SYNTHESIS OF GEMS FROM SHOCK-ACCELERATED CRYSTALLINE DUST IN SUPERBUBBLES: MODEL AND PREDICTIONS.

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GEMS (Glass Embedded with Metals and Sulfides) are highly enigmatic yet common components of anhydrous IDPs. We have recently proposed a model of GEMS formation from shock-accelerated crystalline dust in superbubbles[1] which explains the three most perplexing properties of GEMS: pseudomorphism[2], their chemistry[3], and their size range. In this Abstract, we briefly review the main points of the model, and suggest tests that will either prove or rule out this hypothesis.

1 Superbubble formation and evolution

Most stars are born in massive star-forming regions. The most massive (O and B) stars in the nascent stellar association are thousands of times more luminous than the sun, and are observed astronomically as OB associations. These stars live only a few My before exploding as supernovae (SN). The first SN that explodes in an OB association blows a hot, low-density cavity called a superbubble (SB) in the surrounding high-density interstellar medium (ISM) . Shocks from subsequent SN propagate in this low-density SB. Soon after the SB forms, the ambient material on the wall of the SB collapses into a thin, cold shell. Because it is in thermal contact with the hot interior, this shell evaporates material into the SB interior. Early in the SB evolution, low-metallicity clouds in the SB interior also evaporate material into the interior. The medium inside the SB is thus a mixture of high-metallicity SN ejecta and low-metallicity material evaporated from clouds and the cold SB shell. The efficiency of mixing between these reservoirs of material is highly controversial, and unfortunately there are no astronomical constraints on the metallicity of the hot gas in the SB interior. We assume here that the high-metallicity SN ejecta in the SB core does not mix efficiently with low-metallicity material.

2 Dust in superbubbles

What is the fate of dust that encounters SN shocks in the SB interior? It is known that supernova shocks are extraordinarily efficient particle accelerators: the “gas” of relativistic ions observed directly in the solar system as Galactic Cosmic Rays (GCRs) are unquestionably accelerated by SN shocks. This process is observed to operate efficiently for protons up to $> 10^{14}$ eV. The acceleration mechanism is electromagnetic, and the acceleration efficiency turns out to be limited by particle magnetic rigidity. Meyer, Drury and Ellison[4] have pointed out that a 100nm dust particle with a electric potential of a few volts and the magnetic rigidity of a 10^{14} eV proton has a velocity of 3000 km/sec. Thus, if SN shocks accelerate ions efficiently, they inevitably accelerate dust also. Ellison, Drury and Meyer have modeled this acceleration extensively using Monte Carlo techniques[5], and confirm that SN shocks accelerate dust with a truncated power-law spectrum just as they accelerate ions to produce the GCRs.

3 Concordance with GEMS properties

We propose that a population of crystalline dust in superbubbles is continuously reaccelerated by encounters with SN shocks. These dust grains are amorphized by bombardment with atoms in the ambient medium[6]. In the high-density, low-metallicity ISM these grains would be rapidly destroyed by sputtering, but in the high-metallicity SB interior grains could survive and even grow by implantation as a result of atomic bombardment if the sputtering yields are sufficiently small[7]. Our model predicts that the overall chemistry of the grains will be similar to that of the IMF-averaged core-collapse supernova ejecta. We find close agreement between measurements[3] and theoretical SN yields[11] for all elements that have been reported in the literature. These grains are rapidly amorphized, but only to a depth in the grain corresponding to the range of the heaviest common atoms (i.e., Fe) in the bombarding gas at the maximum velocity achieved by any grain during its life as fast grain[8]. If that range is less than the radius of the grain, then a small crystalline relict may survive. This explains the previously unexplained and seemingly paradoxical observation that GEMS are observed to be mostly amorphous, yet are sometimes pseudo-euhedral[2]. Further, some GEMS contain a small relict crystal that mimics the euhedral shape and orientation of the entire grain.

Using a Monte Carlo, we have modeled the survival and maximum velocity of shock-accelerated grains inside a superbubble[1]. We find that the fraction of grains expected to contain relict crystals is consistent with the observed frequency. We also found that the range of grain sizes expected to survive is quite narrow — between 100 and 500 nm. This is also consistent with the observed and previously unexplained narrow distribution of sizes of GEMS.

4 Predictions of the model for future investigation

4.1 Predictions from GCR observations

This picture explains three previously enigmatic observations about GEMS, but what further tests can be made to confirm or rule out this hypothesis? One clue may come from the GCRs themselves. A consensus is developing among cosmic-ray astrophysicists that, surprisingly, GCRs originate in shock-accelerated dust. This perhaps unintuitive idea is motivated by the observation that refractory elements in GCRs are overabundant compared with volatile elements by a factor of $\sim$5. If our hypothesis about GEMS is correct, they may be a surviving population of shock-accelerated dust that is the long-sought source material for GCRs. Any isotopic anomalies in GCRs would also be present in GEMS — perhaps diluted by a contribution from shock-accelerated material originating in the high-density ISM due to type Ia SN or to occasionaly isolated type II/Ibc SN. The isotopic composition in GCRs has now been measured for all elements from H through Zn, and the isotopic composition at the GCR source has been derived for all major elements in this range[9]. (The observed GCR isotopic composition is not identical to that at the GCR source because of nuclear spallation during GCR propagation.) Despite an expectation that many major isotopic anomalies would be found, only two isotopic anomalies are now unambiguously established: ^{22}Ne/^{20}Ne is about a factor of $\sim$5 larger than the solar value, and ^{58}Fe/^{56}Fe is about 1.7 times solar. All other isotopic ratios are solar within error bars. Our model thus predicts enhanced values of these isotopic ratios, and no strong isotopic anomalies for other sub-iron major elements. To our knowledge, neither ^{22}Ne/^{20}Ne nor ^{58}Fe/^{56}Fe have been measured in GEMS, but other isotopic ratios that have been measured in GEMS are solar[10].

4.2 Beyond iron: r-process enhancements

Core-collapse SN ejecta should be enhanced in the so-called r-process nuclei, which are synthesized in explosive stellar environments. s-process nuclei, which are predominantly formed by slow neutron-capture in lower-mass AGB stars, will be present but not as dramatically enhanced. This effect is observed in the nucleosynthetic yield calculations of Limongi and Chieffi[11]. An exception to this is that a weak s-process component may be present for $A < 90$[12]. This weak s-process occurs during He burning in massive stars. Our model thus predicts enhanced abundances of r-process nuclei in GEMS for $A > 90$. Key trace elemental ratios are Sr/Zr, Sr/Mo (first r-process peak), Te/Ba (second r-process peak), and Pt/Pb (third r-process peak). Since these ratios may affected by chemistry or volatility, isotopic measurements of r-process only isotopes (e.g., ^{96}Zr, ^{100}Mo) are less ambiguous if, unfortunately, more challenging.

Acknowledgements

AJW was supported by NASA grant NAG5-11902. JPB was supported by NASA grants NAG5-10632 and NAG5-10696.

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