A Model Grid for the Spectral Analysis of X-ray Emission in Young Type Ia Supernova Remnants

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Abstract

We address a new set of models for the spectral analysis of the X-ray emission from young, ejecta-dominated Type Ia supernova remnants. These models are based on hydrodynamic simulations of the interaction between Type Ia supernova explosion models and the surrounding ambient medium, coupled to self-consistent ionization and electron heating calculations in the shocked supernova ejecta, and the generation of synthetic spectra with an appropriate spectral code. The details are provided elsewhere, but in this paper we concentrate on a specific class of Type Ia explosion models (delayed detonations), commenting on the differences that arise between their synthetic X-ray spectra under a variety of conditions.

Key words: hydrodynamics, ISM, nucleosynthesis, supernova remnants, supernovae, X-rays

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1 A library of synthetic X-ray spectra for Type Ia supernova remnants

There is little doubt that the X-ray spectra of the supernova remnants (SNRs) originated by Type Ia supernovae (SNe) contain important information regarding the physical mechanism behind these intriguing explosions. Many of these spectra are dominated by emission lines from the shocked supernova ejecta, where the products of thermonuclear nucleosynthesis can be clearly seen. This information, however, is not easy to extract, mainly due to the fact that the X-ray spectra of ejecta-dominated SNRs are very difficult to interpret and analyze.

We have developed a library of synthetic spectra for the analysis of the X-ray emission from young, ejecta-dominated Type Ia SNRs. This library is generated using one dimensional hydrodynamic simulations of the interaction of Type Ia SN explosion models with a uniform ambient medium (AM) and detailed calculations of the ensuing nonequilibrium ionization and electron heating processes in the shocked ejecta. Once the state of the shocked plasma is characterized in this way, synthetic X-ray spectra can be generated with an appropriate spectral code. The relevant techniques are outlined in Badenes et al. (2003) and Badenes et al. (2004) (henceforth, Paper I and Paper II). A detailed comparison between these synthetic spectra and the observations of the Tycho SNR will be the subject of a forthcoming paper (Badenes et al., in preparation). In the present work, we concentrate on a particular class of Type Ia models, the delayed detonations. First, we review the state of the art of the delayed detonation paradigm and discuss the differences between the models in this class. Then, we present a series of synthetic X-ray SNR spectra calculated from different delayed detonation models and examine the properties of the X-ray emission obtained in each case. Our aim is to illustrate the potential of our synthetic spectra by focusing on a class of models which are essentially similar to one another, but whose X-ray spectra in the SNR phase show important differences that are well within the resolving power of the current X-ray observatories.

2 Delayed detonation: a phenomenological model for thermonuclear supernova explosions

The delayed detonation (DDT) paradigm was proposed in Khokhlov (1991) as an alternative to pure deflagrations, which had been the preferred model for thermonuclear supernovae until then. In this paradigm, the burning front inside the white dwarf (WD) starts to propagate as a subsonic flame, but at a given point the flame makes a transition to the supersonic regime, and a
detonation ensues that burns the rest of the WD. This kind of Type Ia SN models is considered the most successful paradigm for reproducing the light curves and spectra of Type Ia SNe (Höflich and Khokhlov, 1996), but it has to be kept in mind that it does not provide a self-consistent explanation for the physics of Type Ia SNe. An important issue that still needs to be clarified is the physical mechanism for the transition from deflagration to detonation, which is always induced artificially in all DDT models. Another issue is the fact that the vast majority of the published DDT models are calculated in 1D, and are becoming obsolete compared to modern 3D simulations. Recently, the interest in the DDT paradigm has been rekindled as a means to avoid the thorough mixing of fuel and ashes that seems to be unavoidable in 3D deflagrations (Reinecke et al., 2002; Gamezo et al., 2003; Travaglio et al., 2004; García-Senz and Bravo, 2004). The first DDT models in 3D have begun to appear in the literature (García-Senz and Bravo, 2003; Gamezo et al., 2005), but the results of these calculations do not converge, and we are still far from a unified picture of the DDT paradigm in 3D. Until the ability of 3D calculations to reproduce light curves and spectra of Type Ia SNe is fully established (see Baron et al., 2003; Bravo et al., 2005), 1D DDT models remain the most successful Type Ia SN models, despite all their misgivings.

In Table 1 and Figure 1, we provide the characteristics of four DDT models in our grid of Type Ia SN explosions. These models can be found in Papers I and II, they are just reproduced here for the convenience of the reader. The fundamental properties of these models, like the chemical composition profile, the density profile and the total nucleosynthetic yields, depend on the main parameter involved in the calculations, $\rho_{tr}$, which represents the density inside the WD at which the burning front is forced to make the transition from flame to detonation. Models with higher values of $\rho_{tr}$, like DDTa, produce more energetic explosions, with a higher amount of $^{56}$Ni (which later decays to $^{56}$Fe), while models with lower values of $\rho_{tr}$, like DDTe, produce less $^{56}$Ni but more intermediate mass elements (IMEs), like Si, S, Ar and Ca. This is explained because for a lower value of $\rho_{tr}$, the detonation propagates into a WD that has expanded more during the deflagration phase, and therefore the

| Model | $\rho_{tr}$ | $E_k$ | $M_{Fe}$ | $M_{C+O}$ | $M_{Si}$ | $M_{S}$ | $M_{Ar}$ | $M_{Ca}$ |
|-------|-------------|------|--------|---------|--------|-------|--------|-------|
| DDTa  | 0.03        | 3.9 $\cdot$ 10^7 | 1.40   | 1.03    | 0.04   | 0.087 | 0.071  | 0.019 | 0.022 |
| DDTbb | 0.01        | 2.5 $\cdot$ 10^7 | 1.31   | 0.99    | 0.05   | 0.10  | 0.084  | 0.022 | 0.027 |
| DDTc  | 0.03        | 2.2 $\cdot$ 10^7 | 1.16   | 0.80    | 0.12   | 0.17  | 0.13   | 0.033 | 0.038 |
| DDTe  | 0.03        | 1.3 $\cdot$ 10^7 | 0.94   | 0.56    | 0.19   | 0.25  | 0.19   | 0.046 | 0.054 |

Table 1
Characteristics of the four DDT models, reproduced from Paper I and paper II. The total ejected mass is $M_{ej} = 1.37 M_\odot$ in all cases. $E_k$ is the kinetic energy.
burning front departs the region of nuclear statistic equilibrium sooner, and the IMEs take over the chemical composition profile at a smaller radius. The speed of the flame during the deflagration phase, which is controlled by the parameter \( \iota \), has a much smaller impact on the final outcome. For more details on the parameters of DDT models and the way the calculations were carried out, see Paper I and Paper II.

3 The signature of \( \rho_{tr} \) in the X-ray spectra of SNRs

Within our simulation scheme, the X-ray spectrum from the ejecta in the SNR is determined by four factors: the SN explosion model, the density of the AM \( \rho_{AM} \), the age of the SNR \( t \), and the amount of internal energy that is deposited in the electrons at the reverse shock \( \beta \), defined as the ratio of electron to ion postshock specific internal energy, see Paper II). In Paper I and Paper II, the impact that each of these four factors has on the X-ray spectra of Type Ia SNRs is analyzed in a general context. Here, we will focus on DDT models and on the imprint of \( \rho_{tr} \).

In the top two rows of Figure 2, we plot the synthetic ejecta spectra for the four DDT models of Table 1 at SNR ages of 430 yr (the age of Tycho’s SNR) and 5000 yr, for \( \rho_{AM} = 10^{-24} \text{g} \cdot \text{cm}^{-3} \). In the first row of panels, no collisionless electron heating has been introduced at the reverse shock \( \beta = \beta_{\text{min}} \), equal to the ratio of electron to ion masses, see Paper II for a discussion).
In this case, the signature of $\rho_{tr}$ is easy to identify, as emission in the Fe L and Fe K$\alpha$ complexes varies from very prominent (DDTa, high $\rho_{tr}$) to hardly detectable (DDTe, low $\rho_{tr}$). Despite the fact that the masses of Si and S in the ejecta vary by a factor 2.5 between the models, the emission in the Si and S He$\alpha$ and He$\beta$ lines does not change much from DDTa to DDTe. Note that the Fe emission increases at late times for DDTe and DDTc, but is always much lower than in DDTa or DDTbb. A remarkable feature of the models with low $\rho_{tr}$ is the enhanced emission from O, Ne and Mg at early times (Ne and Mg are synthesized in minor amounts in the O-rich regions of DDTc and DDTe, and they are only revealed if the Fe L emission is low). If collisionless electron heating at the reverse shock is introduced ($\beta = 0.1$, second row of panels in Figure 2), the flux in the Fe K$\alpha$ complex, which probes material at higher temperatures than Fe L, is enhanced, and the thermal continuum is affected in all cases (this is hard to see in the plots, but becomes apparent if the bremsstrahlung temperature is fitted). In model DDTa, the Fe L emission is significantly reduced, but only at early times, while the excess electron temperature affects most of the shocked ejecta (see Paper II). Given the stratified structure of DDT models, only Fe is severely affected by collisionless electron heating, at least for the values of $t$ that we explore here. The signature of $\rho_{tr}$ in the Fe emission is harder to identify for $\beta = 0.1$, but the presence of O, Ne and Mg is still noticeable for the models with low $\rho_{tr}$.

In the bottom two rows of Figure 2, the spectra of the four DDT models are plotted for different values of $\rho_{AM}$. At higher AM densities ($\rho_{AM} = 5 \cdot 10^{-24} \text{g} \cdot \text{cm}^{-3}$), the SNR models are more evolved at a given age, the emitted X-ray flux is higher, and the ionization state of all the elements in the spectrum is much more advanced. This tends to make the differences between models smaller: Fe L emission, for instance, is now found in all cases, and this makes the O, Ne and Mg emission in DDTc and DDTe harder to detect. The only surviving signature of $\rho_{tr}$ is the higher flux in the Fe K$\alpha$ blend for DDTa and DDTbb, but now the difference is much less noticeable. At lower AM densities ($\rho_{AM} = 2 \cdot 10^{-25} \text{g} \cdot \text{cm}^{-3}$), on the other hand, the SNRs are much less evolved and the emitted flux is much lower. Fe emission is virtually absent in all cases, and the imprint of $\rho_{tr}$ rests again with the O, Ne and Mg emission.

In previous works (Paper I and Paper II), we showed that the X-ray spectra of SNR models obtained from different kinds of Type Ia explosions are very different, and that it is possible to use the SNR observations of modern satellites like *Chandra* and *XMM Newton* to probe the physics of Type Ia SNe. In this short paper, we have focused on delayed detonation models, and we have showed that, although these models are very similar to one another, the X-ray spectra that we obtain still show important differences. In a forthcoming paper (Badenes et al., in preparation), we will make a detailed comparison between our spectra and the observations of the Tycho SNR, and show to what degree can these differences be identified in a real case.
code has no atomic data for Ar.

Here are the X-ray panels in the second row and E spectra in the second row and EPIC MOS1 camera. The gas in the first row, and the X-ray panels in the third row. The Ly$\alpha$ lines of Si, S, Ca and Fe have been marked for clarity. Note the spectral features above 6.0 keV for the Ly$\alpha$ lines and second rows. The ratios of Si, S, Ca and Fe lines and second rows. The Ly$\alpha$ lines of Si, S, Ca and Fe have been marked for clarity. Note that the spectral features above 6.0 keV for the Ly$\alpha$ lines.

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