RADIO AND X-RAY OBSERVATIONS OF THE TYPE Ic SN 2007gr REVEAL AN ORDINARY, NON-RELATIVISTIC EXPLOSION

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Received 2010 May 14; accepted 2010 September 30; published 2010 November 22

ABSTRACT

We present extensive radio and X-ray observations of the nearby Type Ic SN 2007gr in NGC 1058 obtained with the Very Large Array (VLA) and the Chandra X-ray Observatory and spanning 5 to 150 days after explosion. Through our detailed modeling of these data, we estimate the properties of the blast wave and the circumstellar environment. We find evidence for a freely expanding and non-relativistic explosion with an average blast wave velocity, \(v \approx 0.2c\), and a total internal energy for the radio emitting material of \(E \approx 2 \times 10^{56}\) erg assuming equipartition of energy between electrons and magnetic fields \((\epsilon_e = \epsilon_B = 0.1)\). The temporal and spectral evolution of the radio emission points to a stellar wind-blown environment shaped by a steady progenitor mass loss rate of \(M \approx 6 \times 10^{-7} \, M_\odot\, yr^{-1}\). These parameters are fully consistent with those inferred for other SNe Ibc and are in line with the expectations for an ordinary, homologous SN explosion. Our results are at odds with those of Paragi et al. who recently reported evidence for a relativistic blast wave in SN 2007gr based on their claim that the radio emission was resolved away in a low signal-to-noise Very Long Baseline Interferometry (VLBI) observation. Here we show that the exotic physical scenarios required to explain the claimed relativistic velocity—extreme departures from equipartition and/or a highly collimated outflow—are excluded by our detailed VLA radio observations. Moreover, we present an independent analysis of the VLBI data and propose that a modest loss of phase coherence provides a more natural explanation for the apparent flux density loss which is evident on both short and long baselines. We conclude that SN 2007gr is an ordinary Type Ibc supernova.

Key words: gamma-ray burst: general – supernovae: individual (SN 2007gr)

Online-only material: color figures

1. INTRODUCTION

Nearly 25 years have elapsed since Type Ibc supernovae (SNe Ibc) were first recognized as a distinct class of cosmic explosions (Elias et al. 1985; Filippenko & Sargent 1985; Wheeler & Levreault 1985). They are now commonly understood to mark the gravitational core-collapse of massive stars from which an explosion launches ejecta to bulk velocities of \(\sim 10,000\, \text{km s}^{-1}\) \((\text{e.g., Filippenko 1997})\). Motivated by the observed lack of hydrodynamical (and often helium) in their optical spectra, the favored progenitors of SNe Ibc are Wolf–Rayet stars that have ejected their massive envelope through strong stellar winds (Begelman & Sarazin 1986) or interaction with a binary companion (Podsiadlowski et al. 1992). Recently, the observational realization that most long-duration gamma-ray bursts (LGRBs) are accompanied by SNe Ibc has fueled a new surge of interest in these massive star explosions (see Woosley & Bloom 2006 and references therein).

The LGRB–SN connection and the relative rates of these events imply that LGRBs are a rare subclass of SNe Ibc, distinguished by the production of a relativistic outflow that decouples from the bulk SN ejecta during explosion. For many LGRBs, the energy associated with the relativistic blast wave, \(E \approx 10^{48}–10^{52}\) erg, is comparable to that of the non-relativistic SN ejecta, \(E_{SN} \approx 10^{51}–10^{52}\) erg \((\text{e.g., GRB 030329/SN 2003dh; Berger et al. 2003; Hjorth et al. 2003; Mazzali et al. 2003; Frail et al. 2005})\). This duality challenges the standard SN mechanism in which a homologous explosion couples at most 0.01% of the total energy to mildly relativistic ejecta (Tan et al. 2001). It is therefore generally accepted that a “central engine”—an accreting and rapidly rotating compact object (MacFadyen et al. 2001) or a magnetar \((\text{e.g., Thompson et al. 2004})\)—is additionally required to power the energetic and relativistic blast waves of LGRBs. The critical question is whether ordinary SNe Ibc also harbor central engines, and in turn, the ability to produce even weak relativistic outflows.

Identifying engine-driven, relativistic explosions requires direct measurements of the blast wave velocity and energy. While optical SN emission predominantly traces the Nickel-56 synthesized in the bulk SN ejecta (Arnett 1982), radio and X-ray observations directly probe the synchrotron radiation produced as the blast wave shocks material in the circumstellar medium (CSM; Chevalier 1982). Over the past decade, dedicated radio studies of SNe Ibc have consistently pointed to blast wave velocities of just \(v \approx 0.15c\) and associated energies, \(<E> \approx 10^{47}\) erg, in agreement with the expectations for an ordinary core-collapse explosion (Chevalier 1998; Berger et al. 2002; Berger et al. 2003; Soderberg et al. 2005, 2006; Chevalier & Fransson 2006; Soderberg 2007; Soderberg et al. 2008).

Recently, luminous radio emission was detected from the broad-lined Type Ic SN 2009bb pointing to an energetic \((E > 10^{49}\) erg) and relativistic \((v \gtrsim 0.85c)\) outflow powered by a central engine (Soderberg et al. 2010). This discovery marked the first relativistic SN explosion identified without a detected
SN 2007gr was discovered by the Katzmann Automatic Imaging Telescope on 2007 August 15.51 UT (Madison & Li 2007) in NGC 1058 (d ≈ 9.3 Mpc; Silbermann et al. 1996). An early spectrum of the supernova indicated a Type Ic classification based on the preliminary identification of He I features (Chornock et al. 2007) although it has been argued to those of other Type Ibc supernovae and starkly dissimilar properties of other SNe Ibc, SN 2007gr is among the least luminous, about 10^3 times lower than SN 1998bw (associated with GRB 980425; Kulkarni et al. 1998) and SN 2009bb (Table 1).

The statistical positional errors we infer from each epoch reflect only the beam size and the signal-to-noise ratio of the SN detection and they are dwarfed by the systematic errors introduced by the atmosphere. We determine the best estimate for the radio SN position and associated uncertainty by calculating the weighted mean of the centroid positions and find σ(J2000) = 0.0006 ± 0.024′ arcsec, respectively (1σ, standard deviation of the mean).

The radio light curves are shown in Figure 1, spanning Δt ≈ 5 to 150 days. The observations reveal an early peak time of 0.5 days at 8.46 GHz with an associated peak spectral luminosity of Lν ≈ 9.7 × 10^{25} erg s^{-1} Hz^{-1}. In comparison with the radio properties of other SNe Ibc, SN 2007gr is among the least luminous, about 10^5 times lower than SN 1998bw (associated with GRB 980425; Kulkarni et al. 1998) and SN 2009bb.
process, the blast wave accelerates CSM electrons into a power-law distribution, \( N(\gamma) \propto \gamma^{-p} \), above a minimum Lorentz factor, \( \gamma_m \). The interaction of the accelerated electrons with amplified magnetic fields gives rise to nonthermal synchrotron emission. For SNe minimally affected by external absorption processes, a low frequency spectral turn-over is produced by synchrotron self-absorption (SSA) and defines the spectral peak frequency, \( \nu_p \). In this scenario, the radio spectrum is given by \( F_\nu \propto \nu^{3/2} \) below \( \nu_p \) and \( F_\nu \propto \nu^{-(p-1)/2} \) above \( \nu_p \). As shown in Figure 2, our multi-frequency radio observations of SN 2007gr are well-described by a synchrotron self-absorbed spectrum with \( p \approx 3.2 \) across multiple epochs. We note that an extrapolation of the optically thin synchrotron spectrum to the X-ray band is consistent with the observed Chandra upper limit.

### 2.2. Chandra X-ray Observations

We additionally observed SN 2007gr with the Chandra ACIS-I beginning on 2007 August 29.1 UT (\( \Delta t \approx 16 \) days) for 20 ks (Soderberg et al. 2007). We do not detect an X-ray source coincident with the optical and radio SN positions. Adopting a power-law spectral model with photon index, \( \Gamma = 2 \), and a Galactic foreground column density of \( n_H \approx 3.7 \times 10^{20} \) cm\(^{-2} \), we place a 3\( \sigma \) upper limit on the X-ray flux of \( F_X \lesssim 3.9 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \) (0.2–10 keV). At the distance of the SN, this implies a luminosity of \( L_X \lesssim 4.0 \times 10^{37} \) erg s\(^{-1} \) which is a factor of \( 10^3 \) below the afterglow luminosities of sub-energetic GRBs (e.g., GRB 980425; Pian et al. 2000) and similar to the X-ray luminosity of SN 2002ap on a comparable timescale (Sutaria et al. 2003). A comparison with our nearly simultaneous VLA observations indicates a radio-to-X-ray spectral index steeper than \( \approx -0.7 \), consistent with the measured values for other well-studied radio/X-ray SNe Ibc shortly after explosion and during the epoch that inverse Compton emission dominates the X-ray flux (Chevalier & Fransson 2006).

### 3. A SIMPLE MODEL FOR THE RADIO EMISSION

The radio emission from SNe, including those associated with LGRBs, arises from the dynamical interaction of the blast wave with the CSM (Chevalier 1982; Sari et al. 1998). In this

![Figure 1. Radio spectrum of SN 2007gr across multiple epochs—\( \Delta t \approx 5.4 \) (red), 8.4 (green), and 17.6 (blue) days—is well described by a synchrotron self-absorbed spectral model with \( F \propto \nu^{3/2} \) (Chevalier & Fransson 2006).](image)

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![Figure 2. Radio spectrum of SN 2007gr across multiple epochs—\( \Delta t \approx 5.4 \) (red), 8.4 (green), and 17.6 (blue) days—is well described by a synchrotron self-absorbed spectral model with \( F \propto \nu^{3/2} \) (Chevalier & Fransson 2006).](image)
(2006), the amplified magnetic field is directly determined from the observed radio properties,

\[ B \approx 0.43 \left( \frac{\epsilon_B}{\epsilon_e} \right)^{-4/19} \left( \frac{L_{v, p}}{10^{28} \text{erg s}^{-1} \text{Hz}^{-1}} \right)^{-2/19} \left( \frac{v_p}{5 \text{GHz}} \right) \text{G.} \]

At \( \Delta t \approx 5.8 \), and 18 days, the SN 2007gr radio spectra imply \( B \approx 0.55, 0.45, \) and 0.25 G. The minimum energy is

\[ E_{\text{min}} \approx 1.7 \times 10^{44} \left( \frac{B}{1 \text{G}} \right)^2 \left( \frac{R}{10^{15} \text{cm}} \right)^3 \text{erg}, \]

where, by definition of \( E_{\text{min}} \) we have assumed \( \epsilon_e = \epsilon_B = 0.5 \). For our derived values of \( R \) and \( B \) across the three epochs, we infer \( E_{\text{min}} \approx (3.2, 3.5, 6.0) \times 10^{45} \text{erg} \). A more realistic scenario allows for a significant population of shocked protons such that \( (\epsilon_e = \epsilon_B) < 0.5 \). The total internal energy is then \( E \approx (0.5/\epsilon_B) E_{\text{min}} \) and we find \( E \approx (1.6, 1.8, 3.0) \times 10^{46} \text{erg} \) for \( \epsilon_B = 0.1 \).

In stark contrast, applying this same analysis to the observed radio emission from nearby GRB-SNe 1998bw (Kulkarni et al. 1998; Li & Chevalier 1999) and 2006aj (Soderberg et al. 2006) as well as SN 2009bb (Soderberg et al. 2010, points unambiguously to mildly relativistic outflows with \( \Gamma \sim 2 \) and with energies of \( E \gtrsim 10^{46} \text{erg} \). The properties of the SN 2007gr blast wave are clearly dissimilar from those of relativistic explosions and are typical for ordinary, non-relativistic SNe Ibc.

### 3.2. A Dynamical Model

The temporal and spectral evolution of the radio emission can further constrain the properties of the SN 2007gr blast wave and local environment. As the blast wave expands, the optical depth to SSA decreases and, in turn, \( v_p \) cascades to lower frequencies producing the characteristic “bell-shaped” light curves of radio SNe Ibc (Chevalier 1998). In modeling this evolution, we adopt the formalism of Soderberg et al. (2005) which assumes that the blast wave radius and the magnetic field evolve in time as power laws \( R \propto t^p \) and \( B \propto t^q \) while \( \epsilon_e \) and \( \epsilon_B \) are constant fractions of the post-shock energy density (Chevalier 1998).

We perform a global fit of the multi-frequency light curves for four parameters: \( C_F, C_z, \alpha_r, \) and \( \alpha_B \) where \( C_F \) and \( C_z \) are normalization constants of the peak flux density and optical depth at a reference epoch, \( t_0 \) (see Soderberg et al. 2005 for a discussion of \( C_F \) and \( C_z \)). We find a reasonable fit for \( C_F \approx 3.7 \times 10^{-30} \text{gs}^{0.5}, C_z \approx 3.0 \times 10^{33} \text{s}^{3.6}, \alpha_r \approx 0.9, \) and \( \alpha_B \approx -1 \) at \( t_0 = 10 \text{days} \). The resulting model fits are shown in Figure 1 and imply \( R \approx 5 \times 10^{13} (t/10 \text{days})^{0.9} \text{cm} \) (i.e., \( \tau \approx 0.2c(t/10 \text{days})^{-0.1} \)) and \( B \approx 0.4(t/10 \text{days})^{-1} \text{G} \). Thus, the radio observations point to emission from a slightly decelerated interaction region at the outer boundary of the freely expanding ejecta, as expected for young SNe plowing through a stellar wind environment. With these constraints, the total internal energy of the radio emitting material is \( E \approx 2 \times 10^{46} (t/10 \text{days})^{1.7} \text{erg} \) for \( \epsilon_e = \epsilon_B = 0.1 \). These scalings are fully consistent with our preliminary estimates from individual epoch analysis of the radio spectra in Section 3.1.

Next, the electron number density is \( n_e \approx (p - 2)/ (p - 1) \left( B^2 / 8 \pi \gamma_{m} m_{p} c^2 \right) \approx 2 \times 10^5 (r / 5.5 \times 10^{18} \text{cm})^{-2} \text{cm}^{-3} \) with \( \gamma_{m} \approx 2 \) (here we maintain the assumption that \( p = 3 \) and \( \epsilon_e = \epsilon_B = 0.1 \)). The density profile of the circumstellar environment is thus consistent with the expectations for a stellar wind with a constant mass loss rate and wind speed. Assuming a typical Wolf–Rayet wind velocity of \( v_w = 10^3 \text{km s}^{-1} \) (e.g., Cappa et al. 2004), and a nucleon-to-electron ratio of two (appropriate for a predominantly helium stellar wind), we infer a mass loss rate of \( M = 4 \pi n_e m_p R^2 v_w \approx 6 \times 10^{-3} M_\odot \text{yr}^{-1} \) for the SN 2007gr progenitor star. The temporal evolution of the physical parameters associated with the SN 2007gr blast wave and the circumstellar material are displayed in Figure 3. We emphasize that the blast wave dynamics and physical properties that we derive for SN 2007gr are similar to those of ordinary radio SNe Ibc (Berger et al. 2003; Soderberg 2007 and references therein) and fully consistent with dynamical models for radio SNe Ibc (Chevalier 1998; Chevalier & Fransson 2006).

Finally, we note that an independent constraint on the partition fractions can be obtained from the blast wave velocity since the observed synchrotron radiation requires a sufficient energy to accelerate electrons to relativistic speeds. For a non-relativistic or mildly relativistic shock, the requirement that \( \gamma_m > 1 \) implies

\[ \gamma_m \approx 460 \epsilon_e \frac{v_w}{c} \left( \frac{p - 2}{p - 1} \right) > 1 \]

which results in a lower limit of \( \epsilon_e \gtrsim 0.44(v/0.1c)^{-2} \) for \( p \approx 3 \) (Chevalier & Fransson 2006; see also Soderberg et al. 2005). For SN 2007gr, this constraint leads to \( \epsilon_e \gtrsim 0.1 \) for \( v \gtrsim 0.2c \) and is fully consistent with our equipartition model (Section 3.2), therefore supporting our derived energy estimate.

### 3.3. Bulk Ejecta Parameters

Based on modeling of the optical light curves and spectra, Hunter et al. (2009) reported values for the total kinetic energy and mass of the SN ejecta of \( E_{\text{SN}} \approx (1–4) \times 10^{51} \text{erg} \) and \( M_{\text{ej}} \approx (2–3.5) M_\odot \), respectively. The velocity of the bulk ejecta is thus \( v_{\text{bulk}} \approx (1.8 E_{\text{SN}} / M_{\text{ej}})^{1/2} \approx 9000–13,600 \text{km s}^{-1} \).

![Figure 3. Temporal and radial evolution of the physical parameters associated with the SN 2007gr radio emitting material are shown in gray as derived from our dynamical model fit to the VLA data (see Figure 1). For comparison, we show the individual data points for the blast wave radius, energy, and magnetic field intensity as inferred from a single-epoch analysis of the SSA radio spectra at \( \Delta t \approx 5 \) (red), \( 8 \) (green), and \( 18 \) (blue) days (Figure 2). These individual points are overall consistent with our freely expanding and non-relativistic dynamical model characterized by a wind-stratified CSM.](image-url)
(Iwamoto et al. 2003), in line with the observed photospheric velocities (Valenti et al. 2008; Hunter et al. 2009). Theoretical considerations predict that the coupling of energy and velocity within the homologous-expanding SN ejecta is characterized by

$$E(v) \approx 3.7 \times 10^{47} \left( \frac{E_{SN}}{10^{51}} \right)^{3.59} \left( \frac{M_{ej}}{M_{\odot}} \right)^{-2.59} \left( \frac{v}{0.1c} \right)^{-5.18} \text{erg}$$

(Equation (5)).

(Matzner & McKee 1999; Berger et al. 2002). For SN 2007gr, the bulk ejecta parameters predict that the ejecta traveling at $v \approx 0.2c$ carry an energy of $E \approx (0.1–4.5) \times 10^{46}$ erg, which is fully consistent with the energy inferred from our free-expansion model (Section 3.2). Therefore, there is sufficient energy in the high-velocity ejecta to account for the observed radio signal within the framework of a standard homologous explosion.

4. A COMPARISON WITH PARAGI ET AL. (2010)

As detailed in the previous section, the temporal and spectral evolution of the SN 2007gr radio emission points to an ordinary and non-relativistic blast wave with velocity, $\overline{v} \approx 0.2c$, and energy, $E \approx 2 \times 10^{46}$ erg, for $\epsilon_e = \epsilon_B = 0.1$. Similar blast wave parameters are independently inferred from the bulk ejecta properties and expected energy profile of the ejecta (Equation (5)). In stark contrast, Paragi et al. (2010) propose a relativistic blast wave velocity of $\overline{v} \gtrsim 0.6c$ based on their analysis of a low signal-to-noise VLBI observation of the SN at $\Delta t \approx 84$ days from which they claim a lower limit on the blast wave radius, of $R \gtrsim 1.3 \times 10^{17}$ cm. This is a factor of $\gtrsim 3$ larger than our modeling estimate. In the following sections, we address this claim by first considering the implications of a mildly relativistic outflow in the framework of our dynamical model for the SN 2007gr radio light curves and spectra. Following this discussion, we present the results from our independent analysis of the VLBI data.

4.1. Severe Departures from Equipartition?

As shown in Equation (1), the blast wave radius depends only weakly on the partition fractions, $R \propto (\epsilon_e/\epsilon_B)^{-1/19}$. This stems from the fact that the energy in electrons ($E_e$) and amplified magnetic fields ($E_B$) scale with the spherical blast wave radius as $E_B \propto R^{11}$ and $E_e \propto R^{-8}$, respectively, such that the total energy budget ($E_e + E_B$) is minimized at equipartition (Figure 4). Therefore, in order to accommodate a factor of $\gtrsim 3$ increase in the time-averaged velocity within the framework of our spherical blast wave model would require severe departures from equipartition, $\epsilon_e/\epsilon_B \lesssim 10^{-7}$. Such deviations are unprecedented in astrophysical systems and indeed, detailed VLBI studies of other radio SNe that point to relative partition fractions close to equipartition (e.g., $\epsilon_e/\epsilon_B \approx 0.004$ for SN 1993J; Fransson & Björnsson 1998; Chandra et al. 2004) while broadband modeling of GRB afterglows typically indicates $\epsilon_e/\epsilon_B \approx 10$ (Pannaitescu & Kumar 2002; Yost et al. 2003).

Furthermore, Equation (4) shows that a $\overline{v} \gtrsim 0.6c$ outflow requires the relativistic electrons to harbor a significant fraction of the post-shock energy density, $\epsilon_e \gtrsim 0.01$. This is a factor of 10$^2$ higher than the value required to accommodate the VLBI measurement within our spherical blast wave model. To reconcile this inconsistency would require an atypical modification of the electron energy distribution.

Severe deviations from equipartition also impose a significant increase in the total energy of the radio emitting material. In Section 3.2, we report the modest energetics required by a non-relativistic model for the blast wave in equipartition, $E \approx 2 \times 10^{46}$ erg. However, a mildly relativistic velocity of $\overline{v} \gtrsim 0.6c$ would require a magnetically dominated blast wave with an enormous energy of $E \gtrsim 10^{52}$ erg, exceeding the total bulk energy of the explosion (Figure 4).

4.2. A Collimated Outflow?

To avoid severe departures from equipartition, Paragi et al. (2010) propose that the outflow is highly collimated into jets with opening angles of just $\theta_j \approx 15$ deg. Thus, the radio emitting region fills only a fraction of the total solid angle, $f_{\theta} \equiv (1 - \cos \theta_j) \approx 0.03$. Reducing the area of the radio emitting region serves to increase the radius associated with equipartition, thus bringing the minimum of the $(E_e + E_B)$ curve closer to their claimed blast wave radius. In this scenario, they adopt a blast wave energy of $E \approx 3 \times 10^{47}$ erg by allowing for modest departures from equipartition. The associated isotropic-equivalent energy would be $E_{iso} \equiv (E/f_{\theta}) \approx 10^{49}$ erg. Paragi et al. (2010) further adopt a mass loss rate of $M \approx 3 \times 10^{-7}M_{\odot}$, a factor of two lower than our own estimate.

Such relativistic and highly collimated jets are incompatible with the standard expectations for a homologous SN explosion.
Thus, Paragi et al. (2010) appeal to a model in which the blast wave detached from the bulk ejecta at the time of explosion, similar to the model for GRB-associated SNe. In this scenario, the trans-relativistic SN 2007gr jets raced ahead of the bulk spherical outflow and freely expanded until they swept up a circumstellar mass comparable to their own rest mass, causing a deceleration to non-relativistic expansion at a time, $t_{\text{dec}}$ (Waxman et al. 1998). Thereafter, the dynamics of the outflow approach the Sedov–Taylor solution characterized by a radial expansion, $R \propto t^{2/3}$, into a wind environment (e.g., Sedov 1946). Due to lateral spreading of the jets, the outflow also approaches spherical symmetry within a dynamical timescale of $t_{\text{sph}}$. This is roughly the time for the outflow radius to double in size, and thus $t_{\text{sph}} \approx 2^{1/2} t_{\text{dec}}$.

Throughout its evolution leading up to $t_{\text{sph}}$, the blast wave experiences several dynamical phase transitions, from freely expanding to decelerated expansion, relativistic to non-relativistic, and collimated to spherical evolution. These transitions give rise to abrupt changes in the temporal decay of the radio light curves (e.g., Sari et al. 1999, Frail et al. 2000). In particular, spherical and non-relativistic expansion requires a steepening of the optically thin flux density to $F_{\nu} \propto t^{-2.7}$ for $\nu \sim c$, and (2) minimal spreading (see Granot et al. 2005 for a full discussion).

The timescale required for the jets to reach $t_{\text{dec}}$ depends on the rate at which the jets spread sideways. We consider two extreme cases that bracket the range of hydrodynamic evolutions: (1) lateral spreading with a rate, $v \sim c$, and (2) minimal spreading (see Granot et al. 2005 for a full discussion).

In the former case, $t_{\text{dec}} \approx 100(E/10^{53}\text{erg})(M/10^{-9}\text{M}_\odot\text{yr}^{-1})^{-1}$ days, while the latter case is longer by a factor of $f_{\text{sph}}^{-1}$ since it assumes there is no lateral jet spreading during relativistic expansion (Chevalier & Li 2000; Waxman 2004). For Paragi et al. (2010)’s proposed jet parameters, a SN 2007gr relativistic outflow would decelerate at $t_{\text{dec}} \approx 1-30$ days and approach spherical symmetry at $t_{\text{sph}} \approx 3-90$ days. Therefore, even in the unlikely scenario that the SN 2007gr radio outflow was initially jetted, relativistic, and experienced minimal lateral spreading, by the epoch of the VLBI observation ($\Delta t \approx 84$ days) these ejecta would have roughly transitioned to non-relativistic and spherical expansion. Moreover, as noted above, the observed light curves show no evidence for such phase transitions on these timescales.

In summary, the exotic physical scenarios required by a mildly relativistic blast wave with a velocity of $\Gamma \gtrsim 0.6c$ proposed by Paragi et al. (2010) are overall inconsistent with the observed temporal and spectral evolution of the SN 2007gr radio emission. We also show that a homologous free-expansion blast wave model with a non-relativistic velocity, $\Gamma \sim 0.2c$, and an energy, $E \approx 2 \times 10^{46} \text{erg}$, characterized by shock microphysics near equipartition provides an excellent (and more natural) description of the radio observations. We next turn to an independent analysis of the SN 2007gr VLBI data set.

4.3. Very Long Baseline Interferometry Data

SN 2007gr was observed with the European Very Long Baseline Interferometry Network (EVN) on two epochs beginning on 2007 September 6 and November 5 UT ($\Delta t \approx 24$ and 84 days, respectively). We retrieved the data from the EVN archive9 (programs RP007 and GP044; PI Paragi). Both EVN observations were carried out at 4.9 GHz. The first observation was carried out in real-time e-VLBI mode, lasted 12 hr, and included the Darnhall, Medicina, Jodrell Bank, Onsala, Torun, and Westerbork (WSRT) antennas. The data were recorded with four 8 MHz sub-bands in dual polarization and 2-bit sampling, resulting in an aggregate data rate of 256 Mbps. During the phase-referencing cycles, one minute was spent on the reference source J0253+3835 and 4.5 minutes on SN 2007gr. After 2 cycles including SN 2007gr, two additional background quasars (J0230+4032 and J0247+3254) were also observed while 3C 454.3 and 3C 84 were used as fringe finders.

The second observation included the Medicina, Jodrell Bank, WSRT, Cambridge, Torun, Noto, Onsala, Effelsberg, Hartebeestok, and the Green Bank Telescope (GBT) antennas. The observation lasted 10 hr with a recording rate of 1 Gbps for the EVN stations (eight sub-bands of 16 GHz in dual polarization and 2-bit sampling), while the GBT observed with 512 Mbps (same setup, but with 1-bit sampling). The observing scheme was similar to the first epoch, but the two background quasars were observed less frequently (only after four cycles on SN 2007gr).

The original analysis of this data was reported by Paragi et al. (2010); here we present an independent analysis. The data reduction was performed using standard packages within AIPS. Total electron content maps of the ionosphere were used to correct for associated phase changes. A priori amplitude calibration was applied using system temperature measurements and standard gain curves. We performed phase calibration using the data for 3C 84 to remove instrumental phase offsets among the frequency bands. We then fringe-fitted the data from J0253+3835 and transferred the phase calibration to SN 2007gr.

4.3.1. VLBI Epoch 1

In the first VLBI epoch, we confirm the detection of an unresolved source at coordinates, $\alpha(J2000) = 02^h43^m27^s9715, \delta(J2000) = +37\deg 20\arcmin 44\arcsec 687$ (±5 mas in each coordinate, dominated by the positional uncertainty of the phase calibrator) which is within 2σ of our weighted mean VLA SN position. We measure an integrated flux density of $F_\nu = 235 \pm 60 \mu\text{Jy}$ for the source and note that this is the strongest source detected within the 3σ VLA localization region (Figure 5). The likelihood of detecting a source with $S/N \approx 3.9$ (rms noise = 60 $\mu$Jy) in one of the 26 independent VLBI beams within the 3σ position ellipse is roughly $3 \times 10^{-3}$. This, along with the consistent flux of the source with our nearly coincident VLA A-array measurement ($F_{\nu=4.86\text{GHz}} = 233 \pm 76 \mu\text{Jy}$ on September 12.31 UT, Table 1) supports the identification of the VLBI source as SN 2007gr. We note that Paragi et al. (2010) reported a higher flux density and associated uncertainty for the SN by factors of 1.8 and 1.3, respectively, representing a 1.9σ discrepancy from our own measurement. While we are unable to identify the specific cause of this mild discrepancy, we note that self-calibration of VLBI data sets can affect the measured flux density of low signal-to-noise ratio sources.

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8 Here we note that trans-relativistic outflows may not follow formal Blandford–McKee dynamics owing to their low bulk Lorentz factors.

9 http://archive.jive.nl/scripts/portal.php
Since the SN emission is unresolved, the beam size (7.3 × 6.7 mas) implies an upper limit on the diameter of the emitting region of ≤9.3 × 10^{13} cm. Assuming spherical expansion, this constrains the time-averaged velocity to be \( v \lesssim 7.4c \).

### 4.3.2. VLBI Epoch 2

In the second epoch, the longest baselines provided by the GBT and Hartebeesthoek antennas result in a higher resolution image with a synthesized beam of 3.0 × 0.93 mas (natural weighting). In their original analysis of these data, Paragi et al. (2010) reported the weak detection of a source coincident with the first epoch SN position with flux density, \( F_\nu \approx 60 \mu Jy \) (rms map noise, 13 \( \mu Jy \)). In comparison, coincident observations at \( \nu_{\text{obs}} \approx 4.9 \) GHz with the WSRT indicates a significantly higher SN flux density of \( F_\nu, 4.9 \text{GHz} = 259 \pm 40 \mu Jy \) (Paragi et al. SN 2007gr at 4.9 GHz on 2007 November 5 \( UT \), excluding the Green Bank and Hartebeesthoek antennas. The color scale extends from \( F_\nu = -60 \) to 60 \( \mu Jy \) per beam and the contours represent 1.5 \( \sigma \), 2\( \sigma \), and 2.5 \( \sigma \) levels (rms noise is 13 \( \mu Jy \) per beam). Coincident with the position of the SN 2007gr measured in the first VLBI epoch (black cross; 2\( \sigma \) errors), we marginally detect a 2.8\( \sigma \) source with a peak flux density of \( F_\nu \approx 37 \mu Jy \) per beam and integrated flux density, \( F_\nu = 64 \mu Jy \). Fitting a Gaussian in the image plane suggests that the emission region is apparently marginally extended with a major axis of \( 20^{13}_{10} \) mas, an upper limit of \( 9.9 \) mas (3\( \sigma \)) for the minor axis, and a position angle of \( \theta = 98^{+13}_{-10} \) deg after convolution with the restoring beam. We attribute the apparent extension of the marginally detected SN to the low signal-to-noise ratio of the image.

(A color version of this figure is available in the online journal.)

In our independent analysis of the second epoch VLBI data, we attempted to verify the source extension by excluding the data from the Green Bank and Hartebeesthoek antennas resulting in a lower resolution image with a synthesized beam size of 13 × 8.2 mas, comparable to that in the first VLBI epoch. We confirm the presence of a weak and apparently extended source consistent with the position of the SN in the first epoch to within \( \sim 1\sigma \). We measure an integrated flux density of \( F_\nu \approx 64 \pm 31 \mu Jy \) (peak flux density, \( F_\nu \approx 37 \mu Jy \) per beam, rms noise level, \( \sigma = 13 \mu Jy \) per beam; see Figure 6). We consider this 2.8\( \sigma \) source (at peak) to be a marginal detection of the SN. Thus, a modest (1.7\( \sigma \)) VLA–VLBI flux discrepancy persists even on shorter VLBI baselines. We note that Paragi et al. (2010) similarly reported no increase in the flux density when the data from the Hartebeesthoek and Green Bank antennas were excluded. If this effect is attributed to resolved emission from a relativistic outflow, the required velocity is significantly higher, \( v \gtrsim 2.6c \), which implies far more stringent requirements on the properties and dynamics of the blast wave than Paragi et al. (2010)’s proposed value of \( v \gtrsim 0.6c \) (see Section 4).

An alternative interpretation is that the observations suffer from a modest loss of phase coherence, a common phenomenon in phase-referenced VLBI observations which is difficult to correct at low signal-to-noise ratios. Such losses cause an apparent decrease in the total flux density even in excellent weather conditions (Marti-Vidal et al. 2010) and could explain the modest flux discrepancy observed between the nearly coincident

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10 We note that in their independent analysis of this same VLA observation, Paragi et al. (2010) reported a 2\( \sigma \) higher flux density of \( F_\nu \approx 250 \pm 40 \mu Jy \). It is possible that this is due to different weighting of the VLA baselines which would enhance the sensitivity to underlying and extended emission from the host galaxy.
VLBI–VLA measurements.\textsuperscript{11} We therefore propose a more conservative interpretation in which the flux discrepancy and apparent extension of the SN—revealed even on shorter VLBI baselines—are partly the result of modest phase decoherence affecting this low signal-to-noise observation. Under this interpretation, we adopt the beam size as an upper limit on the apparent diameter of the otherwise unresolved SN emission to place a constraint on the blast wave velocity of $\overline{v} \lesssim 2.6c$ which is fully consistent with our non-relativistic spherical blast wave model.

Finally, we consider the modest flux discrepancy observed for the VLA and WSRT measurements near the epoch of the second VLBI observation. Given that the WSRT synthesized beam (3.2 arcsec) is significantly larger than that of our VLA observation (1.4 arcsec, B array), we propose that the WSRT data may be contaminated by diffuse host galaxy emission. To test this hypothesis, we analyzed VLA observations of the host galaxy, NGC 1058, obtained at 4.9 GHz prior to the discovery of SN 2007gr and publicly available from the NRAO archive.\textsuperscript{12} We find that the SN is located in a strongly star-forming region of its host galaxy characterized by enhanced radio emission. From these data, we measure diffuse host galaxy emission at the position of the SN with a flux density per radio emission. Since SNe with low mass loss rates generally give rise to weak radio signals, they are only detectable nearby ($d \lesssim 30$ Mpc) with current cm-band facilities. This, together with the discovery rate of SNe Ibc within $d \approx 10$ Mpc (a few each decade), statistically suggests that SN 2007gr represents one of the most ordinary SNe Ibc studied to date, characterized by explosion and environmental properties that are typical of the bulk population. With the significant improvement in continuum sensitivity enabled by the Expanded VLA (EVLA; Perley et al. 2009), we will soon be able to detect such ordinary SN Ibc to distances of $\sim 100$ Mpc which will, in turn, broaden our understanding of these unique cosmic explosions.

The authors especially thank Mark Reid for helpful discussions. We also thank Dale Frail, Edo Berger, Andrew MacFadyen, and Eli Waxman. A.M.S. is supported by a HubBLE fellowship. R.A.C. acknowledges support from NASA grant NNG06GJ33G.

\section{5. CONCLUSIONS}

In this paper, we present a critical analysis of blast wave properties of Type Ic SN 2007gr following the recent claim by Paragi et al. (2010) that this otherwise ordinary SN produced a relativistic outflow similar to those of nearby LGRBs. We show that the full data set of radio (VLA and VLBI) and X-ray observations for SN 2007gr is more naturally explained by an ordinary, non-relativistic, and homologous SN explosion. Our conclusions stem from the fact that we directly measured the frequency and flux density of $\nu_\pi$ across several epochs. This result underscores the necessity of multi-frequency and long-term radio monitoring of SNe Ibc in the search for relativistic outflows. We conclude with the following points.

1. A freely expanding and non-relativistic blast wave model best reproduces our extensive radio and X-ray observations, indicating an expansion velocity of $\overline{v} \approx 0.2c$ and energy of $E \approx 2 \times 10^{46}$ erg. These blast wave parameters are consistent with those inferred from the bulk ejecta properties given the expected energy profile of the ejecta.

2. Paragi et al.'s (2010) proposed mildly relativistic blast wave velocity would require exotic physical scenarios (severe departures from equipartition or a decelerated, detached blast wave) that are implausible given the requirements of our VLA observations.

3. Through our independent analysis of the VLBI data sets, we confirm the weak detection of a source consistent with our VLA position for SN 2007gr. However, in our conservative interpretation of the low signal-to-noise second epoch detection, we attribute the apparent loss in flux density to modest phase decoherence, instead of relativistic SN expansion. We also suggest that the WSRT observation is contaminated by diffuse emission from the host galaxy.

Finally, we note that while the data for SN 2007gr do not point to a relativistic explosion, they do offer new insight on the nonthermal properties of Type Ibc SNe. In addition to being one of the nearest of such explosions discovered to date, SN 2007gr is also one of the least radio luminous. This can be directly attributed to its low density circumstellar environment that was shaped by a steady mass loss rate, $M \approx 6 \times 10^{-7} M_\odot$ yr$^{-1}$ (Section 3.2). For comparison, this is $10^{–10}$ times lower than the mass loss rates inferred for radio SNe Ibc with the strongest circumstellar interaction (e.g., SNe 2003L, 2003bg; Soderberg et al. 2005, 2006) which are preferentially detected in the radio and X-ray bands thanks to their luminous nonthermal emission. Since SNe with low mass loss rates generally give rise to weak radio signals, they are only detectable nearby ($d \lesssim 30$ Mpc) with current cm-band facilities. This, together with the discovery rate of SNe Ibc within $d \approx 10$ Mpc (a few each decade), statistically suggests that SN 2007gr represents one of the most ordinary SNe Ibc studied to date, characterized by explosion and environmental properties that are typical of the bulk population. With the significant improvement in continuum sensitivity enabled by the Expanded VLA (EVLA; Perley et al. 2009), we will soon be able to detect such ordinary SN Ibc to distances of $\sim 100$ Mpc which will, in turn, broaden our understanding of these unique cosmic explosions.

\textsuperscript{11} Indeed, Paragi et al. (2010) similarly report that the data were “affected by modest phase errors.” Average weather conditions were reported with the exception of high winds, which prevented observations at Onsala.

\textsuperscript{12} http://archive.cv.nrao.edu/
