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Monte Carlo Radiative Transfer Simulations: Applications to Astrophysical Outflows and Explosions

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Abstract. The theory of radiative transfer provides the link between the physical conditions in an astrophysical object and the observable radiation which it emits. Thus accurately modelling radiative transfer is often a necessary part of testing theoretical models by comparison with observations. We describe a new radiative transfer code which employs Monte Carlo methods for the numerical simulation of radiation transport in expanding media. We discuss the application of this code to the calculation of synthetic spectra and light curves for a Type Ia supernova explosion model and describe the sensitivity of the results to certain approximations made in the simulations.

1. Monte Carlo Radiative Transfer

Since almost all we know about astronomical objects is inferred from the radiation which they emit, the theory of radiation transport often has a key role in testing our understanding of astrophysics. Although there are a variety of competitive approaches used for radiative transfer simulations, Monte Carlo methods are particularly well-suited for many modern astrophysical applications. In the Monte Carlo approach, the radiation field is discretized into quanta which represent bundles of photons. By propagating these quanta through a model of an astrophysical object, and simulating their interactions, synthetic spectra and light curves can be obtained. This method has the particular advantage that matter-radiation interactions are always treated locally meaning that multi-dimensionality, time-dependence and large-scale velocity fields can all be incorporated readily.

2. The ARTIS code

Here we describe a new radiative transfer code (ARTIS; Kromer & Sim 2009) which has been developed for application to Type Ia supernova (SN Ia) explosion models. The code is based on a Monte Carlo *indivisible packet* scheme described by Lucy (2002, 2003, 2005) and was developed from the grey radiative transfer code of Sim (2007).

The code is designed to simulate time-dependent, three-dimensional radiation transport in supernova ejecta during the phase of homologous expansion. The optical display of SNe Ia is powered by the energy released in the radioactive decay of isotopes synthesized during the explosion, predominantly ^{56}Ni and its daughter nucleus ^{56}Co. Therefore, the code starts from an initial distribution of ^{56}Ni in the ejecta and then the subsequent radioactive decays are followed. These decays initially give rise to gamma-ray photons which, at least for early epochs when the ejecta are optically thick, are rapidly down-scattered and absorbed by photoelectric processes. This heats the ejecta. The subsequent re-emission of ultraviolet, optical and infrared emission by the ejecta is then simulated to obtain spectra and light curves. The code does not assume local thermodynamic equilibrium (LTE) but includes an approximate non-LTE (NLTE) treatment of ionization and a detailed approach to line scattering and fluorescence. For a complete description of the code see Sim (2007) and Kromer & Sim (2009).

3. Testing ARTIS with a standard explosion model

To test the ARTIS code we have performed a variety of radiative transfer simulations for the well-known W7 SN Ia explosion model (Nomoto et al. 1984; Thielemann et al. 1986). Although this one-dimensional model is considerably simpler than modern three-dimensional explosion models (e.g. Röpke & Niemeyer 2007; Röpke et al. 2007), it is known to predict spectra and light curves in reasonable agreement with observations (e.g. Jeffery et al. 1992; Höflich 1995; Nugent et al. 1997; Lentz et al. 2001; Baron et al. 2006; Kasen et al. 2006) and therefore provides a realistic test model for our radiative transfer simulations.

For our W7 test simulations, the explosion model properties (ejecta density, composition and initial distribution of radioactive isotopes) were mapped to a homologously expanding 50^3 Cartesian grid and the expansion followed for 100 logarithmically-spaced time steps spanning the time interval from 2 to 80 days after explosion. The assumption of homologous expansion in the W7 model has been tested using the STELLA code in a manner similar to that described by Woosley et al. (2007). That test showed that the density structure is affected only slightly during the first weak after explosions and that thereafter homologous expansion becomes a very good approximation. The propagation of a total of five million Monte Carlo energy packet quanta were simulated from their initial release by the radioactive decay of either ^{56}Ni or ^{56}Co until, after multiple radiation-matter interactions, they escaped from the computational domain as bundles of ultraviolet, optical or infrared (UVOIR) photons. The escaping packets were then binned by time of escape and photon frequency to construct time-dependent spectra for the model. Since the W7 model is one-dimensional, it is unnecessary to bin the escaping quanta based on direction of scape but this can be readily done to obtain viewing-angle dependent spectra for multi-dimensional models.

3.1. Synthetic spectra from ARTIS

Figure 1 shows a sequence of three optical spectral snapshots obtained with the ARTIS code for the W7 model. A convenient property of Monte Carlo radiative transfer simulations is the ease with which the propagation histories of the Monte

Carlo quanta can be used to understand the manner in which the spectra features are formed. For each escaping quantum, ARTIS records the details of its last radiation-matter interaction with either a bound-bound, bound-free or free-free event. This information can then be used to identify the processes responsible for features in the spectra. In Figure 1, the areas above and below the total spectrum are shaded to indicate the atomic number of the elements which last affected the escaping quanta for each wavelength bin. This makes it easy to understand how the spectral features are formed and one can readily see how the contributions to the spectra evolve in time. For example, in Figure 1 it is clear from the shading that the early phase spectra are strongly affected by intermediate-mass elements such as Si and S while the later time spectra are dominated by elements of the iron group. This is a well-known consequence of the layered structure of the W7 model. At early times, the outer layers (which are rich in the products of partial nuclear burning) are optically thick. As time passes, however, the expansion of the ejecta causes these layers to become optically thin such that radiation escapes directly from the inner region which is dominated by iron group material.

For comparison, the observed spectra of a fairly normal SN Ia (SN 1994D, Patat et al. 1996) are over-plotted for the same epochs. The overall flux distribution and general properties of the observed spectral features (e.g. the characteristic Si II line at 6355Å and the Ca II infrared triplet at 8549Å) are reasonably well-reproduced by the model, suggesting that the numerical simulations capture much of the necessary physics required for the interpretation of the observations. There are, however, some clear discrepancies between the observational data and the synthetic spectra (e.g. excess emission below ∼4000Å in the early-time model spectra and an extra emission feature around ∼6500Å in the later time spectrum) – but some disagreement is expected since the W7 model has not been fine-tuned to match observations of any specific SN in detail.

3.2. Sensitivity to plasma conditions

Multi-dimensional radiative transfer simulations for SNe Ia require significant computational resources and approximations must currently be made to make the simulations feasible. Two particularly important issues are the completeness of the atomic data set used and the sensitivity of the synthetic observables to the treatment of the plasma conditions (particularly the excitation/ionization state). We have therefore used the W7 model as a standard case to investigate some of these effects with ARTIS; photometric light curves computed from several of our numerical simulations are shown in Figure 2. We also compared our results with those of other SN radiative transfer codes to quantify the extent to which different numerical methods affect the synthetic observables.

Using the SEDONA code, Kasen (2006) showed that realistic atomic data sets containing many millions of spectral lines are required to accurately model radiation transport in SN Ia. This is particularly true at NIR (near-infrared) wavelengths where the spectrum can be significantly affected by fluorescent emission in forests of weak lines of iron-group elements. This is confirmed by our simulations with ARTIS. Figure 2 shows light curves computed with our approximate NLTE treatment of ionization but adopting different atomic data sets drawn from the line lists computed by Kurucz & Bell (1995) and Kurucz (2006).

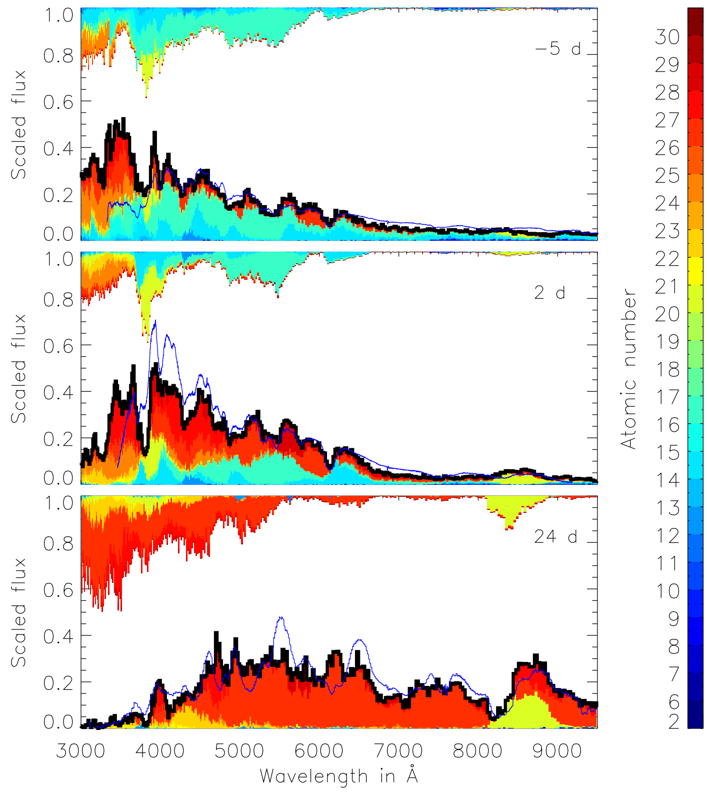

Figure 1. Computed spectra for the W7 model for three epochs: -5, +2 and +24 days measured relative to the maximum of the B-band light curve (which occurs around 19 days after explosion). The emitted model spectra are shown as the heavy black histogram in each panel. The area under the curve is shaded to indicate the elements responsible for the last bound-bound interactions of escaping Monte Carlo quanta in the corresponding frequency bin. The shaded region at the top of each panel identifies which elements were last responsible for removing packets from the corresponding frequency bin (this can be used to identify absorption features in the spectra). The observed spectra of SN 1994D (Patat et al. 1996) are shown for comparison (solid blue lines). These have not been corrected for redshift or extinction.

When we use a reasonably large atomic line list ($\sim 8 \times 10^6$ lines) we obtain NIR light curves which are significantly brighter around their first maximum than with an atomic data set restricted to only $\sim 4 \times 10^5$ lines. The optical light curves are much less affected although there is a tendency for the U, B and V bands to be slightly fainter owing to the flux redistributed from these bands to the NIR. We note that the light curves computed with the larger atomic data set are also in quantitatively better agreement with observations (see Figure 2).

In Figure 2 we also show light curves computed with a pure LTE treatment of the excitation/ionization state of the ejecta. These light curves were obtained using the smaller atomic data set ($\sim 4 \times 10^5$ lines) mentioned above. For early times (up to around 30 days in the optical bands and 20 days in the NIR bands), these light curves agree well with those obtained with our NLTE implementation. This is expected since LTE should be a good approximation when the radiation is strongly trapped. At later times, however, departures from

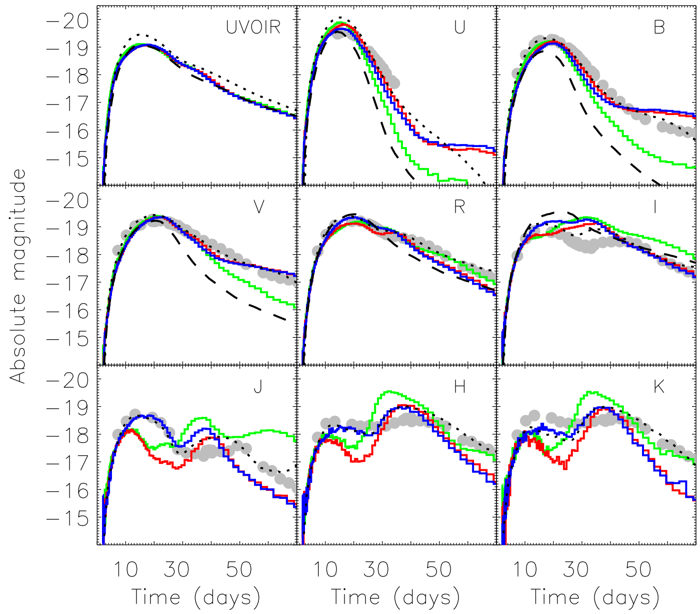

Figure 2. Computed light curves for the W7 model. The panels show the UVOIR bolometric, U, B, V, R, I, J, H and K band light curves obtained from our time-dependent spectra using the filter functions of Bessell (1990) and Bessell & Brett (1988). The solid histograms show the light curves obtained with ARTIS using (i) our approximate NLTE treatment of ionization and an atomic data set containing $\sim 8 \times 10^6$ atomic lines (blue), (ii) NLTE with only $\sim 4 \times 10^5$ lines (red) and (iii) an LTE treatment of ionization with $\sim 4 \times 10^5$ lines (green). For comparison we show observations of SN 2001el (Krisciunas et al. 2003; grey circles) and light curves obtained with the SEDONA (dotted lines) and the STELLA codes (dashed lines; UVOIR, U, B, V, R, and I).

LTE become strong and our NLTE treatment of ionization predicts significantly higher ionization states throughout much of the ejecta. This directly affects the observables causing the U, B and V band to remain significantly brighter than suggested by LTE. This illustrates the sensitivity of the observations to the ejecta properties and highlights the need for a realistic treatment of the plasma conditions if detailed comparisons to observations are to be made.

3.3. Comparison of results from different codes

The agreement between the ARTIS light curves and those obtained by SEDONA (Kasen et al. 2006) and STELLA (Blinnikov & Sorokina 2002; Blinnikov et al. 2006) is encouragingly good (Figure 2). Compared to SEDONA, the ARTIS light curves computed with the larger atomic data set agree very well in all bands up to several weeks after maximum light. The difference which manifest at later times are most likely attributable to difference in the manner in which the codes treat the plasma conditions (see Kromer & Sim 2009 for further discussion). The current version of STELLA adopts an LTE treatment of the plasma conditions with photon redistribution modelled using an approximate source function. As expected, its light curves are similar to those obtained with the LTE implementation in ARTIS. The STELLA light curves shown here were computed with an extended atomic data set containing 2.6×10^7 lines. This atomic data set improves aspects of the comparison with STELLA relative to that shown in figure 7 of Kromer & Sim (2009; the STELLA curves there used only 1.6×10^5 lines). In particular, the initial rise of the STELLA light curves is faster.

4. Future prospects

Our results obtained from the W7 model suggest that our radiative transfer simulations are able to produce realistic synthetic spectra and light curves as required for the testing of SNe Ia explosion models. We have already used the ARTIS code to investigate simple aspherical toy models (Kromer & Sim 2009; Kromer et al. 2009) and will in the near future use it to compute synthetic observables for state-of-the-art hydrodynamical explosions models in order that their predictions can be directly tested against observational data.

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