Giant Shells and Stellar Arcs as Relics of Gamma Ray Burst Explosions

Yuri N. Efremov1, Bruce G. Elmegreen2, Paul W. Hodge3

ABSTRACT

Gamma Ray Burst (GRB) explosions are powerful and frequent enough to make kiloparsec-size shells and holes in the interstellar media of spiral galaxies. The observations of such remnants are summarized. Several observed shells contain no obvious central star clusters and could be GRB remnants, but sufficiently old clusters that could have formed them by supernovae and winds might be hard to detect.

Subject headings: gamma rays: bursts — galaxies: ISM — ISM: bubbles — ISM: supernova remnants

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1. Introduction

The recent discovery of optical afterglows from gamma-ray bursters and the realization that they are at cosmological distances and extremely powerful, raises the issue of their interaction with the interstellar medium of the host galaxy. This revives the old suggestion that some large stellar and interstellar structures such as arcs of star clusters, HI supershells, and dust rings, are caused by super-supernovae (e.g., Shklovsky 1960; Hayward 1964; Westerlund & Mathewson 1966; Hodge 1967).

Optical counterparts to GRBs were found after 20 years of searching when GRB970228 (Groot et al. 1997; van Paradijs et al. 1997) and GRB970508 (Bond 1997) were assigned accurate positions by the X-ray satellite BeppoSAX (Costa et al. 1997; Piro et al. 1998). Absorption lines in GRB970508 (Metzger et al. 1997) place it at a redshift of $z = 0.8$ to 2.3, while the possible signature of extinction suggests $z = 1.09$ (Reichart 1998). There may also be faint galaxies around GRB970228 (Sahu et al. 1997) and GRB970508 (Pedersen et al. 1998). For such distances, the gamma ray energy alone is $\sim 10^{51}$ ergs, and the total fireball energy can be $10^{52}$ erg or more, considering the likely inefficiency of gamma radiation (Waxman 1997; Rees & Mészáros 1998). Optically, GRBs can outshine supernovae by a factor of $\sim 100$ (Pian et al. 1998; Paczyński 1998), and the optical flux from the afterglow can exceed the gamma ray and x-ray fluxes by the same factor (Wijers, Rees & Mészáros 1997).

GRBs and their afterglows at x-ray, optical, and radio wavelengths presumably arise from synchrotron and inverse Compton radiation in the shocked parts of relativistic fireballs and their surrounding interstellar region.
media (Paczyński & Rhoads 1993; Mészáros & Rees 1997; Vietri 1997; Waxman 1997; Sari 1997). The energy could come from the release of gravitational binding energy (~ $10^{54}$ ergs) during the rapid formation of a black-hole. This may occur for neutron stars that acquire too much mass to be stable during binary coalescence (Blinnikov et al. 1984) or Roche-lobe overflow from evolving companion stars (Qin et al. 1998), or it may occur in “failed supernovae” (Woosley 1993) or “hypernovae” collapse of spinning massive stars (Paczyński 1998). The energy liberated in each of these events can be much larger than the observed gamma ray and afterglow energies, so there is a good possibility that a large amount of kinetic energy (> $10^{52}$ erg) in the form of expanding motions and hot gas remains to affect the surrounding interstellar gas for several million years following the explosion.

A possible connection between hypernovae events and HI supershells without central star clusters was mentioned by Blinnikov & Postnov (1998) but not discussed in any detail. If the frequency of such events is comparable to or higher than the frequency of neutron-star mergers or binary accretions, which is about 1 per $10^5 – 10^6$ years in a galaxy the size of ours (Phinney 1991; van den Heuvel & Lorimer 1996), then there should be several visible structures from GRB in the interstellar media of most spiral galaxies. Here we take a further look at the interaction between super-supernovae and interstellar gas.

2. Interaction between Super-supernovae from Gamma Ray Bursts and Interstellar Gas

The photons from a GRB can directly ionize and heat a large volume of the ISM, and the fast ejecta can heat the ISM behind a shock front. At first the GRB blastwave is relativistic, but after it slows to sub-relativistic speeds, the subsequent interaction with the ISM will depend mostly on the energy deposited by the ejecta. The result is a Sedov-Taylor phase expansion, as in a supernova remnant, but with $10 – 100 \times$ the normal supernova energy (Wijers, Rees & Mészáros 1997; Waxman, Kulkarni & Frail 1998).

The Sedov solution has radius $R$, energy $E$, pre-shock density $\rho_0$, and time $t$ related by the equation $R \sim (2Et^2/\rho_0)^{1/5}$. Interior cooling follows the usual supernova evolution. After the swept-up shell cools, the remnant enters the pressure-driven snowplow phase (Cioffi, McKee, & Bertschinger 1988) at the radius $R_{PDS} = 27E_{52}^{2/7}n^{-3/7}$ pc, velocity $v_{PDS} = 490E_{52}^{1/14}n^{1/7}$ km s$^{-1}$, and time $t_{PDS} = 2.2 \times 10^4E_{52}^{3/14}n^{-4/7}$ yrs. Thereafter it grows as $R/R_{PDS} \sim [(4/3)(t/t_{PDS}) - 1/3]^{0.3}$ because of the shell momentum and pressure from the hot cavity, until it merges with the ambient ISM. At this time $t_{\text{merge}} \sim 4.2 \times 10^6E_{52}^{0.32}n^{-0.37}v_1^{-1.43}$ years, the velocity has slowed to 10$c_1$ km s$^{-1}$, and the radius is $R_{\text{merge}} \sim 1.40E_{52}^{0.32}n^{-0.37}v_1^{-0.43}$ pc. Here we use the notation $E = 10^{52}E_{52}$ ergs, with preshock density $n$ in cm$^{-3}$. These results depend only weakly on metallicity. The final radius may be large enough for blowout into the halo, especially if the GRB is offset from the midplane, but not if it is in the midplane with $E_{52} \sim 1$, and ambient magnetic fields confine the gas (Tomisaka 1998).

If GRB come from binary neutron star mergers, then there should be enough events to produce giant remnants in most large galaxies. Observational estimates from binary pulsars of the frequency of such mergers range from $10^{-6}$ (Phinney 1991) to $8 \times 10^{-6}$ per year per galaxy (van den Heuvel & Lorimer 1996). Theoretical estimates from stellar evolution models range from $3 \times 10^{-5}$ (Portegies Zwart & Spreeuw 1996) to $3 \times 10^{-4} – 3 \times 10^{-5}$ per year per galaxy (Lipunov, Postnov & Prohorov 1997a, b). Similarly, the frequency of accretion-induced neutron star collapses in binary systems is estimated to be $\sim 10^{-5}$ yr$^{-1}$ (Qin et al. 1998). When these frequencies are multiplied by the typical remnant lifetime of several $\times 10^7$ yrs, the average number of GRB remnants per galaxy is 10 to 100. We consider in the next section whether such remnants have been observed already.
3. Giant Stellar and Gaseous Shells in Galaxies

The Constellation III region of the Large Magellanic Cloud was the first candidate for a super-supernova explosion (Westerlund & Mathewson 1966; Hodge 1967). This region has a 600-pc long stellar arc noted by these authors, and is surrounded by a 1200-pc diameter HI ring (McGee & Milton 1966; Domgørgen et al. 1995; Kim et al. 1997) dotted with HII regions (Meaburn 1980). There is no obvious bright stellar association in the center that would have moved the ISM around this much (Reid et al. 1987; Olsen et al. 1997; Braun et al. 1997). A similar stellar arc in the galaxy NGC 6946 was attributed to super-SN explosions by Hodge (1967), who also noted the lack of a centralized HII region (this arc is located [106,26] mm from the lower left corner of the large image of NGC 6946 in Sandage & Bedke [1988]). Another is in M101, at the position (193, 165) mm from the lower left corner of the page 12 image in Sandage & Bedke (1988). Both the NGC 6946 and M101 features look like circular rings of enhanced brightness with a regular outer edge and multiple arcs of star clusters inside; they also show up as bright circular spots in Arp’s (1966) Atlas. A dozen other stellar arcs with various sizes were attributed to large-scale explosions in galaxies by Hayward (1964), but most of these are probably not real.

There have been many studies of supershells (Heiles 1979) without obvious central star clusters (Hu 1981; Heiles 1984). Recent studies have found kpc-size holes and rings in irregular galaxies (Puche et al. 1992; Radice et al. 1995) that are also devoid of obvious centralized star formation. Radice et al. concluded that the “supernovae hypothesis for the creation of the HI holes observed in these galaxies is incorrect.” Similarly Stewart et al. (1997) found in Holmberg II that “none of the bright FUV knots lie within the HI holes and that they are more likely to be found immediately outside of a hole boundary.” Rhode et al. (1997) demonstrated for several dwarfs that “in at least several of the holes the observed upper limits for the remnant cluster brightness are strongly inconsistent with the SNe hypothesis.”

These observations support the GRB scenario discussed in the previous section, but the interpretation that there are no central clusters should be viewed with some caution. We recently found (Efremov & Elmegreen 1998) that in the Constellation III region of the LMC, a small cluster of 6 A-type supergiants, ~ 30 My old, could be the remnant of an old OB association that formed Constellation III, and that these Constellation III stars could have caused the continued expansion of the HI hole to make today’s 1200 pc superbubble. The first cluster is barely visible today because its brightest members have evolved off the main sequence and dispersed. Dwarf galaxies like the LMC generally have little shear and a thick disk, so giant bubbles can form slowly around old clusters and their descendants without leaving obvious bright clusters in the center. Similar circumstances occur in the outer spiral arms of galaxies: shear is generally low in spiral arms, the outer gas disk is thick, and the outer arms have very long flow-through times. Under these conditions, OB associations and their descendants, forming and staying in the arms for a relatively long time (50-100 My), can slowly make superbubbles without leaving much evidence for star formation activity in the centers. The ~ 40 My-old Cas-Tau association in the center of Lindblad’s ring (Blaauw 1984) may be an example of such giant bubble formation – in this case there is shear because the solar neighborhood has emerged from the local spiral arm already (Elmegreen 1993). Other giant bubbles are in the southern spiral arm of M83 (Sandage & Bedke 1988) and the northern arm of M51 (Block et al. 1997). The detection of 50-100 My old clusters inside these bubbles may be difficult.

Is there other evidence for giant ISM disturbances? Rand et al. (1990) and Dettmar (1990) found ionized loops and filaments far from the plane in the edge-on galaxy NGC 891, and Dettmar (1992) found the same in NGC 5775. Such loops correlate with midplane star formation activity, so they could be from normal stellar winds and supernovae (Rand et al. 1992; Dettmar 1992).
Kamphuis, Sancisi, & van der Hulst (1991) found a shell in M101 with a size of 1.5 kpc and an expansion speed of $\sim 50$ km s$^{-1}$, giving it a kinetic energy of $\sim 10^{53}$ ergs; they suggested it was made by $\sim 10^3$ supernovae. Kamphuis & Sancisi (1993) found several $10^7$ M$_\odot$ high velocity features with kinetic energies of $\sim 10^{53}$ erg in NGC 6946. Vader & Chaboyer (1995) observed a 3 kpc stellar arc in the spiral galaxy NGC 1620, with a mass of $\sim 10^7$ M$_\odot$ and a likely expansion speed of $20 - 50$ km s$^{-1}$, giving it a kinetic energy of $\sim 10^{53}$ erg; they also found an extremely bright star cluster near the center, so they proposed the source of the expansion was supernovae. Lee & Irwin (1997) found four expanding HI shells at high latitude in the edge-on galaxy NGC 3044, and estimated their masses and kinetic energies to be $\sim 10^7$ M$_\odot$ and $10^{53} - 10^{54}$ erg, but because of the galaxy inclination, no central clusters could be seen. King & Irwin (1997) found two supershells in another edge-on galaxy, NGC 3556, with one requiring $\sim 10^{56}$ ergs of supernova energy input according to standard models. All of these cases are candidates for GRB explosions, but there could be old clusters in them too, hidden by poor viewing angles, or scattered and dimmed with time into unrecognizable forms.

Giant HI shells can also be made by high velocity cloud impacts (Tenorio-Tagle 1981). van der Hulst & Sancisi (1988) suggested that a large HI complex in M101 has this origin, but Lee & Irwin (1997) and King & Irwin (1997) suggested this is not the case for the giant shells they studied because of the relative isolation of the galaxies and lack of evidence for HI clouds around them.

Evidently, there is ample evidence for kpc-size shells with masses of $\sim 10^7$ M$_\odot$, energies of $\sim 10^{53}$ ergs, and no obvious central OB associations. Some of these might be candidates for GRB shells, but the standard explanation in terms of multiple supernova seems acceptable too. Indeed, the size distribution of giant shells (Oey & Clarke 1997) does not reveal a clear second population that might have an origin distinct from that of the smaller shells.

There is a difference between GRB shells and shells made by multiple supernovae. Most of the GRB remnant expansion is the result of momentum conservation after shell cooling and/or blowout, whereas the expansion around multiple supernovae relies on continuous energy input to keep the cavity at a high pressure (Tenorio-Tagle & Bodenheimer 1989). This pressure constraint for the supernova model makes it difficult to build a shell much larger than the disk thickness (MacLow & McCray 1988; Tenorio-Tagle, Rozyczka & Bodenheimer 1990). The multiple supernova model also has a relatively slow energy input that can be lost to radiation inside the cavity. The average energy input rate from 1000 supernova spread over $2 \times 10^7$ years inside a cavity 1 kpc in diameter is $\sim 1 \times 10^{-25}$ erg cm$^{-3}$ s$^{-1}$. This heating rate is comparable to the cooling rate of $\sim 1 \times 10^{-22}n^2$ erg cm$^{-3}$ s$^{-1}$ at 10$^6$ K (Sutherland & Dopita 1993) for normal total interstellar pressures ($P_{\text{ISM}} \sim 3 \times 10^4$ k$_B$). Moreover, most star complexes still have dense cloud debris in their vicinities, so evaporative cooling, and collisional cooling in the high-density cloud envelopes, would remove even more supernova energy. Thus the formation of kpc-size shells by continuous energy input from multiple supernovae might be difficult at solar-neighborhood or greater pressures. Combined GRB + supernova models for kpc-shells, or pure GRB models, might be preferred. In a combined model, a GRB explosion in an aging star complex converts a supernova-dominated $\sim 500$ pc shell into a GRB-dominated 1.5 kpc shell.

4. Conclusions

A GRB may leave a kpc-scale remnant in the interstellar medium of the host galaxy. There is ample evidence for such disturbances in the form of shells and high latitude filaments, and the number of them is
consistent with the expected frequency of GRB, but there is no definitive proof that any of these energetic features actually required a GRB rather than multiple supernovae from a star complex. If it can be shown with realistic simulations and other studies that supernovae alone are not sufficient to make a shell larger than $\sim 1$ kpc, perhaps because of energy losses, disk blowout, or other problems specific to the supernova model, then the observed kpc shells in nearby galaxies could contain GRB remnants.

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