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The Interaction of Type Ia Supernovae with Planetary Nebulae: The Case of Kepler's Supernova Remnant

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Abstract: One of the key methods for determining the unknown nature of Type Ia supernovae (SNe Ia) is the search for traces of interaction between the SN ejecta and the circumstellar structures at the resulting supernova remnants (SNRs Ia). So far, the observables that we receive from well-studied SNRs Ia cannot be explained self-consistently by any model presented in the literature. In this study, we suggest that the circumstellar medium (CSM) being observed to surround several SNRs Ia was mainly shaped by planetary nebulae (PNe) that originated from one or both progenitor stars. Performing two-dimensional hydrodynamic simulations, we show that the ambient medium shaped by PNe can account for several properties of the CSM that have been found to surround SNe Ia and their remnants. Finally, we model Kepler's SNR considering that the SN explosion occurred inside a bipolar PN. Our simulations show good agreement with the observed morphological and kinematic properties of Kepler's SNR. In particular, our model reproduces the current expansion parameter of Kepler's SNR, the partial interaction of the remnant with a dense CSM at its northern region and finally the existence of two opposite protrusions ('ears') at the equatorial plane of the SNR.

Keywords: type Ia supernovae; supernova remnants; planetary nebulae; SN 1604; Kepler's SNR

1. Introduction

Thermonuclear or Type Ia supernovae (SNe Ia) is a class of supernovae that results from the thermonuclear combustion of a carbon-oxygen white dwarf (WD), which is destabilized through the interaction with a companion star. This interaction could appear either via mass transfer from a non-degenerate donor star (single degenerate scenario, SD) or in a merger event with a degenerate companion (double degenerate scenario, DD). However, both scenarios have severe weaknesses and cannot account for all the observed properties of SNe Ia [1]. As a result, despite decades of research the nature of the donor star, the mass transfer process and the explosion mechanism itself remain highly uncertain. Given that SNe Ia have fundamental consequences in a wide range of astrophysical issues (e.g., low mass binary evolution, chemical enrichment of galaxies, cosmology), the identification of their unknown nature is considered to be one of the most crucial quests of stellar astrophysics.

A promising method that attempts to clarify the unknown origin of these cosmic explosions is the study of the SNe Ia aftermath, the Supernova Remnants (hereafter SNRs Ia). There is a consensus that the morphology, kinematics and emission properties of SNRs reflect the interaction of the SN blast wave with inhomogeneous circumstellar medium (CSM) shaped by the mass outflows of the progenitor system. Thus, deciphering the observational data of nearby SNRs Ia, through detailed modeling, we get crucial insights into the structure and the properties of the CSM that was surrounding the explosion center and extract valuable information about the nature and evolution of the progenitor system.

Indeed, several well-studied SNRs Ia exhibit peculiar properties that are only explained by assuming that the SNR is interacting with circumstellar structures formed by its parent stellar system. The most characteristic case is the remnant of the historical SN Ia observed by Kepler (SN 1604), which reveals profound evidence of interaction with dense CSM in its northern and central regions [2,3]. A number of models have been computed aiming to reproduce the observed properties of Kepler's SNR and the general conclusion is that the CSM around Kepler is largely made of material expelled by a wind-losing donor star in the Asymptotic Giant Branch (AGB), member of the parent stellar system [2,4,5]. However, no evidence of the presence of a survived AGB star has been found in the center of Kepler's SNR [6] and thus, a different progenitor model of Kepler's SNR is required. Discrepancies between theoretical predictions and observations are also found in the SNRs Ia of Tycho (SN 1572) and RCW86, which seem to expand in an extended low density cavity [7,8]. The formation of this cavity is attributed to the mass outflows that emanate from the surface of accreting WDs known as 'accretion winds' [9]. However, the existence of accretion winds has been questioned in the literature ([1], and references therein), while for the case of Tycho's SNR such a scenario does not agree with its observed X-ray spectra [10] and a steadily nuclear burning WD progenitor has been recently ruled out [11]. In conclusion, the evidence and constraints posed by the observation of several well-studied SNRs Ia rule out essentially any model suggested in the literature.

In this work, we propose an innovative scenario according to which—at least a fraction of—SNe Ia occur in and subsequently interact with Planetary Nebulae (PNe) formed by the progenitor system (see also [12]). We demonstrate, using hydrodynamical simulations, that this model can account for diverse CSM properties observed to surround several SNRs Ia. Finally, we model the SNR of Kepler within the framework of the studied model and we show that the interaction of the SN ejecta with a surrounding bipolar PN reproduces the overall morphological and kinematic properties of the remnant.

2. Hydrodynamic Modeling of the CSM Shaped by Planetary Nebulae

PNe are formed in the final stages of low mass stars ($M \leq 8 M_{\odot}$) which end their lives as WDs. That means that both SNe Ia and PNe share a common evolutionary path. In addition, observational surveys reveal that most PNe central stars are low mass binaries involving one or two WDs [13,14] i.e., as expected to be the progenitors of SNe Ia. Thus, it is most likely that PNe in the past contributed to modify the properties of the CSM around the progenitor systems.

In order to investigate the ability of PNe to reproduce the CSM properties observed around well-studied SNRs Ia, we employ the hydrodynamic code AMRVAC [15], and we perform a series of simulations modeling the SNe Ia ambient medium shaped by a PN. The extracted results are mainly determined by two parameters: a) the characteristics of the host PN and b) the time delay between the PN formation (i.e., the moment where the newly born WD starts to ionize the surrounding CSM) and the subsequent SN Ia explosion (τ_{delay}). Given that PNe reveal a vast diversity in terms of size, shapes, kinematics etc. [16] while the time delay between the WD formation and the final SN Ia explosion can be from almost zero up to several Gyr [17], the parameter space involved in our modeling is immense. Here, as a first attempt, we consider the case of a *bipolar PN* as this morphology is one the most common PN morphologies. Regarding the delay time between the PN formation and the subsequent SN Ia explosion, we present three cases each of which represents a specific state of the CSM around the explosion center: (a) the SN Ia occurs almost simultaneously with the birth of the WD i.e., the τ_{delay} is negligible compared to the dynamical timescale of the surrounding PN evolution ($\tau_{\text{delay}} = 0 \text{ Myr}$), (b) the WD explodes $\tau_{\text{delay}} = 2 \text{ Myr}$ after its formation and (c) the time delay between the two phenomena is $\tau_{\text{delay}} = 8 \text{ Myr}$.

We perform our modeling on a 2D spherical grid and assume symmetry in the third dimension (Supplementary Materials). Adopting the interactive-stellar-wind model [18–20] according to which the PNe shell are shaped by the interaction of the fast wind from the central star and the remnant of the slow AGB wind, we run our simulations in two steps: (a) we first simulate the formation

of the AGB wind bubble by imposing a continuous inflow in the inner boundary of our grid in the form of a slow stellar wind with $\dot{M} = 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ and $u_w = 5 \text{ km s}^{-1}$, (b) after 0.5 Myr we change the inflow properties at the inner boundary of the grid and we insert a fast tenuous wind of $\dot{M} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ and $u_w = 4 \times 10^3 \text{ km s}^{-1}$ in the computational domain. The fast wind starts to sweep up the previous CSM and forms an inner cavity surrounded by a shell (i.e., the PN). The wind's bipolarity is described following the trigonometric functions: $\dot{M}(\theta) = \dot{M}(0) [1 - \beta |\sin \theta|^k]^{-1}$ and $u_w(\theta) = u(0) [1 - \alpha |\sin \theta|^k]$ where $\dot{M}(\theta)$ and $u_w(\theta)$ is the wind mass loss rate and terminal velocity at the polar angle θ , respectively (see [21–23] for relevant approaches on hydro-modeling of axisymmetric PNe). The α, β and k are constants which determine the polar distribution of the CSM density and velocity. Finally, for the cases where $\tau_{\text{delay}} = 2$ and 8 Myr, we simulate this delay time by turning off the fast wind in the inner boundary of our grid and letting the circumstellar structure evolve for the relevant time intervals. The results of our simulations are illustrated in Figure 1.

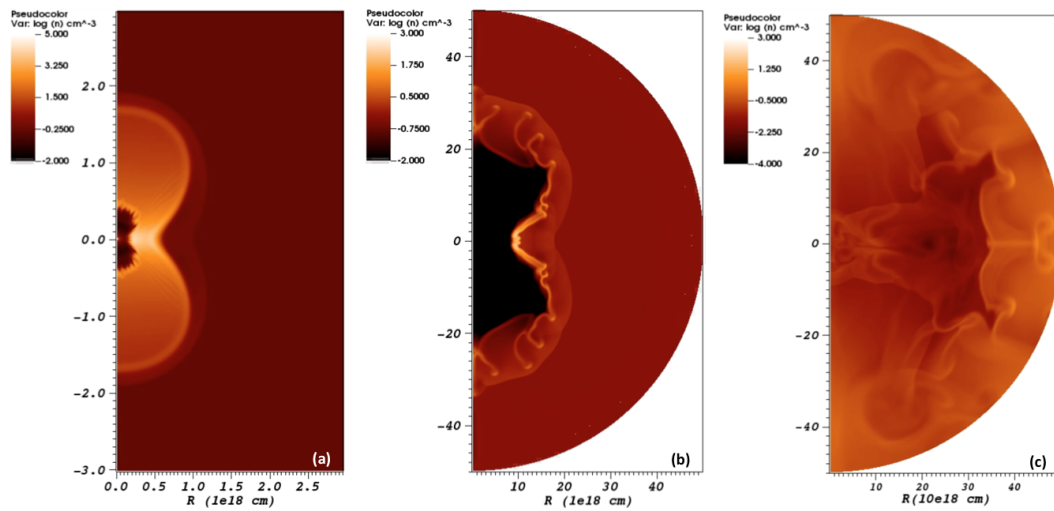


Figure 1. The 2D density contours of the CSM shaped by a bipolar PN for the cases where the SN Ia explosion occurred right after the cessation of the fast wind (a), 2 Myr later (b) and 8 Myr later (c).

The moment the fast wind ceases (Figure 1a) the CSM around the progenitor system is characterized by a typical bipolar PN. The inner cavity of the PN that was shaped by the fast wind, is surrounded by the dense halo of the PN—i.e., the remnant of the AGB wind—and in the boundary of those two regions a shell of shock wind is formed. Such a structure hosts very similar properties with the CSM of SNe Ia that reveal time variable Na ID emission lines (e.g., PTF 2011kx [24]) which have been found to be surrounded by circumstellar shell(s) placed at a distance of 10^{16} – 10^{17} cm from the explosion center. In addition, SNRs Ia that reveal profound evidence of interaction with dense CSM such as Kepler’s SNR appear most likely to have occurred in such a circumstellar structure (see Section 3).

For the case where $\tau_{\text{delay}} = 2$ Myr (Figure 1b), despite the fact that the stellar wind has ceased, due to the high radial momentum of the fast wind, the circumstellar structure will keep on expanding forming an extended low density cavity of ~ 7 pc around the progenitor system. Such a case offers a natural explanation on how the large cavities, observed around several SNRs Ia (e.g., Tycho’s SNR, RCW86) can be formed without requiring the accretion wind mechanism.

Finally, as time progresses ($\tau_{\text{delay}} = 8$ Myr; Figure 1c) the circumstellar structure passes from pressure-driven phase to the momentum-driven phase and inevitably collapses under the pressure of the surrounding medium. The cavity deforms and the CSM around the progenitor system starts homogenizing. Thus, if the SN Ia occurs a couple of tenths of Myr after the cessation of the fast wind, no essential circumstellar structures are expected to be observed to its vicinity, in agreement with a number of SNe Ia and their remnants that show no evidence of interaction with CSM.

3. Kepler's SN: A SNR Resulting by the Interaction of the SN Ejecta with the Surrounding PN

The Galactic SN of Kepler (SN 1604) is one of the best-studied young SNRs (Figure 2c). There is a consensus that the remnant resulted by a SN Ia explosion and currently it is interacting with a dense circumstellar shell in its northern region [25]. The mass contained in the shell has been estimated to be $> 1M_{\odot}$ and its chemical composition reveals elevated nitrogen abundances ($[N/N_{\odot}] > 2$) [3]. The interaction between the SN ejecta and the CSM has substantially affected the dynamics of the SNR, where in the northern region its expansion parameter is $m = V \times (R/t) = 0.35$, much lower than the overall expansion of the remnant which is $m = 0.6$ [26]. The morphology of the SNR is rather spherical, revealing optically bright nebulosity in the northern portion of the remnant and in some central regions due to the interaction with the CSM. The spherical symmetry of Kepler's SNR breaks in the equator of the remnant, where it reveals two synchrotron X-ray bright protrusions that give the impression of two 'ears' in its overall morphology (Figure 2c). Finally, based on the proper motion of the nitrogen-rich knots [27] and the H_{α} narrow component of the remnant [28], it has been found that Kepler's SNR is moving with a high spatial velocity of $u_* \approx 250 \text{ km s}^{-1}$ towards the north.

Chiotellis et al. (2012) [4] modeled Kepler's SNR within the SN Ia framework. The authors reproduced the morphology and kinematics of the historical remnant suggesting that the observed CSM has been shaped by the slow, nitrogen-rich wind of an AGB donor star, member of the progenitor system. The existence of an AGB shaped CSM around the remnant was confirmed by the infrared observations of the SNR which revealed strong silicate dust features [29]. Subsequently, ref. [5] modeled the X-ray spectrum of Kepler's SNR and found that it can also be reproduced considering an evolution of the SNR within an AGB wind bubble as long as a small cavity of radius $r \sim 0.1 \text{ pc}$ is added in the inner region of the CSM around the explosion center. Finally, ref. [2] in order to explain the observed shocked CSM at the central regions of the SNR suggested that the AGB wind bubble had a bipolar shape with high mass concentration at the equatorial plane. Nevertheless, ref. [6] searched at the center of Kepler's SNR and found no surviving AGB donor star, confuting the conclusions of the previously suggested models.

The demands imposed by Kepler's SNR observations and theoretical modeling seem to be perfectly aligned with a bipolar PN origin of the CSM that surrounds the remnant. In particular, considering that Kepler's SN occurred inside a bipolar PN formed by its parent system, we can naturally and self-consistently explain: (a) the current interaction of the SNR with an AGB wind bubble (i.e., the PN's halo), something that explains the observed chemical composition of the CSM and its properties in the IR band, (b) the small cavity of $r \sim 0.1 \text{ pc}$ that surrounds the explosion center needed to reproduce the X-ray spectra, which corresponds to the inner region of the PN where the fast wind dominates, (c) the density enhancement of the CSM at the equatorial region of the SNR and finally, (d) such a model does not require the existence of a survived AGB donor star at the center of the SNR. The only condition demanded by this model is that the SN Ia occurred shortly after the formation of the PN ($\tau_{\text{delay}} \leq 0.1 \text{ Myr}$). Such a demand favors for the core-degenerate scenario which suggests that the SN Ia is triggered by the merge of a WD with the newly born AGB core of the companion star [30].

Encouraged by the remarkable similarities between bipolar PNe properties and these of CSM around Kepler's SNR, we performed hydrodynamic simulations modeling the historical remnant within the framework of the suggested model. We first simulated the formation of the bipolar PN following the procedure described in Section 2. In order to include the observed systemic motion of Kepler's SNR in our modeling, we performed our simulations in the rest frame of the progenitor system and we set the ISM of density ρ_i as an inflow entering the grid antiparallel the y -axis with a momentum $m = \rho_i u_* \cos \theta$, where $u_* = 250 \text{ km s}^{-1}$ (i.e., Kepler's SNR systemic velocity). The resulting circumstellar structure consists of a typical 'hourglass' PN, surrounded by a bipolar halo formed by the AGB wind (Figure 2a). The bipolarity of the halo has been deformed by the systemic motion of the progenitor system where a bow shock is shaped by the interaction of the AGB wind with the ISM flow. Subsequently, we introduce in the center of this circumstellar structure the SN ejecta with energy $E_{ej} = 1.2 \times 10^{51} \text{ erg}$ and mass $M_{ej} = 1.38M_{\odot}$ and we let the SNR evolve and interact with

the surrounding medium. Around 420 yr after the explosion (i.e., the current age of Kepler's SNR) the largest portion of the remnant is well within the circumstellar structure (Figure 2b). However, in its northern region the blast wave has reached and collided with the bow shaped wind shell. In addition, at the equatorial plane of the SNR, the forward shock has penetrated the CSM and has broken out into the lower density ambient medium. As a result, a protrusion is formed in this region, something that explains the morphological peculiarity of Kepler's of the two antisymmetric 'ears'. Figure 2d depicts the expansion parameter (m) of the remnant. The portion of the SNR that remains within the CSM reveals an expansion parameter of $m = 0.6$, while in its northern region that interacts with the AGB bow shell the remnant has been substantially decelerated with $m = 0.35$. These values are consistent with the results from the X-ray observations of Kepler's SNR. Finally, the highest expansion parameter corresponds to the region of the 'ears' ($m = 0.8$) in alignment to the intense X-ray synchrotron emission that is observed at the two antisymmetric lobes of Kepler's SNR.

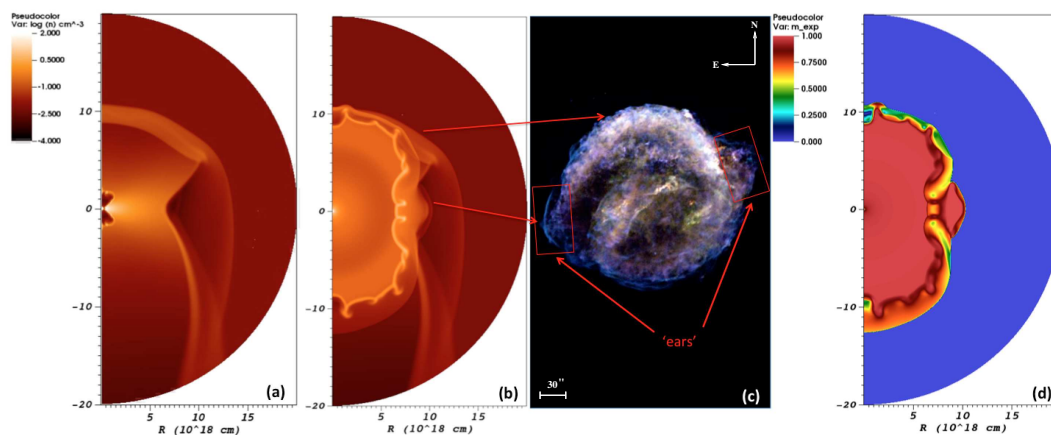


Figure 2. (a): the density distribution of the CSM that surrounds Kepler's SNR at the moment of the explosion. (b) the density contours of the SNR after 420 yr of evolution. (c) The X-ray image of Kepler's SNR [25]. (d) the expansion parameter of the SNR at $t = 420$ yr.

4. Summary

We have presented evidence that the ambient medium shaped by PNe can account for several observables of the CSM that have been found to surround SNe Ia and their remnants. The critical parameter that determines the diverse CSM properties of SNe/SNRs Ia is the delay time between the PN formation and the consecutive SN Ia explosion. This parameter can naturally explain the existence or absence of circumstellar structures around the explosion center as well as the proximity and the density of these structures.

Subsequently, motivated by the intriguing similarities between the properties of a bipolar PN and these of the CSM that surrounds Kepler's SNR, we performed 2D hydrodynamic simulations modeling the historical remnant under the framework of the SNe Ia - PN interaction model. We show that such a scenario reproduces the observational characteristics of Kepler's SNR, namely its interaction with a dense nitrogen-rich circumstellar shell at its northern region, the current kinematics of the remnant and the existence of the two antisymmetric lobes on its equatorial plane.

Supplementary Materials: The following are available at <http://www.mdpi.com/2075-4434/xx/1/5/s1>. We provide two mp4 simulations of the CSM formation by PNe and of the interaction of Kepler's SNR with a bipolar PN at the electronic version of this article.

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Conflicts of Interest: The authors declare no conflict of interest.

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