RARE-EARTH ELEMENTS AS INDICATORS OF SUPERNOVA CONDENSATION.

W. V. Boynton, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Lattimer et al. (1) have provided a detailed description of the major element chemistry expected in supernova condensates. The condensation sequence, particularly in the outer shells, is quite similar to that expected in the case of a cooling gas of solar composition. The major difference is that hydrogen is absent, yielding a far more oxidizing gas since oxygen is present as O_2 rather than as H_2O. Although the major element composition is not very sensitive to the difference between solar and supernova condensation, several trace elements are very sensitive to this difference. Perhaps the most diagnostic group is the rare earth elements (REE). Two of the REE, Ce and Yb, are very sensitive to the oxygen fugacity during condensation and thus provide a means of distinguishing supernova condensation from nebular condensation.

In the solar nebula gas, most of the REE are present as monoxides and thus a condensation reaction to the solid phase can be written as equation 1 illustrated for La. The two exceptions, Ce and Yb, exist in the gas as the dioxide and monatomic species, respectively. Their condensation reactions are given by equations 2 and 3.

(1) $$LaO_{(g)} + 1/4\ O_2 \rightarrow LaO_{1.5(s)}$$

(2) $$CeO_{2(g)} \rightarrow CeO_{1.5(s)} + 1/4\ O_2$$

(3) $$Yb_{(g)} + 3/4\ O_2 \rightarrow YbO_{1.5(s)}$$

An increase in O_2 will tend to drive reaction 2 to the left, making Ce more volatile. Ytterbium demonstrates the opposite effect, in which an increase in O_2 drives the reaction to the right, making it more refractory. The other REE will also become more refractory with an increase in O_2, but the effect is much greater for Yb.

Figure 1 presents values of D, the solid/gas distribution coefficients (relative to La), for the REE calculated by the procedure of Boynton (2). These solid/gas distribution coefficients are quite analogous to conventional mineral/liquid distribution coefficients used by geochemists. Elements with the largest value of D will be the first to condense from the gas and will be most enriched in the early condensates. The supernova values are calculated at 1500K and 10^{-8} atm total pressure, corresponding to an intermediate in the range of conditions considered by Lattimer et al. (1).

Ytterbium changes from being among the more volatile REE in a solar gas to nearly the most refractory in a supernova. In a solar gas, Ce has a volatility comparable to the other light REE, La through Sm, but in a supernova it becomes the most volatile REE by a large margin. If condensation is ter-

REE AND SUPERNOVA CONDENSATES

Boynton, W.V.

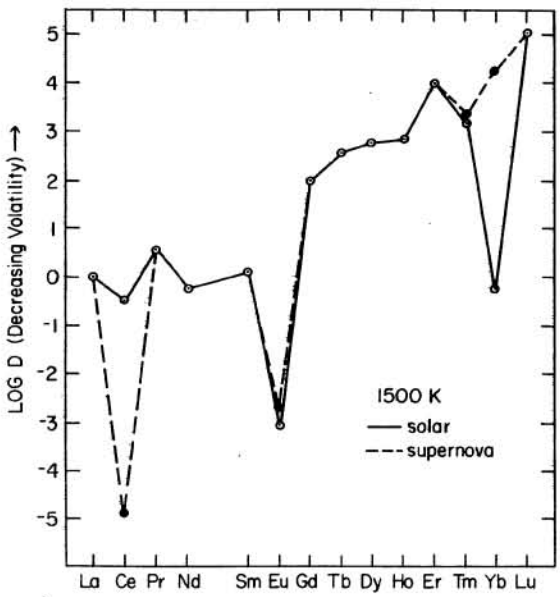

Fig. 1 Solid-gas distribution coefficients for REE. Values for Ce and Yb change drastically in the oxidizing environment of a supernova.

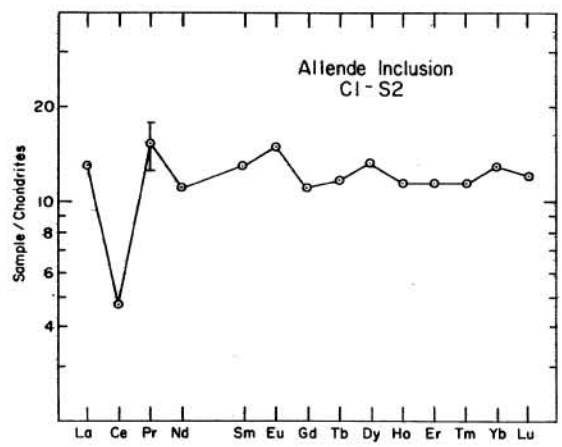

Fig. 2 REE in Ca,Al-rich chondrule (4). The large Ce anomaly suggests this inclusion condensed as supernova ejecta.

minated before the REE are totally condensed, the resulting fractionated REE pattern will distinguish between a solar-nebula condensate and a supernova condensate. In a solar-nebula condensate, one would expect large negative Eu and Yb anomalies and no significant Ce anomalies. This, in fact, is the case for the Ca,Al-rich fine-grained aggreggates in Allende (3,4), which indicates that they formed in a hydrogen-rich environment. In a pure supernova condensate, one would expect a large negative Ce anomaly and a smaller or non-existent anomaly at Eu. Obviously, if condensation continues until all the REE are condensed, an unfractionated pattern will result and no information will be provided.

This difference in behavior of Ce and Yb suggests that if pure supernova grains exist in meteorites, they may be detectable by ion probe or neutron activation analyses. If grains with these anomalous REE patterns are found, they could be considered likely candidates for detailed isotopic investigations that might be considered too time-consuming to perform on grains selected randomly. In order for such grains to be preserved and recognized, the grains must not equilibrate their REE with a substantial amount of solar REE. If the REE become diluted by reaction with either the gas or other grains, the anomalies may not be recognizable.

Most of the Ca,Al-rich inclusions in Allende have unfractionated REE patterns or patterns consistent with a nebular environment rich in H_2.

REE AND SUPERNOVA CONDENSATES

Boynton, W. V.

One notable exception occurs in the chondrule Cl-S2 (4) shown in Figure 2. The REE pattern is relatively flat except for a depletion in Ce of a factor of three. This anomaly suggests that the REE condensed in a highly oxidizing environment, as would be expected in a supernova. Although the nebula can be made much more reducing by a small increase in the C/O ratio, it cannot be made more oxidizing without requiring a very large change in the H/O ratio. It is difficult to conceive of a mechanism in the solar nebula that could generate a large change in the H/O ratio and cause this Ce anomaly.

The anomaly occurs in the bulk inclusion and suggests that a large fraction of the inclusion may be a supernova condensate. If pre-solar material mixing with the supernova material has an unfractionated REE pattern, at least 75% of the REE (except Ce) must be from the supernova. This is surprising, since Lee et al. (6) noted that other elements had normal isotopic ratios, and they specifically argued against an "interstellar marble" origin for the Ca,Al-rich chondrules. This particular inclusion, however, does have peculiar isotopic ratios for Ca and Ba (5,6).

It is generally assumed that extra solar material was mixed with large amounts of normal material in the solar nebula. The REE data, however, suggest that this mixing may have been much less than expected based on isotopic data. This Ca,Al-rich chondrule, and perhaps others, may be nearly pure supernova condensates. Although one might expect that all isotopic ratios in a supernova condensate would be different from normal, this may not be the case. It is likely that both the supernova and the solar nebula formed from fragments of the same interstellar cloud and that they initially had the same composition. As the pre-supernova star evolves, the inner zones will change significantly in isotopic composition, but the heavier elements in the outer zones will change very little. Thus a supernova condensate from the outer zones will appear to have solar isotopic composition except for the lighter elements. The mixing ratios inferred from isotopic data cannot distinguish mixing between inner and outer zones from mixing between inner zones and solar nebula material.

The chemical evidence suggests that much, and perhaps all, of chondrule Cl-S2 may have formed from supernova ejecta. It is hoped that clever isotopic measurements may be able to confirm or deny this conclusion.

REFERENCES - (1) Lattimer J.M., Schramm D.N. and Grossman L. (1978) Ap. J. (In press). (2) Boynton W. V. (1975) Geochim. Cosmochim. Acta, 39:569. (3) Mason B. and Martin P.M. (1977) Smithsonian Contrib. Earth Sci., 19:84. (4) Conrad R.L., Schmitt R.A. and Boynton W.V. (1975) Meteorites 10:384. (5) Lee T., Papanastussiou D.A. and Wasserburg G.J. (1978) Ap. J. Lett. (In press). (6) McCulloch M. T. and Wasserburg G.J. (1978) Ap. J. Lett. (In press).