Type Ia supernovae inside planetary nebulae: shaping by jets

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ABSTRACT

Using 3D numerical hydrodynamical simulations, we show that jets launched prior to Type Ia supernova (SN Ia) explosion in the core-degenerate (CD) scenario can account for the appearance of two opposite lobes (‘Ears’) along the symmetry axis of the SN remnant (SNR). In the double-degenerate (DD) and CD scenarios the merger of the two degenerate compact objects is very likely to lead to the formation of an accretion disc, that might launch two opposite jets. In the CD scenario, these jets interact with the envelope ejected during the preceding common envelope phase. If explosion occurs shortly after the merger process, the exploding gas and the jets will collide with the ejected nebul, leading to SNR with axisymmetric components including ‘Ears’. We also explore the possibility that the jets are launched by the companion white dwarf prior to its merger with the core. This last process is similar to the one where jets are launched in some pre-planetary nebulae. The SNR ‘Ears’ in this case are formed by a spherical SN Ia explosion inside an elliptical planetary nebula-like object. We compare our numerical results with two SNRs – Kepler and G299.2−2.9.

Key words: supernovae: individual: G299.2−2.9 – supernovae: individual: Kepler’s SN – planetary nebulae: general – ISM: supernova remnants.

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are thermonuclear detonations of carbon–oxygen white dwarfs (WDs; Hoyle & Fowler 1960). Four SN Ia scenarios are currently considered, with no consensus on even the leading scenario for SN Ia. (a) The single degenerate (SD) scenario (e.g. Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004). In this scenario, the WD accretes mass from a non-degenerate stellar companion and explodes more or less when it reaches the Chandrasekhar mass limit. (b) The double degenerate (DD) scenario (e.g. Iben & Tutukov 1984; Webbink 1984). According to this scenario a merger of two WDs takes place, but there is no specification of the later evolution, e.g. how long after merger explosion occurs. Recent papers, for example, discuss violent merger and collision (e.g. Kushnir et al. 2013; Pakmor, Kromer & Taubenberger 2013) as an ignition channel of the DD scenario. (c) The core-degenerate (CD) scenario (e.g. Livio & Riess 2003; Kashi & Soker 2011; Soker 2011; Iikov & Soker 2012, 2013; Soker et al. 2013). Here the WD merges with a hot core of a massive asymptotic giant branch (AGB) star. Explosion might occur shortly or a long time after merger. (d) The ‘double-detonation’ mechanism (e.g. Woosley & Weaver 1994; Livne & Arnett 1995), in which a sub-Chandrasekhar mass WD accumulates a layer of helium-rich material on its surface. The helium layer detonates and leads to a second detonation near the centre of the CO WD (e.g. Shen, Guillochon & Foley 2013 for a recent paper).

There is some overlap between these scenarios. In the violent merger model (Pakmor et al. 2012), for example, it is possible that in the merger process of the two WDs the helium is ignited first. In this type of evolution, both the DD and the double detonation operate (Pakmor et al. 2013). The double detonation might operate in the CD scenario as well, with or without a violent merger. In both the SD and the CD scenarios, a circumstellar shell can be formed by ejecting the companion (to the WD) stellar envelope close to the explosion time. A fraction of this mass might be accreted by the WD through an accretion disc. Hence, the ejection of the envelope might be accompanied by the formation of jets launched from an accretion disc around the WD. In the SD scenario the disc is formed during the mass accretion process on to the WD, while in the CD scenario the disc is formed either around the core from the destructed WD material, or around the WD from the destructed core. The formation of a disc as a result of merger of two WDs was discussed before, e.g. Raskin & Kasen (2013) and Ji et al. (2013) for recent papers.

Another possibility in the CD scenario is that the WD accretes mass from the giant stellar envelope and launches two opposite jets before merging with the giant’s core. Such circumstellar matter (CSM) shells are similar to some planetary nebulae (PNe), as the central WD ionizes the CSM. When the SN is finally ignited, the WD mass in the SD scenario and the merger product mass in the CD scenario is expelled by the explosion at high velocities of up to $V_{SN}=20,000\,\text{km}\,\text{s}^{-1}$. If the explosion occurs within

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Figure 1. (a) The Kepler SNR. Merged image between 0.3 and 8 keV taken from Reynolds et al. (2007). Note that our morphological interpretation of the Kepler SNR is different by 90° than that of Burke et al. (2013), who take the equatorial plane to be where we take the symmetry axis on the figure (dashed line). (b) G299.2−2.9 SNR. Merged image between 0.3 and 3 keV taken from Park et al. (2007). Marked in both images are the observed lobe-like features (‘Ears’), which we attribute to jets blown either a long time before the explosion or immediately before the explosion.

\[ \Delta = 0.65 \text{ pc in a run that focuses at early times, } \Delta = 7.78 \text{ pc in a run that studies the late evolution time and } \Delta = 3.2 \text{ pc in all other runs and tests.} \]

\[ \Delta \text{ is the time at which the SN Ia explosion occurs within the CSM and/or during the core–WD merger. In the rare cases when the explosion occurs within } 3 \text{ days, the WD takes place via an accretion disc, which enables jets to be formed. The jets can blow two opposite small lobes (‘ears’) in the nebula as observed in some PNe. Examples of elliptical PNe with ‘ears’ are NGC 6563 (Schwarz, Corradi & Melnick 1992), NGC 7139, IC 418 and NGC 3242 (Balick 1987; their images can be seen in the Planetary Nebula Image Catalogue1). We note that in some cases the two ‘ears’ are not exactly symmetric to each other. As well, in some PNe there are indications that the ‘ears’ are formed by jets (Sahai & Trauger 1998; Balick & Frank 2002).}

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launching of two opposite jets very shortly before the explosion. Based on these, we conduct simulations with two types of initial setups of explosion inside a CSM shell. (a) CSM-lobes model: a spherical shell with two hollow small lobes, mimicking the structure of such two opposite small lobes observed in some elliptical PNe. The initial distribution of the SN ejecta is spherically symmetric. (b) Pre-explosion jets (PEJ) model: a completely spherical CSM shell, with two jets added inside the otherwise spherical SN ejecta. This can occur only in the CD scenario during the core–WD merger process (Soker et al. 2013).

The SN ejecta density is modelled by an exponential density profile (Dwarkadas & Chevalier 1998)
\[ \rho_{\text{SN}} = A \exp\left(-v/v_{\text{ej}}\right)t^{-3}, \]

where \( v_{\text{ej}} \) is a constant which depends on the mass and kinetic energy of the ejecta,
\[ v_{\text{ej}} = 2.44 \times 10^4 F_{51}^{1/2} \left( \frac{M_{\text{SN}}}{M_{\text{Ch}}} \right)^{-1/2} \text{cm s}^{-1}. \]

\[ M_{\text{Ch}} = 1.4 M_{\odot}, \]
\[ E_{51} = \text{the explosion energy in units of} \ 10^{51} \text{erg and} \ A = \text{a parameter given by} \]
\[ A = 7.67 \times 10^6 \left( \frac{M_{\text{SN}}}{M_{\text{Ch}}} \right)^{5/2} F_{51}^{-3/2} \text{g}^{-3} \text{cm}^{-3}. \]

The maximum velocity of the SN ejecta is taken to be \( v_{\text{SNmax}} = 20,000 \text{km s}^{-1}. \) Each simulation starts roughly 8 yr after the explosion took place, besides one run that studies the late evolution time and where the initial time is 30 yr, as we explain in Section 3. By this time the fastest ejecta reached 0.16 pc (0.6 pc in the late evolution time run) from the centre of the explosion. The total energy of the explosion is set to be \( E_{\text{SN}} = 10^{51} \text{erg}, \) and the mass ejected in the explosion is \( M_{\text{SN}} = 1.4 M_{\odot}. \) The CSM initial profile is set to be a constant density (Patnaude et al., 2012), \( \rho_{\text{CSM}} = 3.15 \times 10^{-21} \text{g cm}^{-3}, \) shell within radii 0.24–0.27 pc, so that the total mass of the CSM shell is \( M_{\text{CSM}} \approx 1.6 M_{\odot}. \) (for the late evolution time run, we take \( \rho_{\text{CSM}} = 6.16 \times 10^{-22} \text{g cm}^{-3}, \) and the shell is within radii of 0.9–1.0 pc.) The mass is based on the estimated CSM mass in the Kepler SNR (Borkowski, Blondin & Sarazin 1992; Borkowski, Sarazin & Blondin 1994; Kinugasa & Tsunemi 1999; Blair et al., 2007). The ambient ISM density is taken to be \( \rho_{\text{ISM}} = 10^{-21} \text{g cm}^{-3} \) (Vink 2008).

In the small CSM-lobes model, some of the mass of the CSM envelope is ‘pushed outwards’ to form the ‘Ears’. Each small lobe has an initial half-spherical shell structure within radii 0.065–0.09 pc from the centre of the small lobe. We assume that the small CSM-lobes are formed by jets with low mass, and hence take the total mass of the CSM in the small lobes to be the same as the CSM shell segments they replaced. As the width of the small lobes is the same that of the CSM, the density in the small lobes is lower than that in the CSM, and amounts to a value of \( \rho_{\text{small--lobes}} = 1.56 \times 10^{-21} \text{g cm}^{-3}. \) The initial setup of the small CSM-lobes is shown in Fig. 2(a).

In the PEJ model, jets are added to the explosion itself. The reason is that in the CD scenario the jets might occur during the core–WD merger (Soker et al. 2013), and the explosion may occur very shortly after the merger, e.g., as in the violent merger ignition model of Pakmor et al. (2013). The jets are expected to be launched at about the escape velocity from the massive and compact WD, \( v_{\text{jets,SN}} > 10,000 \text{km s}^{-1}, \) not much different from the SN explosion velocity. To make the model simple, we set the velocity and density radial profiles of the jets to be the same as that of the SN ejecta, but take the density in the jets to be three times larger than that of the SN ejecta at the same radius. The mass of each jet is \( M_{\text{jet}} = 0.03 M_{\odot} \) and the half-opening angle of the jets is \( \theta = 5^\circ. \) The initial setup of the PEJ model is shown in Fig. 2(b). The main features of the two models are summarized in Table 1.

To have better understanding of the process of interaction of the SN ejecta with the CSM at early times (up to \( \approx 20 \) yr), we perform one additional simulation that focuses on the region within the initial radius of the CSM shell. In this setup, each axis still has 512 cells but is only 0.65 pc in length, so that the effective resolution is increased significantly in comparison to the simulation runs described above. As well, in one run we extend the grid to \( \Delta = 7.78 \text{pc} \) and follow the evolution up to a late time of \( t \approx 400 \) yr.

The numerical \( x \sim y (z = 0) \) plane is taken to be in the plane containing the central explosion and the two ‘Ears’ or jets. Initially this plane is a symmetry plane, but we simulate the entire space, so that we assume no symmetry about the \( z = 0 \) axis at \( t > 0. \)

### 3 RESULTS

As the SN ejecta hits the CSM, part of the kinetic energy of the ejecta is deposited in the CSM shell, and the CSM is accelerated outwards. Two shock waves are formed. The first shock (forward shock) runs outwards into the CSM, and then passes to the ISM. The second shock is a reverse shock that runs inwards into the incoming ejecta. There are two contact discontinuities in the flow, one between the shocked ejecta and the shocked CSM, and the other one between the CSM and the ISM (initially pre-shock media, later shocked media). The shocks are clearly seen in all panels of Figs 3 and 4, and are marked on panel 3(b). By ISM we refer to the medium outside the dense CSM shell. This ISM might contain previous stellar wind, and hence is actually a low-density CSM. The reverse shock is best seen in the temperature and pressure maps in Fig. 5, and is marked on panel 5(a).

In our flow setting the shocked CSM is denser than the shocked ejecta. Therefore, as the shocked ejecta accelerates the shocked CSM, the flow becomes Rayleigh–Taylor (RT) unstable, leading to the formation of ‘RT fingers’ and the penetration of the two media into each other. The fingers are clearly seen in Fig. 3, and are marked...
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Figure 3. (a,b): CSM-lobes model whose initial conditions are depicted in Fig. 2(a). (c,d): Spherical CSM with PEJ model whose initial conditions are depicted in Fig. 2(b). Shown is the density structure (colour-coded) at various times as indicated, in the $x-y$ plane. The contour lines distinguish matter located initially in the jets (cyan; only in the PEJ model), in the SN ejecta (blue) and in the CSM shell (black). We emphasize that the ISM might contain significant amount of low-density CSM from a stellar wind prior to the main CSM shell ejection.

Figure 4. Same as Fig. 3, in two additional planes. (a) Spherical CSM with PEJ in the $y=0 (x-z)$ plane. (b) Spherical CSM with PEJ in the $z=0.5$ pc plane.

on panel 3(b). Similar instabilities are present in SN Ia simulations performed by Warren & Blondin (2013). The shocked ISM is of lower density than the shocked CSM. As the shocked ISM slows down, the shocked CSM this contact discontinuity also becomes RT unstable. These unstable regions are best presented in panels 5(c) and (d), as described next. The post shock CSM gas is heated up to temperatures of $\approx 10^9$ K, and slowly cools down mainly via adiabatic cooling. For our initial conditions, the radiative cooling time-scale of the shocked CSM is $\gtrsim 1000$ yr, whereas the flow time in our simulation is up to $\approx 400$ yr.

The initial departure from spherical symmetry (see Figs 3a and c) is ‘magnified’ in absolute size by the sweeping SN ejecta as the lobes are inflated from within by the ejecta–CSM interaction (see Figs 3b, d and 4). In both models, a large-scale deviation from spherical symmetry is formed along the symmetry axis.

The outflow in the inner part of the SNR at late simulation times is mostly governed by the low-velocity ejecta that was located close to the centre of the SN explosion in the beginning of the simulation. Our modelling of this slow ejecta is not accurate due to numerical limitations (pixel size), thus the simulation results of the innermost regions (up to 0.5 pc at 173 yr or up to 1.2 pc at 411 yr) of the SNR are of limited accuracy for these runs. The overall ‘clumpiness’ of the regions dominated by RT fingers resembles the fleecy structure analysed in Warren & Blondin (2013) for the interiors of Type Ia SNRs. As the differences between the results of the CSM-lobes (Figs 3a and b) model and the PEJ model (Figs 3c and d) are small, we choose to focus on the PEJ model for further analysis.

In Fig. 4, we present the density maps in different planes, and in Fig. 5 we present more physical quantities of the flow. Both figures emphasize the main features of the flow, in particular the structure.
and evolution of the instabilities. Figs 5(a) and (b) show temperature and pressure maps. Figs 5(c) and (d) show the ratio of the RT-growth time $\tau_{RT}$ to the time of the simulation $t_{sim}$. This ratio is calculated as

$$\frac{\tau_{RT}}{t_{sim}} = \frac{1}{t_{sim}} \sqrt{\frac{\lambda \rho}{|\nabla P|}},$$

where $\lambda$ is the typical size of the RT instabilities and $\nabla P$ is the pressure gradient in the $x-y$ plane. We scale $\lambda$ as a fraction of the initial CSM shell width, 0.03 pc, and take it to be, somewhat arbitrarily, 0.01 pc. The exact value is of no significance for our analysis. $\lambda$ equals 1.6 times the cell size.

In addition to the nominal resolution runs whose results are presented above, we perform a high-resolution simulation that focuses on early times (around the time of the initial interaction of the SN ejecta with the CSM shell), before the CSM shell expanded to higher radii. In this run, $\lambda = 0.01$ pc equals the size of eight numerical cells. Fig. 6 shows various quantities at early times of the high-resolution simulation, beside panel 6(a) that presents the density map of the nominal lower resolution run presented in Figs 3(c), (d), 4 and 5. While there are differences between the nominal- and the high-resolution runs on small scales, in particular the formation of RT instabilities on the high-resolution density map (compare panel 6a with 6b), the two simulations are similar on large scales. As well, we note that the ‘Ears’ that begin to form in the high-resolution run have ‘sharper’ structure than the ‘Ears’ in the nominal-resolution run. The early times, when the forward shock front is still inside the CSM, are of particular interest for understanding the interaction between the media. Fig. 7 shows the radial profiles of the density, temperature, pressure and the RT instability growth time, at two early times. In panel 7(a), we present the profiles at $t = 6$ yr, when the forward shock front is still inside the CSM (not all the CSM has been shocked yet), while in panel 7(b) at $t = 16$ yr, the shock front is running through the ISM. The profiles are drawn from the centre of the grid along the positive $x$-axis. The formation of the RT instabilities begins at an early time in the simulation, when the SN ejecta first hit the CSM shell. At this time the CSM shell did not move much from its original location at radii of 0.24–0.27 pc (marked in panel 7a). However, the shell’s inner part is hit by the SN ejecta and a shock runs into the CSM and heats the material up to $T_{\text{max}} \approx 10^{10}$ K. As the shock progresses further into the shell, a highly RT-unstable region develops around 0.24–0.26 pc (marked in panel 7b). This region is on the contact discontinuity between the shocked ejecta and the shocked CSM (0.28 pc, where a density jump is seen). Over time, these instabilities develop to the large fingers seen in Figs 3(b), (d) and 4.

In order to study the interaction of the SN ejecta with a CSM shell at a late evolution time (like the current age of the Kepler SNR, $t \approx 410$ yr), we perform an additional run with a larger computational axis length ($\Delta = 7.78$ pc, 512 cells per axis). The longer axes allow us to study the SN at a late time, when the forward shock radius is $\approx 3$ pc, similar to the radius of the Kepler SNR at present time (Sollerman et al. 2003). However, due to computational time constraints we still have only 512 cells per axis; hence, the resolution in this run is lower than that of the nominal runs or the high-resolution run. In order to resolve the flow at all times and avoid smearing for flow near the centre, we set the initial front of the ejecta at 0.6 pc, instead of 0.16 pc in previous runs, and the corresponding initial time is $t = 30$ yr instead of 8 yr in previous

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**Figure 5.** Maps in the $x-y$ plane of several quantities in the spherical CSM with PEJ model. (a) Temperature. (b) Pressure with overlapping velocity vectors. The vectors length is scaled linearly with the velocity, with the longest vectors corresponding to $v \approx 10000$ km s$^{-1}$. (c,d) The ratio of the RT instability growth time to the time of the simulation (marked on each panel) according to equation (4). The darker an area is, the more unstable it is. White areas are stable.
Figure 6. Maps in the $x-y$ plane of several quantities in the spherical CSM with PEJ runs at an early time ($t = 16$ yr). At this time, the forward shock has just passed through the CSM shell and has reached the ISM. (a) Density map in the nominal (lower resolution) run (512 cells, 3.2 pc per axis). (b) Density map in the high-resolution run (512 cells, 0.65 pc per axis). (c) Temperature map in the high-resolution run. (d) The ratio of the RT instability growth time to the time of the simulation (marked on each panel) according to equation (4).

We position the CSM shell at a larger radius as well, between 0.9 and 1 pc. The CSM shell mass is still $M_{\text{CSM}} \approx 1M_\odot$.

In Fig. 6, we present a density map in the $x-y$ plane for this run. The Ears are clearly seen in Fig. 9 that mimics X-ray emission observation. The Ears are particularly distinct if the highest intensity regions marked with a red colour are considered. Using higher mass in the modelling of the jets would allow us to make the Ears larger and more pronounced, but we here limit ourselves to show only the principal role of jets in shaping the SNR.

The main results of our simulations presented above are as follows. (1) In both the CSM-lobes model and the PEJ model, two ‘Ears’ on opposite sides of the SNR are formed. These protrusions are of significant size ($r \approx 0.5$ pc at 170 yr and $r \approx 1.0$ pc at 411 yr for the parameters we used), and may appear as Ears in observations. In the next section, we examine whether the assumed jets can account for the structure of some SNRs. (2) The interaction of the SN ejecta with the CSM shell creates a complex density structure inside the SNR, mainly through evolution of RT instabilities.

4 COMPARISON WITH SNRS

We attempt to qualitatively match some of the features in our numerical results with some morphological features in the SNRs Kepler and G299.2−2.9. The X-ray emission from the asymmetrical Kepler’s SNR has been studied in the past, recently by Burkey et al. (2013). They interpret the observed distribution of CSM in Kepler’s SNR as resulting from a disc seen edge-on, which extends from the centre of the SNR along the line that marks our proposed symmetry axis in Fig. 1. Our interpretation of the observations is different, in that we propose that the line connecting the two ‘Ears’ is actually a symmetry axis and not the equatorial plane. Our conjecture of the direction of the symmetry axis is based on similar interpretations applied to planetary nebulae that possess similar ‘double-Ear’ morphologies (see Section 2). Following these interpretations, we here attribute the ‘Ears’ observed in SNRs to jets. In particular, we examine the Kepler and G299.2−2.9 SNRs.

The exact reconstruction of the expected X-ray emission map from our simulations is beyond the scope of this paper. However, as X-ray emission is proportional to the square of the density we can make a qualitative comparison by constructing an ‘intensity map’ by simply integrating $\rho^2$ along the line of sight (a similar approach was used in Burkey et al. 2013). We take the ‘Ears’ to lie in the plane of the sky. This intensity map is shown in Fig. 9.

Whether the ‘Ears’ will be observed from another angle depends on how much they protrude from the shell. In our model, we can simulate stronger (more massive) jets that will form larger Ears. This will allow us to reproduce the observed Ears when the symmetry axis has a large angle to the plane of the sky. In this first study of shaping by jets, we limit ourselves to the case that the symmetry axis is in the plane of the sky. In the specific simulation run presented in Fig. 9, the Ears will appear in observations as long as the angle between the symmetry axis and the plane of the sky is $<25^\circ$. This amounts to $\sim 40$ per cent probability of randomly detecting the Ears. The existence of jet-shaped ‘Ears’ in one of the few known historical SNe Ia may suggest that our proposed PEJ mechanism can be rather common in SN Ia. However, the numbers are too low to make any quantitative predictions.
Figure 7. Radial profiles of density (solid blue), temperature (dashed red), pressure (dotted black) and RT time-scale (solid magenta), taken from the centre of the simulation grid along the positive x-axis at two early times, for the high-resolution PEJ run (512 cells, 0.65 pc per axis): (a) 6 yr. The shock is inside the CSM shell. The maximum values are \( \rho_{\text{max}} \approx 8.5 \times 10^{-30} \text{g cm}^{-3}, T_{\text{max}} \approx 10^{10} \text{K}, P_{\text{max}} \approx 2 \times 10^{-9} \text{erg cm}^{-3}, \tau_{\text{RT(max)}/\sim 2}. \) (b) 16 yr. The shock front has passed the CSM shell and it is in the ISM. \( \rho_{\text{max}} \approx 1.9 \times 10^{-30} \text{g cm}^{-3}, T_{\text{max}} \approx 8.3 \times 10^{9} \text{K}, P_{\text{max}} \approx 2 \times 10^{-8} \text{erg cm}^{-3}, \tau_{\text{RT(max)}/\sim 30}. \) Note that a lower value of \( \tau_{\text{RT}} \) means faster growth of instabilities.

In order to make a quantitative comparison between the results of our simulations and available observations of the Kepler SNR, we examine two fundamental properties of the forward shock in our simulations: (a) the expansion parameter $\delta$, defined as $R_{\text{FS}} \propto t^p$, where $R_{\text{FS}}$ is the radius of the forward shock; (b) the ionization time-scale for the shocked ejecta, $\langle n_e \rangle t_{\text{ion}}$.

The expansion parameters for different regions of the Kepler SNR were derived from archival Chandra data both by Vink (2008) and by Katsuda et al. (2008). Vink (2008) find that the average expansion parameter for the Kepler SNR is $\delta_{\text{obs}} \approx 0.6$, with some parts having slower expansion ($\delta_{\text{obs}} \approx 0.3$--0.4 in the north-western part of the SNR), and some having slightly faster expansion ($\delta_{\text{obs}} \approx 0.7$ for a filament in the eastern part of the SNR). Katsuda et al. (2008) find the expansion parameter to be $\delta_{\text{obs}} \approx 0.47$--0.82 for different parts of the SNR rim. We calculate the expansion parameter by comparing the radii of the forward shock at two times. For a late evolution time (comparing between the radius of the forward shock at $t = 378$ yr and at $t = 411$ yr), we find $\delta_{\text{sim}} \approx 0.52$. At an earlier time (between 100 and 130 yr), the calculated expansion parameter is larger, $\delta_{\text{sim}} \approx 0.8$. This is to be expected, since our modelling of the SN ejecta density profile is based on an exponential density profile derived by Dwarkadas & Chevalier (1998) for an explosion that occurs inside a uniform-density ISM, and for which the theoretical expansion parameter varies from $\delta_{\text{theory}} \approx 0.8$ at an early evolution time to $\delta_{\text{theory}} \approx 0.4$ at a very late time (that Kepler SNR has yet to reach).

The ionization time-scale is another important observable quantity used to characterize the thermal emission in non-equilibrium ionization plasmas. The ionization time-scale of the shocked SN ejecta for the Kepler SNR was found by Badenes et al. (2007) to be $\log(\langle n_e \rangle t_{\text{ions}}) = 10.08$--10.24 for Si and 9.85--9.92 for Fe. In our PEJ model, the calculated average ionization time-scale for the forward shock at $t = 411$ yr is $\log(\langle n_e \rangle t_{\text{ions}}) = 10.64$, which is within the typical range for young Ia SNRs.

The observed velocity of the forward shock for the Kepler SNR is estimated to be $v_{\text{FS(obs)}} = 2.0 \times 10^3$--$2.5 \times 10^3$ cm s$^{-1}$ (Sollerman et al. 2003). In our simulations, the velocity of the forward shock at a late time ($t = 411$ yr) is slightly higher, with a value of $v_{FS(sim)} = 3.5 \times 10^3$ cm s$^{-1}$. However, the current models for determination of the forward shock velocity from observations of Balmer-dominated shocks might underestimate the forward shock velocity (Badenes et al. 2007; Heng & McCray 2007). Our calculated $v_{FS(sim)}$ may support this notion.

Like several other historical Ia SNRs, Kepler has partially neutral ambient gas ahead of the forward shock (Blair, Long & Vancura 1991). While the goal of this paper is merely to explain the ‘Ears’ properties observed in some SNRs, we did mention the possibility that some SN Ia explode within PNe. If that was the case for the Kepler SN, then the partially neutral ambient gas at an electron density of $n_e \approx 1$ cm$^{-3}$ puts constraints on the PN progenitor evolution. After an evolution time of $\sim 10^4$ yr, a massive central star of a PN has a luminosity of $\sim 30 L_\odot$ and an effective temperature of $T_{\text{eff}} \approx 2 \times 10^5$ K (Bloecker 1995). The rate of emission of ionizing photons (for hydrogen) is $N_e \approx 10^{45}$ s$^{-1}$. This should be compared with the recombination rate of the dense shell of $\sim M_\odot$ which prior to the explosion can be at a radius of $\sim 1$ pc. For an expansion speed of $10$ km s$^{-1}$ this gives an age of $10^8$ yr. The average electron density of such a shell is $n_e \approx 10^3$ cm$^{-3}$, and the recombination rate is $N_{\text{rec}} \gtrsim 2 \times 10^{45}$ s$^{-1}$, depending on the exact density distribution. The inequality $N_{\text{rec}} > N_e$ implies that ionization radiation does not reach the halo. The halo then recombines on a time-scale of $\tau_{\text{rec}} \approx 1.2 \times 10^5$ yr (e.g. Tylenda 1983 for PN haloes).

We conclude that for an evolution time of $\gtrsim 10^8$ yr after merger, the outer medium (ISM) has time to partially recombine. We note that a long evolution time implies that more mass might be located further out, e.g. in denser clumps. Denser clumps of gas, e.g. in an equatorial plane, will recombine faster and will be hard to observe. A more massive ejecta that once was a massive envelope of the AGB progenitor would have facilitated the merger of the WD with the AGB core in the CD scenario (Soker et al. 2013).

Considering our results presented in Section 3 for both the CSMlobes and the PEJ models at a late simulation time (e.g. the resulting density maps shown in panels 3(b), 3(d) and Fig. 8) and making a qualitative comparison between Fig. 9 and the observed images in Fig. 1, we are led to suggest that both our proposed models – the CSM-lobes model and the PEJ model – might explain the observed ‘Ears’ features in Kepler SNR and G299.2--2.9 SNR.

5 SUMMARY

Although many SN Ia remnants exhibit almost spherical large-scale symmetry, there are several remnants of SN Ia (SNRs) that show an axisymmetrical deviation from spherical large-scale structure. The Kepler and G299.2--2.9 SNRs, for example, have two protrusions
Type Ia supernovae inside planetary nebulae

Figure 8. Density map in the $x-y$ plane at a late evolution time for a run with a spherical CSM shell and with PEJ.

Figure 9. Integrated $\rho^2$ for the spherical CSM with PEJ run at a late evolution time (comparable to the current age of the Kepler SNR). A density map of the same run is presented in Fig. 8. Apparent are the two ‘ears’ features, formed by jets close to the time of the SN explosion, in particular in the high-intensity regions marked by the red colour.

(‘Ears’) on the outer rim of the SNR, positioned exactly opposite to each other (see Fig. 1). Noting that some PNe have similar axisymmetrical morphologies with two opposite ‘ears’, and following interpretations that attribute these features to jets, we propose that the ‘Ears’ in these two SNRs can also be attributed to jets.

In Section 2, we discussed two models for the formation of such protrusions. (a) The CSM-lobes model, in which an SN explosion takes place inside an overall spherical shell with two hollow small lobes, mimicking the structure of such two opposite small lobes observed in some elliptical PNe. This model is plausible if the SN explosion takes place via the SD or the CD scenarios. (b) The PEJ model, in which the SN explosion is ignited inside a CSM shell (which might be spherical or not), with two jets added inside the SN ejecta. This can occur only in the CD scenario during the core–WD merger process (Soker et al. 2013). The models are described schematically in Fig. 2.

The initial conditions of the runs were motivated by the Kepler SNR, although we did not try to reproduce its ‘Ears’ one to one. We employed 3D hydrodynamical simulations to follow the interaction of the SN ejecta with the CSM in the two models – CSM-lobes and PEJ.

The main results of our simulations are presented in Section 3, and can be summarized as follows. (1) In both the CSM-lobes model and the PEJ model two ‘Ears’ on opposite sides of the SNR are formed. These protrusions are of significant size ($r \approx 0.5\text{ pc}$ at 173 yr and $r \approx 1.0\text{ pc}$ at 411 yr for the parameters we used), and may appear as ‘Ears’ in observations. (2) The interaction of the SN ejecta with the CSM shell creates a complex density structure inside the SNR, mainly through evolution of RT instabilities.

In Section 4, we compare the results of our simulations with observations, and propose that both our suggested models (CSM-lobes and PEJ) may explain the observed morphologies of the Kepler and G299.2$-2.9$ SNRs. In general, we propose that some SN Ia may blow jets close to the time of the explosion, offering an explanation to the occasionally observed axisymmetrical morphology of the remnants of such SN.

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REFERENCES

Badenes C., Hughes J. P., Bravo E., Langer N., 2007, ApJ, 662, 472
Balick B., 1987, AJ, 94, 671
Balick B., Frank A., 2002, ARA&A, 40, 439
Blair W. P., Long K. S., Vancura O., 1991, ApJ, 366, 484
Blair W. P., Ghavamian P., Long K. S., Williams B. J., Borkowski K. J., Reynolds S. P., Sankrit R., 2007, ApJ, 662, 998
Bloecher T., 1995, A&A, 299, 755
Blondin J. M., Ellison D. C., 2001, ApJ, 560, 244
Borkowski K. J., Blondin J. M., Sarazin C. L., 1992, ApJ, 400, 222
Borkowski K. J., Sarazin C. L., Blondin J. M., 1994, ApJ, 429, 710
Burkey M. T., Reynolds S. P., Borkowski K. J., Blondin J. M., 2013, ApJ, 764, 63
Cassam-Chenai G. et al., 2004, A&A, 414, 545
Dwarkadas V. V., Chevalier R. A., 1998, ApJ, 497, 807
Fryxell B. et al., 2000, ApJS, 131, 273
Han Z., Podsiadlowski P., 2004, MNARS, 350, 1301
Heng K., McCray R., 2007, ApJ, 654, 923
Hoyle F., Fowler W. A., 1960, ApJ, 132, 565
Iiben I., Jr, Tutukov A. V., 1984, ApJS, 54, 335
Ilkov M., Soker N., 2012, MNARS, 419, 1695
Ilkov M., Soker N., 2013, MNARS, 428, 579
Ji S. et al., 2013, preprint (arXiv:1302.5700)
Kashi A., Soker N., 2011, MNARS, 417, 1466
Katsuda S., Tsunemi H., Uchida H., Kimura M., 2008, ApJ, 689, 225
Kinugasa K., Tsunemi H., 1999, PASJ, 51, 239
Kushnir D., Katz B., Dong S., Livne E., Fernández R., 2013, preprint (arXiv:1303.1180)
Livio M., Riess A. G., 2003, ApJ, 594, L93
Livne E., Arnett D., 1995, ApJ, 452, 62
Nomoto K., 1982, ApJ, 253, 798
D. Tsebrenko and N. Soker

Orlando S., Bocchino F., Miceli M., Petruk O., Pumo M. L., 2012, ApJ, 749, 156
Pakmor R., Kromer M., Taubenberger S., Sim S. A., Röpke F. K., Hillebrandt W., 2012, ApJ, 747, L10
Pakmor R., Kromer M., Taubenberger S., 2013, ApJ, 770, L8
Park S., Slane P. O., Hughes J. P., Mori K., Burrows D. N., Garmire G. P., 2007, ApJ, 665, 1173
Park S. et al., 2013, ApJ, 767, L10
Patnaude D. J., Badenes C., Park S., Laming J. M., 2012, ApJ, 756, 6
Raskin C., Kasen D., 2013, ApJ, 772, 1
Reynolds S. P., Borkowski K. J., Hwang U., Hughes J. P., Badenes C., Laming J. M., Blondin J. M., 2007, ApJ, 668, L135
Sahai R., Trauger J. T., 1998, AJ, 116, 1357
Schwarz H. E., Corradi R. L. M., Melnick J. I., 1992, A&AS, 96, 23
Shen K. J., Guillochon J., Foyle R. J., 2013, ApJ, 770, L35
Soker N., 2011, preprint (arXiv:1109.4652)
Soker N., Kashi A., Garcia-Berro E., Torres S., Camacho J., 2013, MNRAS, 431, 1541
Sollerman J., Ghavamian P., Lundqvist P., Smith R. C., 2003, A&A, 407, 249
Sutherland R. S., Dopita M. A., 1993, ApJS, 88, 253
Tylenda R., 1983, A&A, 126, 299
Vink J., 2008, ApJ, 689, 231
Wang C.-Y., Chevalier R. A., 2001, ApJ, 549, 1119
Warren D. C., Blondin J. M., 2013, MNRAS, 429, 3099
Webbink R. F., 1984, ApJ, 277, 355
Whelan J., Iben I., Jr, 1973, ApJ, 186, 1007
Woosley S. E., Weaver T. A., 1994, ApJ, 423, 371

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