Formation of GEMS from shock-accelerated crystalline dust in superbubbles

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**ABSTRACT**

Interplanetary dust particles (IDPs) contain enigmatic sub-micron components called GEMS (Glass with Embedded Metal and Sulfides). The compositions and structures of GEMS indicate that they have been processed by exposure to ionizing radiation but details of the actual irradiation environment(s) have remained elusive. Here we propose a mechanism and astrophysical site for GEMS formation that explains for the first time the following key 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, they exhibit a strikingly narrow size distribution (0.1-0.5 \( \mu \text{m} \) diameter), and some of them contain “relict” crystals within their silicate glass matrices. We show that the compositions, size distribution, and survival of relict crystals are inconsistent with amorphization by particles accelerated by diffusive shock acceleration. Instead, we propose 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. We thus reverse the usual roles of target and projectile. Rather than being bombarded at rest by energetic ions, grains are accelerated and bombarded by a nearly monovelocity beam of atoms as viewed in their rest frame. Meyer, Drury and Ellison have proposed that galactic cosmic rays originate from
ions sputtered from such accelerated dust grains. 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.

Subject headings: cosmic dust, superbubble, galactic cosmic rays

1. GEMS: enigmatic grains in IDPs

GEMS consist of amorphous silicate glass grains with non-stoichiometric concentrations of oxygen, and depletions of Mg, S, Ca, and Fe, relative to Si, compared to solar system abundances. They also contain nanometer-scale inclusions of kamacite (Fe-Ni metal) and pyrrhotite ($\sim$FeS with up to 2% Ni). GEMS are found in a strikingly narrow size range (100-500nm); specifically, small GEMS (<100nm) are conspicuously absent from IDPs. GEMS are often pseudo-euhedral despite the fact that they are structurally amorphous (Fig. 1). This property suggests that GEMS were originally individual crystalline mineral grains that were amorphized by a large fluence of ionizing radiation before they were incorporated into the solar nebula. Some GEMS contain internal relict grains that mimic the external shape and orientation of the euhedral structure of the entire grain. In other words, these GEMS are pseudomorphs (Fig. 1).

Here we propose a mechanism for the formation of GEMS from shock-accelerated mineral grains in the hot, low-density ISM. The organization of the paper is as follows. In section 2 we review the phenomenology of atomic bombardment of submicron grains. In section 3 we consider and reject a model in which GEMS are produced by encounters with isolated supernova shocks. In section 4 we review the theory of dust acceleration by astrophysical shocks. In section 5 we propose an astrophysical site — the hot, low-density cavities blown by OB associations, called superbubbles — in which GEMS are synthesized. In section 6 we discuss the connection between GEMS and galactic cosmic rays. Finally, in section 7 we conclude, and suggest new measurements that would test our hypothesis.

2. Grain modification by high-velocity atomic bombardment

The fact that many GEMS exhibit a pseudo-euhedral shape but are mostly amorphous or exhibit amorphous rims implies that GEMS are single crystals that have been at least partially amorphized by intense irradiation (e.g. Fig. 1)(Bradley 1994). In an effort to
Fig. 1.— (a) Darkfield micrograph of GEMS with an embedded relict pyrrhotite \((\text{FeS})\) crystal. (b) Same GEMS as in (a) with dotted lines highlighting the approximate outlines of the relict pyrrhotite crystal and the GEMS itself. Comparison of the lines indicates that the GEMS is a pseudomorph of the relict pyrrhotite crystal. (See also Bradley & Dai (2004) and Bradley et al. (1999).)

make a laboratory simulation of the amorphization of dust grains in the ISM, Demyk et al. (2001) and Carrez et al. (2002) have demonstrated that olivine can be efficiently amorphized by 1-12.5 keV/amu (400-1500 km sec\(^{-1}\)) He ion bombardment with fluences \(\geq 10^{16}\) cm\(^{-2}\). A natural candidate for the ionizing radiation that could produce amorphization is the population of relativistic ions that fill interstellar space — the galactic cosmic rays (GCRs). Because low-energy GCRs are excluded from the heliosphere, the GCR flux has only been measured for energies >100 MeV/amu. However, the GCR fluence over the lifetime of dust in the ISM is probably insufficient to produce the observed amorphization (Jones 2000).

2.1. Production of pseudomorphs and survival of relict crystals

Relict crystals have been observed in 10-20% of GEMS (Bradley & Dai 2004) We point out that the survival of relict internal crystals is also inconsistent with amorphization by GCRs. The sharp boundaries of relict crystals require a very sharp cutoff in bombarding ion energy, so that the grains are amorphized only to a depth corresponding to the maximum
depth of penetration (range) of the bombarding ions, and no further. GCRs with energies up to at least $\sim 10^{15}$eV are accelerated by diffusive shock acceleration in supernova (SN) shocks (see, e.g., Gaisser (1990).) This mechanism inevitably produces a very smooth, power-law spectrum, with no sharp cutoff in flux with increasing energy.

![Diagram of range vs velocity for ions H, O, Si, and Fe in troilite](image)

Fig. 2.— Range in nm of ions H, O, Si and Fe atoms in troilite as a function of ion velocity. Ranges were calculated using SRIM 2003.26 (Ziegler & Biersack 2003).

The amorphous rims in GEMS vary continuously in thickness from $\sim$10nm to the radius of the entire grain, in which case no relict crystal survives. There may be an observational bias: a GEMS with a 10nm rim could be mistaken for an ordinary unprocessed crystalline mineral grain. However, completely amorphized GEMS are unambiguous even in the absence of a relict crystal. In Fig. 2 we show the range of cosmochemically abundant ions as a function of ion velocity in FeS (density = 4.6 g cm$^{-3}$). At constant velocity, Fe has the largest range of any significantly abundant element. A range of 100nm for Fe atoms in troilite corresponds approximately to a velocity of $\sim 800$ km sec$^{-1}$.

Here we suggest that GEMS are formed from euhedral crystals that are exposed to fast ($\sim 1000$ km sec$^{-1}$) atoms which have a single-valued velocity at any given time. In section 5 we discuss the astrophysical site in which this bombardment can occur naturally.
2.2. Modification of bulk grain chemistry due to monovelocity bombardment by SN ejecta

Although GEMS-rich chondritic porous (CP) IDPs are believed to be the most chemically and isotopically primitive (unaltered) meteoritic materials, they exhibit systematic deviations from solar abundances. In a study of the bulk compositions of 90 CP IDPs Schramm et al. found that they are stoichiometrically enriched in O and systematically depleted in Mg, S, Ca and Fe (Schramm et al. 1999). These compositional trends are even more pronounced in the individual GEMS within CP IDPs. Bradley (1994), Bradley & Ireland (1996) and Keller & Messenger (2004) have measured the bulk compositions of GEMS. They are stoichiometrically enriched in O (up to 80%) and systematically depleted in Mg, Fe, Ca and S (∼40%) relative to solar abundances. This enigmatic abundance pattern is qualitatively similar to that of core-collapse (type II/Ibc) SN ejecta (Fig. 3). Limongi & Chieffi (2003) have calculated the isotopic and elemental abundances in the ejecta of core-collapse supernovae using a numerical hydrodynamic model and an extensive nucleosynthetic network (Limongi & Chieffi 2003). The Limongi and Chieffi (hereafter LC03) abundances, averaged over the Salpeter initial mass function over 13-35 M⊙, give high O (compared to stoichiometric silicates, O/Si=2), high S compared with that inferred in typical IS grains from gas-phase depletion, and low S, Mg, Ca and Fe with respect to Si compared to solar values. (Fig. 3). This is in qualitative agreement with the measurements of GEMS.

We consider chemical modifications of grains bombarded with an instantaneously monovelocity beam of atoms with the composition of IMF-averaged SN ejecta. Atomic or ionic bombardment sputters target atoms from grain surfaces and implants projectile atoms into grain interiors, slowly changing their chemistry. Gray & Edmunds (2004) have recently re-examined the question of the survival of grains during ion bombardment. They confirm previous studies (e.g. McKee (1989) and Jones (1996)) that shocks in gas with cosmic abundances efficiently destroy grains. But they also concluded that in circumstances in which the bombarding gas is very metal-rich, implantation can dominate over sputtering and can even lead to grain growth. If most implanted H and He diffuse from grains and escape, but implanted atoms with Z ≥ 6 are retained in grains, then implantation will dominate over sputtering if the sputtering yield, defined as the average number of sputtered ions per incident bombarding atom, is less than the metallicity of bombarding gas. In this case, bombarded grains will grow.

Following Gray and Edmonds, we modelled the change in chemistry of FeS (troilite) due to intense ion bombardment with a gas with the composition of SN ejecta. The actual change in chemistry and morphology of the grains will be complex because of major changes in chemistry during bombardment. A Monte Carlo computer code written by Ziegler &
Fig. 3.— Comparison of major element abundances, all with respect to Si, normalized to solar values, in GEMS (squares and crosses) and in IMF-averaged core-collapse SN ejecta (circles). Abundances in GEMS (squares) were measured by Bradley & Ireland (1996). The S abundance is a lower limit because S is volatile and some GEMS contain secondary magnetite (Fe$_3$O$_4$) formed by partial oxidation of FeS (and loss of S) due to frictional heating during atmospheric entry. Measurements as reported by Keller & Messenger (2004) (without errors) are shown as crosses. Core-collapse SN yields (13-35 M$_\odot$) from Limongi and Chieffi were integrated over the Salpeter IMF (circles). Error bars in SN yields were calculated assuming that the uncertainty in yield for a SN progenitor mass was equal to the dispersion among the models for that mass. Bulk measurements for GEMS-rich IDPs (Schramm et al. 1999) are also shown for comparison (triangles).

Biersack (2003), SRIM 2003.26, is commonly used for sputtering calculations at lower energies. However, SRIM is not appropriate for the high velocities that we consider here (Ziegler, private communication, 2004). We calculated the sputtering yield as a function of velocity for SiO$_2$ bombarded by monovelocity gas with the average LC03 SN ejecta composition (Fig. 4) using the analytical treatment of Tielens et al. (1994). In order of decreasing importance, sputtering is dominated by He, H, and O. In the absence of any experimental data, we
assume that the sputtering of troilite is similar to that of silicates. In the treatment that follows, we used the expression of Tielens et al., but multiplied the yields by 0.15. This value was chosen so that grains retain approximately their original size during bombardment at 1000 km sec\(^{-1}\). We stress here that calculations of sputtering yields are subject to large uncertainties, so definitive experimental measurements on GEMS analogs, or, preferably on GEMS themselves, are needed to confirm (or not) their robustness to sputtering. We discuss uncertainties in sputtering yields, including the effect of a tough carbonaceous mantle, in section 7. Here we have ignored the effects of grain-grain collisions, which have the overall effect of reducing the number of large grains with respect to smaller ones (Jones 1996). This may be at least partially justified because of the lower average density of grains expected in the site that we propose in section 5.

![Figure 4](image_url)

Fig. 4.— Sputtering yield for FeS (solid line), SiO\(_2\) (dashed line) and graphite (dash-dot line), averaged over the Limongi and Chieffi (LC03) SN yields (Limongi & Chieffi 2003), as a function of velocity. In the progression from FeS, SiO\(_2\) and graphite, the peak sputtering yields occur at successively lower velocities (413, 308 and 218 km sec\(^{-1}\) respectively). The yields were calculated from Tielens et al. (1994), and multiplied by 0.15. If only H and He are lost from grains after implanation, implantation will equal sputtering if the sputtering yield = 0.0114, the metallicity of the IMF-averaged LC03 SN ejecta (horizontal line).

For the purpose of illustration, we calculated the composition of grains bombarded by IMF-averaged SN ejecta at a constant velocity of 1000 km sec\(^{-1}\). We assumed that all of the ejecta was in the gas phase. We define the normalized bombardment \(\xi\) to be the total mass
of bombarding atoms normalized to the original grain mass. For a spherical grain of density $\rho_g$ and radius $r_g$ travelling through a pathlength $x$ in a gas of uniform density $\rho_{\text{ISM}}$,

$$\xi = \frac{3\rho_{\text{ISM}}x}{4\rho_gr_g^2}. \quad (1)$$

We made the simplifying assumption that the grains are completely homogenized during bombardment. This assumption leads to a systematic underestimate of chemical modification: in reality, the grain material would be preferentially sputtered from the surface as compared with projectile atoms, which are implanted deep in the grain and are not, at least at first, susceptible for sputtering. We assumed that C, O, Mg, Si, and Ca have the same sputtering yield as Fe. This is likely to be an oversimplification, but a more elaborate model is not justified given the uncertainties in the theoretical calculation of the sputtering yield. We assumed that H and He were immediately lost after implantation, but that all other elements were retained in the grain. After bombardment by atoms of IMF-averaged SN ejecta with a normalized mass fluence $\xi \gtrsim 25$, the chemistry of the grains at depths down to the maximum range of the bombarding ions becomes subsolar in all the elements considered, normalized to Si. (Fig. 5).

![Graph](image)

Fig. 5.— Atomic ratios Fe/Si, Mg/Si, S/Si, and Ca/Si, all with respect to solar values (Anders & Grevesse 1988) as a function of normalized bombardment $\xi$. The bombarding atomic velocity was assumed to be $1000 \text{ km sec}^{-1}$. 
We next consider two astrophysical scenarios in which grains are exposed to monovelocity beams.

3. Grain bombardment by isolated SN blastwaves

We first consider perhaps the most obvious scenario in which dust grains are bombarded by monovelocity SN ejecta: exposure of dust to SN blastwaves. Can an encounter with a single SN blastwave achieve sufficient fluence to substantially change the bulk composition of IS dust? The material in the SN blastwave has two components: the direct SN ejecta and the swept-up ambient matter in surrounding ISM. Their respective surface densities are

\[ \sigma_{\text{ej}} = \frac{M_{\text{ej}}}{4\pi r_s^2} = 2.8 \times 10^{-7} \text{g cm}^{-2} \left( \frac{M_{\text{ej}}}{15M_{\odot}} \right) \left( \frac{r_s}{30 \text{ pc}} \right)^{-2} \]  

and

\[ \sigma_{\text{swept}} = \frac{1}{3} \rho_{\text{ISM}} r_s = 7.2 \times 10^{-5} \text{g cm}^{-2} \left( \frac{r_s}{30 \text{ pc}} \right) \left( \frac{A_{\text{ISM}}}{1.4} \right) \left( \frac{n_{\text{ISM}}}{1 \text{ cm}^{-3}} \right). \]  

Now we compute the blastwave surface density \( \hat{\xi} \) normalized to the grain mass, that is, the ratio of mass encountered by a grain, if it passes directly through the blastwave without deflection, to the total mass of the grain. This is

\[ \hat{\xi} = \left[ 9 \times 10^{-3} \left( \frac{M_{\text{ej}}}{15M_{\odot}} \right) \left( \frac{r}{30 \text{ pc}} \right)^{-2} + 2.3 \left( \frac{n_{\text{ism}}}{1 \text{ cm}^{-3}} \right) \left( \frac{r}{30 \text{ pc}} \right) \left( \frac{a}{100 \text{ nm}} \right)^{-1} \left( \frac{\rho_g}{4.6 \text{ g cm}^{-3}} \right)^{-2} \left( \frac{A_g}{40} \right) \right]. \]  

If grains were swept over by SN blastwaves with no deflection, their exposure factors in a single blastwave encounter, \( \xi_{\text{SN}} \), would be equal to the normalized blastwave surface densities \( \hat{\xi} \). We conclude that a single encounter with a supernova remnant without deflection (\( \hat{\xi} \sim 2 \)) is insufficient to achieve the required total normalized mass fluence. Of course, grains will not pass straight through shocks, and should have much longer residence times than this. A residence time ten times longer than the straight-through transit time could result in an exposure factor sufficient to substantially change the bulk chemistry. But, as we discussed in section 2, grains in this environment would not survive: the material in the shocks in the average ISM will be dominated by swept-up, relatively low-metallicity material. Grains in such a gas are destroyed quickly because sputtering dominates over implantation (Gray & Edmunds 2004).
4. Grain acceleration in SN shocks

Ions are accelerated by supernova shocks to highly relativistic energies. These relativistic particles — the galactic cosmic rays — fill space in the interstellar medium. The acceleration mechanism, diffusive shock acceleration, is almost unbelievably efficient: between 3% and 10% of the non-neutrino luminosity of supernovae in the galaxy is channeled into the acceleration of this population of mostly relativistic particles. The spectrum of galactic cosmic rays extends as a single power law from $\sim 10$ GeV/amu to $\sim 10^{15}$ eV. (Low-energy GCRs with energies less than $\sim 10$ GeV/amu are partially to completely excluded from the inner solar system by the heliosphere. At high energies, there is a subtle but apparently sudden steeping of the spectrum at $10^{15}$eV — the so-called “knee” — beyond which the spectrum continues as another uninterrupted power law to $\sim 3 \times 10^{18}$ eV. Cosmic rays above this energy — up to $3 \times 10^{20}$eV — are probably accelerated by a different, as yet unknown, mechanism.)

The dynamics of charged particles in the acceleration region of the shock are determined principally by their magnetic rigidities. The maximum energy that can be obtained by acceleration from a single SN shock is $Z \times 10^{14}$eV (Lagage & Cesarsky 1983); thus, SN shocks can accelerate protons by diffusive shock acceleration to at least $10^{14}$eV, corresponding to a magnetic rigidity of $10^{14}$V. The heaviest common element, Fe, can thus be accelerated to $\sim 3 \times 10^{15}$eV, which is close to the observed knee in the cosmic-ray all-particle spectrum. (The energy spectra of individual elements has not yet been directly measured at these energies.)

Building on a suggestion by Epstein (1980) that dust grains with the same magnetic rigidity as single ions should also be accelerated efficiently, Ellison, Drury and Meyer have suggested that dust grains can be efficiently accelerated up to 100 keV/amu, or approximately 0.01c. The magnetic rigidity of a charged grain as a function of velocity $v$, grain average atomic number $\mu$, grain size $a$ and grain electric potential $V$ is

$$R = 6 \times 10^{12} V \left( \frac{v}{1000 \text{ km sec}^{-1}} \right) \left( \frac{\rho}{4.6 \text{gcm}^{-3}} \right) \left( \frac{a}{100 \text{nm}} \right)^2 \left( \frac{\phi}{10 \text{V}} \right) \left( \frac{1}{10 \text{V}} \right) .$$

(5)

This is the magnetic rigidity of a $6 \times 10^{12}$eV (6 TeV) proton. If diffusive shock acceleration becomes inefficient at a magnetic rigidity of $\sim 10^{14}$V, as the kink in the GCR spectrum shows must happen with charged ions, SN shocks will accelerate $a = \sim 400$ nm grains to $\sim 1000$ km sec$^{-1}$. Like the galactic cosmic ray spectrum, the spectrum of accelerated grains is expected to be approximately a power law in magnetic rigidity (Ellison, Drury & Meyer 1997). Ellison, Drury & Meyer (1997) have constructed a detailed model of GCR origin, in which sputtered ions from fast dust grains are preferentially accelerated in shocks, enhancing refractory elements as compared with volatile ones. This model for Galactic cosmic ray origin is consistent with the observed elemental composition of GCRs (Meyer, Drury & Ellison 1997;
We thus reverse the usual roles of target and projectile: instead of being stationary and bombarded by energetic ions, grains are accelerated by SN shocks and are bombarded, as seen in their rest frame, by a monovelocity beam of ambient gas atoms.

4.1. Grain slowing after acceleration

After acceleration, grains principally slow by collisions with atoms (Ellison, Drury & Meyer 1997). From simple kinematics, assuming no change in cross-sectional area:

\[ v(x) = v_0 \exp\left(-\frac{\rho_{\text{ISM}} A}{m} x\right) \]

where \( x \) is curvilinear distance, \( v_0 \) is the initial velocity, \( A \) is the grain cross section, \( m \) is the grain mass, and \( \rho_{\text{ISM}} \) is the ISM density. For a spherical grain, this is

\[ v(x) = v_0 e^{-x/\lambda} \]

where

\[ \lambda = 1100 \text{ pc} \left(\frac{\rho_g}{4.6 \text{ g cm}^{-3}}\right) \left(\frac{n_{\text{ISM}}}{4 \times 10^{-3} \text{ cm}^{-3}}\right)^{-1} \left(\frac{a}{100 \text{ nm}}\right) \]

where \( \rho_g \) is the grain density, \( a \) is its diameter, and \( n_{\text{ISM}} \) is the ISM number density. A grain slows from 1000 km sec\(^{-1}\) to 20 km sec\(^{-1}\) in approximately four slowing lengths \( \lambda \), assuming that there is no change in the cross section of the grain. In the frame of the grain, the fluence \( \Phi \) required to slow by a factor of \( e \) with respect to the gas, assuming cosmic abundances, is

\[ \Phi = 10^{19} \text{ He cm}^{-2} \left(\frac{a}{100 \text{ nm}}\right) \]

This fluence is easily sufficient to amorphize a grain to the depth of penetration of the ions at maximum velocity. Even a small fraction of this slowing (\( \xi \sim 10^{-3} \)) can give a fluence sufficient to amorphize the grain rim, \( \sim 10^{16} \text{ He cm}^{-2} \). This fluence is insufficient, however, to significantly change the grain chemistry, so we conclude that, even including post-acceleration slowing, isolated supernovae are unlikely to be responsible for GEMS synthesis.

Deneault, Clayton & Heger (2003) have recently proposed a model of formation of SiC dust grains in which SiC dust particles are formed in a dense shell formed by a reverse shock in SN blastwaves. An encounter with a second reverse shock then induces a large (\( \sim 500 \text{ km sec}^{-1} \)) differential motion of condensed grains and the surrounding hot metal-rich SN ejecta. The grains are then chemically and isotopically modified by slowing in these ejecta in which
H and He are essentially absent. Clayton (private communication) has suggested that GEMS may form by a similar mechanism within isolated SN blastwaves. Although *prima facie* it appears that the bulk composition (e.g., Mg/Si, Al/Si, Ca/Si) suggested by this model is not consistent with GEMS, it is worthwhile to investigate whether the physical properties of GEMS — their restricted size range, chemical composition and survival of relict crystals — might be explained by a similar mechanism.

5. Proposed site: superbubbles blown by OB associations

Massive evolved stars generate copious amounts of dust. Because of their relatively short lifetimes, such massive stars are principally located near the cloud from which they formed, and are observed astronomically as OB associations. The first stellar winds in a nascent OB association blow a quasi-spherical cavity — a superbubble (SB) — in the surrounding high-density interstellar medium (Mac Low & McCray 1998). These superbubbles are filled with a hot (\(> 10^6\) K), tenuous (\(n = 1 - 4 \times 10^{-3} \text{ cm}^{-3}\)) gas. The swept-up ambient material quickly collapses into a thin cold shell. Because it is in contact with the hot, tenuous interior, the cold shell evaporates material into the SB interior. (We consider the problem of evaporation from clouds in section 5.1). The lifetime of the SB is defined by the lifetime of the longest-living supernova progenitors, about 50 My.

Although there is agreement that a large fraction of core-collapse (type II and type Ibc) supernovae occur in superbubbles, the precise fraction is not well-constrained. McKee (1989) estimated that \(~50\%\) of core-collapse supernovae occur in SB, while Higdon, Lingenfelter & Ramaty (1998) have suggested that the fraction is closer to \(~90\%) In any event, a large fraction of dust formed in circumstellar outflows in the galaxy must pass through superbubbles before mixing with the general ISM.

The fate of dust produced by massive stars in SBs is not well understood. We assume here that dust is not swept out of the SB by SN shocks, but remains near the center of the SB where it was formed.

5.1. Composition of the ambient ISM in the superbubble

Here we adopt the idealized, spherically-symmetric superbubble model of Mac Low & McCray (1998) (hereafter MM88), with an average mechanical luminosity in supernovae of \(10^{38} \text{ erg sec}^{-1}\), embedded in an ISM with a density \(n_0 = 1 \text{ cm}^{-3}\). At an age characteristic of OB associations (McCray & Kafatos 1987) of 50 My, the SB radius \(r_{\text{SB}} = 700 \text{ pc}\) in the
idealized MM88 model. (In practice, superbubbles will blow out of the galactic disk before they reach this radius (Koo, Heiles & Reach 1992).) Its density profile is

\[ n(r) = 1.4 \times 10^{-3} \text{cm}^{-3}(1 - r/r_{SB})^{-2/5}. \]  

(10)

In Fig. 6 we show the integral mass in a SB interior as a function of radius. We also adopt an average supernova rate in OB associations of 3 Myr\(^{-1}\) (Mac Low & McCray 1998). The average number of SN in a typical OB association over its 50 My lifetime is then \( \sim 150 \).

Fig. 6.— Integral mass inside (solid line) and outside (dotted line) a superbubble core in the spherically-symmetric Mac Low-McCray model for SB ages 2, 6, 18 and 50 My. We assume no mixing between the stellar ejecta in the core and evaporated material from cold shell.

In the Mac Low and McCray model, the gas in the interior of the superbubble is dominated by low-metallicity gas evaporated from the cold dense superbubble shell. However, this material is mostly located near the shell (Fig. 6). The fraction of the material in the SB interior that is SN ejecta is about 1\%(Higdon, Lingenfelter & Ramaty 1998). This material will be concentrated in the core. We assume that mixing with material evaporated from the walls is inefficient, so that the interior of the SB from the center to 0.3 \( r_{SB} \) (200 pc for the evolved SB) will be highly enriched in SN ejecta. We refer to this region of the SB interior as the metal-rich core.

Pre-existing low-metallicity clouds enveloped by the SB may evaporate material, thereby
"poisoning" the SB interior, increasing its mean density and lowering its metallicity. Further, fast grains that encounter clouds may stop. McKee, Van Buren & Lazareff (1984) have considered the photoevaporation of clouds in HII regions. The characteristic photoevaporation time for a 1 solar mass cloud is of order 0.4 My, in a medium with number density 1 cm$^{-3}$ at the Strömgren radius, which is of order 70 pc at that number density for a single O6 star. (The Strömgren radius in a SB is equal to the SB radius.) The photoevaporation time goes only as $m^{1/2}$, so even a 100 $M_\odot$ cloud would photoevaporate in $\sim 4$ My. We conclude that clouds near the core photoevaporate early in the SB evolution, and the evaporated gas is swept out of the SB core.

A selection effect could operate here: early in the evolution of the SB, clouds poison the interior and raise the metallicity. Grains accelerated during this phase would be destroyed because they would be slowing in a low-metallicity gas. The dust that we see as GEMS has survived because it was accelerated later in the SB evolution, when the clouds have evaporated and the metallicity in the core is higher.

### 5.2. Propagation of shocks in the SB interior

Spitzer (1978) gives the velocity of an adiabatic shock due to a SN with mechanical energy $E$, expanding into a medium of density $\rho = n_{\text{ISM}}/N_A$:

$$v_s^2 = \frac{2KE}{3\pi \rho r_s^3}$$  \hspace{1cm} (11)

so that

$$v_s = 90 \text{ km sec}^{-1} \left( \frac{E}{0.5 \times 10^{51} \text{ erg}} \right)^{\frac{1}{2}} \left( \frac{n}{4 \times 10^{-3} \text{ cm}^{-3}} \right)^{-\frac{1}{2}} \left( \frac{r_s}{200 \text{ pc}} \right)^{-\frac{3}{2}}.$$  \hspace{1cm} (12)

Shocks thus fall below 20 km sec$^{-1}$ in SBs at approximately 500 pc from the SB center. This is consistent with Mac Low & McCray (1998) who found that all shocks become subsonic before they reach the shell. This has been confirmed experimentally by Chen et al. (2000) who searched for, and found no evidence of, shocked material in the shells of superbubbles in the LMC.

Shocks may become radiative in the low-density SB interior, and so weaken faster as a function of $r_s$. Because diffusive shock acceleration is not expected to operate in radiative shocks, a critical question is whether shocks in the hot, low-density SB interior are primarily adiabatic (energy-conserving) or radiative. Chioffi, McKee & Bertshinger (1988) have studied the evolution of radiative shocks, and conclude that in a sufficiently low-density medium
shocks never become radiative, but remain adiabatic until they merge with the ambient ISM. The critical density below which this is true is $\sim 0.08\text{cm}^{-3}$ for the parameters that we have assumed for the SB interior, and with the assumption that merging occurs at a shock speed twice the local sound speed. This is significantly greater than the range of densities $(1 - 4 \times 10^{-3}\text{cm}^{-3})$ assumed for SB interiors, so we conclude that SN shocks in SB interiors remain adiabatic throughout their evolution.

From straightforward kinematics, assuming a constant cross section, the normalized bombardment for a slowing grain after a single SN encounter in the SB interior is $\hat{\xi} = \ln(1 + t_{\text{SN}}/\tau_{\text{stop}})$; if $t_{\text{SN}}/\tau_{\text{stop}} \ll 1$, then this is approximately:

$$\hat{\xi} = 0.3 \left( \frac{t_{\text{SN}}}{0.3\text{My}} \right) \left( \frac{v}{1000\text{ km sec}^{-1}} \right) \left( \frac{\rho_g}{4.6\text{gcm}^{-3}} \right)^{-1} \left( \frac{a}{100\text{nm}} \right)^{-1}. \quad (13)$$

Assuming that the number of supernovae is $\sim 150$, the total normalized bombardment $\xi$ for a 100nm grain is about 45, which is $\sim 50\%$ more than is required to substantially change the chemistry of the grain; for a 500 nm grain, it is about 9. This is not sufficient to change the grain chemistry by itself. But this normalized bombardment is likely to be an underestimate. First, we have entirely neglected the bombardment within the shock itself; this contributes $\hat{\xi} = 2$ for an undeflected encounter, but since grains reside in the shocks until they diffuse away, this is likely to be substantially larger. Further, this factor assumes complete mixing of the entire grain. This is conservative in two ways: first, it neglects the preserved core of the grain, which is untouched by the bombardment; second, as we mentioned before, it does not take into account the preferential sputtering of grain material early in the bombardment history, which will tend to accelerate the modification of grain chemistry as a function of normalized bombardment $\xi$.

### 5.3. Grain reacceleration in superbubbles

We assume that the metal-rich SB core is swept by a supernova blastwave approximately every 0.3 My. We first ask how much dust grains slow between successive blastwaves. From straightforward kinematics, the velocity of a stopping grain is

$$v(t) = \frac{v_0}{1 + t/\tau_{\text{stop}}}, \quad (14)$$

where we define a characteristic stopping time

$$\tau_{\text{stop}} = \frac{m}{\sigma_d\rho_{\text{ISM}} v_0} = \frac{\lambda}{v_0}. \quad (15)$$
where \( m \) is the grain mass and \( \sigma_d \) is the effective cross-section for drag. Thus,

\[
\tau_{\text{stop}} = \frac{x}{\xi v_0}
\]  

(16)

Numerically, this is

\[
\tau_{\text{stop}} = 1.0 \text{My} \left( \frac{a}{100 \text{nm}} \right) \left( \frac{\rho_g}{4.6 \text{g cm}^{-3}} \right) \left( \frac{n_{\text{ISM}}}{4 \times 10^{-3} \text{cm}^{-3}} \right)^{-1} \left( \frac{A_{\text{ISM}}}{1.4} \right)^{-1} \left( \frac{v_0}{1000 \text{ km sec}^{-1}} \right)^{-1}
\]  

(17)

The fact that the slowing timescale is much longer than the time between SN shock encounters suggests that grains are continuously reaccelerated in superbubbles. A similar idea has been suggested before in a different context. In an effort to explain an unexpectedly large width in a measurement of the 1.8 MeV \(^{26}\text{Al}\) \(\gamma\)-ray line, Sturner & Naya (1999) proposed the existence of a population of fast (~500 km sec\(^{-1}\)), freshly-synthesized grains in the ISM, maintained at high speed by continuous reacceleration by SN shocks. Newer measurements have indicated that this \(\gamma\)-ray line is not anomalously large (Smith 2003). Nevertheless, we revive this idea but apply it to grain reacceleration in superbubbles. Relocation from the warm phase of the ISM to superbubbles solves a problem with the original idea of Sturner and Naya: Galactic magnetic fields in the warm ISM prevent fast grains from propagating large distances, as was required in their model. Fast grains in superbubbles do not travel large distances, but are swept over \textit{in situ} by SN blastwaves.

To model the behavior of reaccelerated grains in SB interiors, we used a simple Monte Carlo simulation of the reacceleration of 100000 individual grains in a metal-rich SB core. We assumed that grains were distributed uniformly throughout the acceleration region, which we took to be a sphere centered on the OB association, with a radius of 150pc — this is the radius from Chioffi, McKee & Bertschinger (1988) where supernova shocks merge with the ambient medium, and can no longer accelerate grains. We did not attempt to model the net outward displacement that grains experience with each shock encounter. We assumed an ISM density of \(4 \times 10^{-3} \text{ cm}^{-3}\) and a temperature \(T = 10^6 \text{ K}\). We chose the time intervals between SN shock encounters randomly on a Poisson distribution, with a mean interval of 0.3 My. Each encounter was treated as follows. First, the grain velocity was translated from the SB rest frame to the frame of the shock. Each grain then was then given a new velocity chosen randomly on a power-law distribution, with an index in velocity of \(-2.1\), which was taken from Ellison, Drury & Meyer (1997, Fig. 3). We imposed a maximum cutoff velocity, corresponding to the observed GCR magnetic cutoff rigidity, \(10^{14} \text{V}\), using eqn. 5. Here a major simplifying assumption was that all grains were uniformly charged to 10V. We then translated the grain velocity back to the SB rest frame. We then calculated the time required for the SN blastwave to merge with the ISM from its current radius, and also calculated the
time to the next SN encounter. We used the minimum of those two times to calculate the adiabatic expansion and the collisional slowing, which were assumed to occur sequentially in that order. (This is justified since the timescale for adiabatic expansion is much shorter than the slowing timescale.) The adiabatic expansion was treated as:

\[ v_{\text{exp}} = v_0 \left[ \frac{r}{\min(r_{\text{merge}}, r_{++})} \right]^{\frac{\gamma}{2}(\gamma-1)} \]  

(18)

where \( v_0 \) and \( v_{\text{exp}} \) are the velocities before and after expansion, \( r_{\text{merge}} \) is the radius of the SN blastwave when it merges with the ISM, \( r_{++} \) is the radius of the SN blastwave at the time of the next SN shock encounter, and \( \gamma = 5/3 \). We assumed that grains that experience velocities at or below 400 km sec\(^{-1} \), near the peak of sputtering yield, are sputtered away and do not survive. In Fig. 7 we show the fraction of grains surviving over the SB lifetime as a function of grain size.

![Fraction of grains surviving over the lifetime of a SB as a function of grain size.](image)

In Fig. 8 we show the individual velocity histories for 25 surviving grains. Grains near the center of SB core experience severe adiabatic losses, and are systematically slower than those closer to the SB core boundary.

The boundary of the relict crystal for an individual grain is determined by the range of the fastest velocity that that particular grain has achieved. For some grains, the fastest
velocities are not much above the average, but in many cases, very high velocities, several thousand km sec\(^{-1}\), are at least temporarily achieved — these grains would be completely amorphized, and would contain no relict crystals. Approximately 20% of grains contain relict crystals; in our model, then, 80% of grains are achieve sufficiently large velocities that they are completely amorphized. In order to check that this fraction is consistent with our model, we followed 100000 reaccelerated grains of fixed size, propagating in the same environment described above. In Fig. 9, we show the average velocity \(\bar{v}\) and \(v_{80}\), the velocity that is exceeded by 80% of the surviving grains. At \(a = 350\) nm, \(v_{80} \sim 1100\) km sec\(^{-1}\). No studies have yet been done of the distribution of GEMS rim thicknesses, but the observed range in one particular 350nm GEMS grain (\(\sim 150\) nm, Fig. 1) gives a velocity, \(\sim 900\) km sec\(^{-1}\), that is remarkably similar to \(v_{80}\) for this size.

Fig. 8.— Individual velocity histories for 25 troilite grains, uniformly distributed in size between \(a = 100\) and \(a = 500\)nm, and uniformly distributed in the SB core. Grain sizes and radial distances from the SB core center are shown above each plot.
Fig. 9.— Average velocity (bottom curve) of surviving grains and their 20th-percentile maximum velocity, $v_{80}$, the velocity that is exceeded by 80% of grains at some point in their individual histories (top curve).

5.4. Confinement in the superbubble core

An important question is whether the accelerated grains are effectively confined to metal-rich core of the superbubble. If they travelled in straight lines at 1000 km sec$^{-1}$ ($\sim$1000 pc Myr$^{-1}$), they could easily escape from the superbubble core. The grains are charged, however, so will diffuse through the ambient magnetic field inside the SB. This magnetic field is essentially completely unknown. We make the assumption that, at worst, the SB interior magnetic field scales with the gas density from the galactic ISM, so that it is at least 10 nG inside the SB.

The curvilinear distance $d_{SN}$ travelled between shock encounters is of order $d_{SN} \sim v_0 t_{SN} = 300$ pc. From Ellison, Drury & Meyer (1997), the Larmor radius for a charged grain is $r_l = R/Bc$ is

$$r_l = 0.16\text{pc} \left( \frac{v}{1000 \text{ km sec}^{-1}} \right) \left( \frac{\mu}{25} \right) \left( \frac{a}{100\text{nm}} \right)^2 \left( \frac{\phi}{10 \text{V}} \right)^{-1} \left( \frac{B}{10\text{nG}} \right)^{-1}. \quad (19)$$

We assume that the scattering length is of order the Larmor radius. Since $\lambda \ll d_{SN}$, this is
essentially a diffusion problem: over the SB lifetime the grains diffuse a linear distance

\[ d_{\text{diff}} = \sqrt{r_l d_{SN}} \sim 85 \text{pc} \left( \frac{v}{1000 \text{ km sec}^{-1}} \right) \left( \frac{\mu}{25} \right)^{1/2} \left( \frac{a}{100 \text{nm}} \right) \left( \frac{\phi}{10 \text{V}} \right)^{-1/2} \left( \frac{B}{10 \text{nG}} \right)^{-1/2}. \]

Thus, small grains are effectively confined to metal-rich core (\( \sim 300 \text{pc} \) radius) by the ambient magnetic fields if the ambient magnetic field is at least 10 nG. With this value of the field, 500nm grains would just be able to diffuse out of the near the end of the SB lifetime. We discuss this assumption in the section 7. We point out that GCRs are not similarly confined, since, at a given magnetic rigidity, they have a velocity that is \( \sim 300 \) times larger than grains.

6. Do GEMS constitute the long-sought GCR source?

As we mentioned earlier in this paper, the enhancement in abundance in GCRs of refractory elements (e.g., Fe, Pt) as compared with volatiles (e.g., S, He, Ne, Ar, Pb) may be most easily understood if GCR nuclei originate in shock-accelerated dust grains (Meyer, Drury & Ellison 1997; Ellison, Drury & Meyer 1997). The Pb/Pt ratio is particularly diagnostic in this regard (Westphal et al. 1998). It is natural to ask how the GCR elemental composition compares with that of the IMF-averaged LC03 SN ejecta. Engelmann et al. (1990) have reported GCR source abundances as derived from measurements by HEAO-3-C2. Their elemental ratios at the GCR source, normalized to the local galactic (equivalent to solar system) values of Anders & Grevesse (1988), are: 

- \([\text{C}/\text{Si}] = 0.415 \pm 0.047, [\text{O}/\text{Si}] = 0.219 \pm 0.022, [\text{Mg}/\text{Si}] = 0.97 \pm 0.072, [\text{S}/\text{Si}] = 0.267 \pm 0.040, [\text{Ca}/\text{Si}] = 0.954 \pm 0.16, [\text{Fe}/\text{Si}] = 0.900 \pm 0.265.\]

The S and O abundances at the GCR source are depressed with respect to Si, in qualitative accord with the observed S and O abundance in GEMS. (C is also depressed with respect to Si, but C has never been measured in GEMS, principally due to contamination problems.) However, Mg, Ca and Fe are apparently solar at the GCR source, within the reported error bars, which range from \( \sim 7\% \) for Mg to \( \sim 30\% \) for Fe. Thus, the comparison does not appear at first to be encouraging, although the error bars for the source compositions, which are due principally to uncertainties in propagation corrections, are still consistent with substantially depressed abundances for these elements as compared with solar values.

Lingenfelter, Ramaty & Kozlovsky (1998) have suggested that GCRs originate specifically in dust grains condensed from SN ejecta, and point out that the GCR source composition compares well with that of SN ejecta, if type Ia supernovae are included. In their model, dust grains that condense in the supernova ejecta overtake the SN shock, making their re-
fractory elements available for sputtering and injection into the acceleration region. Since their original paper, precision measurements of GCR isotopic composition by the Advanced Composition Explorer (ACE) (Wiedenbeck et al. 1999) have shown that the electron-capture isotope $^{59}\text{Ni}$ is almost completely absent in GCRs. Because $^{59}\text{Ni}$ is a clock that measures the time between nucleosynthesis and acceleration, Wiedenbeck et al. (1999) were able to use its nonobservation to set a lower limit on that time of $\sim 10^5$ y, ruling out the possibility that fast dust overtakes the shock. However, the $^{59}\text{Ni}$ result still allows the possibility that supernova shocks can accelerate dust, and therefore cosmic rays, from the ejecta of previous generations of supernovae in superbubbles, since the average time between SN shocks in superbubbles is much longer than the decay time of $^{59}\text{Ni}$.

Although they may originate from a common source, GCRs and GEMS can still have quite different bulk compositions, because GEMS are highly selected. GCRs are accelerated ions sputtered from grains in shocks of both core-collapse supernovae, which predominantly occur in superbubbles, and accretion-induced collapse (type Ia) supernovae, which occur essentially uniformly in the ISM. As we have described, fast dust accelerated by II/Ibc supernovae can survive sputtering and implantation in the metal-rich superbubble core; but regardless of whether a dust grain survives or not, ions sputtered from it will contribute to the GCRs. The grains that survive in this harsh environment are observed in IDPs as GEMS, but grains smaller than $\sim 100$ nm, which constitute a large fraction of the dust mass, do not survive and so are not represented in IDPs. Dust accelerated by most type Ia supernovae is expected to be old dust in the ISM: this dust on average will have a solar composition. However, because dust accelerated in this environment will slow principally in low-metallicity gas, it is efficiently destroyed and so is not represented in IDPs. Thus, our model does not require that bulk GCR and GEMS compositions be similar. However, our picture does suggest that GEMS are a surviving population of accelerated dust grains that are the source of GCR nuclei.

The majority of GEMS have isotopic compositions that are solar within measurement errors. The isotopic composition of GCRs has been now well-measured for all major elements through Ni (Wiedenbeck et al. 2001). Before precise measurements were available, it was widely assumed that GCR isotopic abundances would diverge strongly from solar values, so it was a surprise when GCRs were found to be essentially solar in isotopic composition, with the exception of a strong excess of $^{22}\text{Ne}$ and a mild excess of $^{58}\text{Fe}$ (Wiedenbeck et al. 2001). Although excesses in $^{22}\text{Ne}$ and $^{58}\text{Fe}$ could be due to a small admixture of material from Wolf-Rayet stars, additional anomalies (e.g., in Mg isotopes) should be seen that are not observed. No consistent explanation for these excesses has yet been proposed. Nevertheless, similar excesses should be present in GEMS if these anomalies are due to GCRs originating in superbubbles. Some GEMS do exhibit isotopic anomalies. This may be simply residual
isotopically anomalous circumstellar material, or in may be due to exposure to isotopically anomalous SN blastwaves.

7. Discussion

7.1. Restricted size range of GEMS

In Fig. 7, we have shown in our model that only grains in the size range $100 - 500$ nm survive in the SB interior. In this model, we neglected the possibility of complete penetration of grains by high-velocity atoms, which will further accelerate the destruction of small grains. In grains that are large compared to the range of bombarding ions, implantation can dominate over sputtering since bombarding atoms stop inside the grain, and sputtering occurs only on entry. Such grains can grow with time. In contrast, grains that are small compared to the range of bombarding ions are quickly eroded because bombarding atoms do not stop inside the grain, and sputtering occurs both on entry and on exit, so that sputtering dominates over implantation. Further, since the ions leaving the grain are slower, they will generally be more effective at sputtering (Fig. 4), so the effective sputtering rate will be more than twice that of a large grain. We have confirmed this effect using SRIM.

7.2. Are GEMS typical IS grains?

Astronomical observations have shown that the vast majority of interstellar silicates are amorphous (Kemper & Tielens 2003). The fact that GEMS are also amorphous together with the similarity between the $10 \mu$m feature of IDPs and that of interstellar dust has led to the suggestion that GEMS are typical representatives of the interstellar dust (Bradley 1994; Bradley et al. 1999). The fact that some GEMS exhibit isotopic anomalies indicative of a circumstellar origin support this idea. Keller & Messenger (2004) have recently pointed out, however, that the bulk chemistry of GEMS is inconsistent with the typical elemental composition of interstellar dust as derived from gas phase depletions (Cardelli 1994). They propose that GEMS formed by multiple mechanisms in multiple environments (in the solar system, in presolar environments, and in the interstellar medium, for example). Based on the bulk compositions of GEMS-rich IDPs, they conclude that most GEMS formed in the solar system. However, the bulk compositions of GEMS and the IDPs that contain them are equally inconsistent with a solar system origin (Schramm et al. 1999; Bradley & Ireland 1996; Bradley 1994). Moreover, the presence of relict crystals and the restricted size range of GEMS are not easily understood in terms of a solar system origin. Our model
Fig. 10.— For grains that are large compared to the range of bombarding ions (top), implantation can dominate over sputtering since bombarding atoms stop inside the grain, and sputtering occurs only on entry. Such grains can grow with time. In contrast, grains that are small compared to the range of bombarding ions (bottom) can be quickly eroded because bombarding atoms do not stop inside the grain, and sputtering occurs both on entry and on exit, so that sputtering dominates over implantation.

is also consistent with the observation that while some GEMS have non-solar O isotopic compositions most have normal (solar) compositions (Keller and Messenger, 2004). The model predicts that most of the O atoms in most GEMS were deposited from the gas phase leading inevitably to a highly averaged (solar) O isotopic composition. Nevertheless, nothing in the model that we propose requires that GEMS be representative of average interstellar dust. The absence of average interstellar dust — amorphous silicates with bulk chemistry consistent with ISM gas phase depletions — in IDPs is unexplained. This paper implies that it is appropriate to revisit the topic of abundances of the major solid-forming elements, particularly Si, as derived from gas-phase depletions in the ISM.

We have proposed a mechanism by which GEMS may be formed from shock-accelerated fast dust in superbubbles, and which explains for the first time the basic properties of
GEMS, their restricted size range, their compositions, and the presence of surviving internal relict crystals in some GEMS. Our model is tied intimately to the acceleration of galactic cosmic rays; indeed, parameters in our model are determined from direct observations of galactic cosmic rays in the solar system. The agreement between the predicted and observed GEMS rim thicknesses is particularly striking when we consider that this model includes only one unconstrained parameter — the sputtering correction factor for SRIM. All other parameters are fixed either theoretically (e.g., the size of the SB core) or experimentally (e.g., the maximum cutoff rigidity is fixed by the observed GCR energy spectrum).

We have made a number of assumptions in our model, which we list here:

- We made the *ad hoc* assumption that sputtering yields are substantially smaller ($\sim \frac{1}{6}$) than the values predicted for silicates by Tielens et al. (1994). Although the uncertainties in sputtering yields are subject to uncertainties of a factor of two, we require a more substantial suppression of sputtering rates for GEMS. It is expected that many interstellar grains acquire a thin carbonaceous mantle (Tielens et al. 1994) that should suppress sputtering yields substantially. Indeed, the non-thermal sputtering yield of graphite due to He bombardment for velocities $> 700$ km sec$^{-1}$ is less than 40% of the yield of silicates Tielens et al. (1994, Fig. 11). If such a carbonaceous layer does indeed protect GEMS from sputtering, it must be thin if the external shape of relict crystals is to reflect that of the glassy rims. If this is the case, it may lead to an instability in sputtering: reaccelerated grains that slow to velocities near the peak of the sputtering yield may first lose their protective carbonaceous mantle, then are rapidly eroded because of the enhanced sputtering rate of the bare silicate surface. The preponderance of relict crystalline FeS ($\sim 20\%$ of GEMS) remains to be explained, as does the comparative rarity of relict silicates. We speculate that silicate minerals may sputter more readily than FeS.

- We assumed that the magnetic field in the SB interior scales, at worst, with the ambient gas density, so is no smaller than 10 nG. In fact, the measured GCR spectrum strongly suggests that the magnetic field is orders of magnitude larger than this. There is a long-standing problem in GCR astrophysics: isolated SN shocks should not be capable of accelerating particles much beyond $10^{14}$eV, and yet the GCR spectrum extends continuously, without steps, from 100 MeV through the knee to the ankle at $\sim 3 \times 10^{18}$ eV. The continuity and smoothness of the spectrum strongly suggests that all GCRs over this energy range must be accelerated by the same mechanism. Bykov & Toptygin (2001) have recently suggested that GCRs below the knee at $10^{15}$ eV have been accelerated by individual SN, but GCRs above the knee, up to the “ankle” in the GCR spectrum at $\sim 3 \times 10^{18}$ eV, have been accelerated by multiple SN encounters. Acceleration through the collaborative effects of multiple SN in an association is a compelling picture, but it requires a magnetic field of
30µG in the SB interior — more than four orders of magnitude larger than the minimum field strength required to confine fast grains to the metal-rich core.

- We assumed that the metal-rich SB core near the OB association mixes inefficiently with material evaporated from the cold SB shell, and that cloud poisoning is negligible. The extent of mixing is not well-constrained observationally.

- Finally, and crucially, we assumed that the 10⁶K gas in the metal-rich SB core has the same composition as the IMF-averaged LC02 core-collapse SN ejecta, that is, that the amount of material depleted by grain condensation is negligible. Dust condenses quickly in rapidly-cooling SN ejecta, as observed in SN 1987A. However, we assume that even highly refractory elements from dust destroyed in the hot SB interior does not recondense, and that most dust in SN ejecta is destroyed. This assumption is consistent with our picture, since small (< 100 nm) grains, which contain most of the dust mass, are readily destroyed in the SB interior.

Our model makes specific predictions for future observations. First, $^{22}\text{Ne}/^{20}\text{Ne}$ 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 $^{26}\text{Al}$ and $^{60}\text{Fe}$ 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., $^{26}\text{Mg}/^{24}\text{Mg}$ and $^{27}\text{Al}/^{24}\text{Mg}$. Similarly, although there is no evidence of $^{59}\text{Ni}$ in the “bulk” GCRs, it is possible that relict $^{59}\text{Ni}$ could be found in GEMS if there is substantial inhomogeneity in Ni/Co in the SB interior. Our model also predicts that GEMS exhibit a $^{58}\text{Fe}$ excess if the GCR $^{58}\text{Fe}$ excess originates from core-collapse (type II/Ibc) SN ejecta in superbubbles. So far as we know, no study has yet been made of the distribution of amorphous rim thicknesses as a function of grain size. Our model predicts that relict crystals will preferentially be found in large (> 200nm) grains.

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