GIANT SHELLS AND STELLAR ARCS AS RELICS OF GAMMA-RAY BURST EXPLOSIONS

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Received 1998 March 17; accepted 1998 May 15; published 1998 June 26

ABSTRACT

Gamma-ray burst (GRB) explosions are powerful and frequent enough to make kiloparsec-size shells and holes in the interstellar media of spiral and irregular 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, which could have formed these shells by supernovae and winds, might be hard to detect.

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

1. INTRODUCTION

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

Optical counterparts to gamma-ray bursts (GRBs) were found after 20 years of searching when GRB 970228 (Groot et al. 1997; van Paradijs et al. 1997) and GRB 970508 (Bond 1997) were assigned accurate positions by the X-ray satellite BeppoSAX (Costa et al. 1997; Piro et al. 1998). Absorption lines in GRB 970508 (Metzger et al. 1997) place it at a redshift of $z = 0.8–2.3$, while the possible signature of extinction suggests $z = 1.09$ (Reichert 1998). There may also be faint galaxies around GRB 970228 (Sahu et al. 1997) and GRB 970508 (Pедерсен et al. 1998). For such distances, the gamma-ray energy alone is $\sim 10^{51}$ ergs, and the total fireball energy can be $10^{52}$ ergs or more, considering the likely inefficiency of gamma radiation (Waxman 1997; Rees & Mészáros 1998). Optically, GRBs can outshine supernovae (SNe) 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 media (Paczyński & Rhoads 1993; Mészáros & Rees 1997; Vietri 1997; Waxman 1997; Sari 1997). The energy could come from the release of gravitational binding energy ($\sim 10^{44}$ 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 in the “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 ($>10^{52}$ ergs), 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 H i supershells without central star clusters was mentioned by Blinnikov & Postnov (1998) but was 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 $1 \text{per} 10^{-3} – 10^{4} \text{yr}$ in a galaxy the size of ours (Phinney 1991; van den Heuvel & Lorimer 1996), then there should be several visible structures from GRBs 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 GRBS 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 blast wave is relativistic, but after it slows to subrelativistic 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 et al. 1997; Waxman, Kulkarni, & Frail 1998).

The Sedov solution has radius $R$, energy $E$, preshock density $\rho_0$, and time $t$ related by the equation $R \sim (2Et/\rho_0)^{1/3}$. Interior cooling follows the usual supernova evolution. After the swept-up shell cools, the remnant enters the pressure-driven snowplow (PDS) phase (Cioffi, McKee, & Bertschinger 1988) at the radius $R_{\text{PDS}} = 27E_5^{2/7}n^{-3/7}$ pc, velocity $v_{\text{PDS}} = 490E_5^{0.14}n^{-0.07} \text{km s}^{-1}$, and time $t_{\text{PDS}} = (2.2 \times 10^9) E_5^{4/7}n^{-1/7}$ yr. Thereafter, it grows as $R/R_{\text{PDS}} \sim [(4/3)(t/t_{\text{PDS}}) - 1/3]^{0.3}$ because of the shell momentum and pressure from the hot cavity, until it merges with the ambient ISM. At this time, $t_{\text{merge}} \sim (4.2 \times 10^9) \times E_5^{2/5}n^{-3/7}v_{1}^{1/4}$ yr, the velocity has slowed to $10E_5^{0.3} \text{km s}^{-1}$, and the radius is $R_{\text{merge}} \sim 140E_5^{0.5}n^{-0.37}v_{1}^{0.43}$ pc. Here we use the notation $E = 10^{52}E_5\text{ergs}$, with the preshock density $n$ in units of 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 $E_5 \sim 1$ and ambient magnetic fields confine the gas (Tomisaka 1998).

If GRBs 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 $10^{-6} \text{ yr}^{-1}$ (Phinney

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Giant Bubbles and Gaseous Shells in Galaxies

3. GIANT STELLAR AND GASEOUS SHELLS IN GALAXIES

The Constellation III region of the Large Magellanic Cloud was the first candidate for a supernova explosion (Westlund & Mathewson 1966; Hodge 1967). This region has a 600 pc long stellar arc, which is noted by these authors, and is surrounded by a 1200 pc diameter H i ring (McGee & Milton 1966; Domgörgen, Bomans, & de Boer 1995; Kim et al. 1997) that is dotted with H ii regions (Meaburn 1980). There is no obvious bright stellar association in the center that would have moved the ISM around this much (Reid, Mould, & Thompson 1987; Olsen et al. 1997; Braun et al. 1997). A similar stellar arc in the galaxy NGC 6946 was attributed to supernova explosions by Hodge (1967), who noted the lack of a central H ii region (this arc is located [106, 260] mm from the lower left-hand 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-hand corner of the image in Sandage & Bedke (1988, p. 12). 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 kiloparsec-size holes and rings in irregular galaxies (Puche et al. 1992; Radice, Salzer, & Westpfahl 1995) that are also devoid of obvious centralized star formation. Radice et al. concluded that the "supernova hypothesis for the creation of the H i 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 H i holes and that they are more likely to be found immediately outside of a hole boundary." Rhode, Salzer, & Westpfahl (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 six A-type supergiant, ~30 Myr 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 H i hole, making 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 (Efremov & Elmegreen 1998; Brinks & Walter 1998). 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 Myr), can slowly make superbubbles without leaving much evidence for star formation activity in the centers. The ~40 Myr old Cas-Tau association in the center of Lindblad's ring (Blauw 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 Myr old clusters inside these bubbles may be difficult.

Is there other evidence for giant ISM disturbances? Rand, Kulkarni, & Hester (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, Kulkarni, & Hester 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 ~50 km s⁻¹, giving it a kinetic energy of ~10⁵³ ergs; they suggested it was made by ~10⁷ supernovae. Kamphuis & Sancisi (1993) found several 10⁷ M☉ high-velocity features with kinetic energies of ~10⁵⁰ ergs in NGC 6946. Vuder & Chaboyer (1995) observed a 3 kpc stellar arc in the spiral galaxy NGC 1620, with a mass of ~10⁷ M☉ and a likely expansion speed of 20–50 km s⁻¹, giving it a kinetic energy of ~10⁵³ ergs; they also found an extremely bright star cluster near the center, so they proposed that the source of the expansion was supernovae. Lee & Irwin (1997) found four expanding H i shells at high latitude in the edge-on galaxy NGC 3044 and estimated their masses and kinetic energies to be ~10⁷ M☉ and 10⁴⁷–10⁴⁸ ergs, respectively, 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 ~10⁶⁸ 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 H i shells can also be made by high-velocity cloud impacts (Tenorio-Tagle 1981). Van der Hulst & Sancisi (1988) suggested that a large H i complex in M101 has this origin, but Lee & Irwin (1997) and King & Irwin (1997) suggested that this is not the case for the giant shells they studied because of the relative isolation of the galaxies and the lack of evidence for H i clouds around them.

Evidently, there is ample evidence for kiloparsec-size shells with masses of ~10⁷ M☉, energies of ~10⁵⁰ 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, Röyczka, & 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 supernovae spread over 2 × 10^{22} yr inside a cavity 1 kpc in diameter is \( \sim 1 \times 10^{-25} \) erg s^{-1}. This heating rate is comparable to the cooling rate of \( \sim 1 \times 10^{-22} n_{\text{H}} \) ergs cm^{-3} s^{-1} at 10^8 K (Sutherland & Dopita 1993) for normal total interstellar pressures \((P_{\text{iss}} \sim 3 \times 10^4 k_{\text{B}})\). 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 kiloparsec-size shells by continuous energy input from multiple supernovae might be difficult at solar neighborhood or greater pressures. Combined GRB + supernova models for kiloparsec 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 kiloparsec-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 GRBs, 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 kiloparsec shells in nearby galaxies could contain GRB remnants.

We are grateful to the referee for useful comments and to P. Wannier for finding a typographical error in the manuscript. Yu. N. E. appreciates the support from the Russian Foundation for the Basic Researches, grant 97-02-17358.

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