THE SUPERNOVA TRIGGER AND METEORITIC COMPONENTS. A. G. W. Cameron, *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ85721, USA, (acameron@lpl.arizona.edu).*

Supernova Environment and Triggered Molecular Cloud Collapse: I have been studying the operation of the r-process in a core collapse supernova just after the large flux of neutrinos and antineutrinos has blown the presupernova envelope off the newly formed neutron star [1,2]. The hot (10^{10} K) neutron star surface will emit a wind largely composed of neutrons, but these will only build up r-process products to about A = 80 (A is the mass number) [3]. However, if one now adds the effects of rotation and magnetic fields to this model, the collapse produces a disk accreting toward the neutron star, and the magnetic field is wrapped into a toroid by the differential rotation in the star, so that the increasing magnetic pressure in the equatorial plane generates an extrusion disk. Where these two flows meet a magnetically driven pair of jets will be formed surrounding and parallel to the rotation axis [1]. The material from both the accretion and extrusion flows enters the base of the jets and is ejected upwards at about half the speed of light, or about 140 MeV per nucleon [1]. The r-process takes place in the extrusion disk. The jets will blast their way through the expanding supernova envelope, mostly just depositing energy, but also causing extensive nuclear spallation for which there is evidence in solar system nuclidic abundances and in several meteoritic components [2]. I discuss here the observable effects in primitive solar system material when the supernova in question is the one that triggered the collapse of a molecular cloud core to form the primitive solar nebula.

At LPSC 2002 it was reported that traces of the extinct radionuclide ^{7}Be (half life 53 days) had been found in a CAI [4]. Such effects cannot be produced by solar-accelerated cosmic rays because (1) that would produce a radial gradient in extinct radioactivities, relative to their comparison nuclei, which is not seen; (2) solids in the solar nebula grow to large sizes quickly compared to the duration of the active early Sun [5], which would produce large variations in such ratios; and (3) the strong early solar wind would draw out the magnetic lines of force radially and around the solar nebula, thus guiding the energetic particles away from solid materials.

Meteoriticists generally attribute isotopic effects that they do not understand to "an unknown reservoir in the solar nebula", but also in general there are no such reservoirs. But there was a large and diverse nucleosynthesis factory close by at a suitable time: the triggering supernova itself, which can produce all of the observed extinct radioactivities. It can also produce a great variety of stable isotopic anomalies in its own material and inject that material into the collapsing molecular cloud core at the same time that it injects short-lived radioactivities inside large Rayleigh-Taylor fingers [6]. This is particularly interesting in the case of ^{7}Be, because its half life is comparable to the expansion time of the supernova envelope, although the transit time from the supernova explosion to the injection is about 10^5 years $\pm$ a factor of a few [2].

New Features of Core Collapse Supernovas: Two aspects of core collapse supernovas are relevant here: mixing and spallation. When the core is in its most collapsed state, neutrino and antineutrino production is at its maximum. The central core becomes highly turbulent; cool descending currents are strongly heated and form strongly bouyant bubbles, which drive large-scale mixing in the outer layers of the expanding supernova envelope [7]. When the neutron star jets impinge upon the expanding envelope, both the envelope targets (light to medium nuclei) and the bombarding nuclei (medium to heavy mass numbers) will suffer mutual spallation; the spallation products will overlay the p-, s-, and r-process nuclei throughout the periodic table [2].

Formation of CAIs in the Supernova Envelope: Extinct radioactivities like ^{7}Be and ^{10}Be will be produced by spallation in the carbon-oxygen layer formed by helium-burning in the presupernova, and this region will be mixed with the region of carbon- and oxygen-burning products (call it the silicate layer, see in particular the products of explosive carbon, neon, and oxygen-burning, Figs. 9.2, 9.4, and 9.6 in [8]), in which CAIs will condense upon envelope expansion. The smallest observed CAIs have a dimension of order 50 μm, which is also of the order of the length scale of the observed ^{7}Be abundance fluctuations in the CAI [4]. I interpret this to mean that the medium was turbulent and that most CAIs were built up through turbulence-induced collisions among these condensation units. Adjacent to the silicate layer is the carbon-oxygen layer in the innermost part of which the most abundant nucleus is ^{16}O, so mixing of these layers will bring ^{16}O, ^{12}C, CNO product nuclei, and possibly s-process products, in decreasing order of abundance, together with silicate layer material. The CAIs have excess abundances of apparently pure ^{16}O at the 4 to 5 percent level, which I take to be a measure of the extent of the mixing of the innermost carbon-oxygen layer into the silicate layer prior to CAI formation. The amoeboid olivine aggregates (AOAs) would also condense in the mixed silicate layer after further expansion and cooling of the envelope; these are mostly silicates containing Mg, Fe, Al, Ca, and Cr, and these also have a 4 to 5 percent enrichment of apparently pure ^{16}O. Similar minerals also form rims on CAIs.

During this condensation sequence in the supernova envelope, the injected oxygen will in most places be taken up by the silicates that are formed in the silicate layer. With mixing into the outer helium burning layer (see below), the carbon abundance will be larger than the oxygen abundance, and thus carbon will remain after oxygen has formed as much CO as possible in this layer at the end of cooling. The expansion of this region is precisely the kind of "cooling flow" in which carbon can condense into diamond, and the excess carbon in the silicate layer (or in other layers too) is likely to form nanodiamonds. The nanodiamonds extracted from meteorites have several components and probably come from different kinds of sources, but of particular interest here is the Xe-HL component, which is relatively enriched in the lowest and highest Xe mass numbers relative to the more normal Xe-P3 component [9]. The traditional plot showing this is meaningless in itself, but when replotted as absolute abundance differences between these components, it can be interpreted to show an r-process Xe distribution at the high mass number end which has undergone some spallation to form the lower abundance isotopes at the low mass number end [2].

FUN Inclusions: FUN CAIs are an exotic subset of the CAIs. These have many nuclear abundance anomalies. Extensive analyses have been carried out on two FUN CAIs, named C1 and EK1-4-1. An analysis of the nuclear anomalies in these two CAIs concluded that the heavy elements contained a systematic excess of r-process products relative to their normal isotopic compositions [10]. In EK1-4-1 the r-process excessses are for Sm, 0.38%, for Nd, 0.33%, and for Ba, 0.16%. For C1, the corresponding excesses are 0.02%, 0.03%, and -0.03%. The p-process isotope ^{144}Sm is in excess by 0.31% in EK1-4-1 and by 0.15% in C1. In general these excesses are consistent with this scenario; the very slight deficit mentioned should be examined to see if neutron capture can deplete s-process abundances more than it increases r-process abundances.

Three triple-isotope elements (O, Mg, and Si) are interesting. ^{16}O has its usual 4.3% excess, but ^{17}O and ^{18}O appear to be fractionated with 1 and 2% excesses in EK1-4-1, and 3 and 4% in C1. In Mg the excesses above normal relative to the lightest isotope are larger than in O, but those in Si are smaller. All of these have been considered to be extreme fractionations, but I do not see how that can happen in this scenario. The reactions of a very neutron-rich environment on these light elements should be investigated, as such conditions do exist in this scenario, and the anomalies are consistent in the sense that the most neutron-rich isotope is the most enhanced. Similarly, the heaviest isotopes in several other elements (for example, ^{48}Ca and ^{50}Ti) are enhanced in a non-fractionated manner in a variety of FUN-type samples [11].

Presolar Grains: Meteoritic grains with sizes generally within an order of magnitude of $\sim 1\mu$m appear to come from a variety of sources, but those lacking oxygen have been attributed generally to a supernova origin [12]. These are composed primarily of low density graphite, SiC type X, and Si_3N_4. It has long been concluded that these grains could only be formed by extensive mixing in the supernova. Now we have a better understanding of the mixing mechanism (see above). It is necessary to bring material from the silicate layer together with carbon that has itself mixed with some hydrogen. The giant bubbles generated in the supernova core will induce massive mixing flows that can accomplish this, and will do so before the temperature in the mixed regions has fallen enough to allow chemical condensation to take place. In the presupernova layered structure, the carbon abundance exceeds the oxygen abundance in most of the helium zone where there has been convective helium burning, but not in the innermost part of that zone where helium is of low abundance or exhausted [13]. Mixing silicon into an oxygen-rich layer forms silicates at relatively high temperatures. The intermixed dominant carbon (farther out) and hydrogen will thermonuclearly form nitrogen at the mixing time and carbides and nitrides can form on cooling. This would be a site where the nanodiamonds can form. Although complicated, these phenomena may form a diagnostic for supernova mixing.

CAI–Chondrule Formation Time Differences: It has been known for some time that the ^{26}Al/^{27}Al ratio is significantly smaller in those chondrules where it can be measured than in CAIs (where it is 5×10^{-5}), and the difference has been interpreted to indicate a difference in formation time corresponding to a significant ^{26}Al decay. This ratio has recently been measured in many ferromagnesian chondrules [14], giving results between 2.28×10^{-5} and 4.5×10^{-6}. If the first of these values is assumed to measure the time of the beginning of chondrule formation in the solar nebula, then the time interval between the formation of the CAIs and the start of chondrule formation would be $(0.7 \pm 0.2) \times 10^6$ years, and chondrule formation would extend the total time interval to about 2.4×10^6 years. However, please note that the process of injection of the supernova material into the material of the solar nebula will reduce the ^{26}Al/^{27}Al ratio by dilution of the stable ^{27}Al with solar nebula aluminum, and therefore these numbers are not only upper limits to the real time intervals but are likely to be unrealistically large. As noted above, I have estimated the transit interval between the supernova explosion and the injection into the solar nebula to be about 10^5 years [2]. The formation of chondrules in the solar nebula is very likely due to passage of solids through shock waves in the wakes of large-scale Rossby Vortices [15]. The minimum time interval suggests that chondrules with ^{26}Al formed promptly from material only slightly diluted by mixing molecular cloud material into large Rayleigh-Taylor fingers from the supernova. The maximum time difference would correspond to full mixing between the two sources of ^{27}Al, indicating that the contribution from the supernova was about 10 percent of the material in the final mixture, consistent with the injection simulation by Vanhala and Boss [6].

References: [1] A. G. W. Cameron, Astrophys. J., **562**, 456 (2001); [2] A. G. W. Cameron, Astrophys. J., in press (Apr. 10, 2003); [3] R. D. Hoffman *et al.*, Astrophys. J., **482**, 951 (1997); [4] M. Chaussidon *et al.*, Lunar Planet. Sci. XXXIII (2002), abstract 1563; [5] A. G. W. Cameron Meteoritics, **30**, 133 (1995); [6] H. A. T. Vanhala and A. P. Boss, Astrophys. J., **575**, 1144 (2002); [7] C. L. Fryer and M. S. Warren, Astrophys. J., **564**, L65 (2002); [8] D. Arnett, *Supernovae and Nucleosynthesis*, Princeton Univ. Press (1996); [9] G. R. Huss and R. S. Lewis, Meteoritics, **29**, 791 (1994); [10] G. J. Consolmagno and A. G. W. Cameron, Moon and Planets, **23**, 3 (1980); [11] T. Lee, in *Meteorites and the Early Solar System*, ed. J. F. Kerridge and M. S. Matthews (Tucson: Univ. Arizona Press), 1063 (1988); [12] S. Amari and E. Zinner, in *Astrophysical Implications of the Laboratory Study of Presolar Materials*, ed. T. J. Bernatowicz and E. Zinner, Woodbury, N. Y.: Am. Inst. Phys. (1997); [13] S. E. Woosley and T. A. Weaver, Astrophys. J. Suppl., **101**, 181 (1995); [14] Mostefaoui *et al.*,MAPS, **37**, 421 (2002); [15] H. Li *et al.*, Astrophys. J., **551**, 874 (2001).