SNe Ia, with their remarkably homogeneous light curves and spectra, have been used as standardizable candles to measure the accelerating expansion of the universe. Yet, their progenitors remain elusive. Common explanations invoke a degenerate star (white dwarf) that explodes upon almost reaching the Chandrasekhar limit, by either steadily accreting mass from a companion star or violently merging with another degenerate star. We show that circumstellar interaction in young Galactic supernova remnants can be used to distinguish between these single and double degenerate (DD) progenitor scenarios. Here we propose a new diagnostic, the surface brightness index, which can be computed from theory and compared with Chandra and Very Large Array (VLA) observations. We use this method to demonstrate that a DD progenitor can explain the decades-long flux rise and size increase of the youngest known galactic supernova remnant (SNR), G1.9+0.3. We disfavor a single degenerate scenario for SNR G1.9+0.3. We attribute the observed properties to the interaction between a steep ejecta profile and a constant density environment. We suggest using the upgraded VLA, ASKAP, and MeerKAT to detect circumstellar interaction in the remnants of historical SNe Ia in the Local Group of galaxies. This may settle the long-standing debate over their progenitors.

Key words: binaries: general – circumstellar matter – ISM: individual objects (SNR G1.9+0.3) – ISM: supernova remnants – radio continuum: general – supernovae: general – X-rays: general

1. INTRODUCTION

SNe Ia were classified by Minkowski (1941) as a largely homogeneous group characterized by a lack of hydrogen in their spectra. A major subset called Type Ia, which have early-time spectra with strong Si II (Filippenko 1997), are believed to come from the thermonuclear explosions of degenerate stellar cores (Wheeler & Harkness 1990). Despite their homogeneity, peak absolute magnitudes of SNe Ia are not constant. Phillips (1993) related their peak brightness to the width of their light curve. This allowed Riess et al. (1996) to standardize them as reliable distance indicators. SNe Ia have been used as standard candles, leading to the discovery of the accelerating expansion of the universe (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). As a consequence of their importance in astronomy and cosmology, SNe Ia are the subject of various theoretical and observational studies. Yet, much remains unknown of the stellar systems that produce these explosions.

It is generally agreed upon (Hillebrandt & Niemeyer 2000) that SNe Ia mark catastrophic explosions of white dwarfs near and/or above the Chandrasekhar (1931) limit. Accreted mass, required to destabilize the white dwarf, is transferred from a binary companion whose nature is currently unknown. The single degenerate (SD) model (Whelan & Iben 1973; Nomoto 1982) uses a progenitor system with a white dwarf and a non-degenerate companion. The companion can be a main-sequence, sub-giant, He star, or red-giant. In contrast, the double degenerate (DD) model (Iben & Tutukov 1984; Webbink 1984) relies on the merging of two white dwarfs. Alternative channels, such as supernovae exploding inside planetary nebulae (Tsebrenko & Soker 2015b), have also been suggested.
SD scenario and can be explained by a DD scenario. Thus we favor a scenario in which two degenerate stars collided in a nearly constant density environment to produce the supernova that made SNR G1.9+0.3. We suggest that the way to discern the progenitor systems of SN Ia remnants is to measure the change in radius and flux over time and then compare them with our models to check which one is favored. We also show that, when considering electron cooling due to synchrotron losses, two separate spectral indices should be expected for the X-ray and radio emission. We find that this effect is also observed in SNR G1.9+0.3.

2. SNR G1.9+0.3

Radio surveys that used the Very Large Array (VLA) identified SNR G1.9+0.3 as the smallest (R ∼ 2 pc) and therefore possibly the youngest Galactic supernova remnant (Green & Gull 1984). Chandra X-ray Observatory data confirmed that this young remnant is in the freely expanding phase as an X-ray-synchrotron-dominated shell supernova remnant (Reynolds et al. 2008). Subsequent radio and X-ray observations confirmed its expansion and brightness (Green et al. 2008; Murphy et al. 2008; Borkowski et al. 2014). Spectral variations in X-rays, interpreted in terms of magnetic field obliquity dependence of cosmic ray acceleration, have been used to argue for a Type Ia event (Reynolds et al. 2009). Ejecta distribution asymmetry and inhomogeneous abundances have also been interpreted in the context of Type Ia models (Borkowski et al. 2013). Furthermore, the remnant is not associated with any known star-forming region. Maggi et al. (2015) showed that star formation histories near the locations of remnants provide information about their types. Tsebrenko & Soker (2015a) suggested that the ear-like morphology is evidence for an explosion inside a planetary nebula. Yamaguchi et al. (2014) show that the Fe K centroid and brightness of the remnant are consistent with a DDT SN Ia explosion in a uniform ambient medium. All of these point toward SNR G1.9+0.3 as a young remnant of a thermonuclear supernova, a Galactic SN Ia in the 19th century, unobserved due to the large extinction along the Galactic plane. In this paper we develop a method to discern the progenitor systems of Type Ia remnants and demonstrate it using SNR G1.9+0.3.

3. CIRCUMSTELLAR INTERACTION

Most early emission from supernovae is powered by heating due to radioactive decay, whereas most emission from old supernova remnants is powered by the cooling of shock-heated ejecta and circumstellar matter. Less attention is given to late emission from supernovae and young remnants where radioactive heating becomes less important and is gradually overtaken by circumstellar interaction. SNR G1.9+0.3 provides a unique window into this young remnant stage, where circumstellar interaction is the major source of heating, yet the swept-up mass is low enough that the remnant is in nearly free expansion. This allows us to build a simple model for radio synchrotron emission from a young supernova remnant.

3.1. Initial Conditions

We consider a scenario (see Figure 1) where the ejected mass interacts with circumstellar matter at a radius $R(t)$ (Chakraborti & Ray 2011). Following Chevalier (1982b) we label the mass of the shocked circumstellar matter as $M_1$, and the shocked ejected mass as $M_2$. The density inside the contact discontinuity is $\rho_{\text{in}}$ and the density outside is $\rho_{\text{out}}$. The circumstellar density profile is different in the SD and DD cases. In the SD case, the density is shaped by the mass loss ($\dot{M}$) from the wind (with velocity $v_w$). This can happen in various ways, such as loss from the outer Lagrange point or the winds driven by accretion on to the degenerate companion. In the DD case, where neither star has appreciable winds, the circumstellar environment is essentially provided by the local density, which remains mostly unaltered by the binary and is assumed to be constant for this simple model.

We express the pre-explosion circumstellar density ($\rho_{\infty}$) at a distance $r$ as

$$\rho_{\infty} \propto r^{-s}. \quad (1)$$

In the above equation, the power-law index $s$ is 2 for the SD case and 0 for the DD case. The presence of nova shells does not alter the situation. The age of the remnant under consideration is approximately 150 years (Green et al. 2008), and this is much larger than the time it would take to sweep up the distance between individual shells, which is between 1 and 10 years. Thus, the granularity presented by the shells does not matter in the long-term evolution of the size and flux.

We assume that the fastest moving ejecta has a power-law density profile,

$$\rho_{\text{sn}} \propto v^{-n} r^{-3} \propto r^{-n} t^{-3} \propto r^{-n} \tau^{-3}. \quad (2)$$

This substitution is allowed for the ejecta in a homologous expansion that has not yet interacted with anything. This allows us to use $v \equiv \tau$. Note that only a small fraction of the matter ejected by the supernova move at very high velocities. The steepness of this profile is controlled by the power-law index $n$, which must be greater than five for the total energy in the ejecta to be finite. Colgate & McKee (1969) suggested profiles with $n = 7$ for an explosion of a high-mass white dwarf. Nomoto et al. (1984) used their W7 model to explain the early spectral evolution of of SNe Ia. Models like these often had steep ejecta profiles, prompting some authors to consider exponential profiles (Dwarkadas & Chevalier 1998).
3.2. Blastwave Dynamics

Here we consider the scaling relations of different parameters, depending on the circumstellar density profile and the explosion profile. We begin by finding the mass of the shocked circumstellar matter, $M_1$, as

$$M_1 \propto \int_0^R \rho_{\text{cs}} r^2 dr \propto R^{3-s}. \quad (3)$$

This is simply the mass enclosed in the spherical region that has been hollowed out by the explosion. By evaluating the integral we find $M_1$‘s dependence on radius. Next we find the amount of shocked ejected mass $M_2$ as

$$M_2 \propto \int_0^{\infty} \rho_{\text{sh}} r^2 dr \propto R^{3-s}. \quad (4)$$

This is the mass that has already interacted with the circumstellar medium and has been slowed down. In the same fashion as before, we evaluate the integral to find how $M_2$ depends on radius.

The next useful quantity to evaluate is the pressure. The pressure that the shocked circumstellar matter exerts, $P_1$, and the pressure of the ejected mass, $P_2$, compete to decelerate or accelerate the expansion of the remnant. The pressure provided by the flux of momentum brought in by the matter reaching the contact discontinuity is proportional to the density times the square of the velocity:

$$P_1 \propto \rho_{\text{cs}} (R')^2 \propto \tau^{-2} R^{2-s}, \quad (5)$$

$$P_2 \propto \rho_{\text{sh}} (R')^2 \propto \tau^{-n} R^{2-s}. \quad (6)$$

These two equations are simplified by substituting our expressions for the different densities. We also know that the shell is decelerating as it interacts with the circumstellar material (Chevalier 1982c). This deceleration is proportional to the difference in pressure times the area of the shell, so

$$(M_1 + M_2) R''(t) \propto R^2 (P_2 - P_1). \quad (7)$$

We use this to see how radius scales with time:

$$(M_1 + M_2) \frac{R}{t^2} \propto R^2 (P_2 - P_1). \quad (8)$$

Therefore, after plugging in our previous scaling relationships for $M_1$, $M_2$, $P_1$, and $P_2$, we see that

$$R \propto t^{-\frac{4}{3}}. \quad (9)$$

We call the power-law index of this equation $m$ from now on. So,

$$R \propto t^m, \quad (10)$$

where

$$m = \frac{n-3}{n-s}. \quad (11)$$

3.3. Magnetic Fields and Particle Acceleration

Now we use these scaling relations to figure out how the thermal energy, magnetic field, number of accelerated electrons, and finally, the flux, scale with time. We find the thermal energy by evaluating the kinetic energy lost during the decelerated expansion:

$$E_{\text{th}} \propto M_1 (R')^2 \propto \tau^{(n-3)/(3-s)}. \quad (12)$$

Note that in both the SD and DD cases, as long as $t$ is less than the Sedov time, the bulk of the energy remains locked up in the kinetic energy of the ejecta. The thermal energy $E$ is less than $E_0$ and is steadily increasing during this phase. As more and more gas is shock-heated by the circumstellar interaction, a fraction of this energy is made available for magnetic field amplification and cosmic ray acceleration. This is what drives the radio light curves of late-time supernovae (Chevalier 1982b) and young remnants (Cowsik & Sarkar 1984).

Considering magnetic fields of average strength $B$, produced by turbulent amplification at shocks, total magnetic energy scales as

$$E_B \propto B^2 R^3. \quad (13)$$

Following Chevalier (1982b) we consider that a fraction of the thermal energy goes into producing magnetic fields. Therefore, the magnetic field scales as

$$B \propto (E_{\text{th}} R^{-3})^{1/2} \propto \tau^{(n-5)/(3-s)}. \quad (14)$$

We consider a shock-accelerated electron distribution where the number density of energetic electrons is given by $N_0 \frac{E^{-\gamma} dEdV}{\gamma m c^2}$. Here $N_0$ is the normalization of the spectrum of accelerated electrons and $\gamma$ is the power-law index of the same spectrum. We assume that this distribution extends from $\gamma m c^2$ to infinity, filling a fraction of the spherical volume of radius $R$. Therefore the total energy in accelerated electrons scales like

$$E_e \propto N_0 R^3. \quad (15)$$

Assuming this represents a fraction of the total thermal energy, we find

$$N_0 \propto E_{\text{th}} R^{-3} \propto \tau^{(n-5)/(3-s)}. \quad (16)$$

3.4. Synchrotron Emission

Early non-thermal emission from a supernova is often optically thick, even at radio radio frequencies, due to free–free or synchrotron self absorption. As the optical thickness reduces with time, the flux density often rises. The peaking of the radio light curve can take days to months depending upon the circumstellar density and expansion velocity. However, late-time radio supernovae display optically thin spectra (Chevalier 1982b). Given that the young remnant phase follows after the late supernova phase, we can safely assume that the radio emission ($F_\nu$) at a frequency $\nu \sim 1$ GHz is reasonably approximated by an optically thin spectra. Following Rybicki & Lightman (1979) and Chevalier (1982b),

$$F_\nu = \frac{4\pi R^2}{3D^2} c_3 N_0 B^{(p+1)/2} \left(\frac{\nu}{2c_5}\right)^{-(p-1)/2}. \quad (17)$$

where $c_1$ and $c_5$ are constants (Pucholczyk 1970), and $D$ is the distance to the source. Since we know $R$, $N_0$, and $B$ are functions of time, we can calculate how radio flux density
scales with time:

\[ F_\nu \propto R^3 N_0 B^{7/4} \propto t^{\frac{3(-54 + n(8-5s) + 25s)}{8(n-s)}}. \]  

(18)

We will call the power-law index of time in the above equation $\beta$. So,

\[ F_\nu \propto t^\beta, \]  

(19)

where

\[ \beta \equiv \frac{3(-54 + n(8-5s) + 25s)}{8(n-s)}. \]  

(20)

When we inspect the cases for the SD or DD scenarios we see a striking difference in how the flux scales with time:

\[ F_\nu \propto \begin{cases} t^{\frac{3(n+2)}{8n-m}} & \text{for SD (} s = 2), \\ t^{3-\frac{4n}{m}} & \text{for DD (} s = 0). \end{cases} \]  

(21)

We note that in the SD case, flux decreases with time, but in the DD case flux can increase for explosions with steep ejecta profiles. This is a stark qualitative distinction.

4. SURFACE BRIGHTNESS INDEX FROM CHANDRA X-RAY OBSERVATIONS

Recent X-ray observations from Chandra (Reynolds et al. 2008; Borkowski et al. 2014) tell us that SNR G1.9 +0.3 is expanding and has increasing flux. Borkowski et al. (2014) found that the flux increases at a rate of $F/F = 1.9 \pm 0.4\% \text{ yr}^{-1}$. Reynolds et al. (2008) found that the supernova remnant is expanding globally at a rate of $R/R = 0.642 \pm 0.049\% \text{ yr}^{-1}$. These findings are consistent with the measurement errors with radio measurements from De Horta et al. (2014).

We know from Equation (10) that $R/R = m/f$. We can see from Equation (19) that $F/F = \beta/t$. The right sides of the two relationships are derived from a theoretical standpoint. Their left sides can be determined experimentally as listed above. We can therefore eliminate the age of the remnant and solve for $\beta/m$. This will help us decide the correct circumstellar density profile and find the allowed values of the emission index $n$, which can explain the evolution of the remnant. Therefore, from observations,

\[ \frac{\beta}{m} \equiv \frac{F/F}{R/R} = 2.96 \pm 0.66. \]  

(22)

We name this ratio the surface brightness index because it relates flux and size evolution. It is a dimensionless number that measures how the brightness of the remnant evolves. Since it does not explicitly depend on the age, it can be determined from observations even when the date of explosion is unknown.

The brightness index can also be computed from theory. Using Equations (11) and (20) for $m$ and $\beta$, from theory we can write from

\[ \frac{\beta}{m} = \begin{cases} -\frac{3}{4} \times \frac{n+2}{n-3} & \text{for SD (} s = 2), \\ 3 - \frac{45}{4(n-3)} & \text{for DD (} s = 0). \end{cases} \]  

(23)

Figure 2. Value of the surface brightness index $\left(\frac{\beta}{m}\right)$, which is equal to $\frac{\dot{F}/F}{\dot{R}/R}$, observed from SNR G1.9+0.3 compared with the modeled relationship between $\frac{\beta}{m}$ and $n$ for both the SD and DD cases (Equation (23)). The plotted error margin is $2\sigma$. Note that the prediction from the DD case enters the allowed region, while that from the SD case does not. We can use this to select the DD scenario and reject the SD scenario.

For an expanding remnant, a negative brightness index represents a declining flux, while a positive brightness index denotes a rising flux. The two special cases of $\frac{\beta}{m} = 0$ and 2 represent a constant flux and a constant surface brightness, respectively.

In Figure 2 we graph the observed values of $\frac{\beta}{m}$ (and its range of uncertainty) versus $n$ (using the relationships found in Equation (23)). This allows us to see which model is acceptable and what value of $n$ puts the preferred model in the observed band. Just from the equations we can see that $\frac{\beta}{m}$ will always be negative in the SD case, so it will never yield the observed result of simultaneously increasing flux and size. Thus an SD solution only predicts decreasing flux, which we know to be untrue from the observed data. After selecting the $s = 0$ case based on observations, we can find our allowed range of $n$. Using the chosen values of $s$ and $n$, we determine the age of the remnant in the next section.

5. AGE ESTIMATES

Having selected the DD explanation ($s = 0$) based on observations, we now have to select a fiducial value for $n$. Many authors, including Chevalier (1982a), have used a power-law profile with $n = 7$ following Colgate & McKee (1969). However, based on the recent X-ray observations (Borkowski et al. 2014) and comparison with our models in Figure 2, we note that we needed a steeper ejecta profile governed by a larger value for $n$. From Figure 2 we note that only models with values of $n \gtrsim 11.5$ could explain the data. We chose 12 as our fiducial value of $n$ in the rest of this work.

5.1. DD Case

Now we determine the age of the remnant using our values of $n = 12$ and $s = 0$ for the DD case. To this end, we first find

\[ m = n - 3 = \frac{3}{4}. \]  

(24)
We also know that
\[ \frac{\dot{R}}{R} = \frac{m}{t} = \frac{3}{4t} = 0.642 \pm 0.049\% \text{ yr}^{-1}. \] (25)

Solving for \( t \), we have
\[ t = 116.8 \pm 8.9 \text{ year}, \] (26)
and taking into account that this data was obtained in 2008, we can determine when the supernova exploded. So from this estimate the supernova occurred in 1892 \( \pm \) 9 years.

We can also estimate the age using our equation for \( \beta \) and the change in flux over time. We know
\[ \frac{\dot{F}}{F} = \frac{\beta}{t} = \frac{7}{4t} = 1.9 \pm 0.4\% \text{ yr}^{-1}. \] (27)

Solving for \( t \) in this case, we find
\[ t = 92.1 \pm 19.4 \text{ year}. \] (28)

So, from this estimate, the supernova occurred in 1916 \( \pm \) 19 years.

The weighted mean of these two ages is 109 \( \pm \) 9 years, which gives an explosion date of around 1899 \( \pm \) 9. This is within the upper limits, or the ages of 150 and 180 years proposed by Green et al. (2008) and De Horta et al. (2014), respectively.

5.2. SD Case

Even though the SD case was shown to be inapplicable to SNR G1.9.0.3, for a consistency check we will now determine the age in the SD scenario using \( s = 2 \). So to start once again we find \( m \) for this case:
\[ m = \frac{n - 3}{n - 2} = \frac{9}{10}. \] (29)

In the same fashion as above we will first solve for the age using the value of
\[ \frac{\dot{R}}{R} = \frac{m}{t} = \frac{9}{10t} = 0.642 \pm 0.049\% \text{ yr}^{-1}. \] (30)

So,
\[ t = 140.19 \pm 10.69 \text{ year}. \] (31)

Now, using the relationship for how flux changes over time, we will solve for \( t \) again:
\[ \frac{\dot{F}}{F} = \frac{\beta}{t} = \frac{-7}{6t} = 1.9 \pm 0.4\% \text{ yr}^{-1}, \] (32)
where \( \beta = -\frac{7}{6} \). Thus,
\[ t = -61.40 \pm 12.84 \text{ year}. \] (33)

This points to an explosion date in the future, which is absurd. This result is not physically plausible and merely shows again that the SD case cannot incorporate a rising flux.

6. RADIO FLUX AND SIZE EVOLUTION

Having picked the preferred scenario based on scaling relations, we can now explicitly compute the flux and size evolution. When \( n = 12 \) the following equations describe the progression of the supernova over time for the DD scenario.

We start by looking again at the circumstellar density:
\[ \rho_c = \rho_0. \] (34)

Next we enumerate the density of the supernova ejecta. We assume a broken power-law profile where the slow part has a constant density and the fast part has a power-law profile with \( n = 12 \). The profile is determined by the constant density and the velocity at the point of change. These two values are completely determined by the initial energy and the initial mass of the supernova ejecta. Here \( E_0 \) is the initial energy, \( v \) is the change over velocity, and \( M_0 \) is the initial mass:
\[ \rho_{\text{in}} = \frac{13.0E_0^{9/2}}{M_0^{7/2}v^{12}}. \] (35)

We can compare this with the initial setup and see that the scaling is the same for \( s = 0 \), and \( n = 12 \). Next we can find the masses of the shocked circumstellar matter (\( M_1 \)), and the ejected mass (\( M_2 \)). These were found by integrating the respective densities over the relevant volumes:
\[ M_1 = \frac{4}{3} \pi \rho_0 R^3 \] (36)
\[ M_2 = \frac{18.2E_0^{9/2}v^9}{M_0^{7/2}R^9} \] (37)

We again can see that these agree with the predicted scalings in Section 3.2.

Next, the two pressures are found by multiplying the flux of momentum trying to cross the contact discontinuity. \( P_1 \) is the pressure of the shocked circumstellar matter:
\[ P_1 = \frac{0.640\rho_0}{M_0^2} \left( \frac{\rho_0}{E_0^{9/2}M_0^{17/2}} \right)^{-1/6} t^{-1/2}. \] (38)

\( P_2 \) is the pressure of the ejected mass that collides with the shocked circumstellar matter. Therefore,
\[ P_2 = \frac{0.427\rho_0}{M_0^2} \left( \frac{\rho_0}{E_0^{9/2}M_0^{17/2}} \right)^{-1/6} t^{-1/2}. \] (39)

We can then use Equation (7) to solve for the radius, which comes out as
\[ R(t) = \frac{1.07}{M_0^2} \left( \frac{\rho_0}{E_0^{9/2}M_0^{17/2}} \right)^{-1/12} t^{3/4}. \] (40)

As stated above, thermal energy is less than the initial energy, but is increasing during this phase of the supernova. The kinetic energy lost due to the interaction with the circumstellar medium is the thermal energy,
\[ E_{\text{th}} = \frac{2.56E_0^{15/8}v^{7/12}t^{7/4}}{M_0^{35/24}}. \] (41)

We consider a fraction, \( f \), of the total volume, to be filled with amplified magnetic fields. So the energy in the magnetic field is
\[ E_B = \frac{0.202B^2E_0^{19/8}f^{9/4}}{M_0^{7/8}t^{3/4}}. \] (42)
Assuming that a fraction ($\epsilon_B$) of the thermal energy goes into producing this magnetic field, we get

$$B = \frac{3.56E_0^{3/8}(\epsilon_B f)^{1/2}}{M_0^{7/24}t^{1/4}}.$$  \hspace{1cm} (43)

Similarly, to find the energy in the accelerated electrons, the number density of electrons considered is $N_0E^{-\epsilon_dEdV}$, extending from $\gamma m_e c^2$ to infinity. These electrons are assumed to fill a fraction $f$ of the spherical remnant with radius $R$. So the energy in the accelerated electrons is

$$E_e = \frac{5.08E_0^{9/8}f(\gamma m_e c^2)^{2-\epsilon}N_0^{9/4}}{M_0^{7/8}(p-2)\rho_0^{5/4}}.$$ \hspace{1cm} (44)

Assuming this is a fraction ($\epsilon_e$) of the total thermal energy we find

$$N_0 = \frac{0.503E_0^{3/4}\epsilon_e(\gamma m_e c^2)^{-2}(p - 2)\rho_0^{5/6}}{fM_0^{7/12}t^{1/2}}.$$ \hspace{1cm} (45)

Using Equation (17) and assuming $\epsilon_e = \epsilon_B = 0.01$ we find

$$F_\nu = \frac{8.260 \times 10^{-6}c_5E_0^{81/32}f}{D^2M_0^{65/32}}.$$ \hspace{1cm} (46)

The flux depends directly on the initial energy and inversely on the distance to the supernova. It also increases with time and the initial density of the explosion, in a limited fashion.

7. PREDICTIONS FOR OBSERVED FLUX AND SIZE

Here we recast the equations from the previous section in units that can be used to conveniently predict fluxes and angular diameters, as determined by radio observations.

7.1. DD Case

First, the equation for the evolution of flux gives us

$$F_\nu = 46.6\left(\frac{t}{100 \text{ year}}\right)^{1.31\nu^{-0.75}}\left(\frac{\rho_0}{\text{atom/cc}}\right)^{1.31}\left(\frac{E_0}{10^{51} \text{ erg}}\right)^{2.53}\times\left(\nu \text{ GHz}\right)^{-0.75}\left(\frac{M_0}{1.4M_\odot}\right)^{-1.97} \text{mJy}. \hspace{1cm} (47)$$

This equation shows that the flux depends most strongly on the initial energy of the explosion and rises with time.

Next the angular diameter, $\theta = \frac{2\theta}{D}$, is given as

$$\theta = 42^\circ\left(\frac{t}{100 \text{ year}}\right)^{0.75}\left(\frac{E_0}{10^{51} \text{ erg}}\right)^{0.38}\left(\frac{M_0}{1.4M_\odot}\right)^{-0.29}\times\left(\frac{\rho_0}{\text{atom/cc}}\right)^{-0.08}\left(\frac{D}{10 \text{ kpc}}\right)^{-1}. \hspace{1cm} (48)$$

So the angular diameter is most strongly affected by the distance from the observer to the SNR and the time since the explosion.

7.2. SD Case

Here we provide the corresponding versions of these equations, in convenient units, for the SD case. These are not used for SNR G1.9+0.3 but are provided for reference. First, the flux can be expressed as

$$F_\nu = 33.1\left(\frac{t}{100 \text{ year}}\right)^{-1.05}\left(\frac{M}{10^{-7}M_\odot \text{ yr}^{-1}}\right)^{1.58}\times\left(\frac{E_0}{10^{51} \text{ erg}}\right)^{1.35}\left(\nu \text{ GHz}\right)^{-0.75}\left(\frac{D}{10 \text{ kpc}}\right)^{-2}\times\left(\frac{\rho_0}{1.4M_\odot}\right)^{-1.05}\left(\frac{v_w}{100 \text{ km s}^{-1}}\right)^{-1.58} \text{mJy}. \hspace{1cm} (49)$$

We can see from this equation that flux in this case strongly depends on the distance to the object, $D$. The rate of mass loss, $\dot{M}$, and the velocity of the wind, $v_w$, also affect the flux.

Next the angular diameter can be written as

$$\theta = 63^\circ 9\left(\frac{t}{100 \text{ yr}}\right)^{0.9}\left(\frac{E_0}{10^{51} \text{ erg}}\right)^{0.45}\left(\frac{M_0}{1.4M_\odot}\right)^{-0.35}\times\left(\frac{M}{10^{-7}M_\odot \text{ yr}^{-1}}\right)^{-0.1}\left(\frac{v_w}{100 \text{ km s}^{-1}}\right)^{0.1}\left(\frac{D}{10 \text{ kpc}}\right)^{-1}. \hspace{1cm} (50)$$

The angular diameter depends on the distance from the explosion and the time since the explosion. There is also a large direct dependence on the initial energy.

We provide results for both the DD and SD scenarios so that they can be compared with future observations of other remnants to see which one more accurately models the observed evolution.

8. COMPARISON WITH RADIO OBSERVATIONS

We can use the recent radio observations to estimate the size and flux of the supernova remnant. Equations (47) and (48) let
us find how they depend on external density and initial energy. From Figure 2 in Green et al. (2008), which depicts the azimuthally averaged radial profile of the radio emission in 2008, we inferred a mean emission weighted radius of \( r = 34.5' \) at an age of \( t = 109 \) years. This observed size can be substituted into Equation (48), recast as
\[
\theta = 53''6 E_{51}^{3/8} n_0^{-1/2},
\]
for the distance to the particular remnant and its age. In the above equation the only two unknowns are \( n_0 \) (in units of atoms/cc) and \( E_{51} \) (in units of \( 10^{51} \) erg), as \( \theta \) is known from observations.

From Section 7 we can use Equation (47), with a value of flux \( (F_0) \) for observations at \( \sim 1 \) GHz. This can then be compared to the observed value from the VLA (Green et al. 2008) and the Molonglo Observatory Synthesis Telescope (MOST; Murphy et al. 2008). The numerous MOST observations are grouped into three epochs (1988–1991, 1997–2000, and 2004–2008) and combined to produce the three fluxes in Figure 3. We also use a distance \( D = 8.5 \) kpc. We chose this as the distance to the supernova because we assume it is near the Galactic Center. The time of the observations is measured from our fiducial year of 1899. The mass of the explosion is assumed to be close to a Chandrasekhar mass. First we fit (see Figure 3) the radio observation with
\[
F_\nu = F_0 \left( \frac{t}{100 \text{ year}} \right)^{21/16} \left( \frac{\nu}{1 \text{ GHz}} \right)^{-3/4} \text{ Jy},
\]
to find \( F_0 \), the flux density at the age of 100 years observed at 1 GHz. We did find that \( F_0 = 1.02 \pm 0.05 \) Jy. Next we can plug this information into
\[
F_0 = 64.5 E_{51}^{81/12} n_0^{21/16} \text{ mJy}.
\]

Substituting the observed size and flux into Equations (47) and (48), we can therefore solve for the density, \( (n_0) \), and the initial energy, \( (E_{51}) \). We found that the values, \( n_0 = 1.8 \) atom/cc and \( E_0 = 2.2 \times 10^{51} \) erg, when used in Equations (47) and (48), reproduce the observed flux and size evolution in the radio. We also note that these are reasonable values to expect for the density and initial energy. Note that these values should be seen as consistency checks rather than determinations of the density and energy, because of systematic uncertainties introduced by unknowns like \( \epsilon_f \) and \( \epsilon_B \).

9. EFFECTS OF ELECTRON COOLING

The effects of electron cooling on the broadband spectrum may become apparent when observing the spectrum in both the radio and X-ray bands. Magnetic fields that permeate the SNR cause the electrons to lose energy and cool down. This produces emission that can be described by a power law,
\[
F_\nu \propto \nu^{\alpha}.
\]

However, the radio and X-ray emission may not be explained by the same power law.

9.1. Spectral Model

Above some critical Lorentz factor \( (\gamma_c) \) the electrons have lost enough energy that the slope of the power law changes. According to Piran (1999) the slope before the critical Lorentz factor, possibly at the radio frequencies, is
\[
\alpha = \frac{1 - p}{2},
\]
where we chose \( p \) to be 2.5. Once the electrons’ Lorentz factor is above \( \gamma_c \), the slope changes to (Piran 1999)
\[
\alpha = -\frac{p}{2}.
\]

The Lorentz factor of radiating electrons is related to a corresponding frequency \( (\nu_c) \) of emitted photons. Following Rybicki & Lightman (1979) these can be related as
\[
\nu(\gamma_c) = \gamma_c^2 \frac{q_e B}{2 \pi m_e c},
\]
where \( c \) is the speed of light, \( B \) is the magnetic field, and \( m_e \) is the mass of an electron. The critical Lorentz factor, above which synchrotron losses dominate, is given by (Sari et al. 1998)
\[
\gamma_c = \frac{6 \pi m_e c}{\sigma_T B^{1/2}},
\]
where \( \sigma_T \) is the Thomson cross-section and \( t \) is the age of the remnant. This critical Lorentz factor comes out to be \( \gamma_c \sim 2 \times 10^3 \) after evaluating the expression for SNR G1.9 +0.3. Chakraborti & Ray (2011) expressed the relationship between the critical frequency and Lorentz factor as
\[
\nu_c = \frac{18 \pi m_e q_e}{\sigma^{1/2}} B^{1/2},
\]
where \( q_e \) is the charge of an electron. Following this equation we found that \( \nu_c = 1.3 \times 10^{14} \) Hz, so we expect the value of \( \alpha \) to change at infrared frequencies. We checked our estimates by increasing and decreasing the assumed density by a factor of 10 to see if it would affect the break where the spectrum changes slope. However, even after varying the density the break was still in the infrared. Therefore we expect to see a change in slope somewhere between the radio and X-ray bands, probably in the infrared.

9.2. Observed Spectral Indices

The L- and C-band data from Figure 3 were used to determine the spectral index at radio frequencies. The L-band corresponds to frequencies near 4.8 GHz, while the C-band corresponds to 1.4 GHz in frequency. We found that the spectral index was \( \alpha_{\text{radio}} = -0.725 \pm 0.091 \), in agreement with De Horta et al. (2014).

SNR G1.9+0.3 was observed with the Chandra X-ray Observatory by a team (PI: Kazimierz Borkowski) during Observation 12691 on 2011 May 9. The ACIS-S chip was used for 184.0 ks. To use the data from the X-ray observations we first had to extract the spectra out of the image. Then we imported this spectra into XSPEC to further analyze it. We used the tbabs absorption model and a simple power-law emission model to fit the data. We argue against using the srcut model extending from radio to X-rays, because we expect a synchrotron cooling break below the X-ray band. We therefore fit the radio and X-ray data separately. The X-ray model was decided to be a good fit by simulating 10,000 spectra where only 57% of realizations were found to be
merely a graphical comparison of the predicted spectral indices with the spectral index and compare it with the predictions from our model.

We found that \( \alpha_{X-ray} = -1.335 \pm 0.045 \).

Finally, in Figure 4 we plot the observed values of the spectral index and compare it with the predictions from our fiducial model. Note that this is not a fit, but merely a comparison to show that our model naturally predicts the observed steepening in the spectral index from the radio to the X-rays.

### 10. SUMMARY

We have shown that circumstellar interaction in young supernova remnants is a useful tool for discerning progenitors of thermonuclear supernovae. We have developed a new diagnostic, the surface brightness index, relating flux and the size evolution of remnants. In particular, we favor a DD scenario for SNR G1.9+0.3. Based on the application of our models to SNR G1.9+0.3 and the observed spectra, we convert the photon index, as mostly used in X-ray analysis software, into the spectral index to compare with radio observations. We found that \( \alpha_{X-ray} = -1.335 \pm 0.045 \).

We suggest that further progress can be made by deep radio detections or tight upper limits, thanks to the increased sensitivity of the upgraded VLA, of historical SN Ia in the local group. Radio observations of nearby SNe Ia within a year of explosion (Chomiuk et al. 2015) put tight constraints on SD progenitor scenarios. Late observations will be particularly useful for constraining DD progenitor scenarios, since they predict rising flux densities. Observations of SN 1885A in M31, SN 1895B in NGC5253, and SN 1937C in IC4182 with ~1 Jy level sensitivity will be particularly useful. Future observations of SN 2011fe are also important, even with the current upper limits (which put pressure on SD scenarios), as the DD scenario predicts a rising light curve that may be detectable in the future. In the absence of pre-explosion progenitor detections, for SNe Ia circumstellar interactions may provide the most important insights into their hitherto elusive progenitors.

We thank Alak Ray, Naveen Yadav, Roger Chevalier, Laura Chomiuk, Atish Kamble, Raffaella Margutti, Xiaping Tang, Carlos Badenes, Noam Soker, Dale Frail, Shri Kulkarni, Randall Smith, and Avi Loeb for discussions. This work made use of radio observations from the NRAO VLA. The National Radio Astronomy Observatory is a facility of the National Science Foundation that is operated under cooperative agreement by Associated Universities, Inc. The scientific results reported in this article are based in part on data obtained from the Chandra Data Archive.

### REFERENCES

Badenes, C., Hughes, J. P., Bravo, E., & Langer, N. 2007, ApJ, 662, 472
Borkowski, K. J., Reynolds, S. P., Green, D. A., et al. 2014, ApJL, 790, L18
Borkowski, K. J., Reynolds, S. P., Hwang, U., et al. 2013, ApJL, 771, L9
Chakraborti, S., & Ray, A. 2011, ApJ, 729, 57
Chakraborti, S., Ray, A., Smith, R., et al. 2013, ApJ, 774, 30
Chakraborti, S., Ray, A., Smith, R., et al. 2015, arXiv:1510.06025
Chakraborti, S., Yadav, N., Ray, A., et al. 2012, ApJ, 761, 100
Chandrasekhar, S. 1931, ApJ, 74, 81
Chevalier, R. A. 1982a, ApJL, 259, L85
Chevalier, R. A. 1982b, ApJ, 258, 790
Chevalier, R. A. 1982c, ApJL, 259, 302
Chevalier, R. A. 1984, ApJL, 285, L63
Chevalier, R. A., Fransson, C., & Nymark, T. K. 2006, ApJ, 641, 1029
Chomiuk, L., Soderberg, A. M., Chevalier, R. A., et al. 2015, arXiv:1511.07602
Chomiuk, L., Soderberg, A. M., Moe, M., et al. 2012, ApJ, 750, 164
Colgate, S. A., & McKee, C. 1969, ApJ, 157, 623
Cowxik, R., & Sarkar, S. 1984, MNras, 207, 745
De Horta, A. Y., Filipovic, M. D., Crawford, E. J., et al. 2014, SerAJ, 189, 41
Dwarkadas, V. V., & Chevalier, R. A. 1998, ApJ, 497, 807
Filippenko, A. V. 1997, ARAdA, 35, 309
Green, D. A., & Guell, S. F. 1984, Natur, 312, 527

---

Figure 4. This graph, of the spectral index predicted by the fiducial model and that observed in the data, shows that the model can explain the two different spectral indices at radio and X-ray frequencies. Note that this is not a fit, but merely a graphical comparison of the predicted spectral indices with observed ones.

We have shown that circumstellar interaction in young supernova remnants is a useful discriminator between these possibilities. We have used this technique to demonstrate that the youngest Galactic supernova remnant SNR G1.9+0.3 is likely to be the product of a DD progenitor system. Our model shows that an SD scenario cannot produce a rising flux, whereas the DD case does. Our result shows that SNe Ia can all have DD progenitors or a combination of SD and DD populations. The scenario in which all progenitors are SD is ruled out within the context of the diagnostic developed in this work. Applying our method to more remnants and comparing with complimentary diagnostics may clarify the issue in the near future.

We suggest that further progress can be made by deep radio detections or tight upper limits, thanks to the increased sensitivity of the upgraded VLA, of historical SN Ia in the local group. Radio observations of nearby SNe Ia within a year of explosion (Chomiuk et al. 2015) put tight constraints on SD progenitor scenarios. Late observations will be particularly useful for constraining DD progenitor scenarios, since they predict rising flux densities. Observations of SN 1885A in M31, SN 1895B in NGC5253, and SN 1937C in IC4182 with ~1 Jy level sensitivity will be particularly useful. Future observations of SN 2011fe are also important, even with the current upper limits (which put pressure on SD scenarios), as the DD scenario predicts a rising light curve that may be detectable in the future. In the absence of pre-explosion progenitor detections, for SNe Ia circumstellar interactions may provide the most important insights into their hitherto elusive progenitors.

We thank Alak Ray, Naveen Yadav, Roger Chevalier, Laura Chomiuk, Atish Kamble, Raffaella Margutti, Xiaping Tang, Carlos Badenes, Noam Soker, Dale Frail, Shri Kulkarni, Randall Smith, and Avi Loeb for discussions. This work made use of radio observations from the NRAO VLA. The National Radio Astronomy Observatory is a facility of the National Science Foundation that is operated under cooperative agreement by Associated Universities, Inc. The scientific results reported in this article are based in part on data obtained from the Chandra Data Archive.

### REFERENCES

Badenes, C., Hughes, J. P., Bravo, E., & Langer, N. 2007, ApJ, 662, 472
Borkowski, K. J., Reynolds, S. P., Green, D. A., et al. 2014, ApJL, 790, L18
Borkowski, K. J., Reynolds, S. P., Hwang, U., et al. 2013, ApJL, 771, L9
Chakraborti, S., & Ray, A. 2011, ApJ, 729, 57
Chakraborti, S., Ray, A., Smith, R., et al. 2013, ApJ, 774, 30
Chakraborti, S., Ray, A., Smith, R., et al. 2015, arXiv:1510.06025
Chakraborti, S., Yadav, N., Ray, A., et al. 2012, ApJ, 761, 100
Chandrasekhar, S. 1931, ApJ, 74, 81
Chevalier, R. A. 1982a, ApJL, 259, L85
Chevalier, R. A. 1982b, ApJ, 258, 790
Chevalier, R. A. 1982c, ApJL, 259, 302
Chevalier, R. A. 1984, ApJL, 285, L63
Chevalier, R. A., Fransson, C., & Nymark, T. K. 2006, ApJ, 641, 1029
Chomiuk, L., Soderberg, A. M., Chevalier, R. A., et al. 2015, arXiv:1511.07602
Chomiuk, L., Soderberg, A. M., Moe, M., et al. 2012, ApJ, 750, 164
Colgate, S. A., & McKee, C. 1969, ApJ, 157, 623
Cowxik, R., & Sarkar, S. 1984, MNras, 207, 745
De Horta, A. Y., Filipovic, M. D., Crawford, E. J., et al. 2014, SerAJ, 189, 41
Dwarkadas, V. V., & Chevalier, R. A. 1998, ApJ, 497, 807
Filippenko, A. V. 1997, ARAdA, 35, 309
Green, D. A., & Guell, S. F. 1984, Natur, 312, 527
