1. Introduction

Ic SNe are hydrogen-stripped core-collapse explosions (CCSNe) of massive stars with $M_{\text{ZAMS}} \gtrsim 8 \ M_\odot$ that show no evidence for hydrogen and helium in their spectra (Filippenko 1997). Potential candidates for Ic SN progenitors are massive Wolf–Rayet (WR) stars and stars in close binary systems (Ensmann & Woosley 1988; Gal-Yam 2017). At the time of writing the exact nature of their progenitors is unclear (Podsiadlowski et al. 1992; Smartt 2009, 2015; Yoon 2010; Eldridge et al. 2013; Dessart 2015; Dessart et al. 2015, 2017). Notable in this respect is the recent detection of the progenitor system of the Ic SN 2017ein (Kilpatrick et al. 2018; Van Dyk et al. 2018), which pointed to a massive stellar progenitor with $M \sim 60 \ M_\odot$ in a binary system.

Ic SNe typically show a bell-shaped radio spectrum powered by synchrotron emission and extending all the way to the X-ray band. The spectral peak frequency describes the transition between the optically thick part of the spectrum—below which synchrotron self-absorption (SSA) takes place—and the optically thin portion of the spectrum (Rybicki & Lightman 1979; Chevalier 1998; Chevalier & Fransson 2006). The synchrotron emission is produced by electrons that are accelerated at the shock front between the SN ejecta and the circumstellar medium (CSM). As the shock wave expands, the optical depth to SSA decreases and hence the spectral peak frequency cascades down to lower frequencies with time. In an SN explosion, the X-ray and radio emission resulting from the SN shock propagation in the medium track the fastest material ejected by the explosion, while the optical emission is of thermal origin and originates from the inner ejecta layers.

A small fraction (≈4%) of Ic SNe, called broad-line Ic SNe (BL-Ic SNe), are characterized by broad lines in the optical spectrum implying large expansion velocities of the ejecta ($\gtrsim 2 \times 10^4 \ \text{km} \ \text{s}^{-1}$, e.g., Mazzali et al. 2002; Cano et al. 2017), $\sim 10^5 \ \text{km} \ \text{s}^{-1}$ faster than in “ordinary” Ic SNe (Modjaz et al. 2016). Some BL-Ic SNe are associated with ultra-relativistic jets that generate long duration ($\gtrsim 2$ s) Gamma-Ray Bursts (L-GRBs, e.g., Cano et al. 2017), which are observable at cosmological distances up to $z \sim 10$ (e.g., Cucchiara et al. 2011). In the local universe ($z \lesssim 0.1$) some BL-Ic SNe have also been found in association with mildly relativistic outflows in low-luminosity GRBs (II-GRBs, which are too weak to be detected at larger distances, Lian et al. 2007). As opposed to L-GRBs, II-GRBs show no evidence for collimation of their fastest ejecta, i.e., no jet (Kulkarni et al. 1998; Soderberg et al. 2006b; Bromberg et al. 2011).

A possible interpretation of the observational lack of evidence for L-GRB counterparts in the majority of BL-Ic SNe is the off-axis jet scenario (Eichler & Levinson 1999; Rhoads 1999; Yamazaki et al. 2003; Piran 2004; Soderberg et al. 2006a; Bietenholz 2014; Corsi et al. 2016), where the explosion powers a GRB-like jet that is misaligned with respect to the observer line of sight. In this scenario, as the jet velocity gradually decreases and relativistic beaming becomes less severe, the emission becomes observable from increasingly larger viewing angles. Deep radio and X-ray observations extending to hundreds of days post explosion offer the opportunity to reveal the emission from off-axis jets as well as to recover weak GRBs that would not trigger current $\gamma$-ray observing facilities.
2. Observations

SN 2014ad was discovered by Howerton et al. (2014) on 2014 March 12.4 (MJD 56,728.4) in public images from the Catalina Real-Time Transient Survey (Djorgovski et al. 2011) at $\alpha = 11^h57^m44.44^s$, $\delta = -10^\circ10'15.7''$. Throughout this paper we assume an SN explosion date $t_0 = 56725 \pm 3$ MJD (Sahu et al. 2018); times given are in reference to this explosion date unless otherwise noted.

2.1. Radio Observations with the Karl G. Jansky Very Large Array

Very Large Array (VLA) follow-up observations were carried out between 2014 March 22 (MJD 56,738) and 2016 September 23 (MJD 57,654), from $\sim$13 to $\sim$930 days post explosion, under Proposal VLA/14A-531 (PI: Kamble). Data were taken in eight spectral windows at $L$-band (with baseband central frequencies of 1.3 and 1.7 GHz, respectively), $C$-band (5 and 7 GHz), $X$-band (8.5 and 11 GHz), $Ku$-band (13.5 and 16 GHz), with a nominal bandwidth of $\sim$1 GHz ($\sim$0.4 GHz for $L$-band). 3C286 and J1330-1449 were used as flux/bandpass and phase/amplitude calibrators, respectively. The Common Astronomy Software Application (CASA, v. 4.7.2, McMullin et al. 2007)\(^5\) was used to calibrate, flag, and image the data. Images were formed from the visibility data using the CLEAN algorithm (Högönn 1974). The image size was set to $(1024 \times 1024)$ pixels, the pixel size was determined as one-fifth of the nominal beam width and the images were cleaned using natural weighting. The upper limits on the flux densities were calculated at a $3\sigma$ confidence level (Table 1).

2.2. X-Ray Observations with Swift-XRT

The X-Ray Telescope (XRT; Burrows et al. 2005) on board the Swift Gehrels spacecraft (Gehrels et al. 2004) observed the region of SN 2014ad in Photon Counting (PC) mode several times from 2014 March 19 to 2017 March 11. We find no evidence for statistically significant X-ray emission at the location of SN 2014ad. We extracted the 0.3–10 keV light curve, consisting of $3\sigma$ upper limits, using the web interface provided by Leicester University,\(^6\) which used HEASOFT (v. 6.22). We performed flux calibration by assuming an absorbed simple power-law spectral model (WABS*POWERLAW within XSPEC) with column density frozen to the Galactic value along the SN line of sight, $N_{\H}\text{Gal} = 3.1 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). We assumed a conservative value for the photon index, $\Gamma = 2$, and derived the upper limit to the flux density at 1 keV. Finally, we calculated three light curves with different integration times: $10^5$, $2 \times 10^5$, and $5 \times 10^5$ s, respectively. Table 2 reports the values for the longest timescale having the deepest limits. We also calculated the corresponding $3\sigma$ upper limits on the 0.3–10 keV luminosity.

3. Constraints on the Environment Density from Inverse Compton Emission

Inverse Compton (IC) emission from the upscattering of optical photospheric photons into the X-ray band by relativistic

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\(^5\) https://casa.nrao.edu/
\(^6\) http://www.swift.ac.uk/user_objects/
Table 1
Log of VLA Observations of SN 2014ad

| \( t_{\text{mid}} \) (MJD) | \( t_e \) (days) | VLA Configuration | \( \theta_{\text{FWM}} \) (arcsec) | \( \nu_c \) (GHz) | \( \Delta\nu \) (GHz) | \( \sigma_b \) (\( \mu\)Jy) | \( \Delta(3\sigma) \) (\( \mu\)Jy) | \( L_{25} \) (erg s\(^{-1}\) Hz\(^{-1}\)) |
|-----------------|-------------|-----------------|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|
| 56738.19       | 13.19       | A               | 1.42            | 1.26        | 0.384           | 28.8            | 86.4            | 12.1            |
| 56763.21       | 38.21       | A               | 1.42            | 1.26        | 0.384           | 31.6            | 94.8            | 13.2            |
| 56828.96       | 103.96      | AnD             | 12.02           | 5.0         | 0.896           | 20.7            | 3.9             | 3.2             |
| 56906.76       | 181.76      | D               | 12.02           | 5.0         | 0.896           | 20.7            | 3.9             | 3.2             |
| 57227.81       | 502.81      | A               | 1.24            | 7.1         | 0.896           | 7.2             | 2.1             | 0.5             |
| 57654.66       | 929.66      | B               | 1.15            | 5.0         | 0.896           | 6.6             | 2.8             | 2.8             |

Note. Observation central time \( t_{\text{mid}} \), epoch \( t_e = t_{\text{mid}} - t_0 \) since the estimated explosion date \( t_0 \), VLA array configuration, beam size \( \theta_{\text{FWM}} \), central frequency \( \nu_c \), and its bandwidth \( \Delta\nu \), the uncertainty \( \sigma_b \), the upper limit on the flux density \( S \) (at 3\( \sigma \)), and the relative luminosity \( L_{25} \) (in units of 10\(^{25} \) erg s\(^{-1}\) Hz\(^{-1}\)) of the source. In no case was the source detected with \( \geq 3\sigma \) confidence.

Table 2
Swift-XRT 3\( \sigma \) Upper Limits on the Flux Density at 1 keV (\( F_{\nu} \) 1 keV) and 0.3–10 keV Luminosity (\( L_{0.3–10} \))

| \( t_{\text{mid}} \) (MJD) | \( t_e \) (days) | \( \Delta t \) (days) | \( F_{\nu} \) 1 keV (\( \mu\)Jy) | \( L_{0.3–10} \) (erg s\(^{-1}\))
|--------------------------|---------------|------------------|-----------------|-----------------|
| 56738.1                  | 13.1          | 5.8              | \(< 1.3 \times 10^{-2} \) | \(< 1.0 \times 10^{42} \) |
| 56743.9                  | 18.9          | 5.8              | \(< 1.2 \times 10^{-2} \) | \(< 9.0 \times 10^{41} \) |
| 56749.6                  | 24.6          | 5.8              | \(< 1.7 \times 10^{-2} \) | \(< 1.3 \times 10^{42} \) |
| 56755.4                  | 30.4          | 5.8              | \(< 4.1 \times 10^{-2} \) | \(< 3.2 \times 10^{42} \) |
| 57774.0                  | 1049.0        | 5.8              | \(< 0.11 \)       | \(< 8.5 \times 10^{43} \) |
| 57808.7                  | 1083.7        | 5.8              | \(< 1.1 \)        | \(< 8.5 \times 10^{43} \) |
| 57820.2                  | 1095.2        | 5.8              | \(< 6.7 \times 10^{-2} \) | \(< 5.2 \times 10^{43} \) |

Note. \( t_e = t_{\text{mid}} - t_0 \) is the epoch since the estimated SN explosion date \( t_0 \). \( \Delta t \) is the bin time.

4. Broadband Modeling

We interpret our deep radio and X-ray limits in the context of synchrotron self-absorbed (SSA) emission from either relativistic electrons at the shock front has been demonstrated to dominate the X-ray emission from H-striped CCSNe that explode in low-density environments \( (M \lesssim 10^{-5} \ M_{\odot} \text{ yr}^{-1}) \) at \( \Delta t \lesssim 30 \) days (e.g., Björnsson & Fransson 2004; Chevalier & Fransson 2006). We adopt the IC formalism by Margutti et al. (2012) modified to account for the outer density structure of progenitors of BL-Lc SNe (which are likely to be compact) as in Margutti et al. (2014). The IC emission depends on (i) the density structure of the SN ejecta and of the CSM, (ii) the electron distribution responsible for the upscattering, (iii) explosion parameters (ejecta mass \( M_{\text{ej}} \) and kinetic energy \( E_{\text{k}} \)), and (iv) the bolometric luminosity of the SN: \( L_{\text{bol}} \propto L_{25} \).

For compact progenitors that are relevant here, the density scales as \( \rho_{\text{ej}} \propto r^{-n} \) with \( n \sim 10 \) (see, e.g., Matzner & McKee 1999; Chevalier & Fransson 2006). We further assume a power-law electron distribution \( n_e(\gamma) \propto \gamma^{-p} \) with \( p \sim 3 \) as found in radio observations of type H-striped CCSNe (Chevalier & Fransson 2006) and a fraction of energy into relativistic electrons \( \epsilon_{\text{e}} = 0.1 \). We use the explosion parameters \( E_{\text{k}} = (1.0 \pm 0.3) \times 10^{52} \) erg and \( M_{\text{ej}} = (3.3 \pm 0.8) \ M_{\odot} \). For a wind-like CSM structure \( \rho_{\text{CSM}} \propto r^{-2} \) with a typical wind velocity \( v_{\text{w}} = 1000 \text{ km s}^{-1} \) as appropriate for massive stars (and hence BL-Lc SN progenitors, e.g., Smith 2014), the Swift-XRT nondetections at \( \Delta t < 30 \) days yield \( M < 5 \times 10^{-5} \ M_{\odot} \text{ yr}^{-1} \).
(i) uncollimated (i.e., spherical) nonrelativistic ejecta (Section 4.1), or (ii) relativistic GRB-like jet (Section 4.2).

4.1. SSA Emission from Nonrelativistic Uncollimated Ejecta

We follow Soderberg et al. (2005) and adopt their formalism in the context of the radio emission from nonrelativistic SN ejecta interacting with a wind-like CSM. The brightness temperature of a source is:

\[ T_B = \frac{c^2}{2\pi k} \frac{f_\nu d^2}{v_{\text{ph}} t^2} \nu^2, \]

where \( c \) is the speed of light, \( k \) is the Boltzmann constant, \( f_\nu \) is the flux density at observed frequency \( \nu \), \( d \) is the source distance, \( v_{\text{ph}} \) is the photospheric velocity, and \( t \) is the observational epoch. For SN 2014ad we find \( T_B \lesssim 2.8 \times 10^{11} \) K at \( t \approx 13.2 \) d, where \( v_{\text{ph}} \approx 3.2 \times 10^4 \) km s\(^{-1}\) and \( f_\nu < 86.4 \) \( \mu \)Jy at \( \nu = 1.26 \) GHz (Table 1). Our inferred \( T_B \) does not violate the \( 10^{12} \) K limit of the inverse Compton catastrophe (ICC; Kellermann & Pauliny-Toth 1981), consistent with the expectations from a nonrelativistic spherical SSA source.

In the SSA model radiation originates from an expanding spherical shell of shock-accelerated electrons with radius \( r \) and thickness \( r/\eta \) (here we assume the standard scenario of a thin shell with \( \eta = 10 \); e.g., Li & Chevalier 1999; Soderberg et al. 2005). As the shock wave propagates through the CSM, it accelerates relativistic electrons into a power-law distribution \( N(\gamma) \propto \gamma^{-p} \) for \( \gamma \gtrsim \gamma_m \), where \( \gamma_m \) is the minimum Lorentz factor of the electrons (Chevalier 1982, 1998). In this analysis we assume \( p \approx 3 \) as typically found in H-striped core-collapse SNe (e.g., Chevalier & Fransson 2006). The post-shock energy fraction in the electrons and magnetic field is given by \( \epsilon_e \) and \( \epsilon_B \), respectively; we further adopt equipartition of the post-shock energy density of the radio-emitting material between relativistic electrons and magnetic fields (\( \epsilon_e = \epsilon_B = 1/3 \)).

The synchrotron emission from SNe typically peaks at radio frequencies on timescales of a few days to weeks after the SN explosion (e.g., Corsi et al. 2014); this emission is suppressed at low frequencies by absorption processes. Chevalier (1998) showed that the dominant absorption process is internal SSA for H-striped SNe, and external free–free absorption (FFA) in H-rich SNe, as H-rich SNe tend to explode in higher density media.

Following Soderberg et al. (2005), the temporal evolution of the magnetic field \( B(t) \), minimum Lorentz factor \( \gamma_m(t) \), shock radius \( r(t) \), and the ratio \( \eta = \epsilon_e/\epsilon_B \) can be parameterized as:

\[ B = B_0 \left( \frac{t - t_e}{t_0 - t_e} \right)^{\alpha_B} \gamma_m = \gamma_m(0) \left( \frac{t - t_e}{t_0 - t_e} \right)^{\alpha_m}, \]

\[ r = r_0 \left( \frac{t - t_e}{t_0 - t_e} \right)^{\alpha_r} \eta = \eta(0) \left( \frac{t - t_e}{t_0 - t_e} \right)^{\alpha_\eta}, \]

where \( r_0, B_0, \eta_0, \) and \( \gamma_m(0) \) are measured at an arbitrary reference epoch \( t_0 \), and \( t_e \) is the explosion time. In this paper we adopt \( t_0 = 13.2 \) days (for which \( r_0 \approx v_{\text{ph}} \times t_0 = 4 \times 10^{15} \) cm) and \( t_e = 0 \) days. The temporal indices \( \alpha_r, \alpha_B, \alpha_\eta, \) and \( \alpha_m \) are determined by the hydrodynamic evolution of the ejecta, as described in Soderberg et al. (2005). In particular, \( \alpha_r \) and \( \alpha_m \) can be expressed as:

\[ \alpha_r = \frac{n - 3}{n - s}, \]

\[ \alpha_m = -\alpha_B + 2\alpha_\eta - 2\alpha_\eta, \]

where \( n \) and \( s \) describe the density profile of the outer SN ejecta \( (\rho \propto r^{-s}) \), and of the CSM \( (\rho_{\text{CSM}} \propto r^{-3}) \), respectively. The self-similar conditions \( s < 3 \) and \( n > 5 \) result in \( \sim 0.5 < \alpha_r < 1 \) (Chevalier 1982). In this work we consider a wind-like CSM case (i.e., \( s = 2 \)), and \( n = 10 \) as appropriate for massive compact stars that are thought to be progenitors of H-stripped CCSNe. In the standard scenario (Chevalier 1996), \( \epsilon_e \) and \( \epsilon_B \) do not vary with time, from which we derive through Equation (3) that \( \alpha_\eta = 0 \), implying that:

\[ \alpha_B = \left( \frac{2 - s}{2} \right) \alpha_r - 1, \]

\[ \alpha_m = 2(\alpha_r - 1). \]

Since \( \alpha_0 = 0 \) and under the equipartition hypothesis (\( \gamma = 1 \); Equation (3)), it follows that \( \alpha_r = 0.875 \) (Equation (4)), \( \alpha_B = -1 \) (Equation (6)) and \( \alpha_m = -0.25 \) (Equation (7)). Under these assumptions and through Equation (2), the characteristic synchrotron frequency is:

\[ \nu_m(t) = \frac{\gamma_m^2}{2\pi m_e c} \frac{q B}{\nu_B} = \frac{\gamma_m^2}{2\pi m_e c} \left( \frac{t}{t_0} \right)^{2\alpha_r + \alpha_\eta}, \]

\[ = \nu_m(0) \left( \frac{t}{t_0} \right)^{2\alpha_r + \alpha_\eta}, \]

where \( q \) is the electron charge and \( m_e \) is the electron mass. The frequency \( \nu_m(t) \equiv \nu_m(0) \) depends on \( \gamma_m(0) \) and \( B_0 \) as follows:

\[ \nu_m(0) = \frac{\gamma_m^2}{2\pi m_e c} q B_0. \]

The radio flux density at a given observing frequency \( \nu \) and epoch \( t \) is thus given by:

\[ F(t, \nu) = 10^{26} C_C \left( \frac{t}{t_0} \right)^{4\alpha_r + \alpha_\eta} \left[ 1 - e^{-\tau_\nu} \right]^1/\xi \times \nu^{5/2} F_5(x) F_7^{-1}(x) \text{ mJy} \]

with the optical depth \( \tau_\nu \).

\[ \tau_\nu(t) = C_C \left( \frac{t}{t_0} \right)^{\alpha_r + (3+p/2+2p)/(p-2)\alpha_r + \alpha_\eta - (p+4)/2} F_5(x). \]

Here \( C_C \) and \( C_\xi \) are normalization constants (see Appendix A2 of Soderberg et al. 2005). \( F_7(x) \) and \( F_5(x) \) are Bessel functions with \( x = 2/3(\nu/\nu_m)^{1/2} \). \( \xi = [0, 1] \) describes the sharpness of the spectral break between optically thin and thick regimes. We adopt \( \xi = 1 \).

As we can see from Equations (10), (11), (4), and (8), \( F(t, \nu) \) depends on \( C_C, C_\xi, \alpha_r, \alpha_B, \alpha_\eta, \alpha_m, \) and \( \xi \). From Equations (6)–(8) of Soderberg et al. (2005) \( C_\xi \) and \( C_C \) can be expressed in terms of \( t_0, B_0, \) and \( \eta \); thus, also using (9), \( F(t, \nu) \) can be expressed as a function of \( r_0, B_0, p, n, s, \gamma_m(0), \eta, \) and \( \xi \), which are all fixed apart from \( B_0 \) and \( \gamma_m(0) \). These two free parameters can be further

\(^8\text{\footnotesize s} = 0\) corresponds to the case of ISM-like CSM and \( s = 2\) correspond to the case of wind-like CSM.
expressed as a function of physically more useful quantities, the SN progenitor mass-loss rate ($\dot{M}$) and the total kinetic energy of the radio-bright (fast) ejecta ($E$):

$$B_0 = \left(\frac{2\pi e}{3\eta_0}\right)^{1/2} E^{1/2}$$

$$\gamma_{m,0} = \left(\frac{p-2}{p-1}\right) \frac{2m_p c^2 v_w}{m_e c^2 \rho_0} \left(\frac{E}{\dot{M}}\right),$$

where $m_p$ is the proton mass and $v_w$ is the wind velocity. Consequently, we express $v_{m,0}$ as a function of $\dot{M}$ and $E$ from (9):

$$v_{m,0} = \left(\frac{p-2}{p-1}\right)^2 \frac{2g}{\pi m_p c} \left(\frac{m_p v_w}{m_e c^2}\right)^{5/2} \left(\frac{2\eta_0 c \rho_0}{\eta_0^3 \rho_0^3} E^{5/2} / M^2\right)$$

As a result, $F(t, \nu)$ just depends on $\dot{M}$ and $E$.

We use a grid of $\dot{M}$ and $E$ values to compare our VLA upper limits (Table 1) with the flux densities derived from (10). In Figure 2 we explore the kinetic energy versus mass-loss rate space parameter considering the (i) radio upper limits (hatched) and (ii) the radio limits plus the X-ray limits (red), which results in more stringent constraints: $E \lesssim 10^{42}$ erg for $\dot{M} \lesssim 10^{-6} M_\odot$ yr$^{-1}$ and $E \lesssim 10^{46}$ erg for $\dot{M} \lesssim 10^{-4} M_\odot$ yr$^{-1}$. We end by noting that at these low mass-loss rates the effects of FFA are negligible (e.g., Weiler et al. 1986; Fransson & Björnsson 1998).

4.2. SSA Emission from a Relativistic GRB-like Jet

We generated a grid of radio light curves powered by synchrotron emission from off-axis relativistic jets using the

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9 These parameters are shown in Equations (13) and (14) of Soderberg et al. (2005), respectively.
5.2. Is SN 2014ad Associated with an Off-axis GRB-like Jet?

Our VLA radio observations place stringent constraints on off-axis relativistic jets expanding into an ISM-like CSM (Figure 3) and a wind-like CSM (Figure 4), respectively (Section 4.2). First, we consider the case of a wind-like CSM and a highly collimated jet with $\theta_j = 5^\circ$ (as is typical for cosmological GRBs) viewed off-axis, for $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ (top right panel, Figure 4). These off-axis narrow jets are ruled out regardless of the observer angle for $M \gtrsim 10^{-5} \, M_\odot \, yr^{-1}$ and $E_{k,iso} \gtrsim 10^{52}$ erg (typical value for a GRB). Hence, GRB-like jets expanding either in a low-density CSM typical of BL-Ic SNe ($M \lesssim 10^{-5} - 10^{-6} \, M_\odot \, yr^{-1}$) as is typical for cosmological GRBs (e.g., Laskar 2019b) or in typical GRB environments ($10^{-7} \lesssim M \lesssim 10^{-5} \, M_\odot \, yr^{-1}$; Laskar et al. 2014, 2015) cannot be ruled out.

In the case of off-axis jets with larger opening angles $\theta_j = 30^\circ$, for $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ (top right panel, Figure 4), we obtain stronger constraints, due to their larger jet energy. Specifically, regardless of the observer angle, we can rule out scenarios where $M \gtrsim 10^{-6} \, M_\odot \, yr^{-1}$ and $E_{k,iso} \gtrsim 10^{52}$ erg. Mass-loss rates typically found in the winds of WR stars ($M \lesssim 10^{-5} - 10^{-6} \, M_\odot \, yr^{-1}$, Smith 2014) are mostly ruled out. In the case of wide ($\theta_j = 30^\circ$), slightly off-axis ($\theta_{obs} \leq 30^\circ$) jets for $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ (top right panel, Figure 4), we can rule out the combination of $M \gtrsim 10^{-8} \, M_\odot \, yr^{-1}$ and $E_{k,iso} \gtrsim 10^{51}$ erg. Assuming a progenitor wind velocity of 1000 km s$^{-1}$, all the CSM profiles of all the detected SNe Ibc and most of the GRBs detected to date are rejected (see Figure 5 in Coppejans et al. 2018). We also report the results for a jet propagating into an ISM-like CSM, as the modeling of GRB afterglows often indicates an ISM environment as opposed to a wind-like density profile (e.g., Laskar et al. 2014, 2018). For $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ (top right panel, Figure 3), highly collimated jets with $\theta_j = 5^\circ$ are ruled out regardless of the observer angle for $n \gtrsim 10 \, cm^{-3}$ and $E_{k,iso} \gtrsim 10^{50}$ erg. A jet with $\theta_j = 30^\circ$ is ruled out for $n \gtrsim 10^{-1} \, cm^{-3}$ and $E_{k,iso} \gtrsim 10^{52}$ erg. We obtain deeper constraints for jets with $\theta_{obs} < 60^\circ$: for $\theta_j = 5^\circ$ and $\theta_{obs} = 60^\circ$ a jet is ruled out for $n \gtrsim 10^{-3} \, cm^{-3}$ and $E_{k,iso} \gtrsim 10^{52}$ erg. Hence, GRB-like jets expanding in an ISM-like medium with $n \lesssim 10^{-2} \, cm^{-3}$ and $E_{k,iso} \lesssim 10^{50}$ erg cannot be ruled out: these densities are compatible with those of some GRBs ($10^{-5} \lesssim n \lesssim 10^{3} \, cm^{-3}$; e.g., Laskar et al. 2014, 2015).

We conclude that we cannot rule out the case of an off-axis ($\theta_{obs} \gtrsim 30^\circ$), narrow ($\theta_j = 5^\circ$) GRB-like jet plowing through...
low-density CSM typical of BL-Ic SNe and GRBs; this scenario allows for beaming-corrected kinetic energies \( E_{\text{k,iso}} \approx 10^{52} \text{ erg} \) in environments sculpted by \( \dot{M} \approx 10^6 M_{\odot} \text{ yr}^{-1} \).

5.3. Constraining the \( E_{\text{k}}(\Gamma \beta) \) Distribution of the Ejecta of SN 2014ad

Compared with BL-Ic GRB-less SNe, GRB-SNe seemed to show (i) high mass of \(^{56}\text{Ni}\) synthesized in the SN explosion, (ii) higher degree of asphericity in the SN explosion, and (iii) low metallicity of the SN environment (e.g., Cano 2013). However, Taddia et al. (2019) recently showed that the distributions of these observables for the two classes of BL-Ic SNe are still compatible within uncertainties. Another way to investigate the differences between the two classes is offered by the slope \( x \) of the kinetic energy profile \( (E_{\text{k}}) \) as a function of the ejecta four-velocity \( (\Gamma \beta) \). What is more, this may help to reveal the nature of the explosion (see Figure 2; Margutti et al. 2014). Steep profiles \( (x \lesssim -2.4) \) indicate a short-lived central engine, and hence an ordinary Ibc SN (Lazzati et al. 2012); flat profiles \( (x \gtrsim -2.4) \) indicate the presence of a mildly short-lived central engine, and hence a possible GRB-SN (Margutti et al. 2013); very flat profiles \( (x = -0.4) \) are typical of ordinary GRBs in the decelerating Blandford–McKee phase (Blandford & McKee 1976), whereas very steep profiles \( (x = -5.2) \) are characteristic of a pure hydrodynamical spherical explosion (Tan et al. 2001).

For SN 2014ad we explored a grid of parameters in the \( E_{\text{k}}-\Gamma \beta \) space. \( \Gamma \beta \) is calculated at \( t = 1 \text{ day} \) applying the standard formulation of the fireball dynamics with expansion in a wind-like CSM (e.g., Chevalier & Li 2000)

\[
\Gamma(\text{t=1 day}) \sim 18.7 \left( \frac{E_{\text{k,iso}}}{10^{54} \text{ erg}} \right)^{1/4} \left( \frac{A_*}{0.1} \right)^{-1/4},
\]

where \( A_* \) is the circumstellar density, defined with respect to progenitor mass-loss rate \( \dot{M} \) and wind velocity \( v_w \) as:

\[
A_* = \left( \frac{\dot{M}}{10^{-5} M_{\odot} \text{ yr}^{-1}} \right) \left( \frac{v_w}{1000 \text{ km s}^{-1}} \right).
\]

The allowed regions are derived through the conditions described in Section 5.2 for the case of a highly collimated jet with \( \theta_j = 5^\circ \) (as typical for cosmological GRBs) viewed off-axis in a wind-like CSM (Figure 4; top right panel). Figure 5 shows the allowed region of the beaming-corrected energy \( E_k-\text{ejecta velocity } \Gamma \beta \) space (in the relativistic regime). Relativistic jets for SN 2014ad are possible for progenitors with very low densities \( (\dot{M} \lesssim 10^{-7} M_{\odot} \text{ yr}^{-1}) \); for example, a faster-moving ejecta (with a beaming-corrected energy \( E_k \approx 10^{51} \text{ erg} \)) plowing through a wind-like CSM with a very...
relativistic SNe, where the cocoon emission might be observable.

Previous studies of this source showed that it has a number of properties that, taken together, suggest a possible GRB counterpart. These include a large bulk energy $E_k$ of the slow ejecta, the asphericity in the explosion and ejecta velocity, the large inferred nickel mass, and the low progenitor mass-loss rate $M$. Consequently, we investigated two different physical scenarios for SN 2014ad: (i) a subrelativistic, nearly isotropic explosion of an ordinary BL-Ic SN in a wind-like CSM (Section 4.1); (ii) an off-axis relativistic jet (Section 4.2). These models place strong constraints on the total energy of the fast ejecta ($E$), the progenitor mass-loss rate ($M$), the jet opening angle ($\theta_j$), and the observer angle ($\theta_{obs}$). We obtained the following results:

1. Assuming that the dominant source of X-ray emission at early times is IC emission from the upscattering of optical photospheric photons into the X-ray band by relativistic electrons at the shock front (Section 3), we infer $M < 5 \times 10^{-5} M_\odot$ yr$^{-1}$, for a wind velocity $v_w = 1000$ km s$^{-1}$ for a spherical outflow.

2. If SN 2014ad launched a subrelativistic and isotropic outflow (Section 4.1), assuming equipartition ($\epsilon_e = \epsilon_B = 0.33$) we derive limits of $E \lesssim \epsilon B$ erg for $M \lesssim 10^{-6} M_\odot$ yr$^{-1}$ and $E \lesssim \epsilon B$ erg for $M \lesssim 10^{-4} M_\odot$ yr$^{-1}$. These deep constraints rule out outflows with properties similar to (i) relativistic SN 2009bb and SN 2012ap, for which no associated GRB was reported, and (ii) SN 1998bw, a prototypical GRB-SN, propagating into a similar environment. $E$ and $M$ of the kind seen in the GRB-less SN 2002ap and SN 2010ay, which are characterized by a modest energy budget in the fast ejecta, are not ruled out.

3. If SN 2014ad launched a relativistic jet, we (i) rule out collimated on-axis jets of the kind detected in GRBs and (ii) put strong constraints on the energies and CSM densities for an off-axis jet (Figures 3 and 4). We cannot rule out an off-axis GRB in very low-density CSM environments (e.g., $\theta_{obs} \gtrsim 30^\circ$, $\theta_j = 5^\circ$, in a CSM sculped by $M \lesssim 10^{-6} M_\odot$ yr$^{-1}$, typical of BL-Ic SNe and GRBs). Moreover, we cannot reject the possibility of a radio synchrotron emission dominated by the cocoon created by a GRB jet viewed off-axis that propagates through the stellar progenitor, as expected for relativistic SNe.

With our analysis of the off-axis jet scenario we have demonstrated that it is not possible to rule out off-axis jets expanding into low-density environments (as previously found by Bietenholz 2014 for other SNe). For SN 2014ad we find $M \lesssim 10^{-6} M_\odot$ yr$^{-1}$ (Figure 5). If SN 2014ad was indeed powered by an off-axis relativistic jet, our X-ray and radio observations imply extremely low environment densities and energies coupled to jet (unless the jet was far off-axis).

Deep radio and X-ray observations at early and at late times of a large sample of nearby BL-Ic SNe will clarify whether or not relativistic jets are ubiquitous in BL-Ic SNe.

### 5.4. Constraints on Cocoon Emission in SN 2014ad

The interaction between the jet emission and the outer layers of the progenitor star causes the swelling of the outer envelope of the jet, called the cocoon. The recent broadband spectroscopic analysis of Izzo et al. (2019) of a BL-Ic GRB-SN (SN 2017iuk/GRB 171205A) shows the first direct evidence for the cocoon emission. This cocoon is characterized by a very high expansion velocity ($\sim 0.5c$) and probably originates from the energy injection of a mildly relativistic GRB jet. This discovery could explain the lack of GRBs observed in association with some BL-Ic SNe: the jet, because it transfers a significant part of its total energy to the cocoon, produces the typical GRB emission only if it manages to completely pierce the star photosphere. This conclusion is in agreement with the analysis of De Colle et al. (2018a, 2018b): they show that the radio emission observed in relativistic SNe can be explained as synchrotron emission from the cocoon created by an off-axis GRB jet (either failed or successful), that propagates through the progenitor star. Figure 5 shows the allowed region (red hatched area) for relativistic SNe, where the cocoon emission in principle might be observable: even if the radio emission from SN 2014ad is much fainter than SN 2009bb and SN 2012ap (Figure 1), this region is compatible with $E_k$ of the fast ejecta for an SN 2014ad progenitor with mildly low densities ($M \sim 10^{-5} M_\odot$ yr$^{-1}$). De Colle et al. (2018a) suggest that, in the off-axis GRB scenario, the cocoon synchrotron emission at radio frequencies dominates (i) always for failed GRB/cocoon or weak GRB observed off-axis, or (ii) only at early times for energetic off-axis jets with late-time peaks (timescale of years).

A more quantitative discussion of the cocoon emission for SN 2014ad is beyond the scope of the present investigation.

### 6. Conclusions

We present deep X-ray and radio limits of the BL-Ic SN 2014ad. Radio and X-ray observations are crucial for probing the fastest moving ejecta in the explosion, as the optical emission is produced by the slow-moving ejecta. We present deep X-ray and radio limits of the BL-Ic SN 2014ad. Radio and X-ray observations are crucial for probing the fastest moving ejecta in the explosion, as the optical emission is produced by the slow-moving ejecta.
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