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## The evolution of meteorites and planets from a hot nebula



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**Abstract** Meteorites have a hot origin as planetary materials derive from a supernova, similar to SN1987A, and were acquired by a nearby nova, the Sun. The supernova plasmas became zoned around the nova, mainly by their electromagnetic properties. Carbon and carbide dusts condensed first, followed, within the Inner Planetary Zone, by Ca–Mg–Al oxides and then by iron and nickel metal droplets. In the inner Asteroid Belt, the metals aggregated into clumps as they solidified but over a much longer time in the Inner Zone. ‘Soft’ collisions formed larger ( $< \sim 20$  km) objects in the Asteroid Belt; in the Inner Zone these aggregated forming proto-planetary cores during inwards orbital migration. In the Asteroid Belt, glassy olivines condensed, followed more open lattice minerals growing primarily by diffusion. Brittle silicate crystals were comminuted and only aggregated into the carbonaceous meteorites when water–ices formed. The inner planets differentiated by at least 4.4 Ga. Jupiter and the outer planets grew on asteroidal bodies thrown out into freezing water vapours and only formed by 4.1 Ga, resulting in the Late Heavy Bombardment, initially by meteoritic materials and later supplemented by ices from, and beyond, the Asteroid Belt. Critical factors are the properties of very high temperature supernova plasmas, the duration of the molten iron phase in the inner zone. Evidence usually quoted for a cold origin derives from late stage processes in hot meteorite evolution. While highly speculative, it is shown that meteorites and planets can be formed by known processes as supernova plasmas cool.

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### 1. Introduction

The evidence for whether meteorites formed at high or low temperatures is apparently ambiguous, yet this is fundamental for any understanding of the origin of the Solar System. The oldest components of the oldest meteorites, the highly refractory spheroids (chondrules and Al-rich and Ca–Al inclusions) show clear evidence of partial to total melting (Kurat et al., 2004) indicating temperatures  $> 1500$  °C. Some of their olivine glasses similarly require a very hot, molten origin (Varela et al.,

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2005). In stark contrast, the fine-grained minerals that mantle such spherules include serpentinites, clays and other hydrous minerals that would be destroyed if subjected to even moderate ( $\sim 50$ – $100^\circ\text{C}$ ) temperatures. This coldness was apparently supported by the presence, in meteorites, of ‘reservoirs’ of different isotopic ratios, particularly oxygen (Clayton, 1993). These are considered to have formed by a variety of processes (Clayton, 1993, 2002; Yurimoto and Kuramoto, 2004), long before the Solar System began to form, and then remained cold until now. Such observations are widely taken to indicate that the meteorites, and hence the Solar System, formed under cold conditions. Consequently the presence of molten materials has been considered anomalous and their origin is generally attributed to the chondrules and refractory inclusions having formed as melts in very high temperature zones, close to the Sun, and were then transported into the cold regions of the asteroid belt (Cohen et al., 2004; Shu et al., 2001; Sears, 2004), probably by solar flares but it is unclear why such flares did not heat the reservoir regions. A “cold” origin is contradicted by the meteorites containing elements and isotopes that can only have been created in a supernova and were incorporated into their crystalline mineral hosts within less than 1 Myr of the explosion (Desch et al., 2004; Srinivasan et al., 1996) – possible within a only few thousand years (Luck et al., 2003). As this supernova was very close, less than a light-year (Tarling, 2006), it is inevitable that any pre-existing nebula would have been very strongly heated. Temperatures of  $\sim 1\text{ M}^\circ\text{C}$  are indicated by the nebula remnants heated by supernova SN1987A (Section 2). A “hot” model (Tarling, 2006) is that the Sun had initially been a Gas Giant, of similar size to Jupiter, orbiting the evolving supernova star. This Gas Giant became a nova as hydrogen was accreted from the supernova prior to its explosion and was then protected by its intense electromagnetic activity when the explosion occurred. While this somewhat complicated conjecture forms the sequence for describing the proposed evolution of meteorites (Section 3), most of the processes described in Section 4 onwards would characterize the conditions for any “hot origin” model of the Solar System’s origin. For all such hypotheses, the nature and properties of very high temperature supernova plasmas are fundamental, as they are for cosmological theories. As such plasmas cannot be studied in existing laboratories, their properties are best assessed from observing how they behave in the observed supernovae (Section 2).

## 2. SN1987A – plasmas, dark energy and dark matter

The explosion of a Type II (core-collapse) supernova, SN1987 some  $169 \pm 5$  kyr from the Earth, in the Large Magellanic Cloud, was first seen on February 23rd 1987. Its subsequent evolution has been monitored principally by NASA, using Hubble and the Chandra X-ray Observatory, together with the European Space Agency and JPL-Caltech using NASA’s Nuclear Spectroscopic Telescope Array. It has therefore been intensely studied since it formed. (These agencies are also the main sources for most of this section.) Within four days of the initial observation, the progenitor star was identified on earlier images as being Sandeleak 69° 202, a  $\sim 20$  solar mass Blue Giant. This star had previously been a Red Giant so it would have evolved the usual onion-like structure of concentric shells, with nuclear fusion occurring at the inner

boundaries of each shell and iron “ash” accumulating in its core. A “helium flash”, some 20,000 years earlier, had blown off its external hydrogen shell, so the top of the helium shell became its surface. This hydrogen joined two older debris rings thrown out by earlier violent phases (Fig. 1a where they are illuminated by light from the explosion). The “helium flash” briefly reduced the pressure on the top of the core, reducing the rate of fusion, but iron “ash” continued to accumulate in the core until its mass reached 1.44 solar mass. At that instant, the core fusion ceased and the core rapidly collapsed on itself. The overlying shells immediately began collapsing downwards, but at a slightly slower rate. Pressures within the core became so high that electrons and protons were forced together, forming a small neutron star. The infalling shells raised the already high internal temperature by a further  $10^{6-9}$  degrees (Haxton, 2004). At these extremes of pressure and temperature heavy elements, up to, and probably beyond, Californium ( $^{254}\text{Cf}$ ) were created by the neutron capture process. All of these events, from the start of core collapse to the creation of heavy elements, took place in milliseconds. The pressure wave from the implosion spread upwards, colliding with the infalling shells, and became a shock wave travelling outwards. The explosion, now known to be asymmetric, blasted the neutron star into space together with all other debris in the form of extremely hot, highly ionized plasmas. The initial high luminosity of the explosion (equivalent to 100 M Suns) was dominated by the contributions from radioactive decay. Initially  $^{56}\text{Ni}$  to  $^{58}\text{Co}$  and then to  $^{56}\text{Fe}$  during the first few months; this also generated a burst of



**Figure 1a** Supernova SN1987A in 2004. A wide view showing the surrounding debris as three rings. The inner ring comprises hydrogen blown off when the progenitor Red Giant became a Helium Giant some 20,000 years earlier. These became readily visible when light, mainly UV, from the explosion illuminated it. The bright spot “necklace” is the result of the impact of shock waves that began to arrive in 2001. Credit for the image ESA NASA/Hubble hs-2004-09.

high-energy protons. The peak luminosity was due to  $^{56}\text{Ni}$  to  $^{56}\text{Co}$ , and was followed by the decay of  $^{56}\text{Co}$  to  $^{56}\text{Fe}$ . The decay of  $^{44}\text{Ti}$  still continues. The light radiation, dominated by UV, began to reach the inner hydrogen ring after six months, heating it to  $>11,000^\circ\text{C}$  and generating a burst of X-rays. The two outer rings became more visible shortly after as the light reached them. The illumination of the inner ring gradually faded, but some 11 years later, a bright spot appeared in the inner ring as shock waves began to reach it, increasing its brightness, raising its temperature by up to  $1\text{ M }^\circ\text{C}$  and creating an X-ray flux. Subsequently, a “necklace” of bright spots appeared as the shock waves reached more distant clumps of debris within the inner ring (Fig. 1b). At the centre of the inner ring are two individual blobs that are separating from each other at some  $2\text{--}3\text{ M km/h}$  (Fig. 1b centre) and are the plasmas travelling outwards at around  $1/36\text{th}$  of the speed of light.

Clearly, this supernova is still evolving. Its plasmas should arrive at the inner ring during the next few decades and will provide further information, not only on SN1987A, but on the properties and behaviour of supernova plasmas that are applicable to many other astronomical events, especially the earliest phases of the Solar System and the early “inflation” period of the Universe’s evolution. It is noteworthy that the space within the inner SN1987A ring contains a volume that contains the remains of  $\sim 20$  solar mass and an enormous amount of electromagnetic, kinetic, chemical, latent and radioactive energy. The two central blobs currently reflect some of the light from the inner ring, but otherwise appear dark – suggesting that the protons in the plasmas have cooled sufficiently to combine with single electrons, forming opaque



**Figure 1b** Supernova SN1987A in 2004. A more detailed view showing the innermost debris ring being illuminated by shock waves from the explosion. The two central, fuzzy blobs are separating at  $2\text{--}3\text{ M km/h}$ . A neutron star of  $\sim 1.4$  solar mass was probably ejected from the area when the explosion occurred. The plasmas generated by the explosion have not yet reached the outer debris rings. These are at the centre of the inner ring and carry very high energy and considerable mass, of the order of  $20$  solar mass, and are dark because their temperature means that hydrogen is opaque. Hence these are one of the locations of the so-called ‘Dark Matter’ and ‘Dark Energy’ that are missing from current cosmological concepts. Credit for the image ESA NASA/Hubble hs-2004-09.

neutral hydrogen. They are truly dark matter and carry an enormous amount of energy (Section 8). However, from the point of the evolution of meteorites and planets, it is essential to recognize that such very highly ionized supernova plasmas will be extremely sensitive to electromagnetic fields and relatively insensitive to gravitational fields.

### 3. Just prior to the supernova

This section is somewhat model dependent, i.e. it assumes a supernova explosion close to a very new star. The progenitor supernova star is considered to be almost identical to SN1987A so it had been a Red Giant star that similarly threw off its hydrogen shell in a violent, but brief, “helium flash”, turning it into a Blue (Helium) Giant. It is proposed that some of this expelled hydrogen became attached to a Gas Giant planet orbiting it some  $0.5\text{--}1$  light-year (Tarling, 2006). The sudden increase in the mass of the planet initiated the proton–proton process of fusing hydrogen to helium in the centre of the Gas Giant’s core. Similarly as SN1987A, the loss of the outer shell of the progenitor star briefly reduced the rates of fusion in the shell interfaces, delaying the final supernova explosion for  $\sim 10\text{--}20$  kyr. During this period, the Gas Giant had become a nova, now our Sun, and had entered into a highly active stage, probably as a  $\tau$ -tauri type nova. By the time of the supernova explosion, the hydrogen nebula that had triggered the nova would have been dissipated by the Sun’s own violent radiation, jet streams, mass ejections, etc. The Helium Giant then exploded, creating the heavy elements and a neutron star of  $\sim 1.4$  solar mass. The explosion then blasted them into space. The plasmas were largely, but not completely, homogenized as they were formed. As supernova plasmas often have ‘clumpy’ structures, nuclides of similar composition probably travelled as aggregates, possibly like the Coulomb balls observed in some laboratory plasmas (Arp et al., 2004). The extremely high temperature of the plasmas initially fell extremely slowly as the Coulomb forces were far too weak to trap such fast-moving free electrons into nuclide shells. Hence radiation from the plasmas was inhibited and cooling was mainly by internal collision processes, such as Bremsstrahlung. As these supernova events were all taking place some  $0.5$  light-yr ( $\sim 30,000$  AU) from the Sun (Tarling, 2006) the electromagnetic radiation from the supernova reached the solar area within  $\sim 6$  months, heating (c.  $10\text{--}11,000^\circ\text{C}$  by analogy with SN1987A) and dissipating any remaining nebula. This would be followed shortly by cosmic rays, travelling at close to the speed of light, most of which would have passed straight through the region. The shock waves would arrive a decade or so later, raising the local temperatures by  $\sim 1\text{ M }^\circ\text{C}$ . The hypersonic plasmas, travelling at  $10\text{ s M km/hr}$  (as for both SN1987A and Cassiopea A) would begin to reach the magnetic field of the Sun some  $35$  to  $50$  years after the original explosion.

### 4. The zonation and composition of the solar equatorial disk

When the supernova occurred, most of its plasmas were ejected approximately radially, but not uniformly, into space so only a small percentage, probably  $<5\%$ , reached the region of the new Sun (Tarling, 2006) while in its highly active  $\tau$ -tauri phase so characterized by intense electromagnetic activity. The



plasmas had only slightly cooled during their travel, probably falling below 10–100,000°, so protons could briefly capture electrons, forming neutral, opaque hydrogen. They were further slowed as they began to spiral along the lines of the rotating solar magnetic field in which they became trapped (Alfven, 1978), to form into a rotating cloud around the Sun. At the same time, cones above each of the Sun's polar regions were being evacuated of all matter by the Sun's intense polar jets. The plasmas therefore evolved into a rotating equatorial disk carrying most of the Moment of Inertia of the Solar System – a property that was passed on to the planets as they formed. As the plasmas became increasingly controlled by the solar electromagnetic field, more and more nuclides condensed and became distributed principally under the influence of the solar magnetic field. Only after the plasmas had become substantially de-ionized did the solar gravitation field begin to become more effective than the electromagnetic influences. The solar wind began to carry the lighter isotopes and elements away from the Sun after the neutral hydrogen had captured a second electron ( $< \sim 4000^\circ\text{C}$ ) and so became transparent. Locally, the cooling of the plasmas and their condensates were partially offset by the continuing release of kinetic energy, radioactive decay and the release of latent heats (liquefaction and/or solidification). The composition of the disk around the Sun thus became zoned under the influence of different factors, initially electromagnetic and subsequently gravitational, as the plasmas evolved and cooled.

### 5. The aggregation of the Iron meteorites in the asteroid and inner planet zones

Between  $\sim 3500$  and  $\sim 2500^\circ\text{C}$ , carbon and carbide dusts, and highly refractory Mg-, Ca-, and Al-oxide molecules began to condense, but the local temperatures were continually changing, so the earlier droplets repeatedly evaporated and re-condensed (Engler et al., 2003) but still inherited very similar orbital paths and velocities from their source plasmas, so most were travelling in near-identical circular orbits. This facilitated coalescence during momentary contacts when surface tension forces allowed them to form into globules of a few mm dimensions (Desch et al., 2004; Kurat et al., 2004) – the maximum volume containable by their meniscus forces. Larger globules divided into separate droplets. Between 2800 and 2000 °C, these high-refractory globules began to solidify predominantly as corundum lattice structures. Thus the older meteoritic components, the Ca–Al inclusions (CAI) and parts of the Al-rich chondrules (ARC), solidified as fairly pure, chemically inert globules within which small, variable amounts of the carbon-carbide dusts (the so-called ‘pre-solar’ inclusions of Nittler, 2003) were trapped. Of these inclusions, the spherical carbon grains have the most variable isotopic signatures; probably being closest to those in the plasmas from which they condensed. The ‘pre-solar’ inclusions also contain relict isotopes, such as Xe and Ne, indicating a very recent supernova origin, although their nitrogen isotopic ratios, in particular, have been interpreted as indicating formation in a range of stellar environments of different ages (Sephton, 2004). (The differing concentrations and compositions of the inclusions now account for most of the isotopic variability of the chondrules and globular inclusions in the carbonaceous meteorites.) As these globules were crystallizing, they also incorporated spallation

products (Desch et al., 2004) indicating that they were being bombarded by cosmic ray and UV radiation bursts. This implies that there was one, or more, very active nearby source. While strong radiating sources external to the galaxy cannot be excluded, the optimum source would be the Sun itself, while in its very active phase (Tarling, 2006). The crystallization of the highly refractory globules was very slightly later than the condensation of nickel ( $\sim 2900^\circ\text{C}$ ) and iron ( $\sim 2850^\circ\text{C}$ ) but there was little reaction between the chemically inert spheroids and the very much (2–3 times) higher density molten metals. [Most of the Fe content now in these Ca–Mg–Al spheroids is attributed to diffusion from surface minerals that aggregated on to them at a much later stage (Alexander et al., 2001; Mullane et al., 2004).] The Fe–Ni metals, and their alloys, had been mostly concentrated by electromagnetic and gravitational forces within the zone of the inner (‘terrestrial’) planets but were still significant components of the innermost asteroid belt. These metals and their alloys remained molten over a wide temperature range, some  $1500^\circ\text{C}$ , not solidifying until  $\sim 1540^\circ\text{C}$  (Fe) and  $\sim 1450^\circ\text{C}$  (Ni). During this long liquid phase, molten droplets grew into small globules on brief contact and, as for the earlier high-refractory spherules, their individual volumes were limited by the strength of their surface tension forces. However, the globules of Fe–Ni metals and alloys, because of their high density, chemical affinity and similar orbital vectors, increasingly travelled as clumps of loosely linked globules. The elasticity of these clumps (rather than for an individual clump) enabled them to absorb most objects travelling in similar orbits, while incompatible, low-density materials were squeezed to their surfaces where they served to further soften impacts. The iron-nickel metals and alloys began solidifying around  $1500^\circ\text{C}$  in the Asteroid Belt, but at much lower temperatures in the inner planetary zone where sulphur was in sufficient concentrations to strongly lower the solidification temperature. As cooling continued, the menisci links between the metallic globules also solidified, forming partially solidified networks. As the iron further solidified, the remaining Ni-rich fluids filled any cavities by capillary movement, further increasing the concentration of their mass. While partially molten, the effect of collisions was mainly to compress these clumps into even more dense bodies, increasing their gravitational effects. At diameters of  $\sim 1$  km, their gravity was sufficient to distort the orbital paths of nearby objects, thus making cross-cutting orbits more common and hence increasing the probability of destructive collisions between increasingly brittle solids, although enhancing the growth of the more malleable bodies. In the innermost parts of the asteroid belt, the maximum size of the individual Fe–Ni bodies seems unlikely to have been more than a few 10 s km and most of these now brittle bodies subsequently fragmented during collisions. However, in the zone of the terrestrial planets, Fe–Ni concentrations were much higher and sulphur was also present, acting as a flux that extended the temperature range over which these metals remained molten. Their high densities meant that their mass ( $m_1$ ) increased rapidly, increasing the strength of the solar gravitational force ( $F$ ):

$$F = Gm_1m_2/r^2 \quad (1)$$

This would cause the body to move inwards towards the Sun (mass  $m_2$ ) so the distance from the Sun, ( $r$ ) decreased, amplifying the inwards motion. Consequently their orbits

migrated towards the Sun, taking them into neighbouring more densely populated zones – thus escalating their growth and causing further orbital migration until all available material within that zone had been aggregated. Thus, while still malleable and partially molten, a few very large masses very rapidly aggregated to form proto-planetary cores that were already differentiating; their high density being too compact to incorporate significant lighter components. In the case of the Earth, its core contains little or no radio-active elements and the convection in the inner core is driven by the continuing solidification of the solid inner core (Tarling, 2008). The Earth's mantle is similarly low in radio-active mineral content; the oceanic mantle producing 30% less radio-genic heat than conventionally estimated (Tarling, 2015), i.e., identical to the sub-continental mantle.

## 6. The aggregation of the carbonaceous meteorites in the asteroid belt

Falling temperatures had already enabled other minerals to condense and solidify, such as the fragmented metallic meteorites (Section 5). Below  $\sim 1600^\circ\text{C}$  tetrahedral crystalline structures became stable; most early olivines initially condensing as glasses (Varela et al., 2005) but once crystals had formed, subsequent growth was not by condensation, but primarily by the diffusion of passing gaseous molecules onto chemically active sites on the crystallites. Below some  $1400^\circ\text{C}$ , chain and ring structures were able to form and persist, and interactions were occurring within and between pre-existing minerals, some of which were exsolving, making their crystalline structures more compatible with the decreasing temperature regime and changing chemical environment. The compositions were therefore becoming more complex and the local temperatures variable due to both endo- and exothermic reactions between the accumulating compounds. These changes increasingly incorporated more hydrous and carbonaceous components as their crystal lattice became increasingly open. Some of these metamorphic processes tended to fractionate the more volatile elements, such as strontium, which, once freed, was dispersed by the solar wind. The absence of surface fluids meant that most collisions were between brittle crystals and hard solidified spherules, thereby tending to comminute the individual, more brittle grains even though these still had broadly similar orbital paths. At lower temperatures, some other elements, such as sulphur at  $\sim 450^\circ\text{C}$ , could still condense as liquids, if in sufficient concentrations, but generally the transfer of mass from the nebula was primarily by diffusion. Most sulphur, for example, had already diffused into iron long before native sulphur could condense. As the ambient temperatures fell towards  $0^\circ\text{C}$ , the asteroid belt mostly comprised mineral grains fragments and high-refractory spheroids, mostly less than a few mm in size. Within any one zone, these had broadly similar orbits and velocities, except in the innermost zone where several Fe–Ni bodies had already grown to more than  $\sim 1$  km and the orbits of any objects approaching them were increasingly distorted and tended to fragment further. Water vapour increasingly reacted with mineral surfaces, primarily hydrating them and increasingly permeating into their structures. As the ambient temperature fell close to freezing, ice began to solidify directly from the water vapour. The adhesive properties of an ice–water mix are at a maximum at

$0^\circ\text{C}$ , and then decrease exponentially to zero by  $-25^\circ\text{C}$  (Rosenberg, 2005). Adhesion would also be assisted by the high dielectric constant of hexagonal ice crystals. Consequently, mostly between  $0^\circ\text{C}$  and  $-15^\circ\text{C}$ , water ices served to aggregate the silicate grains with the chondrules and other high-refractory spheroids, to form the relatively small carbonaceous meteorites. As these accreting masses were far less dense than iron meteorites, gravitational aggregation to significantly larger masses was inhibited. Only a few bodies increased their mass further – a handful of bodies reaching dimensions of a few 100 km within which some differentiation and metamorphism occurred. The remains of these bodies are now the sources for the differentiated meteorites ( $\sim 4.3\%$  of recorded falls). After the ambient temperatures fell below  $-25^\circ\text{C}$ , the adhesive properties of water–ice ceased, but the open crystal structures of water–ice are elastic, absorbing most impacts and enabling some further coalescence between contacting bodies. However, the bonding was weak – as in comets – so much of their water–ice sublimated during this time. When the temperatures fell to  $\sim -80^\circ\text{C}$ , carbon dioxide and ammonia began to condense – but the sublimation of  $\text{CO}_2$  had little adhesive effect. It is proposed that most of the oxygen isotopic reservoirs of the solar system (Clayton, 1993) were formed while the carbonaceous meteorites were accreting. The sublimation of water–ice, in particular, would preferentially free the lighter isotopes of oxygen. Such freed isotopes and light elements were then removed from the inner planetary regions by the solar wind. This took them into the more distant regions of the Gas Giants, the Kuiper Belt or possibly even into the Oort Cloud. The oxygen reservoirs formed at this time continue to exist today as their ambient temperatures have continued to fall. This would also suggest that such reservoirs are characteristic of the original distance from the Sun in which they formed, i.e., the aubrite meteorites, which have ‘terrestrial’ oxygen isotopes, may well have originated far nearer to where the Earth formed than did most other meteorites.

## 7. Timing and outer planet formation

The sequence of events described above, was presented in their approximate order of occurrence within a context of cooling supernova plasmas. As the ambient temperatures, at any one time, would be different in different areas, the same processes would be occurring at different times. Furthermore, the same processes would progress at different rates, and for different durations, in different physico-chemical environments. Consequently time scales have only rarely been indicated – despite their obvious importance. Averaged radiometric ages are available for some of the initial stages, albeit with averaged standard deviations of some 1–5 Ma (see earlier and Tarling, 2006). The oldest components – graphite, diamonds, Ca–Al inclusions, etc., – are found in the chondrules of stony meteorites. These inclusions contain evidence of extinct nuclides that were formed in a supernova  $< 1$  Myr previously. The crystal lattices within which they are found have an average oldest radiometric age of  $\sim 4555$  Myr. Thus the supernova occurred 4556 Myr ago. (In the proposed model of the origin of the solar system (Tarling, 2006) the Sun's fusion had been initiated a few kyr earlier, i.e.,  $\sim 4556 \pm 0.002$  Ma.) Some younger types of meteorites have radiometric dates, but these only apply over the next few Myr within the Asteroid Belt, so the

timing of most subsequent Solar System events can best be inferred from specific widespread events. Mercury, Venus, the Earth, Mars and the Moon had grown from the aggregation of meteoritic-like (metal, silicate and carbonaceous) materials within the inner zone. Their internal differentiation structures began to form while they were aggregating, mainly because of the low miscibility of molten iron, thereby forming cores, mantles and rigid lithospheric surfaces. This event was largely completed well before 4.4 Ga, probably nearer 4.5 Ga. The Moon, for example, had a core and an asymmetric lithosphere (due to its near Earth proximity) capable of supporting the differentiated Lunar Highlands well before 4.4 Ga; probably at a very similar time when Mars appears to have differentiated some 30 Myr after the first meteoritic chondrules had formed (Lee and Halliday, 1997), i.e.,  $\sim 4.52$  Ga. The next widespread datable event was when the solid surfaces of these planetary bodies underwent intense meteoritic bombardment, the Late Heavy Bombardment (LHB), which commenced  $\sim 4.1$  Ga. As the inner planetary zone had been largely cleared of meteoritic materials during the growth of its planets, most of this bombardment must have been sourced from the Asteroid Belt. This event was probably initiated by the influence of Mars, but the higher intensity bombardment probably relates to when Jupiter's mass had increased sufficiently to distort the orbits of the more massive objects in the Asteroid Belt. Jupiter therefore developed to close to its present mass some 400–450 Myr after the inner planets were in place and probably when the zone outside the Asteroid Belt had cooled to close to  $0^\circ\text{C}$ . This is based on the presumption that Jupiter's growth was initially by cold, or super-cooled, water vapour condensing directly as solid ice on any available nuclei and that vapours would continue to condense on them by the same gelation processes as for the carbonaceous meteorites (Section 6). The nuclei are likely to have been mainly metallic meteoritic bodies as their masses are the most likely to be disturbed by Mars and later Jupiter as they approached their present mass (see below). However, the behaviour of these growing icy planetoids was very different to that of the metallic bodies that had grown to form the inner planets. These icy bodies were forming in area where matter was more dispersed, of much lower density and the solar gravitational field was far weaker. The gelation forces involved were also weaker than those for the aggregation of the metallic protoplanets. Hence, using Eq. (1), the icy mass,  $m_1$ , was initially increasing very slowly and the incremental increase in the distance from the Sun,  $r$ , was very small. Hence any increase in the gravitation force,  $F$ , was only sufficient to slightly shallow their outwards trajectory. It is probable that one of the several ejected proto-planetary icy masses would have had a trajectory that optimized the quantity of water vapour adhering to it, so would eventually reach a mass that was large enough to gravitationally attract other smaller proto-planetary bodies to them. Such later aggregation would accelerate its acquisition of mass and hence increase the force of solar gravity, pulling larger massive bodies into a more circular orbit that inhibited any further mass increase. The situation for the other outer planets is less clear, but probably similar. The growth of Jupiter would not only increase the meteoritic bombardment of the inner planets, but also throw more asteroidal objects into outer space. Eq. (1) (using the masses of Jupiter or Mars as a constant,  $m_2$ , and a growing asteroid,  $m_1$ ) suggests that the more massive objects would

be preferentially removed, leaving small mass materials in their pre-existing orbits. Such gravitation selection would also account for the present Kirkwood Gaps in the distribution of matter in the Asteroid Belt. The denser, more metallic objects put into outgoing orbits then provided the nuclei on to which the outer planets – Saturn, Neptune and Uranus – could grow. If the region in which Jupiter began to form was at  $\sim 0^\circ\text{C}$ , then the region of the other outer planets was even colder. At temperatures around  $-80^\circ\text{C}$ , carbon dioxide and ammonia begin to condense, although the sublimation of  $\text{CO}_2$  would have little or no adhesive effect. At low temperatures the cryogenic adhesive properties water–ice (Wang et al., 2005) would be increasingly important. These processes could account for the growth of these Outer Planets in a very similar way as the growth of Jupiter, but under far colder conditions and even weaker solar gravitational field. While such processes are even more speculative, whatever the process, the other Outer Planets would have formed very shortly after Jupiter. The outer planets would then drastically affect the orbits of all large masses in, and outside of, the Asteroid Belt and into the Kuiper Belt. This would mark the time when water, methane and other volatiles reached the inner planets, probably starting close to 4 Gyr ago, during the later stages of the LHB. These ices would vaporize long before reaching Mercury or Venus, but it is probable that the Earth, Mars and the Moon acquire most their molten ices at this time, although those on the Moon would be lost because of the Moon's low escape velocity. The arrival of water on the Earth's surface would initiate oceanic tidal drag forces, beginning the Moon's recession from the Earth. However, the Moon's subsequent recession rate would be irregular because of the continually changing distribution of the land areas on the Earth and so altering the magnitude of the tidal drag – longitudinal distributions enhancing them and latitudinal distributions decreasing their effectiveness. Other proto-planets, thrown out of the Asteroid Belt into higher elliptical orbits by the Gas Giants, but with different trajectories, would be incapable of increasing their mass at rates that could form planets. These may remain as planet-like bodies such as Pluto and Sedna, that need not necessarily originate from the hypothetical Oort Cloud.

## 8. Comments

This model presented here contains a great number of speculations that involve interacting astrophysical, chemical and geophysical processes. These will need considerable modification, particularly as the changing environments in an evolving Solar System are so complex. There are also particular uncertainties concerning the properties of very high temperature supernova plasmas. Gross simplifications have been necessary when considering such a vast range of inter-disciplinary evidence and my own knowledge is limited. The temperatures quoted are only approximate, usually being those expected at the Earth's surface, so will differ in the extremely low gravity and pressures of space. Similarly, the presence, or absence, of impurities will have major effects on the phase relations of most solids, fluids and gases. The proposed model certainly does not disprove the NICE model (Tsiganis et al., 2005; Gomes et al., 2005) for the origin of the Outer Planets, which involves a, now disappeared, planetary body (or bodies) that



distorted orbits and caused planetary growth. However, such a hypothesis may no longer be necessary if the outer planets can be formed by orbital migration away from the Sun, thereby leaving the Asteroid Belt largely in its pristine state. Similarly the “Giant Splat” hypothesis for the origin of the Moon, e.g., Mackenzie (2003), becomes redundant as small variations in the composition of the Moon merely indicate that it formed in a similar, but slightly different, region of the Solar System. It is, in any case, difficult to reconcile the “Splat” with the timing of the formation of the internal structures of both bodies. The model presented here does not involve new processes – it mainly places a different emphasis or timing on them. The critical key is the nature of supernova plasmas. It is intriguing that these are probably the locations for ‘Dark Mass’ – and possibly ‘Dark Energy’, although it is unclear how either could increase the rate of expansion of the Universe. However, such an increase may be linked to the increasing quantities of heavy elements present within the Universe since supernovae first began to occur 400 Myr after the Big Bang. Returning to the Solar System, it is clear that the electromagnetic behaviour of such plasma is of fundamental importance to its origin. While some parts of this particular version of events will be invalid, it is clearly possible to derive the meteorites, and subsequently planets, from a hot origin – at the same time as explaining features previously considered as proof of a cold origin.

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