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Exploring the Physics of Type Ia Supernovae Through the X-ray Spectra of their Remnants

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Abstract. We present the results of an ongoing project to use the X-ray observations of Type Ia Supernova Remnants to constrain the physical processes involved in Type Ia Supernova explosions. We use the Tycho Supernova Remnant (SN 1572) as a benchmark case, comparing its observed spectrum with models for the X-ray emission from the shocked ejecta generated from different kinds of Type Ia explosions. Both the integrated spectrum of Tycho and the spatial distribution of the Fe and Si emission in the remnant are well reproduced by delayed detonation models with stratified ejecta. All the other Type Ia explosion models fail, including well-mixed deflagrations calculated in three dimensions.

Key words. hydrodynamics — ISM:individual(SN1572) — nuclear reactions, nucleosynthesis, abundances, — supernova remnants — supernovae:general — X-rays:ISM

1. Introduction

Despite the considerable efforts of the last decades, the physical mechanism responsible for the explosion of Type Ia Supernovae (SNe) still remains obscure (Hillebrandt & Niemeyer, 2000). Traditionally, theoretical calculations of Type Ia SN explosions have been constrained mainly through comparison with optical SN spectra, but the complexity of the radiative transfer calculations involved has only led to a limited reduction of the multitude of possible explosion models (see, for instance Baron et al., 2003). In Badenes et al. (2003) and Badenes et al. (2005) (henceforth Paper I and Paper II), we introduced a new way to explore the physics of Type Ia SN explosions. We have proposed to compare the X-ray emission from the shocked ejecta in Type Ia Supernova Remnants (SNRs) with synthetic X-ray spectra generated from hydrodynamic calculations of the interaction of a grid of Type Ia SN explosion models with the surrounding ambient medium (AM), coupled to nonequilibrium ionization (NEI) calculations and an X-ray spectral code.

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This comparison is possible because, for the first time in history, X-ray observations of SNRs with high spatial and spectral resolution have become available thanks to *Chandra* and *XMM-Newton*. Among the SNRs that can be observed with sufficient detail, many are still young, and their X-ray spectra are dominated by the emission from the shocked SN ejecta. Several of them are thought to be of Type Ia origin, like the Tycho SNR (SN 1572), SN 1006 and the Kepler SNR (SN 1604) in our Galaxy, or 0509-67.5, DEM L71 and N103B in the Magellanic Clouds. Here, we present the results from comparison between our models and the X-ray spectrum the Tycho SNR.

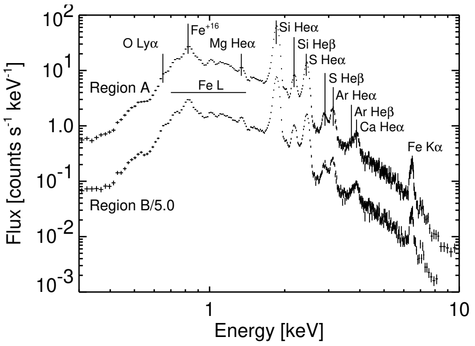

Fig. 1. Spatially integrated *XMM-Newton* EPIC-MOS spectra extracted from two regions (A and B) in the western side of the Tycho SNR. Region A encompasses approximately 40% of the SNR, and region B is a subset of region A. The most important emission lines have been labeled for clarity.

2. Modeling the X-ray Spectrum of the Tycho SNR

Tycho is one of the brightest X-ray SNRs in the sky, and has been observed in great detail at all wavelengths from the radio to γ-rays. In the X-rays, it has been a primary target for all the major satellite missions, including *ASCA*, *Chandra*, and *XMM-Newton*. Among the conclusions drawn from these observations, we highlight the following:

- The outer edge of emission, which coincides in the X-rays and in radio observations, can be identified with the forward shock (FS).
- The integrated X-ray spectrum of the SNR is dominated by strong emission lines from Fe, Si, S, Ar, Ca and other elements.
- The X-ray emission from the shocked AM just behind the FS is a featureless continuum (Hwang et al., 2002; Warren et al., 2005). This implies that all the X-ray line emission has to come from the shocked ejecta.
- The peak of the Fe Kα line emission is at lower radii than that of the Fe L or Si Heα emission (Hwang & Gotthelf, 1997). This Fe Kα emission comes from material with a higher temperature and a lower ionization timescale than the rest of the ejecta (Hwang et al., 1998).

The *XMM-Newton* EPIC MOS spectrum of the Tycho SNR is presented in Figure 1. As shown in Warren et al. (2005), the continuum emission from the AM is produced by a FS whose dynamics is strongly modified by cosmic ray (CR) acceleration (see Decourchelle et al., 2000). This brings the contact discontinuity between shocked ejecta and shocked AM very close to the FS. The reverse shock, on the other hand, is deep into the ejecta, and the material close to it is very hot (as shown by the morphology of Fe Kα emission), so CR acceleration at the reverse shock seems unlikely.

Using these observational results as a starting point, we attempt to model the X-ray emission from the shocked ejecta with the models described in Papers I and II. Since all the X-ray line emission comes from the shocked ejecta, we have used the line flux ratios and line centroids determined from the *XMM-Newton* spectrum to reduce the dimensionality of the problem and identify the most promising models. This is illustrated in Figure 2, where we compare the line emission from the Tycho SNR with the synthetic spectra for the shocked ejecta at a SNR age of $t = 430$ yr of two Type Ia SN models, a one-dimensional delayed detonation (DDTc) and a deflagration calculated in three dimensions (B30U). Each panel of Fig. 2 corresponds to one of the eight line flux ratios (top two rows of panels) and five line centroids (bottom row of panels) that we have considered, for a total of thirteen observ-

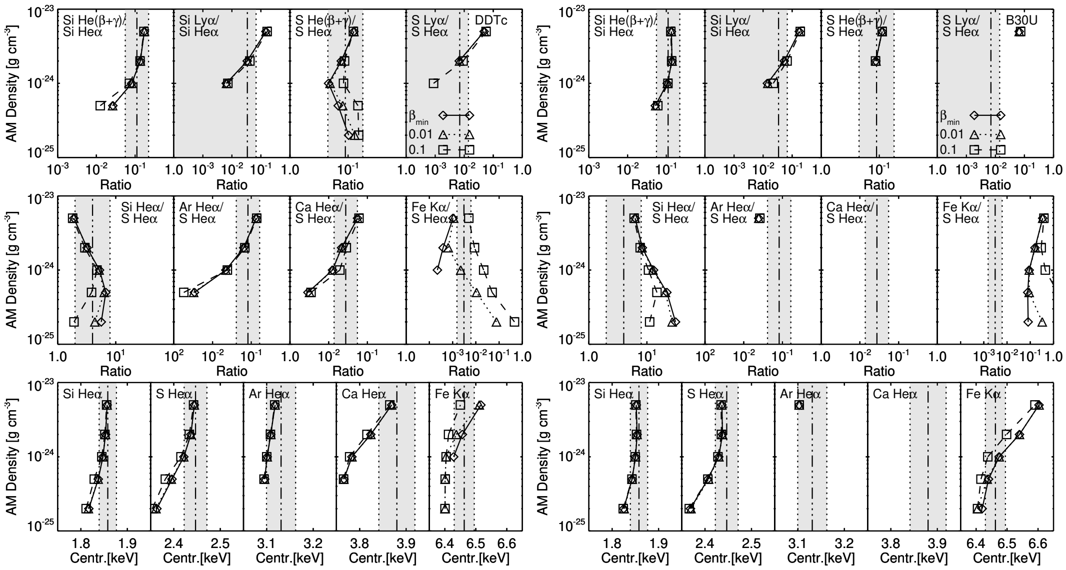

Fig. 2. Line flux ratios and line centroids predicted for the delayed detonation model DDTc (left) and the three-dimensional deflagration model B30U (right). Values are given as a function of ρ_{AM} (vertical axes), and for three different values of β: β_{min} (diamonds, solid line), 0.01 (triangles, dotted line), and 0.1 (squares, dashed line). If a particular flux ratio or centroid is missing, this indicates that the relevant line in the synthetic spectrum is either very weak or altogether absent. The values determined from the *XMM-Newton* spectrum of the Tycho SNR are plotted as vertical lines, and tolerance ranges are given, with allowed regions shaded in grey.

able parameters. The observed values are represented by vertical lines, with appropriate tolerance ranges and allowed regions shaded in grey. For each Type Ia explosion model, we vary the values of ρ_{AM} (the density of the AM that is interacting with the ejecta) and β (the amount of collisionless heating of electrons at the reverse shock, defined as the ratio of electron to ion postshock specific internal energy $\varepsilon_{e,s}/\varepsilon_{i,s}$) within ranges that are reasonable for the Tycho SNR. See Papers I and II for details on the Type Ia models, definitions of the parameters and a complete explanation of the simulation scheme.

Models DDTc and B30U are provided here just as representative examples - a more detailed exploration of the parameter space for Type Ia SN explosions will be given in the forthcoming refereed paper. As can be seen in Fig. 2, model DDTc is much more successful than B30U. At $\rho_{AM} = 2 \cdot 10^{-24}\,\mathrm{g} \cdot \mathrm{cm}^{-3}$ and $0.01 < \beta < 0.1$, model DDTc is capable of reproducing twelve of the thirteen observable parameters, the only exception being the centroid of the Ca Heα line. Model B30U, on the other hand, cannot reproduce even the fundamental properties of the Fe and Si line emission for any combination of ρ_{AM} and β, with important lines like Ar Heα and Ca Heα being altogether absent from the synthetic spectra. When this kind of comparison is performed using other models, the conclusion is that only one-dimensional delayed detonations have any hope of reproducing the fundamental characteristics of the line emission from the Tycho SNR. All other models fail, including one-dimensional deflagrations, sub-Chandrasekhar explosions and pulsating delayed detonations. The three-dimensional deflagration models with well-mixed ejecta also fail, because the absence of stratification in the ejecta cannot account for the different spectral properties of Fe and Si (see discussion in Section 3 of Paper II).

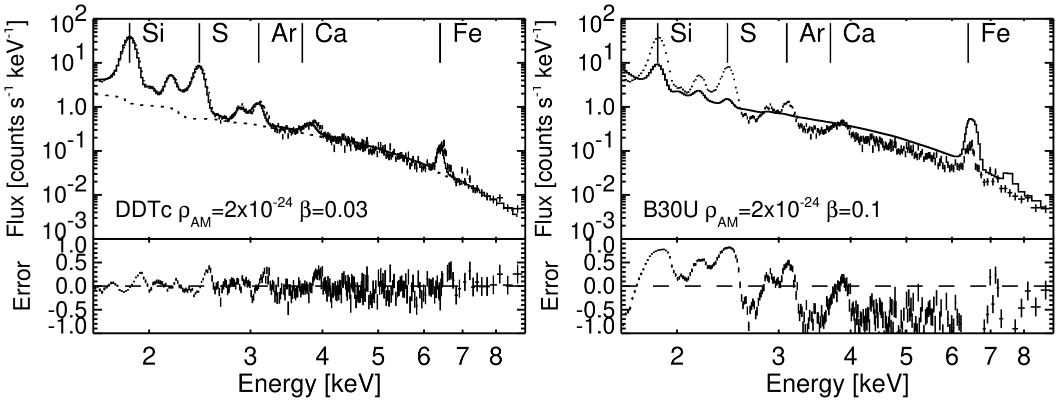

Fig. 3. Comparison of the synthetic spectra with the best combination of ρ_{AM} (in g $\cdot$ cm^{-3}) and β, for models DDTc (left) and B30U (right) with the *XMM-Newton* observation of the Tycho SNR. The dotted line in the DDTc plot represents the power law continuum with index 2.72 (after Fink et al., 1994) added to model the contribution from the shocked AM emission. The continuum from the shocked ejecta in model B30U is so high that the fit did not admit an additional power law component.

Once the most promising values of ρ_{AM} and β have been identified through the properties of the line emission, the entire synthetic spectra can be compared with the observations to evaluate the performance of the models. In Figure 3, we plot the synthetic spectra of model DDTc (with $\rho_{AM} = 2 \cdot 10^{-24}$ g $\cdot$ cm^{-3} and $\beta = 0.03$) and model B30U (with $\rho_{AM} = 2 \cdot 10^{-24}$ g $\cdot$ cm^{-3} and $\beta = 0.1$), alongside the integrated *XMM-Newton* spectrum. The fit obtained with model DDTc is quite impressive, with absolute errors comparable to the quality of the atomic data in the X-ray spectral codes. It is worth noting that the normalization of the flux in the synthetic spectra to the observed flux yields an estimate for the distance D to the SNR. This 'normalization distance' D_{norm} is important, because the effect of CR acceleration at the FS makes it very difficult to constrain D by methods that rely on the dynamics of the FS. In the case of the DDTc model presented here, $D_{norm} = 2.7$ kpc, a value that is within the $1.5 < D < 3$ kpc range proposed by Smith et al. (1991).

Any successful model for the X-ray emission from the Tycho SNR must be able to reproduce the spatial distribution of the line emission as well as the integrated spectrum. In particular, it has to provide an explanation for the fact that the Fe Kα line peaks interior to both Fe L and Si Heα. In Section 2.4 of Paper II we proposed that collisionless electron heating at the reverse shock could provide such an explanation, by increasing the electron temperature in the innermost shocked ejecta and exciting Fe Kα emission close to the reverse shock. We illustrate this in Figure 4, where we plot the surface brightness profile of the Si Heα and Fe Kα lines, along with that of the 4 to 6 keV continuum emission for model DDTc with $\rho_{AM} = 2 \cdot 10^{-24}$ g $\cdot$ cm^{-3} and $\beta = 0.03$. Qualitatively, these surface brightness profiles are similar to those obtained by *XMM-Newton* (Decourchelle et al., 2001) and *Chandra* (Warren et al., 2005), but a detailed quantitative comparison with the data is required in order to draw conclusions. This issue will also be addressed in the forthcoming paper.

We stress that, even though our analysis of the ejecta emission is based on adiabatic one-dimensional models, the approximations we have made are well justified. Sorokina et al. (2004) have claimed that thermal conduction and radiative losses in the SN ejecta need to be taken into account for Type Ia SNRs, but there is no observational evidence to support these claims. No trace of radiatively cooled ejecta has been found Tycho (see Smith et al., 1991), and the morphology of the Fe Kα emission can only be explained if there is a temperature gra-

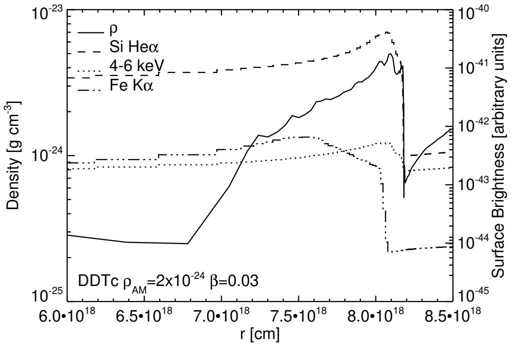

Fig. 4. Surface brightness profiles of the Si Heα line, 4 to 6 keV continuum and the Fe Kα line for model DDTc with $\rho_{AM} = 2 \cdot 10^{-24}\,\mathrm{g \cdot cm^{-3}}$ and $\beta = 0.03$. The region of the model represented here corresponds mostly to the shocked ejecta: the reverse shock is at a radius of $\sim 7.2 \cdot 10^{18}$ cm and the contact discontinuity at $\sim 8.2 \cdot 10^{18}$ cm.

dient in the shocked ejecta, which is incompatible with efficient thermal conduction.

3. Conclusions

In this contribution, we have summarized the main results of our ongoing efforts to use the X-ray emission from the Tycho SNR to constrain the physics of Type Ia SN explosions. These results are very promising: we have found that only one class of models, one-dimensional delayed detonations, is capable of reproducing the fundamental properties of the ejecta emission. Among the delayed detonations, the preferred model is DDTc, with $E_k = 1.16 \cdot 10^{51}$ erg and 0.8 solar masses of ^{56}Ni. This model provides a good approximation to the integrated X-ray spectrum for $\rho_{AM} = 2 \cdot 10^{-24}\,\mathrm{g \cdot cm^{-3}}$ and $\beta = 0.03$. Other constraints, like the surface brightness profile of the most relevant lines, the normalization distance D_{norm}, and the apparent radii of the contact discontinuity and the reverse shock, are also in agreement with the observations (see Warren et al., 2005). More details will be provided in the forthcoming refereed paper.

It is remarkable that the sophisticated three-dimensional deflagration models with well-mixed ejecta published by several groups (see Bravo et al., 2005, for a review) fail to reproduce the fundamental properties of the X-ray emission from Tycho, in particular the fact that Fe and Si have different spectral properties. This indicates that some degree of elemental stratification must exist in Type Ia SN ejecta. The ultimate physical cause of this stratification remains an open issue, and even though some explanations have been proposed, no self-consistent model for Type Ia explosions exists yet.

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