CAN THE EARLY SOLAR SYSTEM BE EXPLAINED WITH PRESENT COSMOCHEMICAL DATA?

D.W. Davis[1], C. Matzner[2], Barlet, G.[1] and Charles, C.[1]
[1]Department of Geology, University of Toronto, 22 Russell St., Toronto ON Canada M5S 3B1
dond@geology.utoronto.ca [2]Department of Astronomy, University of Toronto

We suggest that the large amount of precise data now available on meteorites can be used to construct a scenario for evolution of the protoplanetary disk (PPD) that is consistent with astrophysical and astronomical constraints, thus answering the challenge that Wood [1] posed a decade ago. As a framework, we posit the astrophysical setting for the PPD suggested by Hester and Desch [2], in which development occurs within a dusty nebula in an Orion-type environment close to a massive star. To summarize this model, the stellar UV radiation front clears the surrounding dust to form an expanding ionized bubble (HII region). Density perturbations from this expansion induce local collapse in the adjacent nebula, leading to formation of the proto-sun and PPD. Continued expansion of the HII region blows away the part of the nebula that is not gravitationally bound in the PPD to reveal the disk. The massive star consumes its energy sources in a relatively short period of time and then undergoes a supernova (SN) explosion, seeding the PPD with short-lived radionuclides (SLRs). We argue that all of these proposed events are consistent with the known record, but require changes to some commonly held interpretations.

The time required to collapse a nebular dust cloud and form a PPD is about 1 Ma or less [3]. The preservation of rare micron-size pre-solar grains shows that the pre-planetary nebula was isotopically highly diverse at the dust size level [4]. By the time of formation of calcium-aluminum rich inclusions (CAIs), the earliest dated event at 4568 Ma [5, 6], most elements appear to have been isotopically homogenized, except for nucleosynthetic anomalies in rare fractionated unknown nuclear (FUN)-type CAIs [7].This requires that most, but not quite all, of the PPD was vapourized and recondensed by some process that operated repeatedly on a local scale.

There is evidence for a homogeneous distribution of SLRs (e.g. ^{26}Al) in most CAIs from carbonaceous chondrites (CCs) [8], but ^{26}Al is absent or very low in FUN-type CAIs, fine corundum grains in CCs [9] and in one possible CAI fragment from comet Wild 2 [10]. Most SLRs were considered to have been injected into the nebula from an outside stellar source. If so, this should have been during the CAI formation event to explain the absence of ^{26}Al in some CAIs. However, this event lasted no more than 0.1 Ma and possibly as short as 20 Ka based on ^{26}Al-^{26}Mg ages [8], which requires an unlikely coincidence even on the several Ma time scale of PPD development, unless SLR injection, isotopic homogenization and CAI formation were related events.

A potential mechanism for PPD reprocessing may be large solar outflows associated with FU Orionis eruptions from the early sun [11]. If so, then normal CAIs may be condensates from a vapourized mixture of recently accreted and solar photospheric material that was redistributed back into the disk during outflows. The rarer FUN-type material may have resulted from partial vapourization of unprocessed grains in the disk adjacent to outflows, resulting in their observed fractionated isotopic compositions. Spallation driven by flares in the early solar photosphere is potentially capable of producing SLRs that could have seeded the PPD. Whether multiple solar eruptions and spallogenic processes could have reprocessed most of disk and seeded it with SLRs having observed canonical ratios could potentially be assessed by modeling.

In general, CAIs appear to be closely associated with solar material while silicate chondrules seem to have formed under more oxidizing conditions from dust within the disk [12]. Their formation and accretion into CC parent bodies lasted several Ma but post-dated CAIs by about 2 Ma [13, 14]. The earliest chondrules (4565 Ma) are coeval with present ^{180}Hf-^{180}W [15] and ^{207}Pb-^{206}Pb [16] ages for the creation and impact disruption of planetary cores, and with eruption of basaltic achondrites from melting of planetary mantles[17]. Thus, formation of planetisimals may have been coeval with chondrules.

An important observation is that the concentration of elements in chondrules and matrix in CCs equals the composition of CI meteorites (CCs with no chondrules) when the concentrations are summed according to their model proportions, which are variable among different classes of CCs [18]. Thus, CI meteorites likely comprise the starting material that was processed to form CCs and must pre-date it. It seems reasonable to assume therefore that this material condensed at the same time and from the same heat source as CAIs. Since CI compositions are not noticeably depleted in Al and Ca relative to the solar photosphere [19], most CAI material should have remained coupled to the disk gas or it would have spiraled inward to the sun. The age of CI material would be an important test of this hypothesis, although this would be very difficult to determine because of pervasive alteration.

The detailed structure of layered CR chondrules suggests that they formed as a result of multiple melting events [20], which could also have reprocessed earlier, unrelated CAIs. The fact that modal balance with the original CI composition was preserved indicates that chondrules and matrix were accreted into the parent body with no sorting, hence very shortly after formation. The only environment that we can envision where all these constraints could be satisfied is in a planetary bow shock, which would form if the difference between the Keplerian orbital velocity of a planet and the slower velocity of hydrostatically supported gas were greater than the speed of sound. If the bow-shock pressure were high enough to sustain electrical breakdown, then repeated lightening discharges in the dust cloud could provide the heat source to form chondrules while allowing survival of trace amounts of pre-solar and pristine CAI material.

The ca. 2 Ma delay between CAI and chondrule-planetisimal formation suggests that conditions necessary for dust accretion into planet-size bodies were delayed for this period. Chondrules and CC matrix contain the earliest clear evidence for interaction with water, with a signature of mass independent O isotope fractionation [21]. This was probably produced by reaction between nebular CO and H_2 during exposure to far ultra-violet (FUV) photons from a stellar source. Self-shielding of photons required to decompose $^{12}C^{16}O$ caused the most abundant oxygen isotope, ^{16}O, to be depleted in the interior of the disk [22]. The coincidence of earliest evidence of large amounts of water and planetary accretion suggests that the PPD became exposed to a strong source of FUV at this time and the condensation of water (snow) was the binding agent that allowed efficient accretion to proceed. If so, this may mark the time at which the HII region had expanded sufficiently to expose the PPD to direct radiation from the nearby massive star [2].

Evidence for live ^{60}Fe from measured ^{60}Ni anomalies provides one of the most robust indicators that the PPD was exposed to a nearby SN explosion that could have seeded it with other SLRs. However, the sulfide minerals in which the ^{60}Ni anomalies were originally discovered [23] are likely younger than CAIs, while negative ^{60}Ni anomalies claimed in iron meteorites suggest that addition of 60Fe was a relatively late event [24]. Another indicator of SN exposure is the fact that many CCs lie on a ^{186}Lu-Hf isochron that is significantly older than the age of the solar system [25], apparently because a portion of ^{186}Lu became excited to a short-lived nuclear isomer state, which requires interaction with an intense flux of >1 Mev cosmic rays, which could only have been produced by a nearby SN explosion [26]. This exposure would have had to occur after formation of CCs. An angerite whose minerals clearly show the anomaly has been dated at 4565 Ma [17]. In our current scenario, this likely represents the explosion of the nearby massive star at least 3 Ma after initial collapse of the nebula. A star with this lifetime would have about 60 solar masses and be of spectral type O3. Its luminosity would be about 10^6 that of the sun and must of the radiant energy would be UV. Although much more distant from the PPD than the sun, it may have been a more effective source of water-synthesizing radiation.

Models, no matter how speculative, are essential for testing and making sense of observational data. We hope that these suggestions will provide a useful framework for further investigation and debate.

[1] Wood (2001) *Science, 293, 1581-1584.*
[2] Hester and Desch (2005) *Chondrites and the Protoplanetary Disk, ASP Conf. Series, 341, 107-130.* [3] Reipurth (2005) *Chondrites and the Protoplanetary Disk, ASP Conf. Series, 341, 54-77.*
[4] Nittler (2003) *Earth Planet. Sci. Lett., 209, 259-273.* [5] Amelin, Y. et al. (2002) *Science, 297, 1678-1683*. [6] Bouvier (2010) *Nature Geosci. 3, DOI: 10.1038/NGEO941*. [7] Lee, T. et al. (1979) *Astrophys. J., 228, L93–L98*. [8] Thrane, K. et al. (2006) *Astrophys. J., 646, L159–L162.* [9] Makide, K. et al. (2011) *Astrophys. J. Lett., 733, L31.*
[10] Matzel , J.E.P. (2010) *Science 328, 483-486*.
[11] Malbet, F. (2005) *Astron. Astrophys., 437, 627–636.* [12] Scott, E.R.D. (2007) *Annu. Rev. Earth Planet. Sci., 35, 577–620.* [13] Connelly, J.N. et al. (2008) *Astrophys. J., 675, L121–L124.* [14] Hutcheon I.D. et al. (2009) *Geochim. Cosmochim. Acta, 73, 5080–5099.* [15] Wittig, N. and Humayun, M. (2011) *Goldschmidt 2011 Conf. Abstr. 2168.*
[16] Blichert-Toft, J. et al. (2010) *Earth Planet. Sci. Lett., 296, 469-480.* [17] Amelin, Y. (2008) *Geochim. Cosmochim. Acta,* 72, 4874–4885. [18] Hezel, D.C. and Palme, H. (2010) *Earth Planet. Sci. Lett., 294, 85-93.* [19] Lodders, K. (2003) *Astrophys.l J.l, 591, 1220–1247.* [20] Rubin, A.E. (2010) *Geochim. Cosmochim. Acta, 74, 4807–4828.* [21] Krot, A.N. (2005) *Astrophys. J., 622, 1333–1342.* [22] Clayton, R. N. (2002) *Nature, 415, 860.* [23] Tachibana, S. et al. (2006) *Astrophys. J., 639, L87–L90*. [24] Bizzarro, M. et al. (2007) *Science, 316, 1178-1181.*
[25] Thrane, K. et al. (2010) *Astrophys. J., 717, 861–867.* [26] Albarede, F. et al. (2006) *Geochim. Cosmochim. Acta,* 70, 1261–1270.