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Making Sense of Chondrite Meteorites

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ABSTRACT

I describe the simplification of multitudes of complex data on hundreds of chondrite meteorites to obtain a fundamental relationship that underlies processes during solar system formation. From the relationship derived, generally, it can be concluded that only three processes, operant during solar system formation, are responsible for the diversity of matter in the solar system, as well as for planetary compositions , internal-structures, dynamics and magnetics: (1) Condensation at very high-pressures; (2) Condensation at very low-pressures; and (3) Scouring of the inner solar system by the T-Tauri eruptions during thermonuclear ignition of the sun.

INTRODUCTION

Momentary streaks of light flashing across the night sky, called "shooting stars", are produced when meteors from outer space burn up as they come crashing to Earth (Figure 1). Occasionally, a meteor will survive the fiery trip through the atmosphere, land, and be recovered – then it is called a meteorite. The history of meteorite investigations is rich with the adventure of discovery. Meteorites are the fragmental remains from the time when our solar system was forming, the bits and pieces from which we can derive the nature of processes operant in that ancient time. Through tedious efforts to connect logically and causally seemingly unrelated observations, we can begin to understand the origin of our solar system, the commonalities and differences among the planets, and the nature of planetary interiors.



Figure 1. Meteor lighting the night sky as atmospheric friction melts away its outer surface. Photo courtesy of Alexander Andrews, unsplash.com

Seismological measurements, augmented by moment of inertia considerations, can reveal the structure and physical states of matter within the Earth but not its chemical composition. Presently, that knowledge necessarily must come from inferences drawn from meteorites. Here I simplify the multitude of complex data on hundreds of chondrite meteorites to obtain a fundamental relationship that underlies processes during solar system formation.

METEORITES FROM OUTER SPACE

The ancient literature is sprinkled with accounts of "special" stones, some of which are said to have fallen from the sky, but nearly all accounts are colored with implications of spiritual significance or supernatural properties [2]. The oldest documented, still-preserved "sky-stone" was suspended by a chain in the parish church of Ensisheim in Elsass. Figure 2 shows a hand-colored woodcut depicting the 1492 fall of the Ensisheim meteorite The circumstances of its fall to Earth and collection are described in the following translated extract of one of that church's documents [3]:

"On the 16th of November, 1492, a singular miracle happened: for between 11 and 12 in the forenoon, with a loud crash of thunder and a lasting noise heard far off, there fell in the town of Ensisheim a stone weighing 260 pounds. It was seen by a child to strike the ground in a field near the canton called Gisgaud, where it made a hole more than five feet deep. It was taken to the church as being a miraculous object. The noise was heard so distinctly at Lucerne, Villing, and many other places, that in each of them it was thought that some house had fallen. King Maximilian, who was then at Ensisheim, had the stone carried to the castle: after breaking off two pieces, one for the Duke Sigismund of Austria and the other for himself, he forbade further damage, and ordered the stone to be suspended in the parish church."



Figure 2. Hand-colored woodcut showing the 1492 fall of the Ensisheim meteorite [4]. Photo courtesy of Jörn Koblitz, MetBase Library, 2011

As late as the latter part of the eighteenth century, the natural event of stones falling from the sky seemed too dubious even for scientists to acknowledge. In a paper read before the American Physical Society, March 4th, 1808, Benjamin Silliman and J. L. Kingsley described circumstances of the meteorite shower that occurred on December 14th, 1807 in Fairfield County, Connecticut and the composition of the recovered stones [5]. They said this about the origin:

- These bodies did not originate from this earth.
- They all came from a common source, but that source is unknown.

After reading the Silliman and Kingsley article [5], U.S. President Thomas Jefferson is said to have remarked that it was easier to believe that two Yankee professors would lie than that stones would fall from heaven [6]. Whether urban legend or fact, Jefferson's remark expresses well the widespread skepticism regarding "sky-stones." That skepticism, though, had already begun to abate as further detailed reports had begun to emerge [7]. Then, a great meteorite shower occurred in the early afternoon of April 26th, 1803 in l'Aigle, Lower Normandy, France. The sound of a violent explosion was heard for a distance of 120 km, the fireball was seen from several towns, and two or three thousand stones rained down. The exhaustive report by Jean-Baptiste Biot and the conclusive nature of his arguments "compelled the whole of the scientific world to recognize the fall of stones on the earth from outer space as an undoubted fact" [3, 8].

Now, no longer the subject of fanciful speculation, meteorites became the objects of serious scientific investigations. Collections of meteorites were put on prominent public display in museums, first in Europe, and then throughout the world. Their identification as objects from outer space undoubtedly contributed to their new found popularity. Interestingly, though, the

originator of their extraterrestrial identification was neither Biot [8], nor Silliman and Kingsley [5], but Chladni [9].

Ernst F. F. Chladni, whose reputation had been established by his investigations of the laws governing sound, brought together various observer accounts of bodies falling from the sky. In particular, he called attention to two specific masses of iron metal that he asserted in all probability had arrived on Earth from outer space. One of those masses, originally weighing 682 kg, called the Krasnojarsk meteorite (Figure 3), had been found by a Cossack on the surface of a high mountain in Siberia in 1749. The other, referred to as the Tucuman iron, had been found by Indians searching for honey and wax in the woods of Tucuman in Argentina.



Figure 3. Hand-colored drawing of the Krasnojarsk meteorite from [10]

Chladni argued that neither of those masses of iron could have formed from aqueous processes as each had evidently been exposed to great heat and slowly cooled. The absence of evidence of fire in each area, the extremely hard and pitted crust, the ductility of the iron metal, and, in the case of the Krasnojarsk meteorite, the regular distribution of olivine-filled pores, to Chladni, precluded any theory that they might have originated where found, whether by natural phenomena, such as lightning, volcanoes, or by accidental conflagration. Further, he sought to show that the flight of such heavy objects from space would be the direct cause of the luminous fire-ball observed in other meteorite falls.

During the next two centuries, meteorites were investigated in every conceivable way, drawing upon the skills of mineralogists, metallurgists, chemists, and physicists. As new analytical techniques came into practice, they were applied to meteorites. The overall result was that meteorites were found to be quite diverse. By the middle of the nineteenth century, Partsch [11] recognized two main categories of meteorites that fall from the sky: Stone and Iron. Note, though, the Krasnojarsk iron is not simply an iron, but a collection of olivine crystals, the gemmineral peridot, in a nickel-iron metal matrix. Although still comparatively rare, other stony-

iron meteorites like this are known, some even contain the mineral pyroxene instead of olivine. The more deeply one looks, the more diverse meteorites seem, but amid seeming diversity there was to be found some sense of order and understanding relating to the nature of the Earth [12-15] and to other objects in the solar system [14].

CONNECTION BETWEEN EARTH AND METEORITES

In 1850, Boisse [16] suggested that the composition of meteorites is relevant to the bulk composition of planet Earth. A boost of support for that idea came almost half a century later from the mind of the German seismologist, Emil Wiechert, who lived during a time of extensive industrial iron-making in Europe and was acquainted with the process of molten iron metal settling beneath slag. Wiechert had seen iron meteorites in museums, as well as stone and stony-iron meteorites. Realizing that the mean density of Earth, as measured by Cavendish [17], is too great for the Earth to consist entirely of rock, Wiechert suggested in 1897 that the Earth has at its center a core of iron metal, like the metal of iron meteorites [18]. Less than a decade elapsed before Wiechert's idea received a boost of support from Richard D. Oldham's seismological discovery of the Earth's core [19].

But neither Boisse's suggestion [16] nor Wiechert's idea [18], even in light of Oldham's discovery of the Earth's core [19], could be considered anything more than circumstantial evidence of a connection between the elements of Earth and those of meteorites. New techniques, new measurements, and more precise understanding would be necessary. The mid-nineteenth century idea that there were just two categories of meteorites, stones and iron, while seemingly a grand simplification, obscures the underlying complexity and hides the great diversity [11].

If rocks are cut into very thin slices, many of their minerals become translucent and can be identified microscopically through their response to polarized light [20]. In 1858, Sorby [21] first applied the microscopic thin-section technique to rocks and minerals as a way of gaining insight into their origins. In 1877, when he observed thin-sections of meteorites, Sorby discovered in some a plethora of spherules, typically 0.1-1.0 mm in diameter, called chondrules, that he described as "detached glassy globules, like drops of a fiery rain" [22], in other words, freely suspended, solidified molten droplets whose shape was determined by the surface tension of the melt.

Figure 4 is a modern photomicrograph of a thin-section of an ordinary chondrite showing numerous chondrules.



Figure 4. Thin section of the Brownfield (1937) ordinary chondrite showing a plethora of chondrules. The colors arise from the use of polarized light. Image courtesy of J. M. Derochette

In principle, chondrules, such as shown in Figure 4, might arise from a variety of energetic event mechanisms, such as impact melting [23]. No explanation, however, may be closer to truth than the explanation proposed by Sorby [22]: "residual cosmic matter, not collected into planets, formed when conditions now met with only near the surface of the sun extended much further out from the centre of the solar system".

After Sorby [22], stone meteorites were widely thought of as being either chondrites or achondrites, *i.e.*, possessing or not possessing chondrules. Even today books frequently begin with that classification scheme, but it can be confusing.

Presently, chondrites are classified into fifteen or sixteen groups depending on elemental composition and petrology [23, 24]. For some, such a high degree of classification may be of great value. There is, however, another view wherein one seeks to simplify and to identify the common threads that can be related to fundamental processes. The latter approach has proven to be of great value relating to meteorite impacts on geo- and space science [25].

Wiechert's suggestion that Earth has a core of iron, similar to iron meteorites [18], in conjunction with the discovery of the Earth's core [19], strongly suggested a connection between Earth and meteorites. Soon, that connection was firmly established.

Theodore W. Richards received the 1914 Nobel Prize in Chemistry for making precise measurements of atomic weights. Richards observed that copper from Germany and copper from America have the same atomic weight. He also observed that iron from the Earth has the

same atomic weight as iron from a meteorite. Interestingly, in his Nobel Lecture, Richards [26] noted:

"If our inconceivably ancient Universe even had any beginning, the conditions determining that beginning must even now be engraved in the atomic weights. They are the hieroglyphics which tell in a language of their own the story of the birth or evolution of all matter, and the Periodic Table containing the classification of the elements is the Rosetta Stone which may enable us to interpret them."

A year before Richards' Nobel Prize, Joseph John Thompson discovered that the atomic weight of an element is really an expression of the weighted average of the weights of its individual components, later called isotopes [27]. Isotopic composition is like a fingerprint, forged at the element's birth and, particularly for heavy elements, is virtually unalterable. Thompson made the crucial discovery by being the first to separate an element into its components by electrostatic means in a cathode-ray tube; in this case the element was the illuminating gas neon.

Francis William Aston followed, inventing the mass spectrograph and with it eventually identified about 70% of the 244 naturally occurring stable isotopes now known to exist [28]. Soon scientists throughout the world began to measure isotopic compositions, the fingerprints of the elements from the Earth and from meteorites, and found each element to be identical (Figure 5), except in a few very special circumstances. In other words, the Earth and the meteorites (and, found later, the Moon) formed from well-mixed matter of common origin. The similarity of isotopic fingerprints of Earth and meteorites, however, says nothing of how much of each element was present in the original mix, but that too was subsequently learned.



Figure 5. Comparison of corresponding isotope ratios of 18 elements in terrestrial and meteorite samples. Insets illustrate the isotope "fingerprints" of the elements molybdenum (Mo) and tin (Sn)

Understanding the nature of the solar spectrum was developed during the early part of the nineteenth century, which made it possible to detect the presence of elements in the photosphere of the sun. By 1893, forty one elements were claimed to have been identified in the sun by the absorption lines in the solar spectrum [29].

In the 1920s, astronomers began to tackle the extremely difficult problem of determining the relative amounts of the elements identified through their absorption lines in the atmosphere of the sun [30]. Almost immediately, the relative abundances of elements in the sun and in chondritic meteorites were realized to be quite similar [31]. Yet decades elapsed before a tenfold discrepancy in the abundance of iron was resolved [32].

Evidence indicates that the solar system formed from well-mixed matter having a well-defined chemical composition. Subsequently, physical and chemical processes separated elements from one another. That was clearly the case for iron meteorites among others. Chondrite meteorites are important as many of their non-volatile chemical elements were not separated from one another to any great extent. Even so, chondrites differ substantially from one another.

Chondrites can be divided in to three main groups:

- Carbonaceous Chondrites
- Enstatite Chondrites
- Ordinary Chondrites

The first two groups are comparatively rare, constituting about 2% of the meteorites that were seen to fall and were recovered. By comparison ordinary chondrites are so much more abundant that they were named "ordinary." There is variation even within the groups.

The oxygen-rich Orgueil carbonaceous chondrite and the oxygen-poor Abee enstatite chondrite were found to have quite similar corresponding elemental abundance ratios in the sun, at least for the less-volatile elements, as shown in Figure 6 [33-38]. Moreover, the abundances of the elements were discovered to be related, although in a complex way, to nuclear properties [39]. No longer a circumstantial connection, now it can be said with reasonable certainty that the primordial matter from which Earth, and, presumably, all the bodies of the solar system formed, had a well-defined chemical composition, and that composition to a great extent is yet manifest in the photosphere of the sun and, for less-volatile elements, in certain chondrites, such as Orgueil and Abee.



Figure 6. Comparison of relative element atom-abundances, normalized to iron, in the sun and in the Orgueil carbonaceous chondrite and in the Abee enstatite chondrite

ORGUEIL AND ABEE METEORITE COMPARISON

The two chondrites, Orgueil and Abee, shown in Figure 6 are "primitive" in the sense that their relatively non-volatile element ratios are quite similar to those measured in the photosphere of the sun. Yet these two chondrites are strikingly different. Orgueil is comprised of oxygen-rich low-temperature minerals and even arrived containing water of extra-terrestrial origin [40]. Abee, on the other hand, is composed of oxygen-poor high-temperature minerals and even contains some minerals not found on Earth [41].

Orgueil: On May 14, 1864, a meteorite shower occurred near Orgueil in southern France. About twenty stones were collected (Figure 7) and examined [42, 43]. Eventually, pieces of the Orgueil meteorite were disseminated to museum collections throughout the world which helped to ensure continuing investigations. The Orgueil meteorite is one of just five uniquely similar chondrites that have been variously classified as a "*Type I Carbonaceous Chondrites*" or "*C1 Chondrites*."



Figure 7. Nineteenth century drawing of stones from the 1864 Orgueil meteorite shower. Photo courtesy of Jörn Koblitz, MetBase Library, 2011

In terms of mineralogy and oxidation state, the C1 chondrites are quite unlike other chondrites. Specifically [44, 45]:

- They possess no chondrules.
- The major silicate is a clay-like, hydrous, layer-lattice silicate, instead of the crystalline silicate minerals common to other chondrites.
- Sulfur occurs as the salt, magnesium sulfate, rather than as a sulfide.
- Instead of iron metal, the major iron mineral is magnetite, Fe_3O_4 .

Figure 8 is a series of scanning electron microscope images of magnetic separates from a sample of the Orgueil C1 chondrite.



Figure 8. Secondary electron images of Orgueil magnetic separates. From [46], courtesy of Olga Pravdivtseva

In primordial matter, with a composition similar to the photosphere of the sun, oxygen on an atom basis was eight times as abundant as the sum total of all of the readily condensable elements. If appropriate thermodynamic conditions prevailed, then virtually all condensable elements from that primordial mix would end up as oxides, just like the minerals of C1 chondrites [47]. So, what were those thermodynamic conditions?

In a gas of solar composition, where hydrogen is a thousand times more abundant than iron, the oxygen partial pressure or oxygen fugacity [48] is governed by the pressure-independent gas-phase reaction:

$H_2 + \frac{1}{2}O_2 = H_2O$

Condensation, on the other hand, is a direct function of pressure. At high pressures, substances condense at high temperatures where oxygen is limited, whereas, at low pressures condensation occurs at low temperatures where oxygen is readily available. The matter of the Orgueil C1 chondrite is highly oxidized and can be understood as having formed from primordial matter that condensed at low pressures and low temperatures in the outer regions of the solar system or in interstellar space [12].

The spherical morphology of some of Orgueil's magnetite (Figure 8) appears to have arisen as the consequence of surface tension during condensation while freely suspended in a gas. Similar spheres occur in abundance in coal fly ash which forms by condensation in the hot gases above industrial coal-burners (Figure 9).

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Figure 9. Upper right: Spherical Orgueil magnetite separates from Figure 8b [46]; Upper left: Spherical magnetic particles from coal fly ash [49]; Lower: Back-scattered electron image of a polished section of coal fly ash embedded in epoxy. Note the predominant spherical morphology obtained as a consequence of condensation in a gas. Courtesy of Webeggs: CC BY-SA 3.0

Some of Orgueil's magnetite spheres appear deformed [46]. If that deformation occurred as the result of collisions during condensation, it might suggest that some degree of hydrogen depletion, relative to solar matter, occurred which would result in magnetite condensation occurring at temperatures above 400° K [47, 50].

Abee: In 1862, Nevil Story-Maskelyne discovered in one of the enstatite-meteorites a calcium sulfide mineral, CaS, unlike any mineral known to occur naturally on the Earth's surface. He named the mineral oldhamite [51]. Later, within an oldhamite nodule from the same meteorite, Bannister [52] discovered another "unearthly" natural mineral, composed of titanium nitride, TiN, that he named osbornite.

Enstatite chondrites, containing some strange minerals such as these, are unique in having formed under oxygen-starving, highly-reducing conditions. They are the most highly reduced, i.e., least oxidized, naturally occurring mineral assemblage known. As a consequence, their major silicate, enstatite, MgSiO₃, is nearly devoid of oxidized iron. Moreover, their iron metal contains silicon [53].

On June 9, 1952 the Abee enstatite chondrite fell to ground in Alberta, Canada [54]. A single mass was recovered five days later from a wheat field. Figure 10a shows a nearly complete slice of the roughly basketball-size, 107 kg Abee enstatite chondrite. Abee has been described as an explosion breccia because of its angular fragments [55], but its morphology is quite unique. Peripheries of some of the angular components are shiny, enriched in iron metal that was clearly molten. Figure 10b, is a micrograph showing crystals of the major silicate-mineral, enstatite (MgSiO₃) embayed (surrounded) by iron metal which was liquid at a time when the mineral crystal was solid. Figure 10c is a micrograph of the iron metal, etched with acid, that reveals platelets of *pearlite*, iron carbide, indicative of relatively rapid cooling. M. Lea Rudee and I in 1978 [56] and 1981 [57] published the results of metallurgical experiments that showed during its formation Abee last cooled from 700°C to 25°C in ten hours.



Figure 10. (A) Nearly complete slice of the Abee enstatite chondrite. (B) Micrograph showing its enstatite crystals surrounded by previously molten iron metal. (C) Micrograph showing platelets of iron carbide in its metal [56, 57]

Before 1976, no one understood how the oxygen-starved (highly reduced) parent matter of an enstatite chondrite could have formed from primordial solar matter with the composition of

the sun's photosphere. In 1976, Herndon and Suess [58] showed that condensates at high-temperatures and high-pressures would be oxygen-starved, like the Abee parent matter, provided that such condensate was isolated from reaction with the gas at lower temperatures.

ORDINARY CHONDRITES

The ordinary chondrites are so-named because they represent the great majority of meteorites that were observed to fall and were recovered [59]. Because of their great relative abundance, ordinary chondrites have impacted geo- and space science without the origin of ordinary chondrites ever having been known [60]. Like the thin-section example shown in Figure 4, ordinary chondrites typically display evidence of exposure to high-temperatures. These are composed of iron metal and silicate-rock, along with some iron sulfide.

If an ordinary chondrite is heated to an elevated temperature, the iron metal and iron sulfide meld forming a liquid alloy at temperatures at which the silicates are solid. In a gravitational field, the liquid iron alloy settles beneath the less dense silicates. Since at least the 1940s the interior of Earth, with its liquid iron alloy core and solid silicate mantle, was thought (erroneously) to resemble an ordinary chondrite [61-65]. But unlike the oxygen-poor minerals of the Abee enstatite chondrite, the silicate minerals of ordinary chondrites contain copious amounts of oxidized-iron (FeO).

The major minerals of ordinary chondrites are the following [66].

- Olivine (Mg, Fe)₂SiO₄
- Pyroxene (Mg, Fe)SiO₃
- Troilite (Iron Sulfide) FeS

In the 1960s and 1970s computational models attempted to show (erroneously) that the minerals characteristic of ordinary chondrites could condense from an atmosphere of solar composition [67-69]. However, the FeO content of ordinary chondrite silicates is thermodynamically *inconsistent* with condensation from a gas of solar composition, but *is consistent* with condensation from a gas that is depleted in hydrogen by a factor of a thousand relative to primordial matter [50] and depleted in oxygen by a factor of "several", implying a condensation process involving the re-evaporation of condensed matter after separation from the primordial gases [47].

SIMPLIFICATION FOR UNDERSTANDING

Two centuries of investigations of meteorites by chemists, physicists, metallurgists, mineralogists and petrologists have led to a vast amount of data on hundreds of chondrite meteorites that can be grouped in ways which to a great extent differ from one another. Investigators apply different methodologies in attempts to interpret those data. Some, for example, plot element ratios for different chondrites, e.g., Ir/Ni vs. Ga/Ni, and look for groupings or trends. My own approach differs from others in that I attempt to reduce the many-component problem to one of just a few fundamental components that can be understood.

In 1923, Goldschmidt [70] introduced the idea of simplification by dividing elements into four groups based upon their chemical behavior:

• *Siderophil* – elements concentrated in iron metal

- *Chalkophil* elements concentrated in sulfide magmas
- *Lithophil* elements concentrated in silicate magmas
- *Atmophil* elements concentrated in the atmosphere

That simplification, I later realized, is ambiguous within the Earth. Whether an element, such as calcium, occurs as a sulfide (CaS), initially within Earth's core, or as an oxide (CaO), within the mantle or crust, depends upon the prevailing oxidation state [71, 72].

The simplification method that I find most useful is based upon elemental abundances [47]. As shown in Figure 11, only five major chemical elements account for about 95% of the mass of a chondrite, and by implication, the mass of the Earth:

- Iron (Fe),
- Magnesium (Mg),
- Silicon (Si),
- Oxygen (0), and
- Sulfur (S).

On a molar (atom) basis, iron, magnesium, and silicon are about equally abundant in chondrites. Because of their great relative abundance, conclusions derived, for example, from thermodynamic considerations, cannot be materially altered by any of the other elements. There are simply not enough of the other elements present to make a significant difference. Those five major elements comprise a buffer assemblage that controls the oxidation state. Minor and trace elements are slaves to that buffer assemblage. The minor and trace elements, however, provide a wealth of additional details.



chondrite

CHONDRITE RELATIONSHIPS

For decades, the abundances of major elements in chondrites have been expressed in the literature as ratios, usually relative to silicon (Ei/Si) and occasionally relative to magnesium (Ei/Mg). By expressing Fe-Mg-Si elemental abundances as atom (molar) ratios relative to iron (Ei/Fe), as shown for comparison in Figure 12, I discovered a fundamental relationship bearing on the origin of ordinary chondrite matter [73].



Figure 12. The same major element chondrite data plotted three different ways. The plot on the right, originated by me, shows a relationship that is not evident in the other plots

The rightmost plot of Figure 12 is presented in greater detail in Figure 13 which shows atom (molar) ratios of Mg/Fe vs. Si/Fe from analytical data on 10 enstatite chondrites, 39 carbonaceous chondrites, and 157 ordinary chondrites. The well-defined, linear regression lines are evident only when normalized to Fe, not to Si or Mg. The ordinary chondrite points scatter about a line that intersects the other two lines. Points on the ordinary chondrite line can be represented by mixtures of the two intersecting compositions, point A: *primitive*, and point B: *planetary*. For more detail, see [73]. Near points of intersection, 95% confidence intervals are shown.



Figure 13. Atom (molar) ratios of Mg/Fe vs. Si/Fe from analytical data on 10 enstatite chondrites, 39 carbonaceous chondrites, and 157 ordinary chondrites. Least squares linear regression lines are shown. Near points of intersection, 95% confidence intervals are shown. For references and more detail, see [73]

The relationship I discovered, shown in Figure 13, implies that ordinary chondrites were derived from mixtures of two components, representative of two other types of matter, designated *primitive* and *planetary* and defined by the intersecting points along the ordinary chondrite line. The ordinary chondrites consist of mixtures of a relatively undifferentiated carbonaceous-chondrite-like *primitive* component and a partially differentiated enstatite-chondrite-like *planetary* component where it molar (atom) iron content is only one third that of its magnesium and its silicon content.

The *planetary* component, I posited, was the partially differentiated matter stripped from Mercury's protoplanet by the T-Tauri super-intense solar winds where, in the region between Mars and Jupiter, it fused with in-falling primitive matter [73]. The ordinary-chondrite parent matter thus formed populated the asteroid belt (Figure 14) and added a veneer that fell onto the outer portion of Earth, and to a greater relative degree, onto Mars.



Figure 14. The inner solar system showing the plethora of asteroids

CONCLUSIONS

Since the first hypothesis about the origin of the sun and the planets was advanced in the latter half of the 18th Century by Immanuel Kant and modified later by Pierre-Simon de Laplace, various ideas have been put forward. From the relationship derived here, generally, it can be

concluded that only three processes, operant during solar system formation, are responsible for the diversity of matter in the solar system [12, 14], as well as for planetary compositions, internal-structures [13], dynamics [1] and magnetics [15, 74]:

- Condensation at very high-pressures,
- Condensation at very low-pressures, and
- Scouring of the inner solar system by the T-Tauri eruptions during thermonuclear ignition of the sun.

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