PRODUCTION OF LITHIUM, BERYLLIUM, AND BORON BY HYPERNOVAE AND THE POSSIBLE HYPERNOVA–GAMMA-RAY BURST CONNECTION

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Received 2001 July 25; accepted 2002 August 1

ABSTRACT

We investigate a possible nucleosynthetic signature of highly energetic explosions of C-O cores ("hypernovae" [HNe]) that might be associated with gamma-ray bursts (GRBs). We note that the direct impact of C- and O-enriched hypernova ejecta on the ambient hydrogen and helium leads to spallation reactions that can produce large amounts of the light nuclides lithium, beryllium, and boron (LiBeB). Using analytic velocity spectra of the hypernova ejecta, we calculate the LiBeB yields of different exploding C-O cores associated with observed hypernovae. The deduced yields are much higher than those produced by similar (direct) means in normal Type II supernovae (SNe) and are higher than the commonly used ones arising from shock wave acceleration induced by Type II supernova explosions. To avoid overproduction of these elements in our Galaxy, hypernovae should be rare events, with \( \lesssim 3 \times 10^{-2} \) hypernovae per supernova, assuming a constant HN/SN ratio over time; this result also implies that the HN production of Be is only a fraction of other sources, e.g., superbubbles. Our limit to the HN/SN ratio is in good agreement with that of long-duration GRBs if we assume that the gamma-ray emission is focussed in a solid angle \( \Omega \) so that \( \langle \Omega/4\pi \rangle^{-1} \lesssim 3 \times 10^4 \). This encouraging result supports the possible HN-GRB association. Thus, Galactic LiBeB abundance measurements offer a promising way to probe the HN rate history and the possible HN-GRB correlation. On the other hand, if hypernovae are associated with massive pregalactic stars (Population III), they would produce an LiBeB pre-enrichment in protogalactic gas, which could show up as a plateau in the lowest metallicities of the Be–Fe relation in halo stars.

Subject headings: cosmic rays — gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

An unusual class of very energetic supernovae ("hypernovae" [HNe]) has recently been observed (Iwamoto et al. 1998, 2000; Mazzali et al. 2002). Observationally, these events are identified by their high luminosities and peculiar light curves. Theoretically, these events seem to be the highly energetic core-collapse explosion of C-O cores (Iwamoto et al. 1998, 2000; Woosley, Eastman, & Schmidt 1999; Nakamura et al. 2001; Tan, Matzner, & McKee 2001; Umeda & Nomoto 2002). It has been suggested (Iwamoto et al. 1998; Wheeler et al. 2000) that these may be associated with at least some gamma-ray bursts (GRBs).

The purpose of this paper is to point out that these very energetic stellar explosions are good sites for the copious production of the light elements lithium, beryllium, and boron (LiBeB). This occurs through the collision of the HN ejecta with the circumstellar medium. Fields et al. (1996) noted that such nucleosynthesis occurs in the explosion of all supernovae (SNe) ejecta, when the fastest ejecta collide with the surrounding medium and undergo spallation reactions. Fields et al. found that the LiBeB production is particularly large for exploding C-O cores (resulting from, e.g., W-R explosions or binary interactions). Even so, for explosions of C-O cores with "normal" energies, the net light-element yields are too small to significantly affect the Galactic evolution of LiBeB (Vangioni-Flam et al. 1996).

As we will see, for hypernovae, the LiBeB production efficiency is much higher because of (1) a surface composition of hypernovae that is essentially composed of C and O, ideal parent objects for spallation into lighter isotopes, and (2) a significant fraction of the outer envelope is propelled to high velocities (energies higher than nuclear reaction threshold) because of the very high kinetic energy released in their explosion. For the case of hypernovae, the astrophysical context is reasonably well defined because there are only two key physical parameters (explosion energy, ejected mass), both of which are constrained by observations of the supernova light curves. Adopting a calculated velocity (energy) spectrum of the ejected C and O, it is straightforward to evaluate the absolute yield of light elements by spallation. The only difficulty is that the fast nuclei are slowed down in the course of their propagation and the cross sections are energy dependent. The procedure adopted to take into account these effects is explained in Fields et al. (1996).

In this paper, we combine our theoretical LiBeB yields (§ 2) with observed Be abundance determinations in very metal-poor stars in the halo of our Galaxy (Primas et al. 2000) to place an upper limit on the ratio of HNe to Type II SNe (§ 3). This limit holds assuming a constant HN/SN...
ratio. In addition, if we assume a correlation between hypernovae and GRBs, we can constrain the fraction of GRBs that can be identified as LiBeB-producing hypernovae (§ 4).

The term “hypernova” has been used in different ways by different authors (e.g., Paczynski 1998; Iwamoto et al. 1998, 2000), so it is important to clarify the meaning used here. We define a hypernova as a core-collapse explosion whose detailed mechanism is unknown, whose kinetic energy is much higher than usual, and whose envelope is dominated by carbon and oxygen (rather than hydrogen and helium). Such events are possibly associated with long-timescale GRBs, and we will discuss this possible association in detail in § 4.

2. PRODUCTION OF LiBeB BY DIFFERENT STELLAR PROGENITORS

We now compute the production of LiBeB by hypernovae. As seen in Table 1, the bulk properties of HNe are diverse. In particular, the explosion energies and ejected masses apparently span a considerable range. One would expect that the LiBeB yields are very sensitive to both of these parameters. We will show this to be the case, and we will use analytic expressions to derive the scaling of the yields with these parameters.

Fields et al. (1996) noted that the fastest ejecta of a supernova explosion have energies above the thresholds for nuclear spallation reactions. When these fast particles interact with the surrounding medium, they will therefore produce LiBeB. The light-element production depends on the velocity spectrum of the explosion, particularly that of the outermost layers. The LiBeB yields also scale as the local ISM (target) density, while the irradiation timescale is that of the ionization energy losses and thus scale inversely with density. These density effects cancel, giving an LiBeB nucleosynthesis that is independent of the local density, but depend on the fast particle (and ISM) composition. The Fields et al. (1996) study is based on the numerical simulation of the Type Ic event SN 1994I (Nomoto et al. 1994), which is modeled as the explosion of a 2.1 $M_\odot$ C-O core. In this model the outermost and fastest layers (the only ones that count in our problem) are a mixture of C and O with no H and a small (~10%) admixture of He.

The velocity spectrum of the outermost layers can be calculated analytically, as was shown by Imshennik & Nadyozhin (1988, 1989) and reviewed in Nadyozhin (1994); these results have recently been confirmed and extended into the relativistic regime by Matzner & McKee (1999). Fields et al. (1996) give a full derivation of the relevant formulae for our problem; here we will only summarize key inputs and results. The particle spectrum is determined by the bulk hydrodynamics of the problem, namely, the velocity (or kinetic energy) distribution as a function of mass shell $M(v)$. The ejected particles have an energy spectrum $dN/d\varepsilon = m^2v^{-1}dM/dv$, where $m$ is the mean particle mass. Nadyozhin (1994) and Matzner & McKee (1999) find that the velocity spectrum of the fastest ejecta is a power law,

$$M(v) = \zeta v^s M_{\text{ej}} \left( \frac{v}{v_\text{m}} \right)^{-s},$$

where $M_{\text{ej}}$ is the ejected mass and $v_\text{m} \equiv (E_0/M_{\text{ej}})^{1/2}$ is a characteristic speed associated with the ejecta of an explosion having energy $E_0$. In terms of particle energy per nucleon $\varepsilon = E/A = m_{\text{nucl}}v_\text{m}^2/2$, we have

$$\dot{M}(\varepsilon) \equiv \frac{\dot{M}(v) > v}{M_{\text{ej}}} = \left( \frac{m_{\text{nucl}}E_0\varepsilon^{1/2}}{2M_{\text{ej}}} \right) \varepsilon^{-s/2}$$

$$= 2.2 \times 10^{-4} \frac{E_0}{(10^{51} \text{ ergs})}^{3.6} \times \left( \frac{M_{\text{ej}}}{1 M_\odot} \right)^{-3.6} \left( \frac{\varepsilon}{10 \text{ MeV}} \right)^{-3.6} \text{ for } n = 3.$$  

The constants $\zeta$ and $s$ take on different values depending on the polytropic index relevant to the problem; equation (3) corresponds to our case of $n = 3$, where $\zeta = 1.92$ and $s = 7.2$, from the fits of Matzner & McKee (1999). Equation (1) holds for the fastest, outermost ejecta, i.e., when $\dot{M} \ll 1$. For the relevant energies above the reaction thresholds here (i.e., those in Tables 1 and 3), we have $\dot{M} < 0.1$.

To good approximation, the mass fraction $X_i = M_i/M_{\text{ej}}$ of the ejecta that produce a LiBeB nuclide $i$ via the $i+j \rightarrow i + \cdots$ channel is given by the “thick target” approximation (see, e.g., Lingenfelter & Ramaty 1967):

$$X_{ij} \simeq \frac{A_i}{A_j} X_{i,\text{ISM}} \frac{1}{m_p} \int d\varepsilon \frac{R_i(\varepsilon)X_{ij}(\varepsilon)\sigma(\varepsilon)dM(\varepsilon)}{d\varepsilon},$$

where $X_{i,\text{ISM}}$ is the ISM mass fraction of $j$, $R_i$ is the range of $i$ in units of g cm$^{-2}$, and $\sigma_i$ is the appropriate cross section (see, e.g., Read & Viola 1984). The ejecta have a

| Object | $M_{\text{C-O}}$ | $M_{\text{ej}}$ | $E_k$ | $v_\text{m}$ | $v_\text{m} = (E_k/M_{\text{ej}})^{1/2}$ | Reference |
|--------|-----------------|----------------|-------|-------------|-----------------|-----------|
| SN 1994I | 2.1 | 0.9 | 1 | 0.75 | Nomoto et al. 1994 |
| SN 1997ef | 10 | 7.6 | 8 | 0.73 | Iwamoto et al. 2000 |
| SN 1998bw | 13.8 | 10.8 | 30 | 1.2 | Iwamoto et al. 1998 |
| SN 2002ap | 6 | 4.6 | 22 | 1.5 | Woosley et al. 1999 |
| SN 2002ap | 5 | 2.5 | 4 | 0.6 | Mazzali et al. 2002 |
| SN 2002ap | 5 | 5.1 | 10 | 1.4 | Mazzali et al. 2002 |
| SN Ia | 1.4 | 1.4 | 1 | 0.60 |

$^a$ The reference model of Fields et al. 1996.

$^b$ The two sets of parameters correspond to two different models of SN 1998bw.

$^c$ The two sets of parameters correspond the evaluated range given by Mazzali et al. 2002.
composition $X_{i,j}$. The total yield of $I$ is the sum over all production channels, namely, $X_I = \sum_j X_{i,j}$ and $\langle m_{ej,l}\rangle_{\text{HN}} = X_I M_{ej}$.

We can estimate the yields as follows: The yields in equation (4) are set by a competition between the steeply falling ejecta spectrum $\dot{M}(\varepsilon)$ and the rapid rise of the cross section $\sigma$ to resonance peaks just above the energy threshold found in Table 2. As a result, most of the $l$ production happens at $\varepsilon_{\text{peak}}$, so that

$$X_{i,j} \sim \frac{A_i}{A_i A_j} X_{i,j} \sigma\text{ISM} \frac{R_{i,\text{peak}} \sigma_{\text{peak}}}{m_p} \dot{M}(\varepsilon_{\text{peak}}) .$$

(5)

Since $\dot{M}$ drops rapidly with energy, the production of each LiBeB species will be dominated by the channels with the lowest peak energies. Using values typical for $^8$Be production by fast $\alpha$, $^12$C, and $^16$O nuclei, we have $R_{i,\text{peak}} \approx 0.015$ g cm$^{-2}$ and $\sigma_{\text{peak}} \approx 10$ mbarns. Using these, we can estimate that

$$\langle m_{ej,l}\rangle_{\text{HN}} \approx 2.0 \times 10^{-8} \frac{A_i}{A_i A_j} X_{i,j} \sigma\text{ISM} \left(\frac{E_0}{10^{51} \text{ ergs}}\right)^{3.6} \left(\frac{M_{ej}}{1 M_\odot}\right)^{-2.6} \left(\frac{\varepsilon_{\text{peak}}}{20 \text{ MeV}}\right)^{-3.6},$$

(6)

which agrees well with full the numerical evaluation of equation (4), results from which appear in Table 3.

The key points here are that (1) the particles follow a steep power-law spectrum in kinetic energy per nucleon $\varepsilon$, with $dN/d\varepsilon \propto \varepsilon^{-(s/2+1)} = \varepsilon^{-4.6}$, and (2) the fraction of ejected particles above a particular velocity (or energy) threshold and thus the fraction available for LiBeB production spallation reactions—scales as the very strong power $v_{\alpha}^2 = v_{\text{max}}^2$. Thus, once we adopt the appropriate value of $s$, the spectrum of particles is fixed, as are the ratios among the LiBeB isotopes produced for a given projectile and target composition. These results are (almost) independent of the explosion energy or ejected mass and thus should not vary much from one HN to the next.\(^2\) By contrast, the total LiBeB yield, e.g., $\langle m_{ej,l}\rangle_{\text{HN}}$, depends very strongly on the explosion energy and ejected mass, with scaling $\langle m_{ej,l}\rangle_{\text{HN}} \propto M_{ej}^{\langle p/2\rangle} E_0^{1/2} = M_{ej}^{-2.6} E_0^{0.8}$ seen in equation (6), and thus we can expect strong variations in LiBeB yields among HNe. This suggests that (low-mass) hypernovae can be prolific LiBeB sources.

Results from numerical integration of equation (6) are presented in Table 3 for a grid of exploding C-O core parameters. One can verify that the yields obey the scalings given in equation (6). The most copious LiBeB producers are obviously those with lower mass and higher kinetic energy. Type Ia SNe are a relatively interesting source because of their frequency, but they are less productive than low-mass hypernovae since they eject comparable masses but have 10 times less energy. The high-energy explosions of massive hypernovae are overcompensated by their heaviness. Except for the energy, normal Type Ic SNe are events very similar to the SN 1998bw massive hypernova. The extremely large LiBeB production by low-mass HNe, if they exist, makes them the most efficient LiBeB-producing events known. As such, they could have played a role in the evolution of light elements in the early Galaxy and possibly the intergalactic medium if there were Population III HNe. Note that the calculated B/Be ratio (Table 3), around 30, is consistent with the same ratio observed in stars all along the metallicity scale (Duncan et al. 1997; Primas et al. 2000; Cunha, Smith, & King 2001). Moreover the isotopic ratios of lithium ($^7$Li/$^6$Li $\approx 2.2$) and boron ($^{11}$B/$^{10}$B $\approx 4.2$) are in good agreement with these observations.

3. LiBeB ABUNDANCE CONSTRAINTS ON HYPERNOVA RATES

We now turn to the contribution of HNe to the very early galactic evolution of LiBeB. From this point of view, it is important to note that HNe represent a primary LiBeB production mechanism. That is, because of their self-produced momentum, HNe have very similar to the SN 1998bw massive hypernova. The very low-mass hypernovae since they eject comparable masses because of their frequency, but they are less productive than low-mass hypernovae since they eject comparable masses but have 10 times less energy. The high-energy explosions of massive hypernovae are overcompensated by their heaviness. Except for the energy, normal Type Ic SNe are events very similar to the SN 1998bw massive hypernova. The extremely large LiBeB production by low-mass HNe, if they exist, makes them the most efficient LiBeB-producing events known. As such, they could have played a role in the evolution of light elements in the early Galaxy and possibly the intergalactic medium if there were Population III HNe. Note that the calculated B/Be ratio (Table 3), around 30, is consistent with the same ratio observed in stars all along the metallicity scale (Duncan et al. 1997; Primas et al. 2000; Cunha, Smith, & King 2001). Moreover the isotopic ratios of lithium ($^7$Li/$^6$Li $\approx 2.2$) and boron ($^{11}$B/$^{10}$B $\approx 4.2$) are in good agreement with these observations.

| OBJECT         | $^6$Li | $^7$Li | $^8$Be | $^{10}$B | $^{11}$B |
|---------------|-------|-------|--------|---------|---------|
| SN 1994I       | 0.204E-07 | 0.461E-07 | 0.686E-08 | 0.407E-07 | 0.170E-06 |
| SN 1997ef      | 0.142E-06 | 0.321E-06 | 0.477E-07 | 0.283E-06 | 0.118E-05 |
| SN 1998bw(a)   | 0.663E-05 | 0.150E-04 | 0.223E-05 | 0.132E-04 | 0.553E-04 |
| SN 1998bw(b)   | 0.200E-04 | 0.451E-04 | 0.671E-05 | 0.398E-04 | 0.167E-03 |
| SN 2002AP(1)   | 0.350E-07 | 0.790E-07 | 0.120E-07 | 0.690E-07 | 0.290E-06 |
| SN 2002AP(2)   | 0.570E-05 | 0.130E-04 | 0.190E-05 | 0.110E-04 | 0.470E-04 |
| SN Ia          | 0.647E-08 | 0.146E-07 | 0.217E-08 | 0.129E-07 | 0.540E-07 |

2 In fact, a dependence does remain since the spectrum of eq. (1) is cut off at an energy $E_{\text{max}} \propto v_{\alpha}^2$. This is more difficult to calculate accurately since it depends on the details of shock breakout, but for the steeply falling spectra and high energies we consider here, the results are only mildly sensitive to $E_{\text{max}}$.
and thus the yields of Be are essentially independent of the ambient interstellar medium metallicity. Consequently, we expect a linear scaling between the HN ejecta of Be and O: \(\text{Be} \propto \text{O}\).

Of course, HNe are not the only mechanisms that produce Be. Originally, the principal means of LiBeB production was identified (Meneguzzi, Audouze, & Reeves 1971) with Galactic cosmic rays (GCRs), whose composition was assumed to reflect the ISM metallicity. Since this process depends on the interstellar metallicity, it corresponds to a secondary contribution that scales as \(\text{Be} \propto \text{O}\). In the 1990s, the observations of Be and B in metal-poor halo stars showed that Be scales with the metal tracer iron roughly as \(\text{Be} \propto \text{Fe}\), suggesting that a primary component is necessary. Cassé, Lehoucq, & Vangioni-Flam (1995) proposed such an additional component, in the form of low-energy particles related to SN explosions in star-forming regions. Parizot, Cassé, & Vangioni-Flam (1997) extended this model to superbubbles for energetic reasons. Another interpretation was put forward by Ramaty et al. (1997), who suggested that GCRs have their origin in the acceleration of heavy nuclei from dust grains formed in situ in supernovae, making these a primary production source. Afterward, R. Ramaty and coworkers suggested that the Be evolution can be best understood in a superbubble context (see, e.g., Higdon, Lingenfelter, & Ramaty 1998; Ramaty et al. 2000). However, a controversy on the [Fe/H] versus [O/H] trend measured in halo stars has led Fields & Olive (1999) to question the origin of LiBeB via a primary process. Indeed, the debate on the origin of LiBeB all along the Galactic evolution is still open (see, e.g., the review by Vangioni-Flam, Cassé, & Audouze 2000). In any case, it is clear that very early production of Be is dominated by any primary sources that are present (Fields et al. 2000). In the following, we seek to evaluate an upper limit of the HN/SN ratio in the first stages of the evolution, in the light of recent Be observations in very low metallicity stars.

Relative contribution of primary and secondary processes to Be nucleosynthesis thus depends on the Be-O relation. Unfortunately, O/H is difficult to measure in cool stars, and controversy has arisen as two different O/H (and O/Fe) trends have been claimed. If O/Fe changes in Population II (see, e.g., Israelian et al. 1998, 2001; Boesgaard et al. 1999; Mishenina et al. 2000), Fields et al. (2000) showed that both primary and secondary components are needed, with primary dominating at \([O/H] \lesssim -1.5\) and secondary dominating above. On the other hand, if O/Fe is constant in Population II (see, e.g., Carretta, Gratton, & Sneden 2000; Fulbright & Kraft 1999), then a primary source of LiBeB dominates until the roughly solar metallicities (Vangioni-Flam et al. 1998).\(^5\)

For our present purposes, the key point is that regardless of the O/Fe behavior, there is a need for primary Be at some level and specifically at low metallicity. This conclusion holds regardless of the astrophysical details of the primary process. The quantitative amount of the primary Be/O ratio does depend on the details of O data. In the constant O/Fe case, Be is primary over all of Population II, and we have \(\beta_{\text{obs}} \approx 3 \times 10^{-8}\), where

\[
\beta \equiv \frac{X_{\text{Be}}}{X_{\text{O}}} \approx \frac{16 \text{ Be}}{9 \text{ O}}
\]

is the ratio of Be to O mass fractions. On the other hand, if O/Fe varies, Fields et al. (2000) showed that nevertheless a primary component is present and dominates at low metallicity, where they find \(\beta_{\text{obs}} \approx 8 \times 10^{-10}\). In what follows we will consider the implications of both possibilities for O/Fe.

One can place LiBeB in full chemical evolution context (see, e.g., Vangioni-Flam et al. 1998; Fields & Olive 1999), but a simplified approach, appropriate for Population II, allows one to focus on the physics of the HN contribution to Be. In this approximation, we neglect the (small) astration of Be, and thus the primary production of LiBeB species \(i\) is described by

\[
M_{\text{gas}} \frac{dX_i}{dt} \approx \langle m_{\text{ej},i} \rangle_{\text{HN}} M_{\text{HN}} + \langle m_{\text{ej},i} \rangle_{\text{SN}} M_{\text{SN}},
\]

where \(\langle m_{\text{ej},i} \rangle_{\text{HN}}\) is the mean mass in \(i\) created by one HN and \(\langle m_{\text{ej},i} \rangle_{\text{SN}}\) is the same quantity for one (superbubble) SN; the rates of each event are given by \(M_{\text{HN}}\) and \(M_{\text{SN}}\).

Since we are considering primary production, the yields are independent of the initial ISM metallicity, and in fact equation (8) applies not only to primary LiBeB but also to metals such as O and Fe. Thus, we can write

\[
\beta \equiv \frac{X_{\text{Be}}}{X_{\text{O}}} = \epsilon_{\text{HN}} \langle m_{\text{ej,Be}} \rangle_{\text{HN}} + \epsilon_{\text{SN}} \langle m_{\text{ej,B}} \rangle_{\text{SN}},
\]

where we have assumed a constant ratio

\[
\epsilon_{\text{HN}} = \frac{M_{\text{HN}}}{M_{\text{SN}}},
\]

which we will refer to as the “HN rate parameter.”

Given information about spallation and stellar yields, equation (9) allows us to relate the observed \(X_{\text{Be}}/X_{\text{O}} \approx (16/9)/(\text{Be}/\text{O})\) to the hypernova rate parameter \(\epsilon_{\text{HN}}:\)

\[
\epsilon_{\text{HN}} = \frac{\beta_{\text{obs}} \langle m_{\text{ej,O}} \rangle_{\text{HN}} - \langle m_{\text{ej,B}} \rangle_{\text{SN}}}{\langle m_{\text{ej,Be}} \rangle_{\text{SN}} - \beta_{\text{obs}} \langle m_{\text{ej,O}} \rangle_{\text{HN}}}.\]

Unfortunately, equation (11) as it stands is difficult to evaluate because of the model dependence of the supernova \(\langle m_{\text{ej,B}} \rangle_{\text{SN}}\) and the unknown nature of the HN oxygen yield \(\langle m_{\text{ej,O}} \rangle_{\text{HN}}\).

We can still make progress, however, by setting an upper limit to \(\epsilon_{\text{HN}}\) as follows: First, we note that the largest possible oxygen yield is when the ejecta is pure oxygen: \(\langle m_{\text{ej,O}} \rangle_{\text{HN}} \lesssim \langle m_{\text{ej,Sn}} \rangle_{\text{HN}}\). Even in this extreme case, we find that the Be/O ratios can be large compared to observed \(\beta_{\text{obs}} = X_{\text{Be}}/X_{\text{O}}\) values; e.g., for the smaller of the SN 1998bw Be yields, we have \(\beta \geq 2 \times 10^{-6}\), significantly larger than the observed Population II values. This mismatch requires additional (supernova) sources that have a lower \(\beta\) and “dilute” the HN yields to the observed ones. The HN rate parameter \(\epsilon_{\text{HN}}\) will give the needed dilution.

We also note that the needed supernova dilution is minimized (i.e., the inferred \(\epsilon_{\text{HN}}\) is conservatively large) when we ignore any supernova contribution of Be and only include supernova-produced O. It thus follows that we may limit

\(^5\) Recently, King (2002) has considered the evolution of Be, B traced by the \(\alpha\)-elements metal tracers Z = Mg and Ca. This study finds Be/H and B/H \(\propto Z^{1/2}\) and thus seems to suggest a BeB primary production mechanism, if Mg, Ca/O is constant. On the other hand, in direct examination of Be-B-O, King (2001) concludes with Fields et al. (2000) that both primary and secondary production mechanisms are needed.
the HN rate parameter to be

$$\epsilon_{HN} \leq \frac{\beta_{obs}\langle m_{ej},O\rangle_{SN} - \langle m_{ej},Be\rangle_{SN}}{\langle m_{ej},Be\rangle_{HN} - \beta_{obs}\langle m_{ej},tot\rangle_{HN}}$$

$$\leq \frac{\beta_{obs}\langle m_{ej},O\rangle_{SN}}{\langle m_{ej},Be\rangle_{HN} - \beta_{obs}\langle m_{ej},tot\rangle_{HN}}.$$  (12)

With equation (12) in hand, we can now place limits on the HN rate parameter. We adopt the SN oxygen yield \(\langle m_{ej},O\rangle_{SN} = 2 M_\odot\), which is insensitive to the choice of initial mass function. For the total hypernova ejected mass, we adopt the large and thus conservative value \(\langle m_{ej},tot\rangle_{HN} = 10 M_\odot\). Finally, we must adopt a Be yield for HNe. As Table 3 illustrates, the wide range of HN masses and energies implies a huge range in Be yields, spanning orders of magnitude. We will adopt \(\langle m_{ej},Be\rangle_{HN} \approx 2 \times 10^{-6} M_\odot\), the lower of the two values found for SN 1998bw in Table 3. The energy and ejected mass dependence for this value are as in equation (6). Given our adopted \(\langle m_{ej},O\rangle_{SN}\), we find \(X_{Be}/X/O \approx 10^{-6}\), which is several orders of magnitude larger than the observed value and the values found in superbubbles and Galactic cosmic-ray models of LiBeB production. This excess leads to the constraints we place on HNe.

We can now evaluate equation (12) given a choice of \(\beta_{obs}\). As noted above, this depends on the oxygen data. The weaker limit to \(\epsilon_{HN}\) comes from the constant O/Fe case, in which \(\beta_{obs} \approx 3 \times 10^{-8}\), and thus our fiducial numbers give

$$\epsilon_{HN} \leq 3 \times 10^{-2}.$$  (13)

This evaluation is consistent with the upper limit that can be derived from the beryllium abundance in extremely metal-poor stars, as observed with the VLT by Primas et al. (2000). On the other hand, if O/Fe varies, we have \(\beta_{obs} \approx 8 \times 10^{-10}\), which gives a tighter limit:

$$\epsilon_{HN} \leq 8 \times 10^{-4}.$$  (14)

In either case, we find \(\epsilon_{HN} \ll 1\); i.e., the HN/SN ratio is small.

There are various ways one can physically interpret a limit to \(\epsilon_{HN}\). If one attributes the origin of an HN to a mass effect, then \(\epsilon_{HN}\) is essentially the fraction (by number) of massive stars that become an HN. If we assume that stars above some lower mass limit \(m_{HN}\) become an HN, then for a Salpeter mass function (with massive stars in the range \(10 M_\odot \leq m \leq 100 M_\odot\)), we derive \(m_{HN} > 69 M_\odot\) from equation (13) and \(m_{HN} > 99 M_\odot\) from equation (14). These lie at the upper edge of the allowed range, reflecting the smallness of the HN contribution. The HN origin could also be related to additional physical parameters, such as binary interactions or rotation. In this case, the limit to \(\epsilon_{HN}\) would reflect not only a mass effect but also the fraction of systems where such conditions are present.

The variation in HN energy and ejected mass will also have an important effect on the limits quoted. Had we adopted weaker explosions or more massive ejecta, these would lead to lower Be yields and thus weaker limits on \(\epsilon_{HN}\). One could even imagine turning the problem around: given an independent measurement of \(\epsilon_{HN}\), one could use these limits to infer the mean \(m_{ej}\) for HNe.

Anyway, our calculated evaluations of \(\epsilon_{HN}\) stress clearly that the number of HNe is very low compared to supernova ones, in particular if O/Fe is variable. While this is not surprising, an important implication is that the HN contribution to Be evolution is correspondingly small. Namely, even if the yield of Be per HN is relatively high \((\sim 10^{-6} M_\odot)\) compared to the yield per SN \((\sim 3 \times 10^{-8} M_\odot;\) Ramaty et al. 2000), we can reasonably claim that the contribution of Be by hypernova is only a fraction of that produced by SN in superbubbles.

4. ON THE POSSIBLE ASSOCIATION BETWEEN GRBS AND HYPERNOVAE

The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory detected more than 2500 GRBs from 1991 to 2000. The distribution of these bursts over the sky is highly isotropic, but the number of faint bursts is notably smaller than the expected number if the distribution of bursts was homogeneous in a Euclidean universe (Fishman & Meegan 1995 and references therein). These two facts provide strong evidence that GRBs occur at cosmological distance (Paczynski 1991). This cosmological origin is now firmly established for the long bursts (>2 s) thanks the discovery of their afterglows made possible by the BeppoSAX satellite. These late and fading counterparts are first detected in the X-ray range, then in the optical, and later in the radio range. About 20 optical afterglows have been discovered to date. The redshifts of most of these events have been measured and range from \(z = 0.36\) (GRB 011121) to \(z \approx 4.5\) (GRB 000131). These values represent either a direct measure of the redshift of the afterglow or in a few cases the redshift of the host galaxy.

The two most popular models for the source of GRBs associate them with the coalescence of two compact objects (NS-NS or NS-BH; Eichler et al. 1989; Paczynski 1991; Narayan, Paczynski, & Piran 1992; Mochkovitch et al. 1993) or the collapse of a very massive star into a black hole (collapsar; Woosley 1993). Such collapsars could be either the collapse of a single Wolf-Rayet star endowed with rotation or the merger of the core of a massive star with a black hole or a neutron star and should lead to hypernovae as defined in this paper. The recent observations of the optical afterglows of long bursts and the observations of their host galaxies provide several pieces of evidence in favor of the association with massive stars: the indication of dust extinction in optical afterglows and gas absorption in X-ray afterglows suggest that GRBs occur near star-forming regions (Paczynski 1998; Bloom et al. 1998). The first direct evidence for the GRB–massive star association comes with the supernova SN 1998bw, which is probably associated with GRB 980425 (Galama et al. 1998). GRB 980326 and GRB 970228 might also be associated with supernovae (Bloom et al. 1999; Reichart 1999).

Since the sample of long bursts with a determined redshift is still small, the distribution of GRBs as a function of redshift \(z\) must be estimated indirectly. This has been done by many authors (for a review, see Piran 1999) who fitted the observed peak flux distribution assuming a given comoving GRB rate density \(R_{GRB}(z)\). The other parameters for such a calculation are the luminosity distribution of bursts \(\Phi(L)\), which is usually taken to be independent of \(z\), the assumed spectral shape for the GRBs, and the usual cosmological parameters. The burst rate obtained by this method is very uncertain. Whereas the results of these calculations are weakly sensitive to the adopted values of the cosmological parameters (Cohen & Piran 1995), it has been shown that
the BATSE sample is not large enough to distinguish between two extreme assumptions: a constant rate

$$R_{\text{GRB}}(z) = R_0$$  \hspace{1cm} (15)

or a rate proportional to the cosmic star formation rate,

$$R_{\text{GRB}}(z) \propto R_{\text{SFR}}$$  \hspace{1cm} (16)

where $R_{\text{SFR}}$ is the comoving rate density of star formation. This is true in particular when relaxing the assumption that GRBs are standard candles (Krumholz, Thorsett, & Harrison 1998), which was usually made for the first calculations (Sahu et al. 1997; Wijers et al. 1998) but is not supported by the observations.

In this paper we will only consider the case of long GRBs. We assume that every core collapse we consider here injects (1) an energy $E$ in an isotropic envelope of mass $M_{\text{ej}}$ whose expansion may be mildly relativistic—this leads to the hypernova—and (2) an energy $E_0$ in an ultrarelativistic wind beamed in a solid angle $\Omega$—this leads to the GRB. Since we are interested in putting constraints on such an association between GRBs and hypernovae, we will assume that the burst rate is indeed proportional to the cosmic star formation rate. We will use the results obtained by Porciani & Madau (2001). They did a recent estimation of the GRB rate under this assumption. They used $\Omega_M = 0.3$, $\Omega_A = 0.7$, and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$. The spectral shape of the GRBs was given by the so-called GRB function (Band et al. 1993). This is a phenomenological four-parameter function that is known to fit very well the observed spectra. They used the following parameters: $\alpha = -1.0$ for the low-energy slope, $\beta = -2.25$ for the high-energy slope, and $E_0 = 511$ keV for the break energy, which correspond to the typical values obtained by Preece et al. (2000), who did a detailed spectral study of a large sample of long GRBs. We know from the few GRBs with a measured redshift that the luminosity of GRBs is strongly variable but the luminosity distribution is very poorly constrained. Porciani & Madau (2001) used a power-law distribution:

$$\Phi(L) = C \left( \frac{L}{L_0} \right)^{\gamma},$$  \hspace{1cm} (17)

where $C$ is correctly normalized to have $\int_0^{\infty} \Phi(L) dL = 1$. With all these assumptions and using different estimations of the SFR, they found that their best fits give a GRB rate of about one to two bursts per million Type II supernovae, i.e.,

$$\epsilon_{\text{GRB, 4\pi}} = (1-2) \times 10^{-6}.$$  \hspace{1cm} (18)

Clearly, this is much lower than the HN parameter found in the previous section. With the upper limits that we have derived for $\epsilon_{\text{HN}}$ in the previous section, we get the following lower limits for the rate of GRB per HN:

$$\frac{\epsilon_{\text{GRB, 4\pi}}}{\epsilon_{\text{HN}}} \gtrsim \begin{cases} 
(3-7) \times 10^{-5} & \text{constant \(O/Fe case \},} \\
(1-3) \times 10^{-3} & \text{variable \(O/Fe case \}.} 
\end{cases}$$  \hspace{1cm} (19)

Some breaks observed in the afterglow light curves strongly suggest that the GRB emission is not isotropic but focussed in a solid angle $\Omega$. Then the GRB rate parameter in equation (18) has to be corrected upward by a factor $\left(\Omega/4\pi\right)^{-1}$, which leads to a true GRB per HN rate:

$$\frac{\epsilon_{\text{GRB}}}{\epsilon_{\text{HN}}} \gtrsim \begin{cases} 
(1-4) \times 10^{-2} & \text{constant \(O/Fe case \},} \\
(0.5-2) & \text{variable \(O/Fe case \}.} 
\end{cases}$$  \hspace{1cm} (20)

The observed distribution of beaming factor spans $\left(\Omega/4\pi\right)^{-1} \sim 10^{-2}$ with an averaged value of $\sim 500$ (Frail et al. 2001). Then in the variable O/Fe case, equation (20) indicates that a GRB-HN association with $\epsilon_{\text{GRB}} = \epsilon_{\text{HN}}$ is fully compatible with the observations, and in the constant O/Fe case, the same equation indicates that a full GRB-HN association is also possible, under the condition that the beaming factor $\left(\Omega/4\pi\right)^{-1}$ is underestimated or that the true HN rate parameter is much lower that the upper value derived in this case ($3 \times 10^{-2}$). An association with $\epsilon_{\text{GRB}} = \epsilon_{\text{HN}}$ indeed requires that $\left(\langle \Omega/4\pi \rangle^{-1}\right)^{-1} \sim (\Omega/4\pi)^{-1}/3 \times 10^{-2}$ [$(1-3) \times 10^{4}$ or $\epsilon_{\text{HN}} \sim \left(\langle \Omega/4\pi \rangle^{-1}/500\right)/0.5 \times 10^{-3}$]. Notice that the estimation of $\left(\langle \Omega/4\pi \rangle^{-1}\right)$ by Frail et al. (2001) is based on a small sample of GRBs, where the most beamed GRBs lead to only a lower limit for $\left(\langle \Omega/4\pi \rangle^{-1}\right)$ since the break in the afterglow light curve occurs too early to be observed.

Notice also that our estimation of $\epsilon_{\text{HN}}$ scales with the HN parameters in the same way as the Be yields, i.e., as $M_{\text{ej}}/E_{\text{ej}})^{1/2} = M_{\text{ej}}/E_{\text{ej}}).$ This strong dependence means that a modest change in $E/M_{\text{ej}}$ produces a noticeable shift in $\epsilon_{\text{HN}}$. Thus, in the context of the possible GRB-HN association, one might hope to turn the problem around and use an accurate measure of the mean $\left(\langle \Omega/4\pi \rangle^{-1}\right)$ to infer the mean $E/M_{\text{ej}}$ in HNe. Thus, one might hope to turn the problem around and use an accurate measure of the mean $\left(\langle \Omega/4\pi \rangle^{-1}\right)$ to infer the mean $E/M_{\text{ej}}$.

Despite this encouraging result, important uncertainties remain, especially due to our poor knowledge of the explosion mechanism. If only a subclass of GRB progenitors leads to a hypernova as we have defined, then $\epsilon_{\text{HN}}$ has to be compared to a fraction only of $\epsilon_{\text{GRB}},$ and the constraint on the beaming angle or the $E/M_{\text{ej}}$ ratio becomes more severe. On the other hand, the opposite situation cannot be excluded, namely, that the isotropic envelope expansion that we associate with an HN is always present but the GRB is produced only when certain unknown conditions allow the acceleration of an ultrarelativistic outflow. In this case $\epsilon_{\text{HN}}$ has now to be compared with $\epsilon_{\text{GRB}}$ divided by the fraction of explosions producing a GRB and large beaming angle are allowed, even with the $E/M_{\text{ej}}$ ratio that we have adopted here.

5. CONCLUSION

Motivated by recent theoretical and observational interest in hypernovae, we have considered the LiBeB production by these objects. We find that the LiBeB yields are very sensitive to the explosion energy and ejected mass. If these parameters typically take values as found for SN 1998bw, then the Be yields can be very large because of the high-explosion energy.
Using the yields found for SN 1998bw, we have calculated the impact of HNe on LiBeB evolution in the galaxy. HNe represent a primary source of Be and thus are constrained by the observed primary component of Be versus O. Using the observed Be data at low metallicities, we are thus able to place limits on the HN/SN ratio. If we further associate HNe with GRBs, we can infer a limit on the beaming angle of the GRB emission \((\Omega/4\pi)^{-1} \leq (1.5-3) \times 10^4\) (constant O/Fe assumption) and \((\Omega/4\pi)^{-1} \leq (4-8) \times 10^2\) (variable O/Fe assumption) that are consistent with independent estimates. This agreement is encouraging, although of course significant uncertainties remain.

Under the simple assumption of a constant HN/SN ratio that has been made to derive these limits, there are potentially important consequences for LiBeB evolution. As shown above, the HN/SN ratio being very low (≤1), we can reasonably conclude that the contribution of Be by HN is only a fraction of that from supernovae in superbubbles. The Li-Fe relation shows a small slope (Ryan, Norris, & Beers 1999) that is consistent with standard GCR production of Li (Ryan et al. 2000) but within errors also allows room for other primary Li contributions. Since the Li-Fe relation is measured more precisely, one may be able to detect or limit the Li production by HNe, in addition to that of standard and superbubble cosmic rays.

The assumption that the HN/SN ratio is constant would be true if both arise from massive star formation and a constant, universal initial mass function. While this is probably the simplest assumption, other scenarios are possible. For example, if a first generation of HNe associated with very massive stars (Population III) has existed, it could have produced protogalactic beryllium, along with C and O. If these Population III HNe produce strictly C and O but little or no iron, then this Be component would manifest itself under as a plateau in the Be-Fe correlation at the lowest metallicity (but a linear, primary trend in Be-O). Consequently, if this Be-Fe plateau were observed, it would not necessarily imply that BBN has contributed. In this scenario, the HN rate would not follow the SN rate during the Population III phase. Thus, this picture could be tested by measuring the cosmic SN and HN rates at high redshifts.

We warmly thank Robert Mochkovitch for illuminating discussions, and we thank the anonymous referee for several suggestions that improved this manuscript. F. D. acknowledges financial support from a postdoctoral fellowship from the French Spatial Agency (CNES). This work has been supported in part by PICS 1076 from the CNRS and in part by the National Science Foundation under grant AST 00-92939.

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