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GEMS in Interplanetary Dust: surviving members of shock-accelerated dust at the GCR source?

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Interplanetary dust particles (IDPs) contain enigmatic sub-micron components called GEMS (Glass with Embedded Metal and Sulfides). We have recently proposed that the main features of GEMS can be understood if they are synthesized from shock-accelerated dust in superbubbles. If this idea is correct, GEMS may be surviving members of a population of fast grains that constitute the long-sought source material for refractory elements in galactic cosmic rays, and both GEMS and ultraheavy GCRs should be enhanced in r-process material. In order to test this hypothesis, we plan two experimental tests. First, we plan to measure the isotopic composition of elements in GCRs just beyond iron in the periodic table, in the range $Z = 32 - 42$, using the R-process Isotope Observer (RIO). This measurement will determine the fraction of r-process material at the GCR source in this charge range. We also plan to measure the relative abundances of Zr and Mo isotopes in GEMS using the new Resonance Ionization Mass Spectrometer (RIMS) instruments at Argonne National Laboratory (ANL).

1. Introduction

Chondritic-porous Interplanetary dust particles (CP-IDPs) are widely regarded as the most primitive material in the solar system. A major component of CP-IDPs are enigmatic sub-micron grains called GEMS (Glass with Embedded Metal and Sulfides). GEMS appear to have been amorphized by strong episode(s) of irradiation, yet some GEMS contain pseudo-euhedral crystalline relicts that have experienced comparatively little irradiation. We have proposed a mechanism and astrophysical site for GEMS formation that explains for the first time this and other puzzling properties of GEMS: they are stoichiometrically enriched in oxygen and systematically depleted in S, Mg, Ca and Fe relative to solar abundances, most have normal (solar) oxygen isotopic compositions, and they exhibit a strikingly narrow size distribution (0.1-0.5 μm diameter). In previously published work, we have shown that the compositions, size distribution, and survival of relict crystals are inconsistent with amorphization by particles accelerated by diffusive shock acceleration. Instead, we proposed that GEMS are formed from crystalline grains that condense in stellar outflows from massive stars in OB associations, are accelerated in encounters with frequent supernova shocks inside the associated superbubble, and are implanted with atoms from the hot gas in the SB interior. Meyer, Drury and Ellison have proposed that galactic cosmic rays originate from ions sputtered from such accelerated dust grains [5]. We suggest that GEMS are surviving members of a population of fast grains that constitute the long-sought source material for galactic cosmic rays. Thus, representatives of the GCR source material may have been awaiting discovery in cosmic dust labs for the last thirty years.

2. Signatures of GEMS origin

In our original publication[12], we made specific predictions for future observations that would test our hypothesis. First, ^{22}Ne/^{20}Ne should be much larger ($\sim 5\times$) than the solar value in GEMS, just as it is in GCRs. We would expect systematic compositional differences between grains originating as pyrrhotite as compared with the more rare grains that originate in other types, because of the presence of residual material from the original grain. For example, GEMS containing pyrrhotite relict crystals should have larger bulk S than those containing forsterite or enstatite. The decay products of ^{26}Al and ^{60}Fe may be present, but may not be detectable, unless there is substantial inhomogeneity in Mg/Al or Fe/Ni ratio in the SB interior that would allow the fossil radioactivities to be detected through positive correlations between, e.g., ^{26}Mg/^{24}Mg and ^{27}Al/^{24}Mg. Our model also predicts that GEMS exhibit a ^{58}Fe excess if the GCR ^{58}Fe excess originates from core-collapse (type II/Ibc) SN ejecta in superbubbles.

We would also expect that products of r-process nucleosynthesis to be overrepresented in GEMS if this hypothesis is correct. The reasoning is straightforward. While the astrophysical site of the r-process is still unknown, r-process nucleosynthesis, essentially by definition, occurs in an explosive environment, almost certainly in core-collapse supernova explosions of short-lived massive stars. Recent observations of heavy elements in ultrametal-poor halo stars [10], showing the clear signature of r-process nucleosynthesis early in galactic history, is compelling evidence that r-process nucleosynthesis occurs in core-collapse (type II and Ibc) supernovae. By contrast, s-process nucleosynthesis, which is expected to occur predominantly in old AGB stars, is not expected to contribute as much to superbubble interiors, simply because the timescale for this process exceeds the superbubble lifetimes. We therefore expect to find enhancements in r-process isotopes in GEMS. The site of the p-process is also unknown, but may be ejecta from core-collapse supernovae [9]. Finally, a unique nucleosynthetic signature due to a neutron burst that results from the passage of the explosion shock wave through outer shells has been recognized in presolar SiC from Type II supernovae [7, 4].

3. RIO: Measurement of isotopic abundances of $Z = 32 - 42$ elements in the GCRs

As we discussed above, two key measurements in GCRs (^{22}Ne/^{20}Ne and ^{58}Fe/^{56}Fe), have already been made, and are consistent with this proposal. In order to make further progress, it will be necessary to measure the isotopic composition of ultraheavy GCRs.

We are currently developing the R-process Isotope Observer (RIO), an instrument that will be capable of measuring the isotopic composition of ultra-heavy elements just beyond iron ($Z = 32 - 42$) in the galactic cosmic rays[11]. RIO will have a collecting power sufficient to measure masses of > 100 even-Z elements in this charge range, with a mass resolution better than 0.35 amu. Since many r-only isotopes in this charge range of separated from their nearest stable neighbors by two mass units, this mass resolution should be sufficient to cleanly resolve them. By combining measurements among elements, RIO will be capable of detecting an r-process enhancement relative to solar-system values of 50% at the 5-sigma level.

RIO is an array of passive glass nuclear track-etch detectors, with a design similar to that of the successful Trek instrument that was deployed externally on *Mir* and that made the first measurement of elemental abundances in the Pt-Pb region with sufficient resolution to resolve even-Z elements[13]. Essentially all of the sophistication of the instrument is in the laboratory: on orbit, RIO consists only of glass detectors that require no power or telemetry, so RIO is an exceptionally low-risk instrument. Because of its simplicity, it can be assembled much more rapidly than a complex electronic instrument.

4. Measurement in GEMS of Zr and Mo isotopes using CHARISMA

We also are pursuing isotopic measurements in GEMS. We focus here on relative isotopic abundance measurements of three elements: Fe for which ^{58}Fe is observed to be enhanced in galactic cosmic rays [14]; Zr, for which ^{96}Zr/^{94}Zr and ^{90}Zr/^{94}Zr are expected to be enriched by the r-process and ^{96}Zr/^{94}Zr may be enriched in the ejected shells of supernovae; and Mo, for which ^{100}Mo/^{96}Mo are expected to be enriched by the r-process, ^{92}Mo/^{96}Mo and ^{94}Mo/^{96}Mo are expected to be enriched by the p-process, and ^{95}Mo/^{96}Mo and ^{97}Mo/^{96}Mo are expected to be enriched by neutron burst nucleosynthesis in ejected shells. We propose to make these measurements using the CHARiSMA RIMS instrument and a new RIMS instrument developed for Genesis samples at ANL. Fe isotopes[8], and Zr and Mo isotopes[6], have been measured before in presolar SiC using CHARISMA. GEMS, if produced in superbubbles, will share characteristic compositions with GCRs (as noted above ^{22}Ne/^{20}Ne should be much larger ($\sim 5\times$) than the solar value in GEMS). We would also expect systematic compositional differences between GEM grains originating as pyrrhotite as compared with the more rare grains that originate in other types, because of the presence of residual material from the original grain. It may be possible to investigate these with CHARISMA.

4.1 Sample preparation and analysis

We are acquiring ten chondritic porous IDPs with large S/Fe ratios as measured by EDX. Because the S/Fe is only a rough indicator of GEMS abundance in IDPs, and because separation between GEMS and other IDP components may be difficult, it may be necessary to select GEMS-rich IDPs from among several IDPs.

We will embed the IDPs in epoxy and ultramicrotome them at U. C. Berkeley, or crush individual IDPs and disperse them on a substrate. We will then identify GEMS within the IDPs using analytical tools at Livermore (STEM, EDX), and measure their locations with respect to easily-recognizable fiducials. We will then analyze the GEMS using a new RIMS instrument at ANL. The low power of the RIMS laser is not expected to present a problem for ultramicrotomed sections. The new RIMS instrument is now in the final stages of testing. It is capable of submicron spot analyses using focused laser or ion beams and has a useful yield (atoms detected per atom removed) approaching 50%.

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