Monte Carlo radiative transfer for the nebular phase of Type Ia supernovae

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Type Ia nebular phase

Around tens to hundreds of days after explosion, rapidly-expanding Type Ia ejecta start to become optically thin at most wavelengths. With a weak radiation field and slow collisional excitation rates, only the lowest-energy states of Fe-group ions remain populated, which can only decay to their ground states by radiatively-forbidden transitions. The observed spectra are dominated by emission from forbidden lines of singly- and doubly-ionised species, primarily Fe, Co, and Ni.

High-energy deposition by ^{56}Co

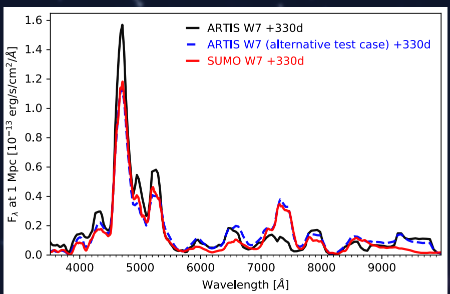
With most of the ^{56}Ni nuclei having decayed before the nebular phase, the energy injection at this time is mostly supplied by the decay of ^{56}Co. These decays release gamma rays and positrons, which Compton and Coulomb scatter with thermal electrons and produce a population of high-energy (~MeV) non-thermal electrons. The non-thermal electrons are crucially important for setting the ionisation balance, as the non-thermal ionisation rates are generally higher than photoionisation for the Fe-group ions in this phase.

ARTIS radiation transport code

ARTIS (Sim 2007, Kromer & Sim 2009) is a multi-dimensional radiation transport code that uses the Monte Carlo method with indivisible energy packets (Lucy 2002) to produce synthetic light curves and spectra. We have extended the range of validity to late times by adding:

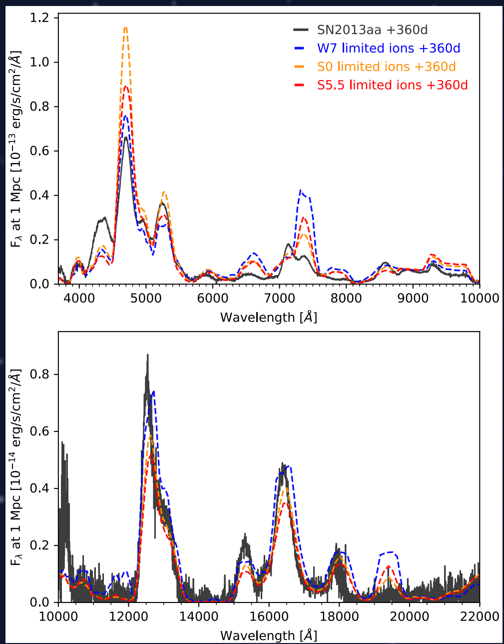
- a non-LTE population solver (including ionisation to/recombination from excited levels),
- a non-LTE binned radiation field model (replacing the dilute blackbody approximation),
- detailed photoionisation rate estimators using the photon packet flight paths (Lucy method)
- a detailed treatment of non-thermal ionisation, excitation and heating (Spencer & Fano 1954, similar to Kozma & Fransson 1992) including Auger electrons that can result in multiple ionisations and,
- a comprehensive new atomic database with forbidden transitions based on the CMFGEN compilation (Hillier et al. 1998) with Fe photoionisation from Nahar (1994, 1996) and Co data from Tyndall et al. (2016).

We validate our implementation by calculating nebular spectra for the well-known W7 deflagration model (Nomoto et al. 1984; Iwamoto et al. 1999), which we compare to results from the SUMO code (Fransson & Jerkstrand 2015). We also show an alternative test case that includes an older recombination rate for Ni^{2+} and limits the maximum ion charge to 2+, as high ionisation stages were not included in the SUMO calculation.



Sub-M_{ch} with gravitational settling

We present synthetic nebular spectra for two 1.06 $M_\odot$ sub-Chandrasekhar detonation models calculated by Michel (2014, thesis): one without gravitational settling prior to explosion (S0), and an upper limit case with a high diffusion coefficient and 5.5 Gyr of settling (S5.5). We find that gravitational settling has a modest effect on the spectrum (due to the transport of n-rich ^{22}Ne to the core leading to increased production of ^{58}Ni). Our spectra and detailed models will be presented in Shingles et al. (2019 MNRAS submitted). One result is the comparison below with SN2013aa observations by Maguire+ (2016). The diversity of features and strengths in the near-infrared (especially [Ni II] 1.9μm) hint at the potential of this region of spectrum to constrain explosion scenarios for Type Ia supernovae.



Future work in 3D

Having produced synthetic nebular spectra for several 1D explosion models, we will soon present nebular spectra for a variety of other explosion models, including the 3D deflagration-to-detonation transition models of Seitenzahl et al. (2013) and the 3D violent merger models of Pakmor et al. (2012). The presence of optical-depth effects on Fe lines is one hint that 3D results could be substantially different from those of 1D. The calculation of full-3D nebular radiative transfer models for 3D explosion composition profiles is incredibly computationally demanding, but we have optimised our simulation code to remain viable when scaling up to 50^3 grid cells and expect to obtain results for 3D models in the near future.

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Image: SNR G299.2-2.9. X-ray: NASA/CXC/U.Texas/S.Post et al, Infrared: 2MASS/UMass/IPAC-Caltech/NASA/NSF