Type Ia Supernova Models: Asymmetric Remnants and Supernova Remnant G1.9+0.3

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Received 2021 April 29; revised 2021 September 23; accepted 2021 October 1; published 2021 December 24

Abstract

The youngest Galactic supernova remnant, G1.9+0.3, probably the result of a Type Ia supernova, shows surprising anomalies in the distribution of its ejecta in space and velocity. In particular, high-velocity shocked iron is seen in several locations far from the remnant center, in some cases beyond prominent silicon and sulfur emission. These asymmetries strongly suggest a highly asymmetric explosion. We present high-resolution hydrodynamic simulations in two and three dimensions of the evolution from ages of 100 s to hundreds of years of two asymmetric Type Ia models, expanding into a uniform medium. At the age of G1.9+0.3 (about 100 yr), our 2D model shows almost no iron shocked to become visible in X-rays. Only in a much higher-density environment could significant iron be shocked, at which time the model’s expansion speed is completely inconsistent with the observations of G1.9+0.3. Our 3D model, evolving the most asymmetric of a suite of Type Ia supernova models from Seitenzahl et al. (2013), shows some features resembling G1.9+0.3. We characterize its evolution with images of composition in three classes: C and O, intermediate-mass elements (IMEs), and iron-group elements (IGEs). From ages of 13 to 1800 yr, we follow the evolution of the highly asymmetric initial remnant as the explosion asymmetries decrease in relative strength, to be replaced by asymmetries due to evolutionary hydrodynamic instabilities. At an age of about 100 yr, our 3D model has comparable shocked masses of C+O, IMEs, and IGEs, with about 0.03 M⊙ each. Evolutionary changes appear to be rapid enough that continued monitoring with the Chandra X-ray Observatory may show significant variations.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Type Ia supernovae (1728); Hydrodynamical simulations (767); Ejecta (453); Supernova dynamics (1664)

Supporting material: animations

1. Introduction

Type Ia supernovae (SNe Ia) perform vital functions in the universe: providing the majority of iron, as well as significant quantities of other high-Z elements; serving as standardizable candles for cosmography; and accelerating cosmic rays with very fast shocks in low-density media. Given that importance, our poor understanding of the progenitor systems, the immediate surroundings, and the fundamental mechanisms of the explosion is a serious embarrassment. The general agreement that SNe Ia result from exploding white dwarfs is now over 30 yr old. However, the decades of work since then have failed to resolve the question of the ignition mechanism or the nature of the nuclear burning front that disrupts the star. Detonation, deflagration, delayed detonation, pulsed delayed detonation, and gravitationally confined detonation models are still discussed and considered as viable models. The ignition of either a subsonic (deflagration) or a supersonic (detonation) thermonuclear burning front is a very complex astrophysical problem; consequently, initial conditions for both are often implemented in astrophysical simulations in an ad hoc manner. Even putting aside the fraught question of the nature of the progenitor systems (a degenerate or nondegenerate companion, that is, single- or double-degenerate systems), tremendous uncertainty surrounds the basic nature of the explosion. See Hillebrandt & Niemeyer (2000), Hillebrandt et al. (2013), and Ruiter (2020) for recent reviews.

While the basic idea of a Chandrasekhar-mass white dwarf exploding (somewhow) attractively explains the general homogeneity of SN Ia light curves and spectra, at least compared to core-collapse events, evidence for SN Ia diversity continues to increase (Benetti et al. 2005; Taubenberger 2017), from the seminal discovery of the luminosity–width relation (Phillips 1993) to the range of subclasses proposed in the last few years, including SN 2002cx–like or SNe Iax (Jha et al. 2006; Foley et al. 2013), underluminous or SN 1991bg–like (Li et al. 2001), and SN 2002ic–like or SN Ia–CSM (Silverman et al. 2013), among others. One promising avenue to explain this diversity, especially of spectral properties near maximum light, is the viewing-angle dependence of the appearance of asymmetric explosions (Maeda et al. 2010). Asymmetry in explosions can result from off-center ignition (Kasen et al. 2009; Maeda et al. 2010) or, for instance, gravitationally confined detonation (Plewa et al. 2004).

Asymmetries in the supernova events themselves produce various signatures, such as expansion velocity gradients (Maeda et al. 2010) or nonzero polarization (e.g., Wang et al. 2007). These have been used to constrain explosion models, though it is often the case that multiple models can reproduce the same observations (Hillebrandt et al. 2013). However, one avenue for investigation of the nature of SNe Ia has been historically underutilized: the detailed examination of Type Ia supernova remnants (SNRs). The historical Type Ia SNRs
Tycho, Kepler, and SN 1006 have all been observed with long exposures by all functioning X-ray satellites, and important clues to the Type Ia phenomenon have been obtained. Spatially resolved spectroscopy provides direct information on anisotropies obtained only with difficulty, if at all, from observations of the supernovae themselves. Tycho has a light-echo spectrum indicative of a completely normal SN Ia (Krause et al. 2008), and its X-ray spectrum shows substantial radial and azimuthal asymmetries that can be traced to the initial supernova ejecta distribution (Miceli et al. 2015). Far above the Galactic plane, SN 1006 is expanding into quite low-density material and is consequently less evolved than Tycho or Kepler. One manifestation of this is that very little shocked iron is observed in X-rays (Yamaguchi et al. 2008), indicating that large-scale overturn has not occurred to move iron to large radii. However, even when unshocked iron seen in absorption in the UV (Winkler et al. 2005) is included, the total iron mass seems anomalously low. Kepler’s SNR is sufficiently peculiar that its classification was still in doubt until quite recently, although evidence has mounted for years pointing to its thermonuclear nature (see Reynolds et al. 2007 for a summary of the arguments). But Kepler also shows unmistakable signs of interaction with a circumstellar medium (CSM) modified by the progenitor system (Burkey et al. 2013; Chiotellis et al. 2013; Kasuga et al. 2021), indicating a single-degenerate origin. One additional remnant of probable Type Ia origin is RCW 86 (Williams et al. 2011), which shows evidence that the explosion took place off-center in a wind-blown cavity. More recently, Seitenzahl et al. (2019) detected coronal emission lines from iron in the young Type Ia SNR 0509−67.5 and 0519−69.0 in the LMC, originating from the nonradiative reverse shock. These observations allow discrimination among models of differing progenitor mass.

Multidimensional models of SNe Ia are now within reach of modern computational resources (Hillebrandt et al. 2013), and modelers have produced families of such models under various assumptions about the number and location of ignition points and other variables (Kasen et al. 2009; Seitenzahl et al. 2013). These explosion models are sometimes used to generate predicted light curves and spectra (e.g., Sim et al. 2013; Fink et al. 2014; Noebauer et al. 2017). Since SN Ia progenitors have such low masses, the explosions become ballistic (that is, unaffected by pressure forces) in times of order 10–100 s, and typical explosion models easily reach this stage. This is important because subsequent evolution can then be described with these models as initial conditions for pure hydrodynamic codes, following the evolution for hundreds or thousands of years. Such calculations then open a whole new area of potential confrontation between models and observations: the detailed comparison of SNR properties with theoretical predictions. This area holds great promise for advancing our understanding of the Type Ia phenomenon.

In recent years, several groups have considered the supernova-to-SNR transition using hydrodynamic modeling. To study two core-collapse remnants, SN 1987A (Orlando et al. 2015) and Cas A (Orlando et al. 2016), 1D supernova models were used as input. Full evolution of 3D SN Ia models to the SNR stage is relatively new. Orlando et al. (2020) presented a full 3D MHD simulation of SN 1987A, and Orlando et al. (2021) performed a similar calculation aimed at Cas A. Ferrand et al. (2019, 2021) evolved some of the models of Seitenzahl et al. (2013) to an age of 500 yr, focusing on the morphology of the forward and reverse shocks and the contact discontinuity. Tycho’s SNR appears to have been a fairly normal SN Ia (Krause et al. 2008), but symmetric initial conditions apparently cannot account for some asymmetry as deduced from spatial power spectra (Ferrand et al. 2019). Ferrand et al. (2021) evolved another quite asymmetric model from Seitenzahl et al. (2013; model NSdtt; see below), again focusing on shock morphology. Here we describe a similar evolutionary calculation to explain a highly unusual young SNR. We shall require the most asymmetric of all the models of Seitenzahl et al. (2013). We consider both morphological and abundance structure, as the target of our study is remarkable in both dimensions.

2. A New Test Case: G1.9+0.3

One major difficulty afflicts the study of SNRs to learn about their supernovae: separating ejected material from swept-up surrounding unmodified interstellar medium (ISM) or modified CSM. Abundance clues are powerful but have limitations. Ideally, one would observe the youngest possible remnant that is large enough for adequate spatial resolution. That remnant appears to be the youngest Galactic SNR, G1.9+0.3 (Reynolds et al. 2008; see Figure 1). This object is about 100” in diameter, the smallest angular size of any confirmed Galactic SNR. Unfortunately, it is highly absorbed, with an X-ray column density of about $5 \times 10^{22} \text{cm}^{-2}$ (Reynolds et al. 2009), implying $\text{AV} \sim 23^m$, so radio and X-rays are the only useful observational channels. The angular expansion rate of 0.64 arcsec yr$^{-1}$ obtained from comparing X-ray images from 2007 and 2009 (Carlton et al. 2011) gives an upper limit for the age of about 160 yr, less if (as is almost certainly the case) deceleration has occurred; spatial variations in expansion rate (Borkowski et al. 2014) are consistent with an age of about 100 yr, or a date of around 1900. The high extinction would have rendered it unobservable in optical telescopes of that era. Furthermore, its X-ray spectrum is almost entirely synchrotron emission, making it a member of the small class of X-ray synchrotron-dominated SNRs. However, long observations with Chandra have allowed the detection of thermal emission from small regions (Borkowski et al. 2011, 2013b), with spectroscopic widths of $\sim 14,000 \text{km s}^{-1}$ confirming the large expansion proper motion, refined with a second Chandra observation (Carlton et al. 2011). The distance is still uncertain; the high column—higher than the entire Galactic column along nearby sight lines—suggests an association with the Galactic center, and a provisional distance of order 8.5 kpc has been assumed. Nearer would be very unlikely in view of the high absorption, but too much farther would make the expansion proper motion unreasonably large. An H I observation with the Giant Metrewave Radio Telescope (Roy & Pal 2014) has been used to set a lower limit of 10 kpc, certainly consistent with the known properties of G1.9+0.3.

While the supernova type of G1.9+0.3 is not absolutely confirmed as Ia, most indicators point in that direction. The very high expansion speeds even after $\sim 100$ yr, the clear presence of superson as iron (Fe Kα) in several regions (Borkowski et al. 2013b), the absence of any pulsar-wind nebula in the center (although a neutron star itself would be too highly absorbed to be detected), and the bilateral symmetry of the synchrotron X-rays suggesting a parallel with SN 1006 all point to a Ia origin. A core-collapse scenario can be constructed with difficulty, but it requires a highly unusual event with a low
mass but very high energy at explosion and a low-density surrounding medium. We shall assume for the remainder of this work that G1.9 + 0.3 originated in a thermonuclear event.

Careful analysis of the total current Chandra exposure of about 1.7 Ms has shown clear evidence for Si and S Kα emission, as well as Fe Kα (Borkowski et al. 2011, 2013b). Remarkably, Fe is found at quite large radii, and the Si/Fe ratio varies considerably. There is tentative evidence for a broad feature centered at 4.1 keV from the remnant center, attributed to an electron capture in 44Sc, formed in the decay chain of 44Ti and indicating a 44Ti mass of about 1 × 10⁻⁵ M⊙ (Borkowski et al. 2010, 2013a). The Fe lines are quite broad, consistent with the presence of Fe at large projected radii from the remnant center; Borkowski et al. (2013b) found FWHM values of 15,000 km s⁻¹.

The high observed velocities and proper motions of G1.9 + 0.3 indicate that it is at quite an early evolutionary stage. Defining the deceleration parameter m of a region at radius r by r ∝ tᵐ, Borkowski et al. (2014) compared the 2007, 2009, and 2011 Chandra observations to obtain m values varying spatially, from ≤ 0.5 for the outer blast wave to ≤ 0.7 for inner features identified with the reverse shock. In the Sedov self-similar phase, we have m = 0.4 throughout, so the expansion is considerably less decelerated. However, the expansion velocities in G1.9 + 0.3 vary by a large factor. Borkowski et al. (2017) used a nonparametric method to measure the expansion throughout the remnant and found velocities varying strongly with position over a factor of 5 in magnitude (Figure 2). In particular, expansion to the north was found to be several times slower than in other directions, strongly suggesting a recent encounter with denser material. Such an encounter could explain the peak in radio intensity found there, as a higher density of accelerated electrons would be expected, but the slower shock velocity would result in a lower maximum accelerated electron energy, explaining the lower X-ray brightness to the north. Such denser material almost certainly originated in asymmetric presupernova mass loss rather than the dynamics of the explosion itself, although such a possibility cannot be ruled out.

The total mass of shocked ejecta in G1.9 + 0.3 is still quite small. An analysis based on the average expansion rate found 0.033 M⊙ (Carlton et al. 2011), while one based on scaling the energetic explosion model WS15DD3 (Hachinger et al. 2013) produced about twice as high a value, 0.064 M⊙ (Borkowski et al. 2013b). While these values are much less than the total

Figure 1. Shown is G1.9+0.3 in X-rays in 2011 (based on the deep Chandra observations described by Borkowski et al. 2013b). Red, 1–3 keV; green, 3–4.5 keV; blue, 4.5–7.5 keV.
The ejecta mass, we observe that Fe makes up a significant fraction of material already shocked. The presence of high-velocity shocked Fe is especially problematic in G1.9+0.3, as it was presumably near the outer edge of the expanding ejecta at a very early time. One might expect evidence of such fast Fe in observations of SNe Ia themselves; while high-velocity features are seen in a large fraction of all SNe Ia (e.g., Maguire et al. 2014), Fe is rarely seen, and when it is, the estimated mass is very small. Fitting of supernova spectra with stratified models (“supernova tomography”; e.g., Stehle et al. 2005; Tanaka et al. 2008; Sasdelli et al. 2014; Mazzali et al. 2015) also shows little evidence for high-velocity Fe. This raises the question of whether current SN Ia models will evolve to resemble G1.9+0.3 in this property, as well as in the bulk expansion velocity and observed spatial heterogeneity of Si, S, and Fe. In this paper, we address this question using two multidimensional SN Ia models as initial conditions and following their expansion into uniform media with the VH-1 hydrodynamics code.

3. Simulations

The VH-1 hydrocode is a conservative, finite-volume code evolving the Euler equations for an ideal gas, based on the piecewise parabolic method with the Lagrange–Remap implementation (Colella & Woodward 1984). It is particularly well suited to resolving shocks and other discontinuities and has been extensively used for the study of SNRs (see, for instance, 3D hydrodynamic simulations of Type Ia SNRs; Warren & Blondin 2013). It can be used in one, two, or three dimensions: in two dimensions with either \( r, z \) cylindrical coordinates or \( r, \theta \) spherical coordinates and in three dimensions using the overset spherical grids known as “Yin-Yang” (Kageyama & Sato 2004) that eliminate the singularities on the axis of symmetry. Here we shall perform 2D simulations in cylindrical \( r, z \) coordinates and 3D ones using the Yin-Yang grids. We do not include the effects of energy losses due to cosmic rays, which can increase the compressibility of the gas (Blondin & Ellison 2001), but we use a uniform adiabatic index of 5/3. Our 2D cylindrical grid has a resolution of 512 \( \times \) 1024 and expands to follow the evolution of the SNR. The 3D simulation also expands with the blast wave. It has an angular resolution of 0.24 \( ^{\circ} \) (384 \( \times \) 1152 angular zones in each of the Yin and Yang grids). For the radial coordinate, we cover the inner half of the grid with 84 zones and the outer half with 300 to maximize the resolution in the region between the shocks. This gives a maximum fractional resolution of 1.65 \( \times \) 10\(^{-3} \) of the maximum grid radius for the outer 50% of that maximum radius.
We use two initial SN Ia models (F. Röpke 2011, private communication). Table 1 gives the compositions of both. Our 2D model comes from the family described in Kasen et al. (2009), in which 2000 otherwise identical 1.4 $M_\odot$ C/O white dwarfs (50% each) were ignited with varying numbers and locations of ignition points. The model was provided with a resolution of $512 \times 1024$. Our 3D model is model N3 from Seitenzahl et al. (2013), with three slightly off-center ignition points. The mass is 1.40 $M_\odot$, the radius is 1.96 $\times 10^8$ cm, and the central density is $\rho_c = 2.9 \times 10^9$ g cm$^{-3}$. The composition is also equal parts $^{12}$C and $^{16}$O (with 2.5% $^{22}$Ne to account for the approximately solar metallicity of the zero-age main-sequence progenitor). The white dwarf undergoes a delayed detonation; a detailed discussion of the ignition setup is given in Seitenzahl et al. (2013). This model was chosen as the most asymmetric of the suite of 14 models in Seitenzahl et al. (2013). We describe each simulation in more detail below.

### 3.1. 2D Simulation

Our 2D simulation was conducted at the same resolution as that of the initial model, $(r, z) = (512, 1024)$. The initial model at an age of 100 s is shown in Figure 3, showing the location and iron content of the ejecta, as well as the location of the contact discontinuity. The composition is given in Table 1; the total asymptotic kinetic energy is $1.45 \times 10^{51}$ erg, and the total mass is 1.408 $M_\odot$. The model initially expands into an unrealistic number density of $10^6$ cm$^{-3}$, but it is straightforward to scale this to an arbitrary value. (Figure 4 shows that the outermost ejecta density is more than 3 orders of magnitude larger; the ram pressure $\rho v^2$ is about $10^8$ dyn for an initial expansion velocity of 10,000 km s$^{-1}$, while the unrealistically high-density initial CSM still has a pressure of only $nkT \sim 10^{-5}$ dyn, even for a temperature of $10^6$ K.) The radial distribution of elements is also shown in Figure 3, where we combine elements into intermediate-mass elements (IMEs) and iron-group elements (IGEs). The CSM represents all surrounding material. The azimuthally averaged density profile is fairly well fit by an exponential (Dwarkadas & Chevalier 1998), as shown in Figure 4.

The model was then evolved for two different values of constant upstream density, one chosen to match the value of $0.022$ cm$^{-3}$ found from the expansion measurements of Carlton et al. (2011), and the other a value of $1.08$ cm$^{-3}$, calculated to bring the reverse shock farther in (see below). Figure 5 shows the angle-averaged forward- and reverse-shock locations for the high-density run compared to a 1D simulation using the exponential fit to the initial density profile shown in Figure 4.

Figure 6 shows the distribution of elements at the current size of G1.9$+0.3$ ($r = 2.0$ pc) as mass fractions in the low-density calculation. The contact discontinuity is visible as the bound of IMEs; IGEs are well inside at all radii (except for an artifact along the polar axis). The relatively low resolution of the initial 2D model results in a slight shape distortion in the outermost contour visible in Figure 3. In the low-density case, this slightly rectangular shape persists to the age of G1.9$+0.3$, but in the more highly evolved high-density case, it has evolved away by this time. The remnant age is 104 yr for the low ambient density; the total swept-up mass is 0.026 $M_\odot$. About 0.06 $M_\odot$ of ejecta have been shocked, quite close to one of our estimates based on the observed expansion rate. However, only a minuscule amount, $7 \times 10^{-5} M_\odot$, of that is IGEs, clearly inconsistent with the observations.

Figure 7 shows the elemental distribution for the high-density model at an age of 173 yr. This age is, of course, inconsistent with the observational data, and the shock velocity and expansion rate are far too low, but some such combination of unrealistic parameters is required to obtain a significant fraction of shocked iron from this initial model. Iron-rich

### Table 1: Initial Model Compositions

| Element | 2D Model Mass ($M_\odot$) | 3D Model Mass ($M_\odot$) |
|---------|---------------------------|---------------------------|
| C+O     | 0.0853                    | 0.0624                    |
| IME     | 0.378                     | 0.121                     |
| IGE     | 0.945                     | 1.22                      |
| $^{56}$Ni | 0.698                    | 1.10                      |
| Total   | 1.41                      | 1.40                      |

Figure 3. The 2D model. Left: 2D distribution. Black contour: contact discontinuity between CSM and ejecta. Purple contour: IMEs. Color scale: mass fraction of IGEs. Right: initial mass fractions, azimuthally averaged.
material is nearing the reverse shock. (Note the much more
developed Rayleigh–Taylor structures beyond the contact
discontinuity.) Figure 8 compares the azimuthally averaged
mass fractions for the two models. In the low-density case that
matches the size and expansion rate of G1.9+0.3, very little
iron ($\sim 7 \times 10^{-5} M_\odot$) has passed through the reverse shock to
become heated and visible in X-rays. The very high density of
the other case is required so that at an age of a few hundred
years, a significant (but still small) amount of iron has been
shocked, as the observations require.

3.2. 3D Simulation

Our 3D model, model N3 from Seitenzahl et al. (2013), has
the composition given in Table 1. The total kinetic energy is
$1.61 \times 10^{51}$ erg, and the total mass is $1.40 M_\odot$. We illustrate
the initial spatial distribution of elements and kinetic energy
using Mollweide (equal-area) projections of the entire surface.
Figure 9 shows the sky distribution of kinetic energy and ejecta
composition (masses) in three bins (unburned C/O, IMEs, and
IGEs). Scales refer to masses in g pixel$^{-1}$ and kinetic energy
in erg pixel$^{-1}$, where 1 pixel subtends $1.72 \times 10^{-3}$ sr. Substantial
asymmetries are evident. A ring of enhanced IMEs correlates
with an absence of IGEs, which are enhanced in the opposite
hemisphere. Histograms show the distribution of values in each
plot. The strong variation in distribution of IGEs reflects the
substantial anisotropy of the initial model. Angle-averaged total
density and mass fractions are shown in Figure 10, along with
an exponential and power law (not fit) for comparison. The
exponential shown has an e-folding radius of $3.3 \times 10^{10}$ cm,
and the power-law index is 5.5.

The model was evolved to an age of about 2000 yr, assuming
a uniform ambient medium of density $n_0 = 0.022$ cm$^{-3}$
($\rho_0 = 5.08 \times 10^{-25}$ g cm$^{-3}$; Carlton et al. 2011). Frames were
extracted from the simulation for ages of 13, 33, 75, 100, 200,
400, 800, and 1800 yr; the fourth is about the estimated age
of G1.9+0.3. Montages of Mollweide projections for various
quantities are shown in Figures 15–22.

The evolution of the angle-averaged forward- and reverse-
shock radii is shown in Figure 11. The current observed shock
radius is about 2 pc $\cong 6 \times 10^{18}$ cm, consistent with our age
estimate of 100 yr. Figure 12 shows the forward-shock
deceleration parameter $m = d \log R / d \log t \equiv \nu t / R$; while it
shows variations, the deceleration of the average shock radius
evolves fairly smoothly toward the Sedov value of 0.4. A 1D
thin-shell analytic model fit to the remnant’s current size and
mean expansion rate (Carlton et al. 2011) gave $m = 0.69$,
between the average and maximum values we find here. At the
end of the simulation, the total swept-up mass is about 12 $M_\odot$,
which time Sedov dynamics should be a good approx-
imation. The reverse-shock deceleration drops to zero and
becomes negative as the reverse shock begins to move inward
at an age of around 2000 yr. It cannot be observed directly.

Shocked masses and emission measures (EMs) of the
different composition categories are shown in Figures 13 and
14. Here $EM = \int \rho f_i n_e dV$, where $\rho$ is the total density,
$f_i$ are the mass fractions of different species, and $n_e$ is the electron
density, calculated by approximating 11/13 electrons per amu
of CSM and 1/2 electrons per amu of all other species. We
have assumed full ionization of all species; the observed EMs
will reflect various confusing effects, such as time-dependent
ionization. The IMEs in the simulation are fully shocked by
about $10^{10}$ s, while the IGEs approach being fully shocked only
near the end of the simulation (Figure 13). Of course, the
shocked CSM mass continues to climb. The shocked CSM EM
also continues to climb, but ejecta EMs peak once all of the
masses are shocked and then drop as $R^{-3}$.

The sequence of equal-area Mollweide plots (Figures 15–22)
shows the development of hydrodynamic instabilities, most
obvious near the end of the simulation. At early stages, the
shocked masses are all quite small and show very pronounced
spatial variations, but as more material is shocked, these
variations decrease in amplitude. Near the age of G1.9+0.3
(about 100 yr; Figure 18), however, substantial asymmetry
remains on the relatively large scale with which it was
imprinted in the explosion. Significant variations in kinetic
energy in different directions, still apparent out to 75 yr, have
mostly been smoothed away by 100 yr and are thereafter
dominated by hydrodynamic instabilities. Comparing the
sequence of images shows where material is shocked. Note

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**Figure 4.** Azimuthally averaged density of 2D model, with superimposed least-squares fit to an exponential, which describes the data fairly well.

**Figure 5.** Forward- and reverse-shock locations. Points: azimuthal averages from 2D simulation. Curves: results from a 1D simulation using the exponential fit to the initial density profile (Figure 4). The time and radius are scaled to the present age of G1.9+0.3. At these early times, the shock positions in the exponential model are quite close to those from the 2D calculation.
in particular the concentration of shocked iron in one hemisphere, surrounded by a deficit.

Figure 23 shows perspective views at ages of 25–400 yr, during which time the increasing smoothness of forward- and reverse-shock surfaces can be observed. Iron-group ejecta (blue in the last column of Figure 23) are dominated by unburned C+O and IMEs for the viewing angle shown at earlier times but become more prominent with time.

4. Discussion

4.1. 2D Results

The 2D simulations of the evolution of the model from Kasen et al. (2009) show that for an ambient density that can reproduce the observed size and expansion rate of G1.9+0.3, almost no IGEs will have been shocked after 100 yr (Figure 8), contrary to observations. The asymmetries in the initial
Figure 8. Mass fractions at the size of G1.9+0.3 for the two values of ambient density in the 2D simulation. Left: $n_0 = 0.022 \text{ cm}^{-3}$. Right: $n_0 = 1.08 \text{ cm}^{-3}$. Vertical lines indicate the average positions of forward and reverse shocks. Only material at larger radii than the reverse shock would be visible in X-rays.

Figure 9. Mollweide (equal-area) projections of the 3D model N3 for (left to right, top to bottom) kinetic energy and total (shocked and unshocked) masses of C/O, IMEs, and IGEs. Histograms of values show the distributions. Subsequent composition images show shocked masses only.

Figure 10. Left: angle-averaged density of the initial 3D model. Also shown are exponential and power-law curves for comparison (not fits). Scaling radius for exponential: $3.3 \times 10^{10} \text{ cm}$. Power-law index: 5.5. Right: angle-averaged mass fractions of different species.
explosion model are substantial but not sufficient to give rise to the overturn (iron beyond silicon and sulfur) observed in G1.9+0.3. Far greater initial asymmetries will be required to reproduce these observed features. The high-density model illustrates what is required to obtain sufficient shocked iron; it is completely inconsistent with the observed size and expansion rate of G1.9+0.3.

4.2. 3D Results

Our 3D simulation begins with the most anisotropic of the suite of models of Seitenzahl et al. (2013). With only three ignition points, all in the same hemisphere, the N3 model might be expected to show strong variations, and Figure 9 substantiates this expectation. While we focus on the evolution
to SNR stages, the appearance of such a supernova would clearly have a substantial dependence on viewing angle. Most iron is ejected preferentially in a relatively small solid angle, roughly on the opposite hemisphere from IMEs. The hemisphere opposite to the direction of most iron injection is relatively smooth. The viewing-angle dependence of the calculated spectra and light curves for the N3 model is discussed in some detail in Sim et al. (2013).

As time advances (Figures 15–17), the amount of ejecta passing through the reverse shock increases. At an age of 13 yr, relatively little iron is shocked. The histogram shows that most pixels have a small amount of iron, but a few reach much higher values. At 75 yr, most pixels now have larger amounts of shocked iron. (The overall mass of iron that is shocked is still relatively small, about 0.01 $M_\odot$; see Figure 13.)

At the age of G1.9+0.3, Figure 13 shows comparable masses in all shocked components: CSM, ejecta C and O, IMEs, and IGEs. In particular, only about 0.02 $M_\odot$ of $^{56}$Fe (originally $^{56}$Ni) has been shocked, though this is far larger than the amount of shocked $^{56}$Fe found by an age of 100 yr in the 2D simulation. The total shocked mass is about 0.1 $M_\odot$, somewhat larger than in the 2D case. This is also about three
Figure 16. Same as Figure 15 but at an age of 33 yr.

Figure 17. Same as Figure 15 but at an age of 75 yr.
Figure 18. Same as Figure 15 but at an age of 100 yr. This is about the age of Gl.9+0.3.

Figure 19. Same as Figure 15 but at an age of 200 yr.
Figure 20. Same as Figure 15 but at an age of 400 yr, roughly that of the remnants of Kepler's and Tycho's supernovae.

Figure 21. Same as Figure 15 but at an age of 800 yr.
times larger than that estimated from observations of G1.9+0.3 as described in Section 2 above. The preferential ejection of iron in some direction could be identified with the stronger Fe features in the north rim of G1.9+0.3 (Borkowski et al. 2013b). By the age of G1.9+0.3 (Figure 18), a significant amount of shocked Fe can be seen to the right of center in the images.

As the remnant continues to evolve, the spread in all quantities decreases, as shown by the histograms. At our earliest epoch of 13 yr, different pixels vary in amount of iron by 8 orders of magnitude, while kinetic energy varies by a factor of about 30. At 100 yr, the spread in kinetic energy is less than 1 order of magnitude. The nature of the asymmetries varies as well. Large-scale asymmetries visible in the initial model dominate to an age of 100–200 yr, at which point smaller-scale irregularities ascribable to Rayleigh–Taylor instabilities become apparent (see Figure 19). By an age of 800 yr, kinetic energy values spread by only about a factor of 4, while shocked iron ranges only about 20. The reverse shock has become very smooth at late times (a small range of values), so the finite extent of radial zones results in artifacts visible in the lower right panels of Figures 21 and 22. By the end of our simulation, roughly the age of the likely Type Ia SNR RCW 86 (Williams et al. 2011), unburned C and O still have a spatial distribution reminiscent of the initial model, while IMEs and IGEs are fairly smooth.

An alternative view of the evolution of asymmetries is presented in Figure 23, showing isosurfaces of various quantities for different ages: forward- and reverse-shock surfaces and mass fractions and 2D slices through the remnant center of mass fractions for one particular viewing angle. The same trends apparent in the Mollweide projections can be seen here.

Our simulations show that the imprint of a highly asymmetric thermonuclear explosion is clearly detectable in the remnant for at least 500–1000 yr, though it decreases in prominence as evolutionary asymmetries due to instabilities take over. Of course, we have assumed a uniform external medium; when strongly asymmetric ISM or CSM is present, morphological changes can be expected, though compositional asymmetries should not be affected. The north rim of G1.9+0.3 expands five times more slowly than other parts of the remnant (Borkowski et al. 2017), a circumstance likely due to asymmetric surroundings.

A similar simulation focusing on the morphology of the forward and reverse shocks and contact discontinuity was recently presented by Ferrand et al. (2021), who evolved two models from the same suite of Seitenzahl et al. (2013), N 5 and N 100 (that is, with five and 100 ignition points, respectively). The results of their N5 simulation bear resemblances to our N3 results, but the N3 model is even more asymmetric. The shock locations we find do show a strong initial imprint of the asymmetries, though in percentage terms, these are less dramatic than the compositional asymmetries (not presented in Ferrand et al. 2021). Only three ignition points produce clear global-scale asymmetries, already distinct from the pattern (in the contact discontinuity) seen at an age of 1 yr in the N5 simulation of Ferrand et al. (2021). Both models evolve toward greater symmetry with smaller-amplitude variations, as might be expected. The interpretation of SNR observations can profit greatly from the investigation of initial supernova models in this way.

5. Conclusions

The youngest SNRs can be expected to exhibit the dynamics of their birth event most clearly. The youngest Galactic SNR,
G1.9+0.3, shows remarkable levels of asymmetry in the location of ejecta of different composition, with shocked iron at large radii, sometimes beyond IMEs such as silicon and sulfur.

Our hydrodynamic simulations of the evolution of two different asymmetric SN Ia models show that such pronounced asymmetries at an age of about 100 yr are not easily produced.
Our 2D model produces far too little shocked iron, and at too small radii, to reproduce the Chandra observations of G1.9+0.3. This is perhaps not surprising in view of the fairly symmetric distribution of iron in the initial model (Figure 3), but it is not obvious that evolutionary effects are unable to produce adequate shocked iron, as our calculation demonstrates. The most extreme 3D model, N3 from Seitenzahl et al. (2013), shows that somewhat larger ejecta masses are shocked by this age, possibly consistent with the observations. It must be borne in mind that ejecta are detected at all only in a few regions in G1.9+0.3, whose X-ray spectrum is dominated by nonthermal synchrotron radiation.

The strong asymmetries observed in G1.9+0.3 also argue against currently popular models of sub-Chandrasekhar (0.8–1.1 M\(_{\odot}\)) detonations for SNe Ia, since pure detonations tend to produce little in the way of asymmetry (e.g., Sim et al. 2010; Chamulak et al. 2012), unless the companion also explodes (e.g., Pakmor et al. 2012). In particular, the high-velocity Fe required is difficult to produce unless progenitors possess a high-mass He layer, as in some double-detonation models (e.g., Woosley & Weaver 1994; Sim et al. 2012). However, these models also produce amounts of \(^{44}\)Ti in conflict with observations (Borkowski et al. 2010; Weinberger et al. 2020).

We exhibit the evolution of the initial asymmetry of our model in a series of equal-area projections of the entire surface, which illustrate the character of the asymmetries of model N3. In particular, a large plume of IME-rich material can be seen, directed approximately opposite to iron-group material, though the angular variation in initial expansion velocity and kinetic energy is less pronounced. After a few hundred years, the imprint of the initial explosion asymmetry has faded, being replaced by the development of hydrodynamic instabilities on smaller scales and lessening, though not eliminating, compositional traces of the explosion asymmetry.

For the particular case of G1.9+0.3, explosion asymmetries should still dominate, although confused by an apparently strongly asymmetric ambient medium. However, changes on timescales of decades can be seen in Figures 17 and 18. The most recent Chandra observations were done in 2019–2020, 13 yr after the initial discovery. We may be able to observe the fading of the explosion imprint as time goes on, though the dominant nonthermal component of the X-ray spectrum, which is still increasing (Borkowski et al. 2017), continues to impede more detailed compositional studies. In any case, G1.9+0.3 challenges models of SNe Ia, and its continuing study should be highly informative for the development of such models. In general, our results illustrate the value of detailed observations of the dynamics of the youngest SNRs and their power to constrain supernova explosion models.

This work was supported by the National Science Foundation through grant AST-1062736 to NCSU’s REU program and NASA through the Chandra Guest Observer program (GO1-12098A and B). A preliminary version of this work was presented at the 2011 meeting of the High-Energy Astrophysics Division of the American Astronomical Society (Griffeth et al. 2011).

Appendix

Figures 24–28 show animations of the evolution of the forward shock, reverse shock, shocked CO mass, shocked IMEs, and shocked IGEs from ages of 5 to 2000 yr. Figures 15–22 show still frames at different ages from those animations. However, the images in those figures have been rescaled to track the ranges of those quantities; the changing ranges are shown in the histograms. For the animations, fixed ranges of quantities are maintained throughout the evolution.
Intermediate Mass Elements  Time = 320 yrs

Iron Group Elements  Time = 320 yrs

Figure 27. Shocked IME animation. The animation runs from 5 to 2000 yr with a real-time duration of 4 s. (An animation of this figure is available.)

Figure 28. Shocked IGE animation. The animation runs from 5 to 2000 yr with a real-time duration of 4 s. (An animation of this figure is available.)

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