Thermalization effects in late-time Type Ia Supernova light curves

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Abstract

We investigate how sensitive the late-time light curves of supernovae Ia are to magnetic fields and sources of radioactivity, and assess whether these effects are sufficient to explain the differences observed in the light curve tails of "twin" supernovae 2011fe and 2011by. This will further our understanding of how stars explode as supernovae and may help explain the origin of energetic lepton anti-particles that are found in our galaxy.

Introduction

Type Ia supernovae (SNeIa) are believed to be explosions of white dwarfs that have been accrediting matter from nearby companions until reaching the Chandrasekhar limit of 1.4M$_\odot$. As standard candles, they are useful cosmological distance indicators, and have been instrumental in providing evidence for the expansion of the universe and dark energy. In late times, SNe Ia become optically thin and transition to the nebular phase. In the standard SNe model, energy from positrons emitted in the decay of 56-Cobalt heats the SN ejecta and provides the late-time luminosity. The late-time light curve therefore serves as a window into the nucleosynthesis powering the supernova.

"Twin" SNe 2011fe and 2011by

The bolometric light curves of twins SN2011by and SN2011by peak on similar time scales, and have nearly identical rates of decline out to fairly late times. However, in the nebular phase, SN2011fe fades more quickly in brightness. Their distinct late-time light curves may reflect differences in the ability of the supernova remnants to **absorb** leptons' kinetic energy. The similar light curve shapes imply similar mass and explosion energies, making the late time discrepancies all the more puzzling. Differences in late-time luminosity (thermalization) might point to differences in the magnetic field, or different sources of radioactive energy.

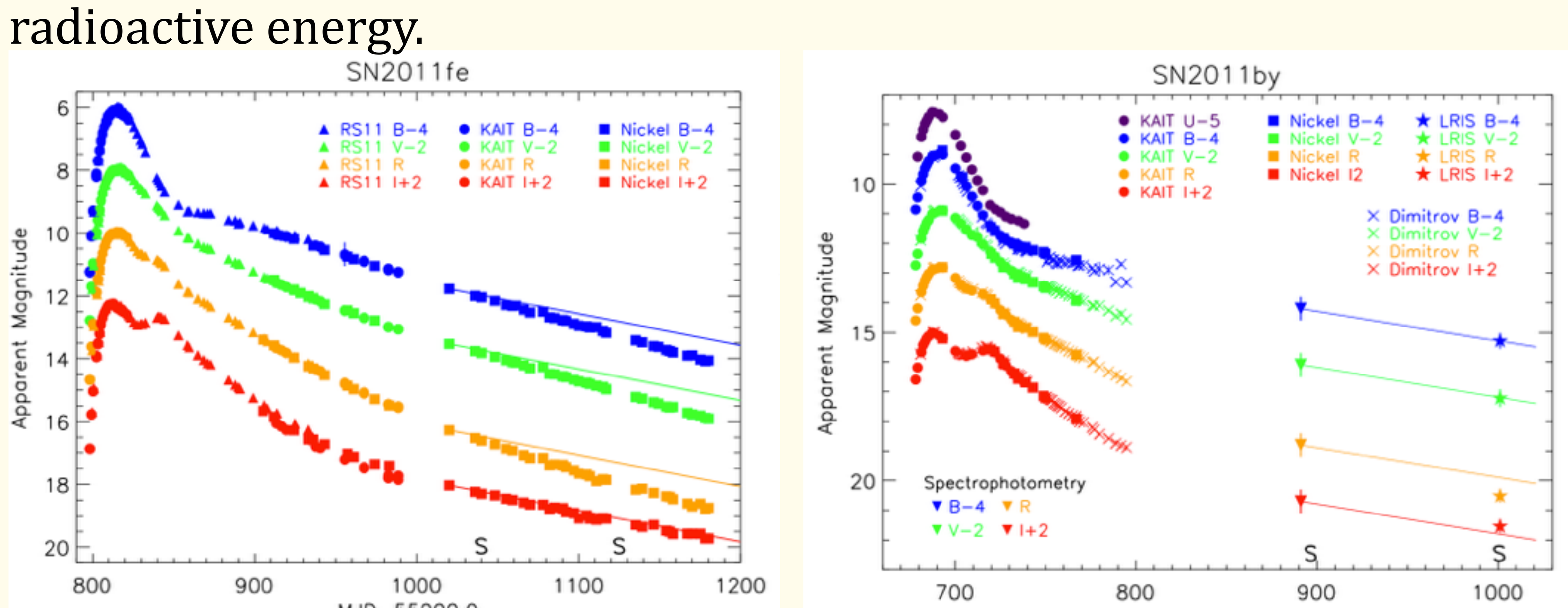


Figure 1: Light curves of SN 2011fe (left) and SN 2011by (right from Graham et al. 2104.. For both plots, a line representing cobalt decay of 0.01 mag day^{-1} has been extended from a light-curve point around day +200.

Possible explanations for distinct late-time light curves

- **toroidal or tangled** fields trap leptons in the ejecta and **enhance heating.** Leptons will move out of the ejecta easier in a **radial** field
- **radioisotopes** other than Cobalt-56 are produced, and their distinct emission profiles **impact heating**

Thermalization Model

Thermalization in the ejecta depends on:

- **composition** because it sets the properties of background material such as **isotope mass**, **atomic number**, and **ionization energy** which influence energy loss rates (see formulae below)
- mass and velocity set the **ejecta density**, which is important because higher densities thermalize faster
- initial **energy** of the positrons emitted
- **magnetic fields** because they influence charged particles' trajectories through the ejecta

Energetic positrons born inside the ejecta lose energy while traveling through the material. The main energy loss is due to **ionization and excitation** of atoms. This energy loss rate is:

$$\dot{E}_{IE} = \frac{2\pi r_e^2 m_e c^4 n_{e,b}}{v_\beta}\Pi(E)$$

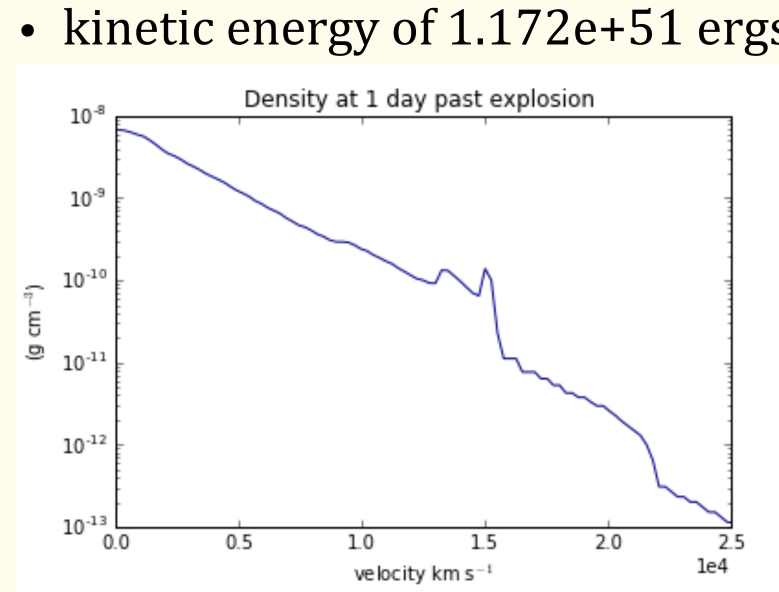
where $n_{e,b}$ is the number density of bound electrons

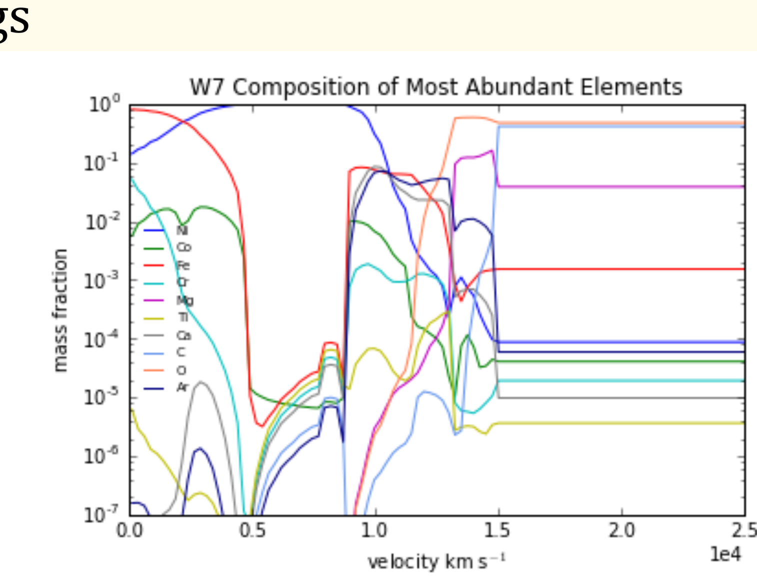
$$\Pi(E) = \ln\left(\frac{\sqrt{\gamma-1}\,\gamma\beta}{\bar{I}/m_e c^2}\right) + \frac{1}{2}\ln(2) - \frac{\beta^2}{12}f(\gamma)$$

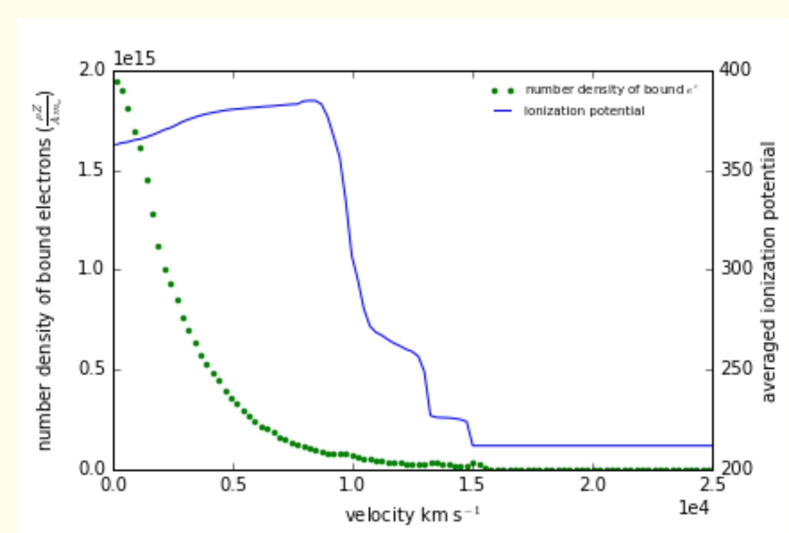
From above, $\bar{I}$ is an average ionization/excitation potential, and $f(\gamma)$ is a function that accounts for relativistic effects. We use mass-fraction averaged quantities for $\bar{I}$ and $n_{e,b}$, which we calculate at every point in velocity space.

SN Ia Model: W7 (pure deflagration)

- ejected mass of 1.378 M$_\odot$
- nickel mass of 0.78 M$_\odot$
- kinetic energy of 1.172e+51 ergs
- quasi-exponential density profile
- composition that varies in space







- higher densities toward the center of the ejecta result in more efficient thermalization.
- lighter elements have lower ionization potentials, and thermalize slightly more efficiently than heavier elements

Preliminary Results

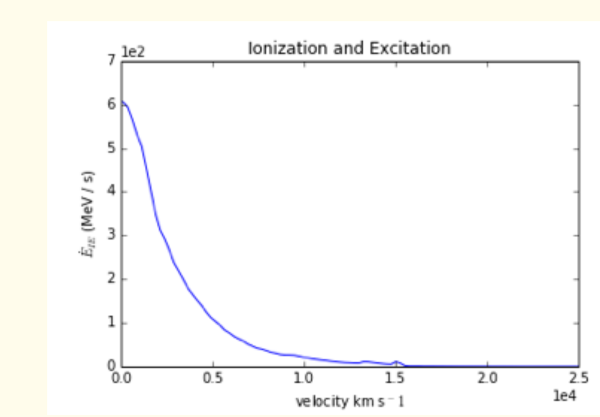
Calculating thermalization efficiencies

We calculate thermalization numerically. Positrons emitted from the decay of 56-Co are propagated through a 3D grid where they interact with the ambient medium as described in the second panel. The simulation tracks energy losses in these interactions.

Positron energy loss rates

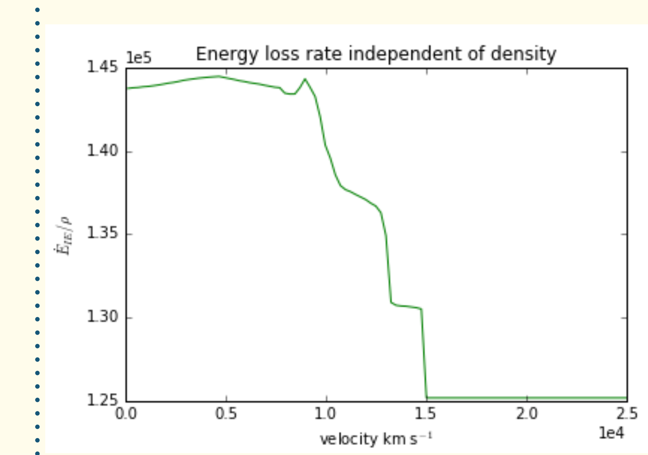
Effect of density

- density is the most important factor for energy loss rates



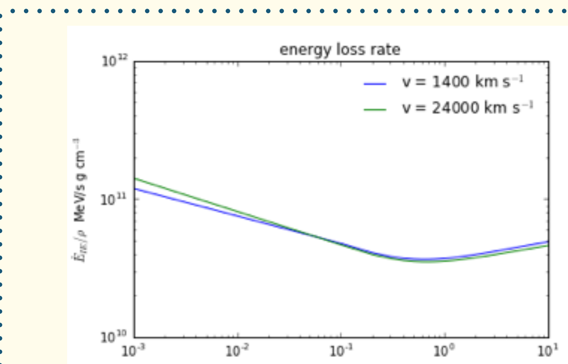
Effect of composition

- compositional gradients have a minor effect on heating

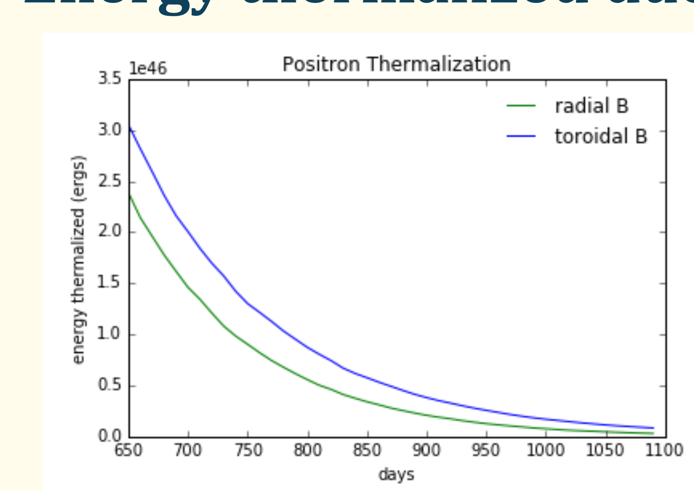


Effect of positron energy

- we show the dependence of energy loss rates (normalized to mass density) on the positron's kinetic energy



Energy thermalized due to varying magnetic fields



- Thermalization of positrons is sensitive to ejecta properties
- We study energy thermalized for radial and tangled fields
- Toroidal fields thermalize more energy by 25% at 650 days

Further Analysis

- Thermalization due to random magnetic fields has not been explicitly calculated. However we know radial and toroidal fields form our bounds
- We will account for other radioisotopes such as 44-Ti and analyze if their distinct emission profiles impact heating
- We will look at different supernova models

References:

For SN2011fe and SN2011by properties: Graham et al. 2014 (MNRAS 443:2887)
On thermalization in SNeIa: Chan & Lingenfelter, 1993 (ApJ 405:614)
For W7 Model: Nimoto et al. 1984