METEORITICAL ASTROPHYSICS: A NEW SUBDISCIPLINE. A. G. W. Cameron, *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (acameron@lpl.arizona.edu).*

A recent remarkable discovery by Katharina Lodders [1] showed that the abundances of extinct radioactivities (relative to reference nuclei) in chondrites, achondrites, and irons are proportional to the squares of their mean lives, whereas no such abundance-mean life relationship is apparent for the data of calcium-aluminum rich inclusions (CAIs) and a variety of other inclusion types. In this talk I shall interpret these results in terms of galactic and solar nebula processes.

The first step in organizing the data for interpretation is to require that both the abundance of the extinct radioactivity (as measured by its decay product abundance) and that of the reference nuclide should have the same nucleosynthesis history, or else that a correction to the ratio be made to compensate for the ratio of the two different production processes. The striking feature of this diagram is that the lower edge of the data (the Lodders Line) is remarkably straight; most of the data are derived from chondrites; and its slope on the log-log diagram is two. So the extinct radioactivities are present in proportion to the square of their mean lives. All the other data lie above the Lodders line in this diagam; the sources of that data are in general somewhat larger particles than those that have contributed to the Lodders Line.

A straight relationship between abundances of extinct radioactivities and their mean lives means that these radioactivities originated from a common reservoir, the interstellar medium (ISM), and that they were isolated from the rest of the ISM at some point in the past, which is when the solar nebula formed. If the extinct radioactive abundances had accumulated into the solar nebula gas at constant rates they would have become proportional to the first power of the mean lives, a relationship often assumed for this as a galactic process. Thus to find that they are proportional to the second power of the mean lives indicates that a major new process was involved. This relationship can be obtained if the injection of radioactive material into the patch of gas in the interstellar medium, that will form the solar nebula, starts and then increases in injection rate in proportion to the elapsed time since the beginning of the accumulation. Since the observed relation includes the abundance of ^{146}Sm (mean life 1.49×10^8 years), which is very long compared to the lifetime of the solar nebula, one must conclude that a galactic process is involved, with the radioactive accumulation beginning much earlier than that mean life prior to formation of the solar system.

This relation is derived as follows. Assume that the abundance N of a particular species increases proportional to the time t for a total time T with a proportionality constant a. Let this go on during the time T, with the species decaying with a mean life τ. The total amount of a species injected is given by

$$N_{tot} = \int_0^T atdt = aT^2/2$$

The amount of the radioactive species surviving at the end of the period T is

$$N = \int_0^T ate^{-t/\tau}dt = a\tau^2(1-(T/\tau+1)e^{-T/\tau})$$

If $T \gg \tau$, then $N \approx a\tau^2$. Hence

$$N/N_{tot} \approx 2\tau^2/T^2$$

One cannot directly know the total amount of radioactive material injected, so it is necessary to compare the surviving abundance to the abundance of a reference isotope of the same element that acts as a proxy for the total production of the radioactivity. Thus the reference isotope must be made in the same source(s) as the radioactive one, and be carried together with the radioactive one in small particles within the ISM, and the radioactive decay product must be lost from the small particles (by recoil, evaporation, or other means). It would also be helpful if the reference isotope had the same nucleosynthetic history as the radioactivity, but usually things cannot be that simple. If the particles carrying the radioactive isotope and its reference isotope are so big that the radioactive decay products cannot be lost while in the ISM, then the above derivation would not be applicable. However, the decay products must be retained once the particles are in the solar nebula by incorporation into larger bodies (meteorites).

For much of the last four decades the general paradigm in the meteoritical community has been that the solar nebula formed hot and that inclusions such as CAIs were chemical condensates from a cooling gas of solar composition. What should this picture be replaced by if instead the inclusions were not formed in the solar nebula? The great majority of relevant nucleosynthesis in the galaxy occurs in supernova explosions. The evolution of massive stars leading to such explosions occurs in a series of concentric thermonuclear burning shells, and it has been argued that condensations in such shells could not therefore form solids derived from a full solar composition. However, it has been found in numerical simulations that intense heating in the center of the star leads to neutrino heated bubbles that expand violently away from the center, and also that the supernova shock wave that propagates through the interior causes strong Rayleigh-Taylor instabilities at shell boundaries, so that violent Rayleigh- Taylor fingers shoot forward at such boundaries. Both proccesses induce strong mixing, and the work of Kifonidis *et al.* has shown that the result is a good approximation to a solar composition except in the outermost part of the stellar atmosphere [2]. Thus in an expanding supernova remnant the cooling will be of an approximately solar composition gas. The result is that chemical condensation will occur, but at something like seven orders of magnitude lower density than would be the case for a hot solar nebula. What difference does that make?

Chemical condensation calculations have been carried out by Katharina Lodders for a large range of pressures in a solar composition gas. The results show that the chemical condensation in the supernova would occur at about 300 degrees C lower temperature than would be the case in the solar nebula, but the condensation lines of the individual chemical species are nearly parallel, and indeed the sequence is indistinguishable from a solar nebula case.

Does the solar nebula have a part to play in any of this? Yes. It has been apparent for some time that strong shock waves in the solar nebula heat chemically condensed materials, partially vaporizing some of them and in general melting the others and leading to recrystallization upon cooling. For this reason I call the condensed objects that become CAIs and AOAs in the nebula protoCAIs and protoAOAs while they are in the interstellar medium. The shock waves also melt "dust balls" of interstellar grains into chondrules. Where do such shock waves originate? The meteoritic community has apparently remained ignorant of the theory of the Rossby Wave Instability process in accretion disks developed in 2001 [3]. This process needs much further investigation, but the existing simulations show a group of 3 or 5 such elliptical vortices formed around a circle in an accretion disk, with shocks trailing each end of a vortex. We do not know how many such circles of vortices there can be, nor where they are most likely to be located in the nebula, so this is a subject needing much further investigation.

When the supernova initially expands, the higher pressure at the center causes it to expand more rapidly than the surface region, and so the exploding star comes to resemble an expanding uniform density sphere [4] (except for some central fallback), mixed throughout and closely approximating a solar composition. The surface layers of such a supernova expand at about 10,000 km/sec (3 percent of light velocity), whereas near the center the expansion is relatively slow. Prior to the explosion the star loses significant mass in the form of a Wolf-Rayet wind, expanding at about 3,000 km/sec, and this will slow down the supernova shock somewhat. But a chemical condensate of 1 cm radius ejected from the surface will be travelling fast enough so that in most cases it would escape from the galaxy and wander in intergalactic space. But such objects from near the center would remain locally in the ISM.

Recent submillimeter observations of the Cas A and Kepler supernova remnants [5,6] indicate that between 1 and 4 $M_\odot$ of micron-size grains were ejected. A similar amount of larger protoCAIs and protoAOAs (which I collectively call “interstellar marbles”) should also be ejected. When the solar nebula is formed it therefore is already filled with the variety of condensates needed to make meteorites.

Thus the conclusion follows that the interstellar medium is filled with supernova condensates in the size range from microns to several centimeters radius. These, together with other condensates from red giant star envelopes, form the subject matter of meteoritical astrophysics. There is a particularly important property of these objects: whereas the gas in the interstellar medium moves in response to local gas pressure, the interstellar marbles are largely decoupled from the gas because of their size and mass, and therefore they will fall through the gas in response to gravitational potential gradients, retarded somewhat by friction with the gas through which they move.

To gain some insight into this behavior, I constructed a numerical model of a Giant Molecular Cloud (GMC), central temperature 35 K, central density 10^6 hydrogen molecules per cc, radius one parsec. Free fall velocity starting at 1 parsec reaches the center at 1.56×10^5 cm/sec after a fall time of 2.4 million years, well within the lifetime of a GMC. A 1 cm. radius marble reaches the center nearly as fast (1.49×10^5 cm/sec), whereas a 1 micron radius marble takes twice as long and is slowly drifting. The larger marble thus acts like a damped pendulum; so do smaller marbles but their velocities are smaller. Unlike a pendulum, marbles falling from an initially smaller radius get to the GMC center sooner with smaller velocities, so a dense cloud of marbles will build up there and settle into a central object. Subsequent collisions will continue to build up a new type of stellar object that I call a *condensar*, composed of chemical condensates. My model GMC has a total mass of 65 $M_\odot$, of which a little over 1 $M_\odot$ would be condensates and grains, so allowing for inefficiencies the condensar formed at the center would have a mass of a few tenths of a solar mass. Lacking internal hydrogen, there would be no thermonuclear reactions, so the condensar would be nearly nonluminous.

This is a good match to the properties of MACHOs (MAssive Compact Halo Objects), which have been discovered by their microlensing effects on background stars in the Magellanic Clouds, amplifying their luminosity by a substantial factor as they pass through the line of sight. Until now, these MACHOs have been a mysterious form of dark matter, possessing a gravitational field but undetected by optical instruments. The MACHO Project has been a significantly large-scale effort to detect their unique signature in amplifying light from background objects, and a result of their investigation is the production of a maximum likelihood set of contours relating probable mass and the fraction of MACHO mass in the halo (about 0.2, probably representing condensars released in the halo when our galaxy captured other smaller galaxies in the course of its history). The maximum likelihood mass of the MACHOS ranges from 0.1 to 1.0 $M_\odot$ [7,8].

These studies suggest that the subject matter of meteoritical astrophysics goes well beyond the study of meteorites themselves. However, the study of meteorites and their components must be a vital part of the development of this subject. There also needs to be better intercommunication between meteoriticists, astrophysicists, and physical chemists concerned with condensation processes.

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References: [1] K. Lodders and A. G. W. Cameron, Lunar and Planetary Science Conf. XXXV, Houston (2004), abstract 1186; [2] K. Kifonidis *et al.*, Astron. Astrophys., **408**, 621 (2003); [3] H. Li *et al.*, Astrophys. J., **551**, 874 (2001); [4] D. Arnett, Supernovae and Nucleosynthesis, Princeton University Press, Princeton, N.J. (1996); [5] L. Dunne et al., Nature, **424**, 285 (2003); [6] H. L. Morgan et al., Astrophys. J., **597**, L33 (2003); [7] C. Alcock, Science, **287**, 74 (2000); [8] C. Alcock et al., Astrophys. J., **542**, 281 (2000).