OPENING A NEW WINDOW ONTO THE PHYSICS OF TYPE Ia SUPERNOVAE

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The excellent X-ray observations of Type Ia Supernova Remnants (SNRs) provided by Chandra and XMM-Newton, together with hydrodynamic + nonequilibrium ionization (HD+NEI) modeling, can put strong, quantitative constraints on the physics of Type Ia supernovae (SNe).

- Physics of Type Ia SN explosions: still many open issues.
- From SN to SNR: challenges and techniques. HD+NEI simulations.
- Results:
  - Tycho SNR: only delayed detonation models can explain the fundamental properties of the X-ray emission. All other explosion paradigms fail (in particular, 3D deflagrations with well-mixed ejecta can be confidently discarded).
  - SN1006 SNR: preliminary results also suggest a delayed detonation model.
- Conclusions.
The Physics of Type Ia SNe: Ejecta Structure

- Thermonuclear explosion of a C+O WD in a binary system (but many important details are still obscure).
- Type Ia SNe: ejecta structure ↔ physics of the explosion.
- This relationship has been explored extensively with 1D codes:
  - More recently, 3D simulations have become available: Roepke et al. 2006 A&A 448, 1

SNRs: Light From The Ashes

- **Supernova Remnants (SNRs):** interaction between SN ejecta and the surrounding ambient medium (AM).

- **Supersonic shock waves** (~$10^3$ km.s$^{-1}$) heat AM and ejecta to X-ray emitting temperatures ⇒ centuries after the light of the SN fades away, the ejecta are revealed once again.

- **Chandra** and **XMM** provide observations of excellent quality ⇒

- The dynamics and X-ray emission of young SNRs (Tycho, SN1006, Kepler, Cas A) are dominated by SN ejecta.

There is a lot of information about the structure of the SN ejecta in the X-ray emission of the SNR, but it needs to be properly analyzed and interpreted.
From SN explosion to SNR (I)

3D Type Ia SN model by F. Röpke

t=10 s

Hydrodynamics
Nonequilibrium Ionization
X-ray emission

9 decades in time!

➢ Low ρ plasma in SNRs is in Nonequilibrium Ionization (NEI).

From SN explosion to SNR (II)

- Complete hydro + nonequilibrium ionization simulation in 1D, uniform AM.
- Parameters: AM density, $\rho_{AM} = 10^{-24} \text{ g.cm}^{-3}$; SNR age, $t_{SNR} = 430 \text{ yr}$; amount of collisionless $e^-$ heating at the RS, $\beta [\equiv \epsilon_{e,s}/\epsilon_{i,s}] = \beta_{\text{min}} \ldots 0.1$.
- Different chemical elements emit X-rays under different conditions.

SN Explosion model:

- Parameters: $\rho_{AM} = 10^{-24} \text{ g.cm}^{-3}$; $t_{SNR} = 430 \text{ yr}$; $\beta = \beta_{\text{min}} \ldots 0.1$.

Synthetic SNR X-ray spectrum:

- Different chemical elements emit X-rays under different conditions.

HD + NEI simulation
Tycho SNR: Evidence for Cosmic Ray Acceleration

- FS is very close to CD ($R_{CD} \approx 0.93R_{FS}$) ⇒ Cosmic Rays are being accelerated at the FS [Warren et al. 2005, ApJ 634, 376].


- RS is NOT accelerating CRs:
  - Not close to CD.
  - Traced by hot Fe Kα

- CR acceleration at the FS does not appear to disturb the dynamics of the shocked ejecta [Blondin & Ellison 2001, ApJ 560, 244].

⇒ standard HD+NEI models seem appropriate for the shocked ejecta

Tycho SNR: Models vs. Data – The Winner

➢ Compare ejecta emission to observed spectrum ⇒ add AM emission: Power law with $\Gamma=2.72$ [Fink et al. 1994 A&A 283, 635].

➢ Best model: DDTc (1D delayed detonation), $\rho_{AM}=2\times10^{-24} \text{ g.cm}^{-3}$, $\beta=0.03$.

Things to note:

➢ Only $N_H$ and the normalizations are fitted.

➢ The ejecta model reproduces the emission from ALL elements: O, Si, S, Ar, Ca, and Fe.

➢ Fit is very good, but not perfect.

➢ Continuum is mostly nonthermal AM emission.
Other delayed detonations are also successful at high energies (E>1keV).

Low-energy (E<1keV) emission ⇒ strong constraints on the amount of $^{56}\text{Ni}$ and O synthesized in the explosion ⇒ $\rho_{tr}$. 

![Graphs showing normalized abundances and fluxes for different models of the Tycho SNR.](image)
Tycho SNR: Models vs. Data – The Losers

- All models that are NOT delayed detonations FAIL:

  - Best Pulsating Delayed Detonation
    - PDDa ($p_A = 0.2$, $\beta = 0.005$); $N_H = 0.76$

  - Best 1D Deflagration
    - W7 ($p_A = 0.5$, $\beta = 0.1$); $N_H = 1.07$

  - Best sub-Chandrasekhar
    - SCH ($p_A = 0.5$, $\beta = 0.01$); $N_H = 1.03$

  - Best 3D Deflagration
    - b30_3d_768 ($p_A = 0.2$, $\beta = 0.01$); $N_H = 2.33$
The thermal X-ray emission in SN1006 is also dominated by ejecta.

Model DDTe ($\rho_{AM} = 2 \times 10^{-25}$ g cm$^{-3}$, $\beta = 0.1$) + powerlaw + absorption.

Work in progress, but DDT models are the only ones that work well so far...
Looking back, looking ahead

➢ So far:

➢ 1D HD+NEI models without CR acceleration can reproduce the fundamental properties of the spatially integrated X-ray emission from SN ejecta in Tycho and SN1006.

➢ Direct link to explosion physics. For Tycho, model DDTc: $E_k = 1.16 \cdot 10^{51}$ erg, $M_{\text{Fe}} = 0.8 \ M_\odot$, $M_{\text{O}} = 0.12 \ M_\odot$, $M_{\text{Si}} = 0.17 \ M_\odot$, $M_{\text{S}} = 0.13 \ M_\odot$, $M_{\text{Ar}} = 0.033 \ M_\odot$, $M_{\text{Ca}} = 0.038 \ M_\odot$.

➢ Description of BOTH X-ray emission and ejecta dynamics.

➢ The library of synthetic spectra is PUBLIC!

➢ For the future:

➢ CR acceleration is needed to explain the dynamics of young SNRs.

➢ Understanding the spatially resolved X-ray emission from the SN ejecta will require multi-D HD+NEI simulations.
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- **Relevance to Type Ia SNe:** SNRs provide results that are completely independent from those obtained using optical light curves and spectra.

- **Relevance to SNRs:** understand the X-ray emission from the SN ejecta (and hence dynamics, CR acceleration, etc.).

**RESULTS:**

- **Tycho SNR:** only delayed detonation models can explain the fundamental properties of the X-ray emission. All other explosion paradigms fail (in particular, 3D deflagrations with well-mixed ejecta can be confidently discarded).

- **SN1006:** preliminary results also suggest a delayed detonation model.