THE ASTROPHYSICAL JOURNAL, 562:664–669, 2001 December 1

PREEXISTING SUPERBUBBLES AS THE SITES OF GAMMA-RAY BURSTS

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Received 2001 April 27; accepted 2001 July 31

ABSTRACT

According to recent models, γ-ray bursts apparently explode in a wide variety of ambient densities ranging from $\sim 10^{-3}$ to 30 cm^{-3} or more. The lowest density environments seem, at first sight, to be incompatible with bursts in or near molecular clouds or with dense stellar winds and hence with the association of γ-ray bursts with massive stars. We argue that low ambient density regions naturally exist in areas of active star formation as the interiors of superbubbles. The evolution of the interior bubble density as a function of time for different assumptions about the evaporative or hydrodynamical mass loading of the bubble interior is discussed. We present a number of reasons why there should exist a large range of inferred afterglow ambient densities whether γ-ray bursts arise in massive stars or some version of compact star coalescence. We predict that many γ-ray bursts will be identified with X-ray bright regions of galaxies, corresponding to superbubbles, rather than with blue localized regions of star formation. The lack of evidence for winds may imply low wind densities and hence low mass-loss rates combined with high velocities for any massive star progenitor. The problem would be avoided in a binary neutron star model.

Subject headings: gamma rays: bursts — ISM: bubbles — ISM: jets and outflows — stars: formation — supernovae: general

1. INTRODUCTION

There is circumstantial evidence that γ-ray bursts are associated with the collapse of massive stars. The events seem to occur in galaxies with active star formation (Hogg & Fruchter 1999). Sokolov et al. (2001) use spectral synthesis of γ-ray burst host galaxies to conclude that their sample galaxies have large star formation rates (SFRs) and appear to be below L_* only because of dust extinction. Some γ-ray burst afterglows seem to reveal evidence for supernova light (Bloom et al. 1999; Reichart 1999; Galama et al. 2000). Recent observations reveal evidence for iron that may be ejected from the explosion (Piro et al. 2000; note, however, that the abundance of the iron is very model-dependent and that the observed features may be consistent with a solar abundance of iron; Rees & Mészáros 2000).

If γ-ray bursts occur in massive stars, then there are two expectations for their environment. The immediate environment should be dominated by a strong stellar wind, and the larger environment should be typical of the star-forming region. If the local environment in which the γ-ray burst explodes is associated with molecular cloud cores, densities could significantly exceed 10–100 cm^{-3}, reaching values as large as 10^4–10^6 cm^{-3}. By contrast, recent multiwavelength analysis of selected γ-ray burst afterglows by Panaitescu & Kumar (2001) has shown that the ambient density of some γ-ray bursts can be as low as $\sim 10^{-1}$ to 10^{-3} cm^{-3} and perhaps even less for their particular afterglow shock model. These low densities might be regarded as incompatible with the hypothesis that γ-ray bursts are associated with massive stars. We argue here that, on the contrary, such small densities may arise if γ-ray bursts explode within the preexisting interiors of superbubbles, themselves the remnants of earlier massive star formation, and that even the range in densities can be understood. We investigate the implications of this hypothesis for the nature of γ-ray bursts.

In § 2 we summarize the information on the ambient densities of γ-ray bursts and describe models of superbubbles and their evolution. In § 3 we discuss the expected variation in afterglow densities, and in § 4 we outline various ways in which γ-ray bursts could be born in and interact with superbubbles. We present our conclusions, including important constraints on the progenitor wind, in § 5.

2. AFTERGLOWS AND SUPERBUBBLES

Panaitescu & Kumar (2001) analyze the multiwavelength data of the afterglows of four well-studied γ-ray bursts, assuming that the emission is due to the interaction of a collimated relativistic shock with the ambient medium and subsequent emission of synchrotron and inverse Compton-scattered radiation. They find that each of these bursts is incompatible with the interaction with a $1/r^2$ wind but is compatible with an interstellar medium of constant density. The values they derive for the ambient density are remarkably low: GRB 980703, $\sim 8.0 \times 10^{-4}$ cm^{-3}; GRB 990123, $\sim 8.1 \times 10^{-3}$ cm^{-3}; GRB 990510, $\sim 2.2 \times 10^{-1}$ cm^{-3}; and GRB 991216, $\sim 2.4 \times 10^{-4}$ cm^{-3}. Other studies have obtained a generally higher range for the ambient density. Wijers & Galama (1999) and Frail et al. (2000) find about 0.5 cm^{-3} for GRB 970508. Higher densities, ~ 30 cm^{-3}, have been associated with some events (Kumar 2001; private communication; Harrison et al. 2001). Piro et al. (2001) ascribe a density of $\approx 4 \times 10^4$ cm^{-3} to GRB 000926, and Masetti et al. (2001) argue for a density in excess of $\approx 10^5$ cm^{-3} for GRB 010222 (but see Cowsik et al. 2001).

At face value, the lowest of these ambient densities and the lack of evidence for a $1/r^2$ stellar wind are difficult to reconcile with the hypothesis that the "long" γ-ray bursts with afterglows arise in massive stars. Massive stars must inevitably blow a stellar wind, and they are often associated with dense interstellar clouds. Both of these issues must be addressed if the association of γ-ray bursts with massive stars is to be maintained in the presence of low ambient densities. Here we focus on the properties of superbubbles,

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but the constraint of the wind remains severe. We return to that topic in the discussion of § 5.

The low ambient density for some γ-ray bursts is actually not so exotic but is characteristic of the densities inside superbubbles formed by the H II regions, winds, and supernovae of clusters of massive stars (Weaver et al. 1977; Tomisaka & Ikeuchi 1986; McCray & Kafatos 1987; MacLow & McCray 1988; Tomisaka 1992, 1998), just the environment one might associate with massive star progenitors of γ-ray bursts. There is observational evidence for such structures and associated low-density interiors. The "Local Hot Bubble" and the Loop I Superbubble in Sco-Oph, which are currently interacting, have interior densities estimated from model fits to X-ray spectra of about 2×10^{-3} cm^{-3} for the Local Bubble and $(2–5) \times 10^{-2}$ cm^{-3} for the Loop I Superbubble (see Egger 1998; Breitschwerdt, Freyberg, & Egger 2000 and references therein). Many external galaxies show evidence for large H I holes that may be associated with superbubbles (see Walter 1999 for a summary).

The density in a superbubble depends on a number of parameters: the ambient density into which the bubble expands (itself perhaps porous); the time-dependent power input from H II regions, winds, and supernovae; the evaporation of clouds and of the compressed shell of ambient gas; turbulent attrition of the shell; and the time since the onset of the power input, among others. To represent the density evolution, we adopt the expression from Shull & Saken (1995) for the interior density of the bubble. Shull & Saken assume an isothermal interior in pressure balance and hence derive an interior density loaded by conductive mass evaporation from the shell that is radially constant interior to the bubble shell. They give (their eq. [12])

$$n_b(t) = 1.6 \times 10^{-2}\ \mathrm{cm}^{-3}\ L_{38}^{6/35} n_a^{19/35} t_6^{-22/35} k_0^{2/7}\ , \quad (1)$$

where L_{38} is the power input from winds and supernovae in units of 10^{38} ergs s^{-1}, n_a is the ambient number density into which the bubble propagates, t_6 is the time since the bubble was initiated in units of 10^6 yr, and k_0 is a factor of order unity that accounts for possible suppression of conductivity by magnetic fields or enhancement by evaporation of engulfed clouds (Silich et al. 1994, 1996). Equation (1) is very similar to the formula given by MacLow & McCray (1988) based on the solution of Weaver et al. (1977), except that MacLow & McCray include a spatial dependence factor $(1 - r/R)^{-0.4}$, where R is the shell radius, that causes the density to rise near the shell.

The numerical coefficient in equation (1), and perhaps even the scaling with parameters, depends on the assumption that the bubble interior is mass-loaded by classical evaporation from the interior of the shell. Silich et al. (1994, 1996) have performed three-dimensional nonhydrodynamic simulations of superbubbles expanding into cloudy ambient media with different cloud filling factors (and other parameters) and find that the mass loading is dominated by evaporating engulfed clouds rather than evaporation from the superbubble shell. Figure 1 in Silich et al. (1994) indicates interior densities larger than given by equation (1) (when scaled to the same L_{38}) by a factor of 3 at 10 Myr for an assumed cloud filling factor of 0.1. Inspection of their figures indicates that the time scaling of $n_b(t)$ is roughly consistent with the $t^{-2/3}$ scaling in equation (1), although it depends somewhat on the parameters.

In contrast, magnetic fields can suppress conduction even if they are dynamically unimportant. Strickland & Stevens (1998) present two-dimensional hydrodynamic simulations of wind-blown bubbles in which evaporation is completely neglected. In their simulations, the interior bubble density is determined by the mixing of dense shell material into the hot interior caused by shear motions between the interior and the dense shell that is corrugated by instabilities. Their Figure 4 shows an order-of-magnitude decrease of the interior bubble density relative to the Weaver et al. (1977) classical conduction solution. Strickland & Stevens do not present the time evolution, so we cannot say whether the time scaling would be similar to equation (1).

That the time dependence of n_b in equation (1) depends on the type of mass loading of the bubble interior can be seen by considering the rate of change of n_b due to mass loading at rate $\dot{M}(t)$ and bubble expansion as

$$\frac{dn_b}{dt} = \frac{3\dot{M}}{4\pi R^3 m_p} - 3\,\frac{n_b}{R}\frac{dR}{dt}\ , \quad (2)$$

where m_p is the average mass of a particle in the bubble interior. If the shell radius scales as $R \propto t^{3/5}$ (Weaver et al. 1977; this implies $n_a =$ const, see below), then the second term (no mass loading) gives a contribution to $n_b(t) \propto R^{-3}$ that varies as $t^{-9/5}$. For the first (mass loading) term, Shull & Saken (1995) find a classical conduction mass input rate $\dot{M}$ that scales approximately as $t^{1/6}$. Using $R \propto t^{3/5}$, this term gives a contribution to $n_b(t)$ that scales as $t^{-19/30}$, just the scaling ($t^{-2/3}$) given by Shull & Saken, showing that their result for $n_b(t)$ is dominated by the conductive mass loading. Since mass loading by hydrodynamic effects should occur even in the absence of conduction (Strickland & Stevens 1998), the no-conduction case should lie between these two extremes. For example, if $\dot{M}$ and n_a are constant, then the mass-loading term yields $n_b(t) \propto t^{-4/5}$. We continue to use the classical conduction solution $t^{-2/3}$ as given by Shull & Saken (1995), with the understanding that the time dependence may be steeper. In what follows, we will adopt the approximate expression for the bubble interior density to be

$$n_b(t) = 1.6 \times 10^{-2}\ \mathrm{cm}^{-3}\ L_{38}^{1/6} n_a^{4/7} t_6^{-2/3} \theta\ , \quad (3)$$

where θ accounts for the uncertainty in the mass-loading rate. The discussion above suggests $0.1 \lesssim \theta \lesssim 3$. We know of no empirical estimates of the mass loading factor θ for superbubble winds. For the larger starburst-driven galactic winds, claims of the importance of mass loading by evaporation of engulfed clouds have been made based on *ROSAT* X-ray spectra (Suchkov et al. 1996; della Ceca, Griffiths, & Heckman 1997), but they are very uncertain (Strickland & Stevens 2000). For a constant ambient density n_a, the time for the bubble to reach a given interior density, n_b, will be

$$t_6 = 63 L_{38}^{1/4}\left(\frac{n_b}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-3/2} n_a^{6/7} \theta^{3/2}\ . \quad (4)$$

We need to modify equation (3) for $n_b(t)$ to account for the fact that the density into which a bubble expands will depend on its size, e.g., $n_a(t) = Br^{-p}$, where r is the radius of the region. Statistically, the cool interstellar medium density structure can be characterized as a fractal from $\sim$0.1 to 100 pc (Beech 1987; Bazell & Desert 1988; Scalo 1990; Dickman, Horvath, & Margulis 1990; Falgarone, Phillips, & Walker 1991; Vogelaar, Wakker, & Schwarz 1991; Vogelaar & Wakker 1994) or even to much larger (Mpc) scales (Westpfahl et al. 1999). In three dimensions, a region of size r is likely to contain an interior mass proportional to r^d, which is equivalent to $\rho(r) \propto r^{d-3}$. Nearly all the above studies find $d \sim 1.3$ for the two-dimensional *projected* density distribution, or $p = 3 - d \sim 1.7$. There are, however, questions concerning how these "perimeter-area" dimensions for a projected density distribution should be changed (if at all) for the three-dimensional distribution. Although there is good agreement concerning the area-perimeter dimension using various tracers, this dimension applies to the appearance of the real three-dimensional structure projected onto the sky. The relation of the three-dimensional to projected dimension is uncertain and is summarized in Westpfahl et al. (1999). They point out that for opaque Borel sets, the projected dimension should be the intrinsic dimension, or 2, whichever is smaller. This would suggest a three-dimensional dimension of 1.3 for the interstellar medium (ISM). This value would, however, give a mass-radius relation that is much shallower than observed (see Elmegreen & Falgarone 1996); the observed scaling would give a three-dimensional dimension (although not formally the same as the perimeter-area dimension) of about 2.3. Elmegreen & Efremov (1999) derive a similarly large dimension from the distribution of cloud sizes. We are inclined to adopt the three-dimensional fractal exponent as 2.3, not 1.3, because (1) the structures studied are not opaque but (virtually) transparent; (2) the methods of estimating the dimension that yield 2.3 correspond more closely with the physical basis of our model, i.e., the number of particles or mass or average density within a region of a certain size, rather than the perimeter-area dimension; and (3) if young stars trace out the structure of the gas from which they formed, then the study of the manner in which the number of star formation aggregates scales with imposed smoothing scale in *HST* images of 10 galaxies by Elmegreen & Elmegreen (2001) strongly suggests a fractal dimension of about 2.3. This choice of d would give $p = 3 - d \sim 0.7$. One should also bear in mind that the distribution is actually multifractal (Chappell & Scalo 2001).

For simplicity, we adopt as a fiducial scaling relation Larson's (1981) scaling relation for molecular clouds, $n_a(r) \sim 10^3\ B_3\ \mathrm{cm}^{-3} r_{\mathrm{pc}}^{-1}$, where $B_3 \sim 1.7$ is a normalization constant representing the number density in units of 10^3 cm^{-3} at the scale of 1 pc. We realize that this relation may be seriously affected by selection effects (Kegel 1989; Scalo 1990). We also examine the cases for $p = 0.7$ and 1.7 to check the sensitivity. For the case $p = 1$ we obtain

$$n_b(t) = 0.1\ \mathrm{cm}^{-3}\ B_3^{5/7} L_{38}^{1/42} t_6^{-23/21} \theta\ . \tag{5}$$

The interior bubble density decreases more rapidly with time than in the case for constant n_a because the interior volume is increasing more rapidly with time. For comparison, if mass loading dominates but with a constant mass injection rate $\dot{M}$, $n_b(t) \propto t^{-5/4}$, while if there is no mass loading and n_b is governed completely by expansion, $n_b(t) \propto t^{-9/4}$. If we took $p = 0.7$ (our preferred value), n_b would be larger by about a factor of 2. If we took $p = 1.7$, n_b would be smaller by about a factor of 7.

Solving equation (5) for the time to reach internal density n_b, we get

$$t_6 = 66 B_3^{15/23} L_{38}^{1/46} \left(\frac{n_{b,3}}{\theta}\right)^{-21/23} . \tag{6}$$

This time would be longer by a factor of about 5 if $p = 0.7$ and shorter by a factor of about 12 for $p = 1.7$. Any constraints on the lifetime of the progenitor star thus depend rather sensitively on the structure of the ambient medium. We will return to this topic in § 4. For now we conclude that afterglow density estimates less than about 0.1 cm^{-3} are consistent with γ-ray bursts exploding into preexisting superbubbles, independent of the specific mechanism of the γ-ray bursts. In addition, the factor θ expressing the uncertainty in the mass-loading rate was estimated to be in the range 0.1–3. With hydrodynamical mass loading and no conduction (Strickland & Stevens 1998), the bubble density will be smaller by an order of magnitude and the corresponding time larger by about the same factor.

3. VARIATIONS IN AFTERGLOW DENSITIES

There are a number of effects that will provide variations in the density into which a γ-ray burst might explode within the context of the hypothesis that γ-ray bursts propagate into superbubbles. Each of these has potentially different implications for the progenitors of γ-ray bursts.

1. Even if the γ-ray burst explodes within the cluster that produced the superbubble so that the γ-ray burst is roughly centrally located in the bubble, there are bound to be variations in the ambient density n_a. For example, if the wind initially expands within a giant molecular cloud (GMC), the mean density may be 100 cm^{-3}, but there will be variations in the mean value from cloud to cloud and GMC internal density fluctuations of several orders of magnitude. Most of these internal cloud density fluctuations will be on scales smaller than the bubble size at later times. The effects of superbubbles that begin their expansion at different distances from the midplane of a galactic disk (Silich et al. 1994, 1996) will introduce further variations in ambient density. Note that even large variations in the cluster wind kinetic energy L_{38}, reflecting different masses of clusters, will not substantially affect our results (cf. eq. [5]).

2. Superbubbles have a variety of ages, and hence interior densities into which γ-ray bursts may explode. If the clusters giving rise to the superbubbles are born with a rate that is a function of time given by $B_\gamma(t)$, then the probability distribution of superbubbles with interior density n_b is given by

$$f(n_b) = \frac{B_\gamma[t(n_b)]}{|\,dn_b/dt\,|}\ . \tag{7}$$

Assuming a constant rate of cluster formation and taking $|\,dn_b/dt\,|$ from equation (5) gives $f(n_b) \propto n_b^{-44/23}$ showing that we are much more likely to observe a γ-ray burst exploding into a superbubble of low density, basically because the superbubbles decelerate with time so more shells occur at large ages and small densities. It can be shown using the relations given above that in the limits of expansion or mass loading dominance, the exponent of $f(n_b)$ would be $\sim -3/2$ to -2, nearly independent of the dependence of R on n_a. Thus the conclusion that the inferred afterglow densities would be dominated by the smallest values of n_b in the absence of other effects is robust with respect to assumptions about the mass loading. The γ-ray bursts may not, of course, explode randomly, but may be correlated in time and space with a given superbubble.

3. Given the sizes of superbubbles, $\sim$ 10 pc to 1 kpc, it is likely that a given superbubble has engulfed another, younger, cluster. In this case, a γ-ray burst exploding in an

engulfed cluster will expand somewhere within the earlier superbubble (and within the ambient medium of its host cluster). The conduction solution of Weaver et al. (1997) and the no-conduction simulations of Strickland & Stevens (1998) exhibit radial density profiles with significant variations, from 1 to 2 orders of magnitude. Thus, although the γ-ray burst is most likely to explode in the " plateau " region of the density distribution (basically given by eq. [1]), there is a significant probability that it will explode in smaller or larger densities. We point out that Chu & MacLow (1990) proposed that supernova remnants explode off-center in superbubbles in order to explain the X-ray emission of H II complexes in the LMC.

4. Considering the collimated nature of the γ-ray burst explosion in the model of Panaitescu & Kumar (2001) and suspected in general (e.g., Frail et al. 2001), the shock has a probability of encountering either one of the clouds engulfed by the superbubble or one of the many supernova blast waves that impose sizeable density fluctuations within the superbubble.

Given all these considerations, we conclude that it is likely that the inferred ambient densities for γ-ray burst afterglows could span a range of four or five orders of magnitude, as inferred empirically by Panaitescu & Kumar (2001), and we can easily explain both the lower and higher inferred ambient densities. The very lowest densities (e.g., $n_b \sim 2.4 \times 10^{-4}$ cm^{-3} for GRB 991216) might require relatively extreme values of the mass-loading parameter, θ, the density distribution parameter, p, variations in the bubble density profile, or perhaps a preexisting bubble. For instance, using equation (3) in the case of a constant ambient density, this low value of n_b could be attained for $\theta = 0.1$, an ambient density of 0.2 cm^{-3}, and a cluster age of about 5 million years; this case would suggest explosion into a preexisting bubble or at least a low-density void within the larger molecular cloud complex. Alternatively, from equation (6) this value of n_b could be attained for $\theta = 0.1$, $p = 1.7$, and an age of about 3 million years: this case suggests an unusually steep value of the local fractal dimension, variations of which are expected because of the multifractal nature of the density distribution (Chappell & Scalo 2001). At the other extreme, the highest densities may, indeed, require conditions reminiscent of dense molecular cloud cores.

A consequence of our proposal that γ-ray bursts explode in preexisting superbubbles is that, at high resolution, γ-ray bursts with low ambient densities should be spatially associated not with the bluest regions of galaxies but with X-ray bright spots associated with superbubbles. Perhaps this explains why Holland et al. (2001) find that GRB 980703, one of the low-density cases, shows no connection with any special features of the host. With a resolution of about 0″.5, *Chandra* X-ray observations would only be able to resolve medium size, 100 pc, superbubbles at distances less than $\sim$20 Mpc. The best H I 21 cm interferometer mappings of holes in galactic gas can reach somewhat larger distances. This resolution limit corresponds to a redshift of about $z = 0.003$. Since the mean redshift of γ-ray bursts is $\gtrsim 1$, the probability of finding such a nearby γ-ray burst is $\lesssim 3 \times 10^{-8}$ per event.

4. CONSTRAINTS ON PROGENITORS

The evolution of superbubbles is potentially complex, so evaluating the implication of γ-ray bursts occurring in superbubble environments is uncertain. Here we will survey some of the reasonable possibilities.

One possibility is that γ-ray bursts occur in some type of coalescing binary, e.g., neutron stars. Such a possibility requires rather short-lived binaries since all identified γ-ray bursts so far are within the optical contours of the host galaxy (A. S. Fruchter, private communication) and hence cannot have drifted very far before coalescence. Such a model might be consistent with both an overall correlation with star formation and with a lack of universal correlation with specific blue knots of recent star formation. Drifting binary neutron stars might be expected to randomly sample the complex ISM expected in a star forming galaxy that blows bubbles, as outlined in § 3. Binary neutron stars would also avoid the problem of the progenitor wind discussed in § 5.

In the remainder of this section, we will consider possible constraints on massive stars as the progenitors of γ-ray bursts. We will consider constant power input to the bubbles, but according to the models of Shull & Saken (1995), varying the power input, e.g., from continuous to coeval, star formation will not change any of these conclusions substantially.

The simplest hypothesis is that there is a coeval burst of star formation in a cluster after which the stars themselves blow winds to make the bubble and eventually die as supernovae. This hypothesis is especially interesting because it implies that if the γ-ray bursts that go off in the low density environments are, in fact, within such self-generated bubbles (cf. points 1 and 2 of § 3), then the stars that produce the γ-ray bursts are not the most massive stars. Some stars must already have evolved with strong winds and perhaps died to blow a sufficiently low density bubble. This raises the possibility of placing an *upper limit* on the progenitor mass of γ-ray burst progenitor stars.

Equation (4) applies to the simple case of coeval evolution of the stars and expansion of the bubble into a constant density environment. The implication is that for a bubble driven with approximately constant power, the ambient density into which the bubble propagates must be very low, $n_a \lesssim 0.05$ cm^{-3}, to allow time, about 5 million years, for, say, 30 $M_\odot$ stars to evolve and explode in a bubble of mean interior density of $n_b = 10^{-3}$ cm^{-3}. Such a low value of n_a suggests a preexisting bubble, a case we consider below. If the mass loading of the bubble is hydrodynamical rather than by conduction, the ambient density for the γ-ray burst can be significantly larger; however, if the mass loading is due to evaporation of engulfed clouds, the required ambient densities must be somewhat smaller. If the ambient density is higher, then even lower mass stars must have had time to evolve before the first γ-ray burst went off at such low bubble densities.

The possibility of a γ-ray burst progenitor of mass $\lesssim 30$ $M_\odot$ in order to give time for a coeval starburst to form a low-density bubble is strongly constrained by considering the rate of occurrence of γ-ray bursts. Scalo & Wheeler (2001) estimate that the ratio of γ-ray bursts to supernovae is about one in several thousand if collimation is neglected. Even with rather strong collimation into one part in 100 of 4π steradians, the lowest mass that could contribute to γ-ray bursts would be over 100 $M_\odot$. Only if the collimation of γ-ray bursts were substantially smaller could the rate of γ-ray bursts be comparable to the rate of death of stars of 30 $M_\odot$ or less. This seems extreme, but we note that models for the afterglow imply that some bursts are collimated to this degree (Panaitescu & Kumar 2001; Frail et al. 2001). Other ways to avoid excessively large γ-ray burst rates with the low-mass progenitors demanded in the coeval bubble picture are that γ-ray bursts do not arise from stars with an upper limit threshold mass, but occur in a narrow mass range or from a small fraction of events with some special extreme of character, e.g., rotation or magnetic field, over a broad range of masses.

This picture is modified somewhat if we consider bubbles expanding into a fractal density distribution, as described by equation (6). For $B_3 \sim 1$ and $p \lesssim 1$, the time to reach low densities, $n_b \sim 10^{-3}$ cm^{-3}, is very long so that unrealistically small progenitor masses would be required. For $p = 1.7$, however, the time to reach these small bubble densities is fairly short. The upper limit to the progenitor mass of a γ-ray burst might be consistent with the estimated rates of γ-ray bursts and still allow time for even higher mass stars to blow the requisite bubble. The upper limit would clearly be a rather sensitive function of the parameter p describing the distribution of ambient gas. There is additional uncertainty due to the mass loading parameter, θ. Another interesting alternative is explored by Shull & Saken (1995). They investigate the scenario proposed by Doom et al. (1985) wherein lower mass stars, say about 15 $M_\odot$, are born first and the most massive stars are only born later, after an interval of 10–20 million years. In this case, the older, lower mass stars blow the bubble, but the younger, higher mass stars could provide the γ-ray bursts. This possibility obviously precludes determining an upper limit to γ-ray burst progenitors. Rather, it might be possible to constrain the lower limit, but this would depend on the parameter, p, of the ambient density structure, the mass loading parameter, θ, and the time history of the SFR.

The inevitability of bubbles in regions of active star formation leads to the possibility that a γ-ray burst will explode in a cluster that has itself been engulfed by an older, independent superbubble, cf. point 3 of § 3. In this case, an older cluster could have blown a bubble and then a younger cluster, perhaps formed by the compression of the shell of the first one, could produce the γ-ray burst. In this case it is difficult to put any constraints at all on the progenitor of the γ-ray burst. One problem with this possibility is that the remnant density in the younger star cluster might be larger than can be tolerated for the lowest densities revealed by the afterglows.

5. CONCLUSIONS

The low densities in which some γ-ray burst afterglows propagate provide interesting clues to the environment of γ-ray bursts and to their progenitors. Our principle conclusion is that superbubbles can easily provide such environments. In general, to attain low densities $\sim 10^{-3}$ cm^{-3}, the superbubbles must propagate into relatively low ambient densities or must be rather old. The expected evolution of superbubbles favors large, low density bubbles. Young superbubbles could account for densities ~ 10 cm^{-3}. Even larger densities, $\gtrsim 10^4$ cm^{-3}, may require molecular cloud cores.

The evidence for the lowest densities should be reexamined with more general models involving, for instance, variations in Lorentz factor across the jet or a clumpy medium. The evidence for very high densities should also be reexamined. In some cases (e.g., GRB 010222), this evidence involves early deceleration to nonrelativistic shock speeds, a point that remains controversial (Masetti et al. 2001; Dai & Cheng 2001 and references therein). Galama & Wijers (2001) have derived high densities (~ 500 cm^{-3}) by considering X-ray absorption column depths and dust destruction by the γ-ray burst for some of the same bursts (GRB 980703, GRB 990123, GRB 990510) for which Panaitescu & Kumar (2001) derive low ambient densities. The constraints invoked by Galama & Wijers may not hold if the gas responsible for the column depth is not colocated with the volume containing the dust, destroyed or not.

The low afterglow densities could be consistent either with the hypothesis that rather young and slowly drifting neutron star binaries randomly sample the large expected density variation of active star forming galaxies or with a variety of possibilities associated with massive star progenitors. The low ambient densities for some afterglows do not a priori preclude massive star progenitors for γ-ray bursts.

The expected superbubble properties of star-forming galaxies can, in principle, constrain the progenitor masses if γ-ray bursts arise in massive stars, but in practice uncertainties in ISM structure, bubble mass loading, SFR history, cluster evolution, and stellar mass functions make it difficult to do so quantitatively.

While the interior of superbubbles provides a natural environment for low ambient afterglow densities, the self-contamination of such a low-density environment by a stellar wind remains a severe problem for the massive star hypothesis. To be compatible with the lack of any evidence for such a wind, the wind density must be very low. This sets constraints on either the mass loss rate, the wind velocity, or both. For a stellar wind characterized by a constant velocity wind at $10^8 v_8$ cm s^{-1} carrying mass at a rate $10^{-5}\dot{M}_{-5}\, M_\odot$ yr^{-1}, the baryon number density is

$$n = 30\ \mathrm{cm}^{-3}\ \dot{M}_{-5} v_8^{-1} R_{17}^{-2}\ , \tag{8}$$

ignoring whether the baryons are single or incorporated in nuclei, at a radius, R_{17}, in units of 10^{17} cm characteristic of that to which afterglows propagate. Such a wind, as might characterize a typical O or Wolf-Rayet star, is incompatible with the lowest afterglow ambient densities inferred. For the density in such a wind to be less than the lowest ambient densities $\sim 10^{-3}$ cm^{-3} at a radius $\sim 10^{17}$ cm, one requires $\dot{M}_{-5} v_8^{-1}$ to be less than $\sim 10^{-4}$. This is a rather extreme requirement, but it may be fulfilled by stripped cores with fast winds and atmospheres dominated by heavy elements, e.g., carbon and oxygen, that are difficult to expel by radiation pressure due to their large weight. The arguments for a metal-rich atmosphere suggest that for the wind of a massive star to not affect the afterglow, something like a Type Ic supernova makes a natural progenitor, a point made in other contexts (Woosley 1993; MacFadyen & Woosley 1999; Wheeler et al. 2000). On the other hand, heavy ions will have more lines to interact via radiative acceleration, so it is not clear that the winds can be suppressed. Another possibility is that the mean wind density is high but that a small column, for instance along the rotation axis, has a much lower density.

SN 1998bw might represent the behavior of a relevant massive star progenitor. Weiler, Panagia, & Montes (2001) derive a nearly r^{-2} density profile with a mass loss rate of $\sim 3.5 \times 10^{-5} M_\odot$ yr^{-1} for an assumed wind velocity of 10^6 cm s^{-1} with some 30% radial variations on the scale of 5×10^{16} to 1.5×10^{17} cm, just the region where an afterglow might form. For a perhaps more reasonable wind velocity of 10^8 cm s^{-1}, the mass-loss rate would be as high as $\sim 3.5 \times 10^{-3}$ $M_\odot$ yr^{-1}. For this wind speed, the wind perturbations detected by Weiler et al. would have formed only 16–47 yr before the explosion, e.g., in the very final stages of evolution. Unless wind asymmetry effects are very important, the results of Weiler et al. suggest that a progenitor like that of SN 1998bw would be difficult to reconcile with the low densities attributed to some γ-ray burst afterglows. The nature of the wind must be addressed to reconcile the low ambient afterglow densities with massive star progenitors.

Note that the column depth in a wind is

$$l = 50 \text{ g cm}^{-2}\ \dot{M}_{-5} v_8^{-1} R_{10}^{-1}\ , \tag{9}$$

where the radius is in units of 10^{10} cm, characteristic of the outer radius of the core of a massive star. For $\dot{M} v_8^{-1} \sim 1$, the column depth is high enough to suppress γ-ray bursts emitted at $R \sim 10^{10}$ cm. If $\dot{M}_{-5} v_8^{-1} \lesssim 10^{-4}$ in order to provide low densities at large distances, then there will also be negligible column depth in the wind.

We predict that the γ-ray bursts with low ambient densities will be identified with X-ray bright regions of galaxies and H I holes, corresponding to superbubbles, rather than with blue localized regions of star formation.

We are grateful to Andy Fruchter, Peter Höflich, Pawan Kumar, and Brad Schaefer for discussions of γ-ray bursts and their afterglows and to Doug Swartz for discussions of superbubbles. We especially thank Sally Oey for guiding us to relevant literature on superbubble interiors that formed the basis for this work. This research was supported by NSF grants AST 98-18960, AST 99-07528, and NASA grant HST-GO-08688.09.

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