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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 grew 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.

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 (∼50–100 °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 ∼1 M °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 ± 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 ∼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 neuron 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}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}Ni to ^{58}Co and then to ^{56}Fe during the first few months; this also generated a burst of

Figure 1a Supernova SN1897A 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.