

PTF 12gzk—A RAPIDLY DECLINING, HIGH-VELOCITY TYPE Ic RADIO SUPERNOVA

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Received 2013 June 17; accepted 2013 September 15; published 2013 November 6

ABSTRACT

Only a few cases of Type Ic supernovae (SNe) with high-velocity ejecta ($\geq 0.2 c$) have been discovered and studied. Here, we present our analysis of radio and X-ray observations of the Type Ic SN PTF 12gzk. The radio emission declined less than 10 days after explosion, suggesting SN ejecta expanding at high velocity ($\sim 0.3 c$). The radio data also indicate that the density of the circumstellar material (CSM) around the supernova is lower by a factor of ~ 10 than the CSM around normal Type Ic SNe. PTF 12gzk may therefore be an intermediate event between a “normal” SN Ic and a gamma-ray-burst–SN-like event. Our observations of this rapidly declining radio SN at a distance of 58 Mpc demonstrates the potential to detect many additional radio SNe, given the new capabilities of the Very Large Array (improved sensitivity and dynamic scheduling), which are currently missed, leading to a biased view of radio SNe Ic. Early optical discovery followed by rapid radio observations would provide a full description of the ejecta velocity distribution and CSM densities around stripped massive star explosions as well as strong clues about the nature of their progenitor stars.

Key words: radio continuum: general – radio continuum: stars – supernovae: general – supernovae: individual: (PTF12gzk) – X-rays: general

Online-only material: color figures

1. INTRODUCTION

There are two diagnostics provided by radio emission from supernovae. First, radio (and X-ray) emission is generated as fast-moving ejecta collide with the circumstellar medium (CSM; Chevalier 1982; Chevalier 1998; Weiler et al. 2002; Chevalier & Fransson 2006). Thus, radio and X-ray observations can be used to measure the density of optically thin CSM. Next, radio and X-ray emission can be used to trace the *fastest* moving ejecta. In contrast, the optical emission is reflective of the bulk of the ejecta, where the optical depth to visible-light photons is determined, which is necessarily of lower velocity. From radio measurements, one can infer the ratio of the mass-loss rate to the escape velocity (wind velocity) of the progenitor star—the mass-loading parameter. The mass-loading parameter and the shock wave velocity derived from radio observations are in good agreement with the picture that Type Ic supernovae arise from stripped massive star progenitors (e.g., Chevalier & Fransson 2006).

Both of these diagnostics (mass-loading parameter and shock wave velocity) came to the fore for supernovae associated with gamma-ray bursts (GRBs). The first example was SN 1998bw (a broad-lined Type Ic; Ic-BL), which is associated with the nearby, low-luminosity gamma-ray burst GRB 980425 (Galama et al. 1998). Radio observations established that the fastest moving ejecta were mildly relativistic *and* carried a significant amount of the explosion energy (Kulkarni et al. 1998). The same approach (using radio observations to measure the ejecta velocity) showed that SN 2009bb (Type Ic-BL) also had mildly relativistic ejecta and it has been reasonably argued that either SN 2009bb did not produce gamma-rays or that the associated GRB was likely not pointed toward us (or we missed detecting the gamma-rays;

Soderberg et al. 2010a). It is worth noting that in both cases, the optical line features were very broad, i.e., $0.1 c$. This discussion naturally raises the issue of whether or not there exist supernovae which are intermediate (in the above two senses, i.e., relativistic and associated with a GRB) between ordinary⁷ Ic supernovae and SN 1998bw and SN 2009bb.

Here, we report on radio observations of PTF 12gzk, a Type Ic supernova that showed high-velocity optical features and a luminous optical emission (indicative of large radioactive ⁵⁶Ni yield), but no detection of gamma-ray emission. PTF 12gzk turned out to be a fast-evolving radio supernova (SN), but with a lower shock wave velocity (inferred from the radio emission) and energy than SN 2009bb. At the same time, the velocities inferred from the optical spectra resemble those of SN 1998bw and SN 2009bb. This raises the possibility that PTF 12gzk is an intermediate object, connecting normal SNe Ic with GRB-SNe (as discussed above).

In Section 2, we describe our observations and analyze them in Section 3. We then discuss the nature of PTF 12gzk in Section 4. We summarize our results and discuss their implications on future studies in Section 5.

2. MULTI-WAVELENGTH OBSERVATIONS

2.1. The Optical Discovery of PTF 12gzk

The Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009) discovered the peculiar SN Ic PTF 12gzk (Ben-Ami et al. 2012a), as reported in Ben-Ami et al. (2012b). In short, PTF 12gzk was discovered on 2012 July 24 UTC in the galaxy

⁷ Here, we consider ordinary Ic SNe as being non-relativistic SNe with ejecta velocities (inferred from the radio) of $\sim 0.1 c$ which are not associated with GRBs (non-engine-driven events).

SDSS J221241.53+003042.7, 58 Mpc away ($z = 0.0137$). The SN was not detected in previous images taken by the PTF on July 19, down to a 3σ limiting magnitude of 20.6 mag. The SN was detected at a magnitude of $m = 20.1$ mag in the r band and reached a peak magnitude of $m = 15$ mag ($M = -19$) on 2012 August 7. Based on the optical rise time, Ben-Ami et al. (2012b) estimate the explosion time to be $t_0 = 2012$ July 24.0 ± 1 days. Follow-up optical data suggest that PTF 12gzk is a peculiar Type Ic supernova, with high expansion velocities, long rise time, and a large radioactive ^{56}Ni mass, pointing toward an energetic explosion. PTF follow-up programs were rapidly triggered (see Gal-Yam et al. 2011 for a summary of PTF rapid follow-up programs and an example of rapid PTF follow-up time line), including the *Swift* satellite (PI Kasliwal), the Karl G. Jansky Very Large Array (VLA; PI Horesh), and the Combined Array for Research in Millimeter-wave Astronomy (CARMA; PI Horesh) to observe PTF 12gzk in X-ray, centimeter-wavelength, and millimeter-wavelength, respectively. Additional follow-up observations and analysis (including *Hubble Space Telescope* UV spectroscopy) are presented in S. Ben-Ami et al. (2013, in preparation).

2.2. Radio Observations

We observed PTF 12gzk using the VLA⁸ on UTC 2012 August 1. The observation was undertaken in the 6 GHz (C) band using a 2 GHz bandwidth. The VLA configuration at that time was the B configuration (1'' resolution). In our observation, we used J2215 – 0335 as a phase calibrator and 3C48 as a flux calibrator. The data were reduced using the AIPS⁹ software (Greisen 2003).

We detect a source with a flux of $77 \pm 11 \mu\text{Jy}$ at the position $\alpha = 22^{\text{h}}12^{\text{m}}41^{\text{s}}.55$, $\delta = 00^{\circ}30'43''.1$, which is consistent with the optical position of the SN within $0''.5$. The radio luminosity is thus $L_{\nu} = 3 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$. Splitting the data into two sub-band frequencies, we measured a flux of $79 \pm 16 \mu\text{Jy}$ and $82 \pm 14 \mu\text{Jy}$ at 4.8 GHz and 7.4 GHz, respectively, implying a spectrum with a power-law index of $\alpha = 0.1 \pm 0.6$.

Further VLA observations were performed on UTC 2012 August 3, using 6 GHz (C), 14 GHz (Ku), and 20 GHz (K) bands and on UTC 2012 August 5 using the 6 GHz band. We do not detect the supernova ($>3\sigma$) in both the second and third epochs in all bands.

On UTC 2012 August 3, we also observed PTF 12gzk with CARMA at a frequency of 95 GHz. The observation was performed in the E array and 3C446 was used as the phase calibrator. The data were reduced using the MIRIAD software (Sault et al. 1995). The SN was not detected with a 3σ upper limit of 3.6 mJy. The log of the centimeter- and millimeter-wavelength observations can be found in Table 1.

2.3. X-Ray Observation

PTF 12gzk was observed by the X-Ray Telescope (XRT; Burrows et al. 2005) and the ultraviolet imaging telescope (Roming et al. 2005) on the *Swift* satellite. XRT measurements, beginning at 13:39 UTC on July 31, detected no source at the location of PTF 12gzk. We estimate a dead-time-corrected limit on the XRT count rate of $<2 \times 10^{-3} \text{ ct s}^{-1}$. Assuming a power-law spectrum with a photon index of 2, this corresponds

Table 1
Summary of Radio Observations of PTF 12gzk

Day	Age (days)	Frequency (GHz)	Flux (μJy)	Observatory
1.42	~ 8	4.8	79 ± 16	VLA
1.42	~ 8	7.4	82 ± 15	VLA
3.33	~ 10	6.1	≤ 33	VLA
3.33	~ 10	14	≤ 42	VLA
3.33	~ 10	20	≤ 90	VLA
3.34	~ 10	95	≤ 3600	CARMA
5.55	~ 12	6.1	≤ 33	VLA

Notes. Day is given in UTC days in 2012 August. The age of the SN is in days after explosion and is based on the estimated explosion time of $t_0 = 2012$ July 24.0 ± 1 days (Ben-Ami et al. 2012b). The error in the flux is the rms error measured in each image. Upper limits are 3σ limits.

to a limit on the X-ray flux of $<7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ ($L_X < 2.8 \times 10^{40} \text{ erg s}^{-1}$).

2.4. A Search for High-energy Emission

We have searched the available public archives for GRBs contemporaneous with PTF 12gzk. Using the inferred constraints on the explosion date from early optical observations (see Section 2.1), we find no reported GRBs from either the Inter-Planetary Network (IPN; Hurley et al. 2010) or the *Fermi* γ -ray Burst Monitor (GBM; Meegan et al. 2009). Unlike the GBM, the IPN provides essentially continuous all-sky coverage, to a limiting fluence (10 keV–5 MeV) of $S_{\gamma} \lesssim 2 \times 10^{-6} \text{ erg cm}^{-2}$, so we shall adopt this value as a limit on any high-energy emission associated with PTF 12gzk.

The lack of gamma-ray emission from PTF 12gzk therefore suggests that an associated GRB (if one exists) had to be an off-axis event.

3. SHOCK WAVE PROPERTIES AND ENERGETICS

We next approximate the lower limit on the shock wave radius, and therefore its velocity, using the formulation of Chevalier (1998; Equation (13)). Assuming equipartition (i.e., the fraction of shock wave energy converted to electron acceleration is equal to the fraction of energy converted to a magnetic field), and adopting the lower limit on the peak flux at 5 GHz $F_p \geq 77 \mu\text{Jy}$, yields a lower limit on the shock wave radius of $R_s \geq 4.8 \times 10^{15} \text{ cm}$. The shock wave radius can be translated into a lower limit on the shock wave velocity, assuming that the time of the peak is $t \leq 7$ days.¹⁰ Thus, $v_s = R_s/t \geq 80,000 \text{ km s}^{-1}$. This can also be graphically inferred from the Chevalier luminosity–peak time diagram (Figure 1). The errors associated with the shock wave radius and velocity due to the flux measurement error and the uncertainty in the SN distance are 7% and 6%, respectively. An additional uncertainty of $\sim 25\%$ is associated with interstellar scattering and scintillation (ISS; see text below).

In the same manner, we can approximate the mass-loss rate from the progenitor prior to explosion, using Equation (23) from Chevalier & Fransson (2006) and assuming that the CSM around the SN was deposited by a stellar wind with a constant velocity, v_w , and a constant mass-loss rate, \dot{M} . Adopting the value for

¹⁰ The limit on the time of the peak is estimated based on the explosion time from Ben-Ami et al. (2012b) and the assumption that the emission is already fading on UTC 2012 August 1. If the emission was still rising on UTC 2012 August 1, then we should have detected the SN on our second epoch of observation less than two days later.

⁸ VLA program 12A-363 (PI: Horesh).

⁹ <http://www.aips.nrao.edu>

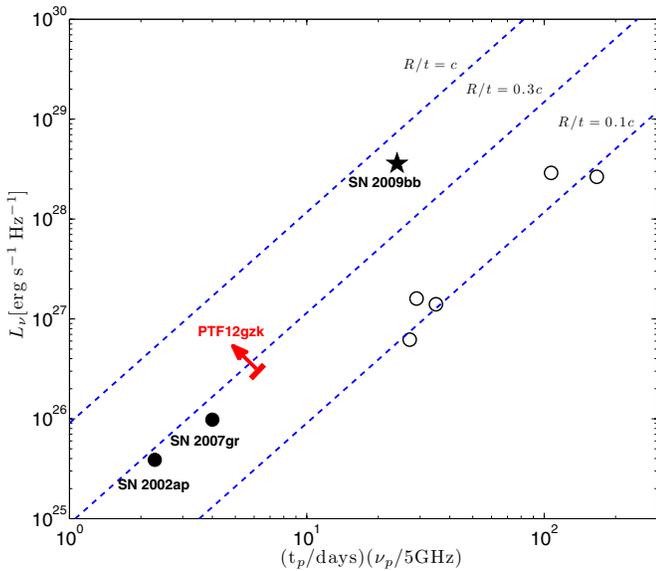


Figure 1. Chevalier luminosity–peak time diagram. The open black circles are measurements of the “normal” (with radio emission peaking at low frequencies at ≥ 10 days) Ic SNe: SN 2004cc, SN 2007bg, SN 1990B, SN 1994I, and SN 2003L (Wellons et al. 2012; Salas et al. 2013; Chevalier & Fransson 2006 and references therein). The 5 GHz luminosity of PTF 12gzk is 3×10^{26} erg s $^{-1}$ Hz $^{-1}$ on UTC 2012 August 1. This likely corresponds to a post-explosion epoch of eight days. The radio emission is already decaying. Therefore, the peak time is ≤ 7 days. From this, we conclude that PTF 12gzk is a high speed Ic supernova with mean ejecta velocity (of the leading edge) in excess of 80,000 km s $^{-1}$.

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

the fraction of energy of the shock wave that is converted into a magnetic field $\epsilon_B = 0.1$, we find that the mass-loading parameter, defined as $A = (M/4\pi v_w)$, is $A \leq 6 \times 10^{10}$ g cm $^{-1}$. This is also consistent with the upper limit on the X-ray flux, assuming that any X-ray emission originates from inverse-Compton emission (see Chevalier & Fransson 2006; Soderberg et al. 2012; Horesh et al. 2013).

We note that in our analysis so far, we have assumed equipartition ($\epsilon_e = \epsilon_B$; ϵ_e is the fraction of shock wave energy in relativistic electrons). However, as previous studies show, equipartition is not necessarily the case (Soderberg et al. 2012; Horesh et al. 2013). Adopting a more extreme value of $\epsilon_e/\epsilon_B = 500$ (motivated by the result of Horesh et al. 2013) lowers the lower limit on the shock wave velocity to $v_s \geq 60,000$ km s $^{-1}$ ($v_s \propto (\epsilon_e/\epsilon_B)^{-1/19}$).

At this point, we would also like to note that the change in radio flux between the first and second epochs is significantly larger than would be predicted by a t^{-1} decay (for a shock wave with a constant velocity and electron energy power-law index of $p = 3$). However, the flux that we measure may be effected by ISS, and therefore may be intrinsically lower.

Taking into account the flux modulation due to ISS, the intrinsic flux of PTF 12gzk can be as low as 45 μ Jy. In this case, the shock wave velocity lower limit reduces from 80,000 km s $^{-1}$ to 60,000 km s $^{-1}$. Moreover, the difference between the observed reduced flux in the first epoch and the flux limit on the second epoch, is consistent (within the errors) with the expected change in the Chevalier (1998) synchrotron emission model.

The minimum internal energy of the emitting material is

$$E_{\min} = \frac{B^2 R^3}{6} \left(1 + \frac{\epsilon_e}{\epsilon_B}\right) f, \quad (1)$$

where B and R are the magnetic field strength and the shock wave radius, respectively, and f is the volume fraction of the radio emitting region. Here, we derive the limits for B and R using Equations (13) and (14) in Chevalier (1998). We find that the internal minimum energy of the emitting material is $E_{\min} = 7.3 \times 10^{45}$ erg. The energy of an ejecta velocity component in a pure explosion is given by

$$E(v) = E_0 \left(\frac{v}{v_0}\right)^{-5}, \quad (2)$$

where v_0 is the maximum velocity of the ejecta and E_0 is the energy carried by it. Considering a radiative progenitor star (polytropic index of $n = 3$), i.e., a Wolf–Rayet or a blue supergiant star, and substituting the equations of Matzner & Mckee (1999)¹¹ for v_0 and E_0 (see also Nakar & Sari 2010 for the normalizations that are used here) into the above equation, the energy¹² can be now expressed as

$$E_{ej}(v) = 2.3 \times 10^{52} \left(\frac{M}{M_\odot}\right)^{-2.46} \left(\frac{E}{10^{51} \text{ erg}}\right)^{3.48} \times \left(\frac{v}{10,000 \text{ km s}^{-1}}\right)^{-5}. \quad (3)$$

Plugging our velocity lower limit, $v_0 \geq 80,000$ km s $^{-1}$, into the above equation and adopting the ejecta mass and explosion energy values from Ben-Ami et al. (2012b; $M_{ej} = 7.5 M_\odot$ and $E = 7 \times 10^{51}$ erg) yields $E_{ej} \approx 4.3 \times 10^{48}$ erg. Therefore, there is more than enough energy in the ejecta to account for the shock wave minimum energy that we measure.

4. COMPARISON WITH A SAMPLE OF RADIO-DETECTED SNe IC

The two most comparable SNe Ic that also exhibit high shock wave velocities, but are not relativistic, are SN 2002ap (Berger et al. 2002) and SN 2007gr (Soderberg et al. 2010b). Both of these sources are believed to be ordinary core-collapse explosions (see, Paragi et al. 2010). Both SNe had radio emission that evolved relatively fast, with SN 2002ap peaking at $t \sim 2$ –3 days (4.86 GHz) and SN 2007gr peaking at $t \sim 3$ –4 days (8.46 GHz) after explosion. The radio analyses by Berger et al. (2002) and Soderberg et al. (2010b) both suggest shock wave velocities of ≈ 0.2 – $0.3 c$. For PTF 12gzk, as seen in Figure 1, the lower limit is about $0.3 c$, similar to the velocities of SN 2002ap and SN 2007gr. However, the two latter SNe had fainter radio luminosities by factors of ~ 10 and ~ 3 compared with PTF 12gzk, respectively. The brighter radio emission from PTF 12gzk may suggest that the shock wave velocity is even higher in this case.

The optical spectra of SN 2002ap, SN 2007gr, and PTF 12gzk show significant difference. The spectra of SN 2002ap (Type Ic-BL) exhibit broad lines formed by emission from ejecta with a broad range of velocities. The velocity of the line centers suggests a bulk velocity of $\sim 38,000$ km s $^{-1}$ 7 days prior to optical peak (B -band) that decreased to 15,000 km s $^{-1}$ at peak (Gal-Yam et al. 2002). In the case of SN 2007gr (normal Ic), there are no broad lines and the absorption line

¹¹ Equations (32) and (37) in Matzner & Mckee (1999).

¹² This is the energy of the fast-moving ejecta originating from the outer layer of the progenitor star, in contrast to the energy carried by the bulk ejecta that originates from the inner parts of the star.

Table 2 A_* Values of PTF 12gzk Compared with Other Radio-detected SNe Ic

SN	Type	Velocity (optical) km s ⁻¹	A_*
1990B	Ic	17,700	2.0
1994I	Ic	17,500	2.8
2003L	Ic	12,000	34.0
2004cc	Ic	...	13.0
2007bg	Ic-BL	18,000	...
2002ap	Ic-BL	38,000	0.04
2007gr	Ic	13,000	0.06
PTF 12gzk	Ic	35,000	≤ 0.12

Notes. The top part of the table includes Type Ic SNe with radio emission peaking at ≥ 10 days after explosion. The bottom part of the table includes Type Ic SNe with rapidly declining radio emission. The table excludes relativistic Ic SNe (which are usually associated with GRBs). The optical velocities are taken from Wheeler & Harkness (1990), Matheson et al. (2001), Millard et al. (1999), Matheson et al. (2003), Harutyunyan et al. (2007), Gal-Yam et al. (2002), Hunter et al. (2009), and Ben-Ami et al. (2012a), respectively. The A_* values of SN 1990B, SN 1994I, SN 2003L, and SN 2002ap are from Chevalier & Fransson (2006) when equipartition is assumed and we adopt the value of $\epsilon_B = 0.1$. The A_* values of SN 2004cc and SN 2007gr are from Wellons et al. (2012) and Soderberg et al. (2010b), respectively. SN 2007bg has a complex CSM density structure and therefore its A_* value is not presented.

blueshifts suggest a velocity of less than 13,000 km s⁻¹ (Hunter et al. 2009). PTF 12gzk, in contrast, does not show broad lines¹³ as SN 2002ap does, but based on line blueshifts, it does exhibit high expansion velocities of $\sim 35,000$ km s⁻¹, which is a factor of ~ 3 higher than the velocity of SN 2007gr. This higher velocity is consistent with our inference that the shock velocity traced by the radio observations is larger than 0.2–0.3 c .

Another property that PTF 12gzk has in common with SN 2002ap and SN 2007gr is the inferred mass-loading parameter of the SN progenitor. In Table 2, we list the normalized mass-loading parameter, A_* , values of these three SNe and a few other Ic SNe, where $A_* = A/5 \times 10^{11}$ g cm⁻¹. PTF 12gzk, SN 2002ap, and SN 2007gr all have A_* values which are at least a factor of 10 lower than the values for the rest of the listed SNe. This is an interesting clue worthy of further investigation, which may suggest more compact progenitors for these objects driving faster winds. A larger sample of this type of SNe with fast declining radio emission is required in order to fully characterize their properties and understand their nature.

5. SUMMARY AND FUTURE IMPLICATIONS

We observed PTF 12gzk in millimeter-, centimeter-wavelength, and X-rays, starting eight days after explosion. Our radio observations reveal a rapidly declining emission that can be explained by a very fast $\geq 80,000$ km s⁻¹ shock wave ploughing through an optically thin CSM, which was deposited by a stellar wind prior to the explosion. We also calculate the limit on the mass-loading parameter $A \leq 6 \times 10^{10}$ g cm⁻¹, which is consistent with our X-ray observations. Note that the sparse data (lack of a full wide-band radio spectrum) prevents us from performing detailed modeling of PTF 12gzk and allow us only to derive the latter limits. Observations of PTF 12gzk can be explained by an ordinary pure explosion supernova (i.e., not a GRB-like event), and do not require an engine-driven event.

However, its inferred high-velocity shock wave (based on our radio analysis), together with the high velocity of the bulk of the ejecta (based on the optical spectra; Ben-Ami et al. 2012a), may indicate that it is an intermediate event between a “normal” SN Ic and a GRB-SN like event. This conclusion is further supported by the fact that the inferred ejecta mass and kinetic energy (based on optical data; Ben-Ami et al. 2012b) are more similar to what is expected in an engine-driven SN than in a normal SNe Ic (Drout et al. 2011). The latter argument, i.e., optical properties similar to those of engine driven events, was also used to suggest that SN 2005bf (a Type Ic SN that later evolved to a Type Ib SN) was an intermediate event (Folatelli et al. 2006). However, observations obtained with the old VLA at day 20 after explosion resulted in a null-detection (Soderberg et al. 2005).

The fraction of rapidly declining (peak emission at 5 GHz in less than 10 days) radio SNe Ic is not well constrained. While the discovery rate of SNe Ic by PTF is ~ 25 yr⁻¹ on average, many of these past events were discovered many days after explosion. Recently, PTF has adopted a higher survey cadence that enables the discovery of SNe within one day of explosion. Figure 1 in Soderberg et al. (2010a) reveals that most of the radio observations of SNe Ic took place at late times (See also Soderberg et al. 2006 for a collection of Type Ib/Ic SNe observed at ≥ 100 days after explosion). Therefore, most rapidly declining events like PTF 12gzk would have been missed by current observing strategies. Thus, it is possible that the average shock wave velocities of 0.1–0.15 c observed in normal SNe Ic may not represent the average velocity of the general SN Ic population.

The improved sensitivity of the VLA (Dougherty & Perley 2010; Perley et al. 2011) offers the opportunity to detect radio emission from high-velocity SNe Ic out to larger distances. Past studies probed only nearby (≤ 10 Mpc) rapidly evolving SNe Ic such as SN 2007gr and SN 2002ap, due to limited sensitivity. More distant SNe, such as SN 2005ek (Drout et al. 2013), that were observed early but with the old VLA, were not detected in the radio. Assuming an rms of 10 μ Jy in the 6 GHz band, the current detection horizon of the VLA for SNe Ic with a shock wave velocity of 0.3 c and with an A_* value similar to that of PTF 12gzk is 70 Mpc. Even in cases where the A_* values are lower by a factor of 10 than that of PTF 12gzk, the detection horizon is still not negligible at 20 Mpc. Relativistic events, such as SN 2009bb, will be detectable out to a distance of 100–300 Mpc if they will have an A_* value similar to that of PTF 12gzk or even lower.

Another possible strategy to better study rapidly evolving radio SN is to conduct the observations at lower frequencies (e.g., 1.4 GHz). The radio emission at 1.4 GHz for events such as PTF 12gzk, SN 2007gr, and SN 2002ap is expected to peak after more than 10 days after explosion. Therefore, future surveys at low frequencies such as Apertif (Verheijen et al. 2008) and ASKAP (Johnston et al. 2008) have the potential to discover and follow many such SNe.

One of the main challenges in studying radio emitting SNe Ic at larger distances by either the VLA or future low-frequency surveys is ISS. As we probe further out, the angular size of the source decreases and therefore the effect of ISS increases. At this point, nature is becoming the main source of noise due to ISS.¹⁴ According to Figure 2, an SN-CSM shock wave, expanding at a velocity of 0.3 c , for example, will still exhibit more than 20%

¹³ PTF 12gzk has narrow lines with a dispersion lower by a factor of ~ 4 compared to broad-lined SNe Ic (see Ben-Ami et al. 2012b for details).

¹⁴ The flux modulation due to ISS is larger than the measurement errors.

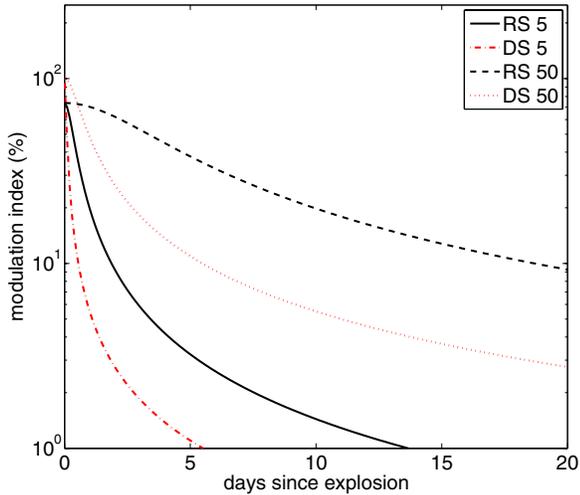


Figure 2. Flux modulation index for observations in the 5 GHz band of a supernova at a distance of 5 Mpc and 50 Mpc and expanding with a blast wave speed of 10^5 km s^{-1} . We assume $\log(\text{SM}) = -3.63$, where SM is the scattering measure. The scattering strength is above unity and so both refractive broad-band scintillation (RS) and diffractive (narrow band) scintillations (DS) are seen. ISS calculations are based on Walker (1998).

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

variability due to ISS at a distance of 50 Mpc after 10 days. At the same time, one can take the approach of undertaking high-frequency (millimeter-wavelength) observations which are less susceptible to ISS flux modulation. Since high-frequency emission in PTF 12gzk-like events is expected to peak at ≤ 1 day after explosion, this approach will be effective only if immediate observations are initiated after the detection of an SN.

To summarize, it is now clear that there exists a phase space of fast SNe Ic that is still relatively unexplored. The improved capabilities of radio observatories combined with early discoveries by optical transient surveys will allow us to probe this new population of radio SNe. Such studies will provide a better understanding of the properties of the progenitor stars and their explosion energies, complementing previous work based on late-time observations.

We thank the VLA, *Swift*, and CARMA staff for promptly scheduling this target of opportunity. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester. PTF is a fully automated, wide-field survey aimed at a systematic exploration of explosions and variable phenomena in optical wavelengths. The participating institutions are Caltech, Columbia University, Weizmann Institute of Science, Lawrence Berkeley Laboratory, Oxford, and University of California at Berkeley. The program is centered on a $12\text{K} \times 8\text{K}$, 7.8 deg^2 CCD array (CFH12K) re-engineered for the 1.2 m Oschin Telescope at the Palomar Observatory by Caltech Optical Observatories. Photometric follow-up is undertaken by the automated Palomar

1.5 m telescope. The research of A.G. is supported by grants from the ISF, BSF, GIF, and Minerva, the EU/FP7 via an ERC grant, and the Kimmel award for innovative investigation.

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