Lopsided explosion models for Type Ia supernovae

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Abstract. In recent years, considerable progress has been made in the hydrodynamical modelling of possible Type Ia supernovae scenarios and fully three-dimensional explosion simulations can now be carried out, as required for a realistic treatment of turbulent combustion. Some multi-dimensional explosion models predict significant departures from sphericity – one such class of model is that in which ignition takes place off-centre, leading to a lop-sided distribution of the products of nuclear burning. We discuss such a model and present our recent results from multi-dimensional radiative transfer calculations for light curves. We show that viewing-angle effects are significant in such explosions and that they may have a role to play in explaining some unusually bright events.

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INTRODUCTION

The study of Type Ia supernovae (SNe Ia) has relevance to a wide range of astrophysical topics including stellar evolution, the chemical enrichment of galaxies and probing the expansion history of the Universe. Despite their importance, however, these events remain incompletely understood - although the paradigm that they are thermonuclear explosions of white dwarfs with mass close to the Chandrasekhar limit is widely accepted, neither the progenitor systems nor explosion mechanisms are firmly established.

In order to understand and explore possible explosion mechanisms, considerable effort is currently being invested in the advancement of hydrodynamical modelling of SN Ia explosions. In particular, in recent years it has become possible to perform fully three-dimensional hydrodynamical simulations as required to reliably treat the instabilities and turbulence which have key roles in the explosion (e.g. Reinecke, Hillebrandt & Niemeyer 2002; Gamezo et al. 2003, Röpke & Hillebrandt 2005; Röpke et al. 2006; Röpke et al. 2007a; Jordan et al. 2008). To fully test these models it is necessary to undertake multi-dimensional radiative transfer simulations to compute theoretical spectra and light curves. This is a challenging problem involving time-dependent, non-LTE radiation transport in a chemically inhomogeneous environment including both the γ-rays from radioactive decays (which power the SN light curve) and the more readily observable optical-infrared photons. Monte Carlo (MC) methods are particularly well-suited to multi-dimensional radiative transfer and Lucy (2005) has outlined a powerful MC approach which is capable of addressing the requirements of the multi-dimensional SN Ia problem. The utility of his method has been convincingly demonstrated in several subsequent studies (e.g. Kasen, Thomas & Nugent 2006; Maeda, Mazzali & Nomoto 2006, Kasen & Plewa 2007). Following Lucy (2005), we have developed a fully-three

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dimensional Monte Carlo radiative transfer code (Sim 2007) and have used it to study observable consequences of certain classes of aspherical explosion scenarios (Sim et al. 2007; Hillebrandt, Sim & Röpke 2007). Here we described results from one such investigation, for a class of models in which the SN explosion leaves a lop-sided distribution of the products of nuclear burning.

BOLOMETRIC LIGHT CURVES FOR LOP-SIDED MODELS

Three-dimensional hydrodynamical simulations have shown that successful SN Ia explosions could occur following off-centre ignition in a white dwarf (e.g. Röpke et al 2007b). Such an explosion can lead to a significant departure from spherical symmetry in the ejecta leaving a lop-sided distribution of ^{56}Ni (see e.g. fig 5 of Sim et al. 2007). Since SN Ia light curves are predominately powered by the decay of ^{56}Ni and its daughter nucleus ^{56}Co, this can be expected to make observables such as the light curve sensitive to the orientation of the observer line-of-sight. To quantify this effect and establish its possible role in the interpretation of observations we have undertaken a series of radiative transfer simulations to obtain light curves for such models (Sim et al. 2007). These simulations follow the emission and propagation of γ-rays from the decay of ^{56}Ni and ^{56}Co in detail but adopt a simplified grey-approximation for the transport of ultraviolet, optical and infrared (UVOIR) radiation.

Figure 1 shows results obtained with a very simple toy model of a lop-sided explosion; this model consists of uniform density ejecta in homologous expansion with the initial ^{56}Ni distributed in a spherical blob which is shifted 10 per cent off-centre in the z-direction (see centre-left panel of Figure 1). The region outside this blob is assumed to be completely devoid of ^{56}Ni. The total ejecta mass was assumed to be 1.4 $M_\odot$ and the mass of ^{56}Ni to be 0.4 $M_\odot$. The bolometric (UVOIR) light curves computed for five different viewing directions are shown in the Figure and compared to the angle-averaged light curve. As one would expect, the light curve is brightest when viewed from the direction in which the Ni blob is displaced and dimmest when seen from the opposite side. The light curve also rises somewhat more rapidly when viewed from the direction in which the Ni is displaced. The spread in peak magnitude in this toy model is $\sim$0.5 mag which is significant compared to observational uncertainties (e.g., in the sample of well-observed supernovae used by Stritzinger & Leibundgut 2005, the estimated errors on bolometric fluxes are $\sim 10 - 20$ per cent) and comparable to the range of scatter in the local Hubble diagram (see fig 11 of Sim et al. 2007).

We found a similar viewing-angle induced spread in peak bolometric magnitude for a real off-centre explosion model (the 3T2d200 model of Röpke et al. 2007b; see fig 7 of Sim et al. 2007) although the full three-dimensional structure in that model led to a more complex dependence on viewing direction. We also investigated slightly more extreme versions of the toy model geometry described above. In particular, we considered a model with the same geometry but a larger ^{56}Ni mass (0.89 $M_\odot$) for which we found that the peak bolometric magnitude could be almost $M_{\rm bol} = -19.9$ despite the angle-averaged light curve peaking at only $M_{\rm bol} = -19.6$. We suggested that such a combination of off-centre geometry and suitable line-of-sight might account for certain anomalously bright SNe Ia such as SN 2003fg (Howell et al. 2006) without

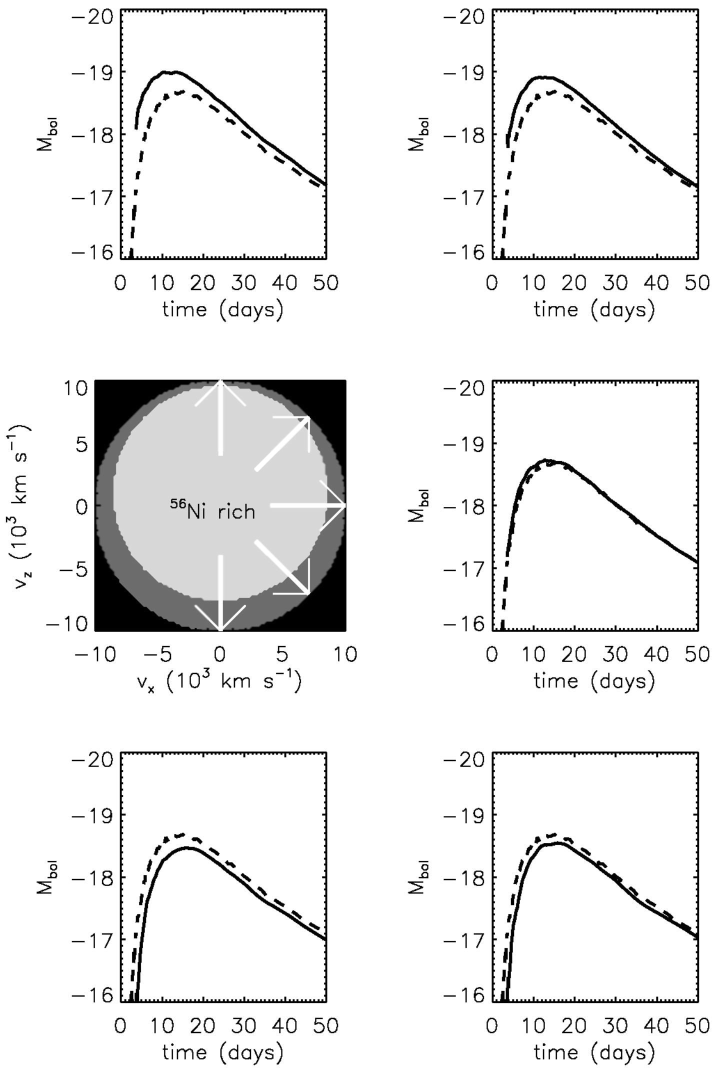

FIGURE 1. The influence of viewing angle on the bolometric light curve for the toy model described in the text. The centre-left panel shows a slice through the model in the x-z velocity plane (the model is symmetric under rotation about the z-axis). The light grey region is initially rich in ^{56}Ni while the dark grey region is devoid of ^{56}Ni and the black regions are empty. The white arrows indicate viewing orientations for which the bolometric light curves are computed. The remaining five panels (ordered clockwise) show computed bolometric light curves (solid lines) compared with the angle-averaged light curve (dashed line) for inclination angles of 0, 45, 90, 135 and 180 degrees relative to the *z*-axis.

the need to invoke very large ^{56}Ni masses (Hillebrandt, Sim & Röpke 2007). More detailed investigation of this model requires non-grey radiative transfer simulations to study spectral features and photometric-band light curves but we note that the late-time nebular spectra of a similarly bright SN Ia (SN 2006gz) are also not suggestive of a large ^{56}Ni mass (Maeda et al. 2008; see also Maeda & Koichi 2008).

FURTHER WORK

The results described above indicate that aspherical explosion models such as those motivated by modern hydrodynamical simulations can predict viewing-angle effects which are relevant at the precision of modern astronomical observations. However, the calculations presented here yield only bolometric light curves – complete calculations of photometric band light curves and spectra are required for more detailed comparison with observations. Therefore, we are continuing to develop our code to incorporate a full treatment of UVOIR radiation as described in the article by Kromer et al. in this volume. Once these developments are complete we will re-examine the observable properties of multi-dimensional explosions such as the lop-sided explosion model in order to build a more complete picture of the role of departures from spherical symmetry in the interpretation of spectra and light curves of SNe Ia.

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