrule fragments, CAI fragments, and very fine-grained nebular dust as well as some material that was infalling along the midplane from the molecular cloud (Rubin 2010, 2013). It is interesting to note that the matrix of some enstatite chondrites has a significant quantity of flakes or chips of iron-nickel metal and sulfide minerals embedded in a mainly silicate matrix (Rubin 2010). The chemistry of chondrules varies considerably but there is a trend related to distance from the proto-Sun and the volatile content of the chondrules increases with heliocentric distance. Many investigators think that the Disk-Wind model of Bans and Konigl (2012) and Salmeron and Ireland (2012) looks promising as an explanation for the origin of chondrules. In general, chondrules are a few million years younger than CAIs and were formed by significantly different thermal processes. There is, however, evidence that there may be some overlap in time of formation (Brearley and Jones 1998).

As chondritic meteorites and associated CAI particles are formed, an accretion process begins. There are probably several embryonic planetary nucleation sites early in the accretion process, but in the later stages only a few would remain in the accretion torus (an accretion torus is a heliocentric doughnut-shaped geometric form from which smaller bodies are gravitationally attracted to participate in the planet-building process). The accretion torus, then, constitutes the "feeding" zone for the planet accretion process.

The chemical composition of the resulting planet or planetoid is determined by the composition of the particles in the accretion torus. For example, if the material in the accretion torus is mainly CAI material, then the planet or planetoid will be composed of CAI chemistry. If the accretion torus has particles and agglomerates of particles that are rich in iron, then the resulting planet or planetoid will be rich in iron and have a high specific gravity relative to a body composed mainly of silicates. Thus, the composition and density of an accreted body probably reflects the composition of the particles that were in the accretion torus.

In general, I think that nearly all (and possibly all) features of a Solar System origin model, from the origin of CAIs, chondrules, and the matrix of chondritic meteorites, and their derivative bodies, are involved in the processes that led to the formation of the terrestrial planets (e. g., the twin sister planets, Venus and Earth) and associated Vulcanoid planetoids and Asteroids, as well as the outer (gaseous) planets.

Figure 2.1 is composed of two simplified scale diagrams of the orbits of the planets of the Solar System. Figure 2.1a shows the orbits of the outer (gaseous) planets relative to the orbit of Mars. Figure 2.1b shows the orbits of the inner (terrestrial) planets relative to the orbit of Jupiter. The reader may ponder the following question: Why involve a large slice of the Solar System when discussing the condition of planets Venus and Earth? A reasonable answer is that when dealing with a capture origin for the Moon as well as a capture origin for a satellite for Venus, it is necessary to have a place of origin for the Moon and related planetoids. The best fit, both chemically and physically, seems to be a Vulcanoid Zone (Wiedenschilling 1978; Leake et al. 1987; Evans and Tabachnik 1999, 2002) between the orbit of Mercury and the Sun. Thus it appears necessary to involve at least the zone inside the orbit of Mercury and out to the vicinity of Earth's orbit.

Then we have the problem of a large volume of ocean water on Earth as well as the possibility of water on Venus in an earlier era [i. e., the "Venus Oceans problem" (Donahue 1982, 1999)]. I think that the model of Albarede (2009) explains the origin of ocean water problem fairly well. His suggested source is water-bearing asteroids from the middle to outer Asteroid Zone. Thus, our sphere of influence needs to be extended to include the entire Asteroid Zone.

Then we need a delivery system for the Aquarioid Asteroids (my name for the water-bearing asteroids). The most reasonable delivery mechanism for getting the Aquarioids from the Asteroid Zone to near Earth orbit is a process of gravitational perturbations by a combination of Jupiter and Saturn, a process that has been studied by celestial mechanicians for many decades.

Since there is also an interest in explaining the source of water for planet Mars, we must explain the deuterium to hydrogen (D/H) ratio of the water associated with that planet. [For readers who are not familiar with the importance of the deuterium/hydrogen ratio, some definitions and an explanation are in order. The hydrogen atom (H) (also called protium) has only one proton in the nucleus. Deuterium (D) has both a proton and a neutron in the nucleus and has twice the atomic weight as hydrogen. In many cases thermal processes will cause molecules with the lighter hydrogen to be separated from those with heavier hydrogen. As a result many substances can be characterized by their D/H ratio.] Since the D/H ratio of martian water is much different from that of Earth we must search for a source of martian water. Well, the D/H ratio of martian water is similar to that of comets (Robert 2001). Most investigators think that the effective source of these comets is the Asteroid Zone and that these comets are Jupiter-captured bodies: i. e., captured into heliocentric asteroid-like orbits after a close encounter with Jupiter. The apparent ultimate source of all comets, however, is the Oort Cloud/Kuiper Belt which is

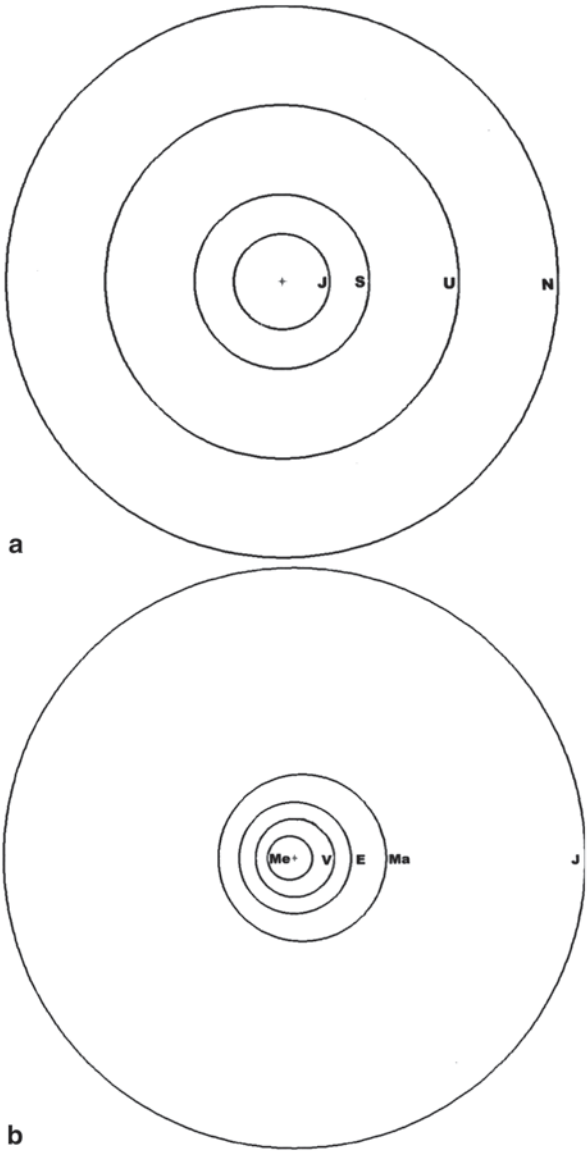

Fig. 2.1 Relative geometry of the orbit of the planets of the solar system as viewed from the North Pole of the Solar System. Note that all orbits are nearly circular except those of Mars and Mercury. **a** Outer Solar System orbits: *N* Neptune, *U* Uranus, *S* Saturn, *J* Jupiter. **b** Inner Solar System orbits: *Ma* Mars, *E* Earth, *V* Venus, *Me* Mercury

beyond the orbit of NEPTUNE. In order to transfer these comets from their place of origin to the vicinity of Jupiter's orbit, it is difficult to exclude gravitational interactions with planets Neptune, Uranus, and Saturn. [Note: The origin of water for Earth and Venus will be discussed further in Chap. 5.]

In addition to aiding in the transfer of the water-bearing bodies for Mars, Earth, and Venus, planet Jupiter, and its accomplice Saturn, apparently have played a significant role in maintaining habitable conditions on Earth for a long stretch of geologic time by powering a major component of the Milankovitch cycles (Berger et al. 1992). The

Earth's periodic variations in heliocentric orbit eccentricity, an oscillation from 0 to 6% in eccentricity with major periods of 100 and 400 Ka, are due to gravitational perturbations by a combination of planets Jupiter and Saturn (Imbrie and Imbrie 1979; Berger 1980). These oscillations of the eccentricity have been operating from a very early era in Earth history (Berger et al. 1989a, b).

Two other components of the Milankovitch Model are the precession cycle (~20,000 years) and the obliquity (or tilt) cycle (~40,000 years). Both of these cycles are dominated by gravitational interactions with the Moon (Imbrie 1982; Berger et al. 1992).

Thus, it seems imperative that we spend some time on the problems associated with THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM. For origin and early evolution, I favor a combination of (1) the X-WIND MODEL (Shu et al. 2001), (2) the DISK WIND MODEL (Salmeron and Ireland 2012), (3) the FU Orionis model (Bell et al. 2000), and (4) the T-Tauri model (Calvert et al. 2000). This combination of activity appears to explain most of the "FACTS TO BE EXPLAINED BY A SUCCESSFUL MODEL" for the Solar System (this list of facts is in the next section of this chapter). Although this combination of models may not be perfect (and we must remember that all models in science are amendable to modification, improvement, and replacement), it does explain a good bit. In some cases models can be used to explain much more than for which they were designed. In my opinion this feature is the hallmark of a successful hypothesis (model).

2.1 List of Some Important Facts to be Explained by a Successful Model

1. Chemical composition and body density (compressed and uncompressed) patterns of the Moon, Mercury, Venus, Earth, Mars, the asteroids, Jupiter and the other outer planets and their satellites, and comets in addition to the various groups of chrondritic and achondritic meteorites. (see Fig. 2.2 and Table 2.1 for body density patterns.)
2. Composition and dates of formation of calcium-aluminum inclusions (CAIs) that occur in chondritic meteorites as well as an explanation of the processing that results in the various types of CAIs.
3. Patterns of oxygen isotope ratios for bodies of the Solar System (see Fig. 2.3 for some trends of oxygen isotope ratio patterns).
4. Composition and dates of formation of chondrules and chondritic meteorites as well as the devolatilization patterns associated with volcanic asteroids, planets, and chondritic meteorites. (See Fig. 2.4 for the potassium content relative to uranium for these bodies.)
5. Magma ocean development on the Moon, in particular, but this explanation may include the development of magma oceans on other bodies such as the Vulcanoid planetoids and Mercury.
6. Patterns of magnetization of minerals, rocks, and planetary crusts on various solar system bodies as well as on meteorites and asteroids.

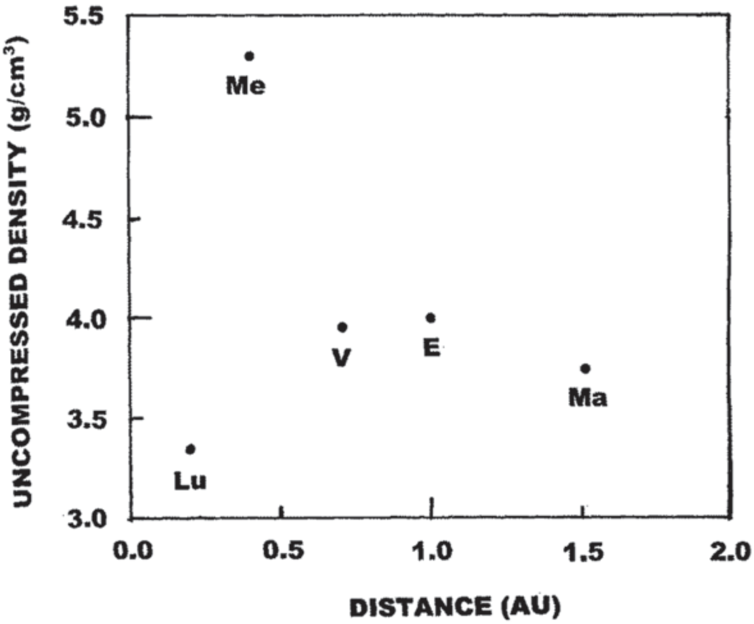

Fig. 2.2 Plot of uncompressed densities for the Moon (*Lu* Luna), Mercury (*Me*), Venus (*V*), Earth (*E*), and Mars (*Ma*). The exceptionally low uncompressed density of Luna as well as the exceptionally high uncompressed density of Mercury need to be explained by a successful model for the origin and evolution of the Solar System. (Numerical values are from Lodders and Fegley (1998, p. 91))

Figure 2.2 is a plot of uncompressed densities for the terrestrial planets and the Moon and Table 2.1 gives numerical values for the bodies in Fig. 2.2 as well as for other Solar System entities. Compressed density of a planetary body is the density of the body as it exists in nature (i. e., in a compressed state). The mineral structures in the lower layers of the planet are denser than they would be at the surface. Small bodies, bodies the size of the Earth's Moon or smaller, have about the same density in the compressed and uncompressed states. The uncompressed density of a planetary body is estimated by theoretically decompressing the mineral structures of successive layers within the planet. The uncompressed density yields a much better estimate of the density of the material of which the body is composed. For terrestrial planets the uncompressed density relates fairly directly to the mineralogical and chemical composition of the meteoritic material that was in the accretion torus before the planetary body was formed.

Before we develop a working model for the evolution of the Solar System we need to discuss some features of the Oxygen Isotope plot in Fig. 2.3 and the Potassium abundance relative to Uranium plot in Fig. 2.4. The hypothesis (model) to be tested is that all volcanic asteroids were formed in heliocentric orbits between ~0.10 AU and the orbit of planet Mercury in the earliest history of the Solar System. The starting material was the composition of calcium-aluminum inclusions (CAIs) of all types (Groups I through VI) (Taylor 2001) that were generated by the thermal and dynamic activity of the X-Wind (Shu et al. 2001). During the early stages of the X-Wind

Table 2.1 Values of compressed density and uncompressed density for various solar system entities. (Sources: Moon through Sun (Lodders and Fegley 1998, pp. 91–95); Asteroids (Kowal 1996, p. 45); Angrite grain density (Britt et al. 2010, 1869.pdf))

Solar system body	Compressed density (g/cm^3)	Uncompressed density (g/cm^3)
Moon	3.34	3.34
Mercury	5.43	5.30
Venus	5.24	4.00
Earth	5.52	4.05
Mars	3.93	3.74
Jupiter	1.33	0.10
Saturn	0.69	0.10
Sun	1.41	(0.10)
4 Vesta	3.3	3.3
Angra	~3.3	~3.3
Ceres	2.7	2.7
Pallas	2.6	2.6

activities the temperatures may have been too high for the refractory minerals of CAIs to crystallize. As the peak temperatures decreased, the various mineral products of the X-Wind began to collide, fragment, and accrete into larger bodies. According to Taylor (2001) the oxygen isotope ratios in CAIs tend to be fairly uniform and the environment during CAI formation was rich in oxygen-16 relative to that during chondule formation. But the oxygen isotope ratios in the purported Vulcanoid planetoids in Fig. 2.3 are not identical. Thus we need to develop an explanation for the formation of Vulcanoid planetoids that can have somewhat different oxygen isotope ratios.

An Attempt to Explain the Similarities of Oxygen Isotope Ratios of Earth and Moon

In the author's view the oxygen isotope signature of CAIs depends on the mixture of material infalling along the nebular mid-plane. The dust to gas ratio of infalling material is important because the nebular dust is enriched in O-16 and the gas is enriched in O-18 (Clayton 2003). Thus each major pulse of infalling material could yield a somewhat different dust to gas ratio and thus a different oxygen isotope signature. Perhaps the CAIs that are associated with the various types of carbonaceous chondrites (the main depository of nearly all of the extant CAIs) were all from the same phase of the X-Wind activity. Pursuing this concept a bit further, perhaps Luna accreted CAI material that mainly, by happenstance, matches very closely with the oxygen isotope ratios for Earth; perhaps 4 Vesta accreted from a slightly earlier or later batch of CAI material that was even richer in O-16; and perhaps Angra accreted from CAI debris that was intermediate in oxygen isotope ratios. Using this rationale, one can see how two independent bodies, separated by 0.85 AU of space (e. g., Earth and Luna) could end up in about the same position on a $\Delta^{17}O$ vs. $\Delta^{18}O$ plot.

Now we return to a possible explanation for the formation of Vulcanoid planetoids. As soon as a batch of CAI material gets formed, the particles in the mid-plane begin

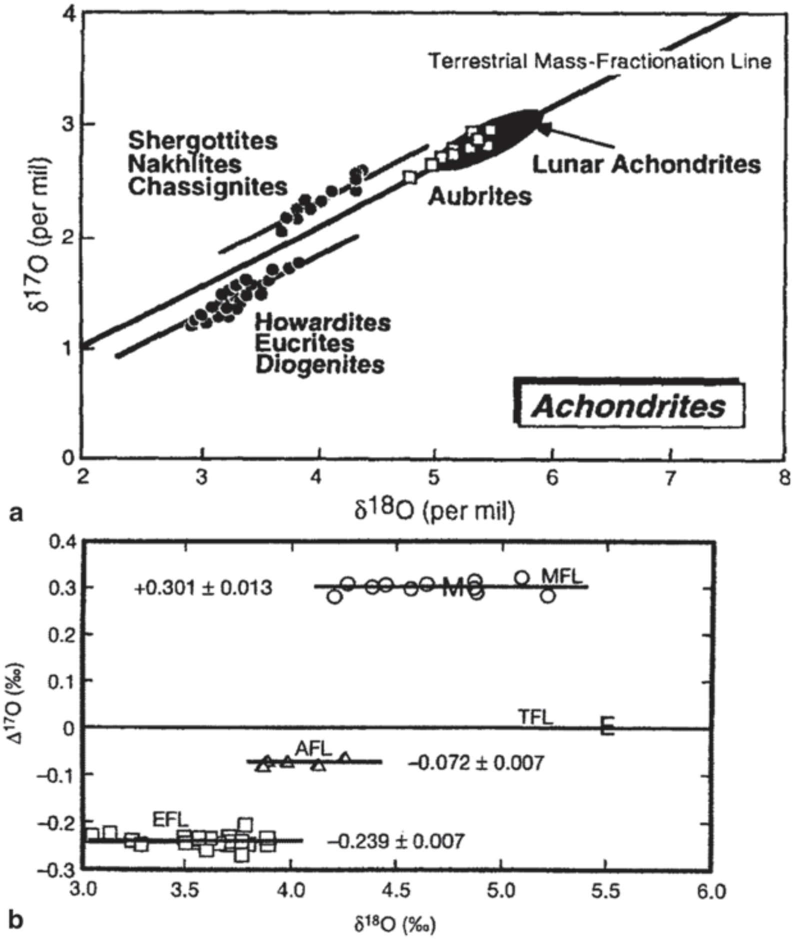

Fig. 2.3 Plots of some basic oxygen isotope information for some solar system bodies. **a** Three-oxygen isotope plot showing the position of the terrestrial fractionation line as well as the position of lunar achondrites (meteorites interpreted to be from the Moon), SNC meteorites (interpreted to be from Mars), and HED meteorites (interpreted to be from 4 Vesta). (Diagram from McSween (1999, Fig. 4.4), with permission from Cambridge University Press). **b** A delta 17 oxygen vs. delta 18 oxygen plot showing the terrestrial fractionation line (*TFL*), the Mars fractionation line (*MFL*), the eucrite parent body fractionation line (*EFL*), and the angrite fractionation line (*AFL*). Note that both Earth (*E*) and Moon (*not shown*) are essentially on the terrestrial fractionation line. Again, all of this information needs to be explained by a successful model for Solar System origin and evolution. (Diagram from Greenwood et al. (2005, Fig. 2), with permission from Nature Publishing Group.)

to collide and accrete into larger planetoid units; the CAIs that are near the edge of the mid-plane can be hurled to various distances in the surrounding solar system. This process of formation, limited ejection, and subsequent accretion continues for many cycles. The yield of the cycles can vary considerably. As more CAI material forms and accretes, some bodies will attain stable orbits as calculated by Evans and

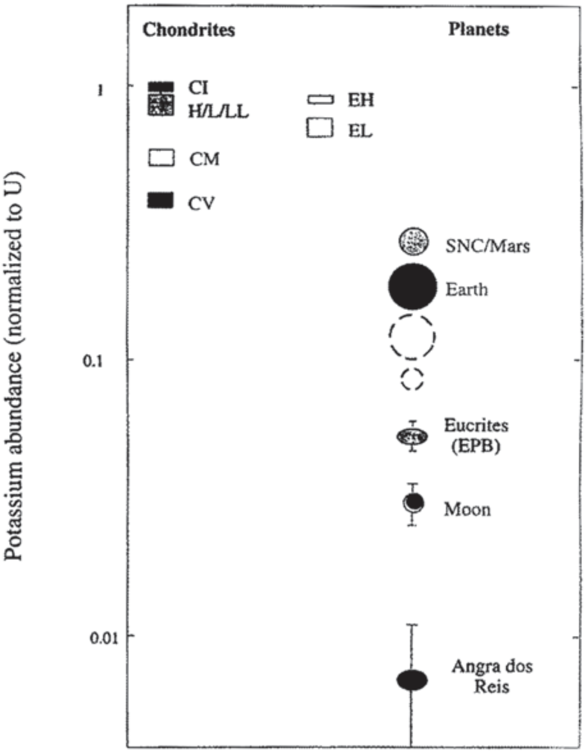

Fig. 2.4 Plot of potassium abundances (normalized to uranium) for various bodies of the Solar System as well as for various classes of meteorites. Angra dos Reis represents the Angrite meteorites; Eucrites are basaltic meteorites that are thought to be from the Eucrite Parent Body which, in turn, is considered to be Asteroid 4 Vesta; *EH* and *EL* are enstatite chondritic meteorites; *H*, *L*, and *LL* are ordinary chondritic meteorites; *CV* and *CM* are types of carbonaceous chrondrites, and the *CI* type is the most primitive carbonaceous chondrite meteorite (see McSween 1999, for more details on classification). The two *open circle* patterns in the Planets and Planetoids Column represent my prediction for the position of the potassium abundance (normalized to U) for planets Venus and Mercury. [Note: There is limited information from Venus via the Venera 8 mission. Vinogradov et al. (1973) report that the K/U ratio for magmatic rocks of Venus is very similar to magmatic rocks on Earth]. (Diagram adapted from Humayun and Clayton (1995, Fig. 1), with permission from Elsevier)

Tabachnik (1999, 2002) and others will collide, fragment, and eventually accrete onto a Vulcanoid planetoid in a more stable orbit.

Concomitant with the generation of the refractory CAI material, thermal pulses associated with the X-Wind systematically devolatilize the material in the proto-solar mid-plane as well as the region of the terrestrial planets and perhaps the Asteroid Zone. Taylor (2001, p. 110) suggests that temperatures as high as 1500 °K at 2.5 AU may have been attained spasmatically during the early stages of infall of gas along the nebular mid-plane. These high temperature pulses can be intimately associated with the solar accretion cycles fueling the X-Wind activities. Perhaps the Potassium abundance normalized to Uranium (the K-Index) in Fig. 2.4 is a product of this devolatilization of the inner part of the Solar System. While solar magnetic field line snapping and reconnection activity is releasing very high energy thermal pulses that systematically devolatilize the material near the nebular mid-plane, some Vulcanoid planetoids have close encounters with sibling planetoids and are perturbed into the proto-sun while others are propelled to more distant regions of the Solar System: i. e., into the realm of the terrestrial planets. As the X-Wind action gradually diminishes due to a decreasing volume of material infalling along the nebular mid-plane, the newly formed CAIs as well as any material left over from previous cycles will accrete into larger bodies that are in somewhat stable orbits.

As the X-Wind phase of solar accretion, radiation, material generation, and devolatilization diminishes, there is a gradual shift to the Disk-Wind (Salmeron and Ireland 2012) activity. The wavelength and intensity of the resulting radiation is lower but the magnetic-field-generated thermal pulses continue. The Disk-Wind proceeds to "flash melt" dusty materials that have sufficient density to be processed into glass beads (chondrules). The dust that results in chondrule formation has already been systematically devolatilized with the volatiles being removed to the outer regions of the terrestrial planet realm, the Asteroid Belt, and on out to the heliocentric distance of the orbit of planet Jupiter.

As the Disk-Wind processes dust into chondrules, flash melting cycle after flash melting cycle, the chondrules along with a low percentage of CAI material, as well as the material still falling in along the nebular midplane accrete to form a multitude of planetoids that eventually accrete into the terrestrial planets. The chemistry of the resulting terrestrial planet is determined by the material in its accretion torus and the state of devolatilization of the material in the torus changes with heliocentric distance from the heat source (the proto-sun).

Following the major phases of terrestrial planet formation, the proto-sun still has material periodically falling in along the mid-plane. The resulting radiation events in the microwave range can be related to the FU Orionis model (Bell et al. 2000; Calvet et al. 2000). The thermal "spikes" (to be discussed in the next section of this chapter) occur with a frequency of a few 10^3 years. I propose that the FU Orionis sequence of thermal-radiation events is responsible for melting, or remelting, all Vulcanoid planetoids between 0.10 AU and the orbit of planet Mercury as well as partially melting the outer portion of planet Mercury. This sequence of heating events could cause thermal (and hydrothermal, if water is available) metamorphism in the region beyond planet Mercury. Future modeling will help to determine the extent of this thermal activity.

A major question raised by this discussion is: Which is more important for determining the original heliocentric distance of formation of a planet or planetoid? Is it the K-Index or is it the ratio of Oxygen Isotopes on a Δ^{17}O vs. Δ^{18}O plot?

Since the X-Wind thermal-radiation events would be the most powerful and the CAIs form only during the waning stages of the X-Wind action, I think that the X-Wind activity, in its earlier stages, is the main cause of the devolatilization. The newly formed and accreting bodies are small at this stage so that the thermally-powered devolatilization process is very efficient. The X-Wind activity would transition into the Disk-Wind heating and "flash-melting" events which are gradually decreasing in intensity throughout the chondrule-forming events and the subsequent small-body accretion events.

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