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The effects of stellar populations on Type Ia supernovae

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Abstract. Recent observations of high-z SNe Ia provide evidence that the Universe is accelerating due to a dark energy that permeates space. Since the determination of distances from supernovae (and the claim for dark energy) is currently based on a fortuitous empirical relationship between luminosity and lightcurve shape, it is crucial to come up with a theoretical understanding of such relation, the identification of the SN progenitors, and an understanding of the explosion mechanism. While the claim for dark energy is based on a fairly large statistical sample, its reality ultimately depends on our understanding of the systematic errors, one of which could be due to the evolution of the SN progenitors with redshift. In fact, there is observational evidence indicating a correlation of SN properties with those of their host galaxies and stellar populations. This suggests that the SN properties could be affected by the age or metallicity of their progenitors. In this work, we use our models to study the influence of the main sequence mass and composition of the white dwarf progenitor on the properties of the supernova light curve. A main finding is that variations in mass could lead to a 0.2 mag difference in peak magnitudes. Further systematic observations are needed to better understand the relation between Type Ia supernovae and their environment.

Key words. Cosmology: theory – Stars: evolution – Supernovae

1. Introduction

Type Ia supernovae (SNe Ia) are probably the best standard candle we have: luminous as their host galaxy, a very low dispersion at maximum absolute magnitude and easily detected and identified by systematic surveys on time scales of weeks. Proposed to be used to determine extragalactic distances more than 20 years ago (Colgate 1979 and references therein), in the last years the observations of high redshift supernovae have lead to the conclusion that the expansion of the Universe is accelerating (Perlmutter et al. 1999, Riess et

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al. 1998, Riess et al. 2001, Schmidt et al. 1998).
This conclusion relies on the application of an empirical relation between light curve (LC) shape and maximum luminosity which is obtained for the well observed nearby SNe Ia occurring in galaxies at known distance (Phillips et al. 1999, Riess et al. 1997). At this point, the major concern are systematic errors, in particular, those that could be derived from evolutionary effects.
Note that the observations show evidences of a correlation between SN Ia properties and their host galaxy (Branch et al. 1996, Cappellaro et al. 1997, Hamuy et al. 2000, Ivanov et al. 2000 and Wang et al. 1997) the brighter (slow declining) SNe Ia occurs only in blue (spiral) galaxies. This may indicate a relation with the stellar population from which SN Ia progenitor comes from.
In the next years new observational facilities and on going systematic searches would provide and increasing amount of SNe Ia data at all redshifts. To take advantage of this information and to study the nature of the dark energy, we have to understand these objects.

2. State of the art

It is generally accepted that SNe Ia are the thermonuclear explosion of a Chandrasekhar mass C-O white dwarf (WD) (Hoyle & Fowler 1960), however the evolutionary path that leads to this massive WD and the explosion mechanism itself are still open problems.
In single stellar evolution, C-O WDs are formed with masses between 0.5 and 1 $M_{\odot}$ at the end of the evolution of low and intermediate mass stars (Becker & Iben 1979). For a C-O WD to achieve the Chandrasekhar mass a phase of accretion from a companion (single degenerate scenario, SD) or merging with another WD (double degenerate scenario, DD) is required. Both scenarios are possible and there are observational evidence of both, however none of them have been reproduced satisfactorily by numerical simulations.
The propagation of the burning front is a 3D problem and lot of progress has been done recently (Khokhlov 2000, Gamezo et al. 2002 and Reinecke et al. 2002) but a successful SN Ia explosion has not yet been obtained.
From the above, it seems that to study the evolution of the unknown progenitors with redshift and its influence on the observational outcome through an unknown explosion mechanism is hopeless. However the observations and our knowledge of Ia supernova physics allow us to approach the problem.
The absence of unburnt material in the spectra indicate that practically all the WD is burnt, this means that the explosion energy of is rather similar for all of them. Within this picture, the observed relation between LC shape and maximum light could be understood as due to different amounts of ^{56}Ni produced; this maybe be achieved by changing the density at which the nuclear burning occurs. In a deflagration this situation comes naturally, the velocity of the front is smaller than the velocity of sound, this allows a pre-expansion of the WD before the burning reaches the outer zones (Domínguez & Höflich 2000), then the burning front should move fast, as in delayed detonation models (DD, Khokhlov 1991).
We have chosen the DD explosion because this parametrized mechanism, in 1D, accounts for most of the observational constraints. In DD the key parameter is the transition density, ρ_{tr}, the density at which the deflagration turns into a detonation (Höflich 1995 and Höflich & Khokhlov 1996).

3. Models: pre-SN evolution, explosion and light curves

Going back in time, we expect a change in the stellar population from which SN Ia progenitors come out, low metallicity and more massive, rapid evolving progenitors, would be more numerous. We have studied the influence of the progenitor of the C-O WD in the LCs, with all other parameters fixed. The evolution of low and intermediate mass stars, in the range $1.5 \leq M/M_{\odot} \leq 8$ and initial metallicities, 10^{-10} to Z=0.02 is calculated from the pre-main sequence to the thermal pulse AGB phase. The 1 D hydrostatic code FRANEC is used in these calculations (see Chieffi & Straniero 1989, Chieffi et al. 1998, Domínguez et al. 1999 and Straniero et al. 1997). The mass and chemical structure of the obtained degenerate CO core, the *future* CO white dwarf, depends on the initial mass and composition (Mazzitelli & D'Antona 1986, Salaris et al. 1997 and Domínguez et al. 2001). Accretion of H on the WD is performed at high rates up to the central C ignition at ρ_c=2.0 10^9 g/cm^3. At that time, the mass of the CO WD is close to 1.37 $M_{\odot}$. The final amount of C and O in the accreted matter is nearly equal (C/O≈1). Then the DD explosion, detailed post-processing and light curves are computed by means of a 1D radiation-hydrodynamic code (see Höflich & Khokhlov 1996 and Domínguez et al. 2001). The description of the velocity of the deflagration front is based on 3D simulations (Domínguez & Höflich 2000) and the transition density is taken equal to 2.7 10^7 g/cm^3.

4. Results

Our main results are the following:

The metallicity of the progenitor of the exploding WD does not influence the average C/O ratio within the WD; changes are smaller than a 9 %, as a consequence the amount of ^{56}Ni produced in the explosion and the kinetic energies are rather similar. For this reason metallicity does not influence the maximum luminosity, nor the LC shape, changes are smaller than $\Delta M_V \leq 0.05$ mag at maximum.

We identify the initial mass of the exploding WD as one of the key parameters in the evolution, it modifies the average C/O in the WD up to a 22 % and, as a consequence, the ^{56}Ni mass and the kinetic energy. Progenitors with greater masses produces less luminous and slightly faster decline LCs, changes up to 0.2 mag when applying the maximum-LC shape relation may be obtained. For the more massive progenitors/less luminous models, the expansion velocities are smaller up to 2000 km/s. Notice that the correlation between LC shape and expansion velocity maybe used to reduce further the scatter in the empirical relation from which the maximum luminosity is obtained.

4.1. Numerical experiment: DD vs. SD

Looking both, for a greater change in C/O in the exploding WD composition and for basic differences between the DD (two WDs) and the SD (one WD) progenitors, we found that variations up to a 46% in the average C/O may be expected. This comes directly from the fact that in DD two previous convective He burning cores, which are C depleted, are involved, while it is just one in the SD. This is firmly established, as it relies on the He burning conditions. Notice that this variation in C/O doubles that obtained for the whole stellar initial mass range.

5. Last remarks

It is clear that just with a non-parametrized 3D explosion it would be possible to connect the progenitors of Type Ia supernovae with their observational properties. It is not known how the local chemical gradients, the extension of the central carbon depleted region or the temperature structure influence the runaway, acceleration of the burning front or the formation of plumes or bubbles, work is in progress (Khokhlov 2000, Gamezo et al. 2002 and Reinecke et al. 2002). So our results stands for a *minimum* influence, due to a change in composition, it could be amplified or somehow overpassed by the explosion itself.

It is obvious that a pre-requisite to study evolutionary effects is to identify the progenitors, both observing them and understanding the physics involved (accretion, rotation, etc).

More observations are needed in all steps: evolution with redshift of galaxies, of stellar populations and of the properties of the ISM; correlations between SNe Ia properties and those of their host galaxies; well studied nearby SNe Ia; more observed SNe Ia at all redshifts; identification of the progenitors by searching for stars with peculiar properties (composition, motion, etc).

Finally, let's summarize saying again that we obtain changes in the LC of type Ia supernovae of the same order of those found among the local and high-z supernova samples just varying the main sequence mass of the progenitor of the C-O WD.

Note that any variation in the C-O WD composition would lead to changes of a 10% as much, because that is the nuclear energy difference between burning C or O, but a 10% order is crucial for Cosmology.

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