PROCEEDINGS OF SCIENCE

Type Ia Supernovae

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The progenitor system and explosion mechanism of Type Ia Supernovae (SNe Ia) is still uncertain, despite the large amount of observational data we have today. Given the importance of SNe Ia for different fields including nucleosynthesis, galactic chemical evolution and cosmology this is clearly unsatisfactory. Here we show results of consistent multidimensional modeling of three different explosion scenarios from the onset of the first thermonuclear flame to synthetic lightcurves and spectra. This way, we can predict the optical display of our models, compare it to observations and ideally identify the actual progenitor system and explosion mechanism. Contrary to previous results, we find that they all show good agreement with observations, so we cannot rule out any of these scenarios just yet, but they are possibly all realized in Nature. In this case, additional information like binary population synthesis will have to be taken into account to determine the dominant scenario among all SNe Ia.

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1. Introduction

Recent years have brought an enormous increase of observational data of SNe Ia that will increase further in the near future. By now, several objects have been observed in great detail. At the same time, recent transient surveys have dramatically increased the overall number of observed SNe Ia. Thus, from a theorists perspective, we have a lot of information about both, single objects and the whole ensemble of SNe Ia.

It is unfortunate that neither the progenitor system nor the explosion mechanism of SNe Ia is known for certain. There is general consensus that they are thermonuclear explosions of carbon-oxygen white dwarfs in binary systems. We discuss the three most important explosion models here, which are Chandrasekhar-mass delayed detonations, sub-Chandrasekhar-mass double detonations and violent mergers.

All these models are in principle able to explain at least some of the observed SNe Ia, but also have weaknesses. Thus, in-depth modeling the explosion of a SN Ia is needed to make detailed predictions for all explosion models that can be compared to observations. This comparison will allow us to learn which of these scenarios are realized in Nature.

2. Modeling

The modeling of all scenarios presented here is quite similar. It is broken into a sequence of three parts, owing to different physical conditions and mechanisms at work. The starting point is the hydrodynamical modeling of the explosion, taking into account the energy release from nuclear burning. To this end the LEAFS code developed at MPA is applied [1, 2, 3]. With this code we follow the explosion until the nuclear burning ceases and the ejecta reach homologous expansion. Because following the nucleosynthesis in detail along with the explosion is too expensive, we instead apply a second postprocessing step using a large nuclear reaction network. We evaluate trajectories recorded by tracer particles added to the hydrodynamics simulation [4]. The detailed isotopic composition and density structure of the expanding ejecta are finally input to radiative transfer calculations that produce synthetic lightcurves and spectra [5]. Comparing these synthetic observables with observations then provides us with constraints on the explosion model.

3. Chandrasekhar-mass delayed detonations

In this scenario a carbon-oxygen white dwarf ignites a deflagration flame close to its center when it approaches the Chandrasekhar mass. After burning a part of the star, a detonation front is formed that burns the remaining parts. This scenario reproduces the main characteristics of normal SNe Ia [6, 3, 7, 8, 9, 10] well. Synthetic lightcurves from multidimensional simulations of Chandrasekhar-mass delayed detonations are in good agreement with observations [11].

However, despite looking very promising at this point, the scenario still has some problems. While recent studies indicate that the transition from an initial deflagration to a detonation is possible in SNe Ia [12, 13, 14], it is still not completely understood. A more fundamental problem is the lack of progenitor systems that will lead to Chandrasekhar-mass carbon-oxygen white dwarfs

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compared to the observed SNe Ia rate [15]. Potential additional problems are the absence of hydrogen in nebular spectra of SNe Ia [16, 17, 18] and the lack of X-ray emission from early-type galaxies [19].

4. Sub-Chandrasekhar-mass double detonations

Sub-Chandrasekhar-mass explosions were studied already by [20, 21], but dismissed until they recently gained attention again [22, 23]. In these models, a massive carbon-oxygen white dwarf builds up a helium envelope. When this envelope is thick enough, it becomes unstable and detonates. As shown by [22] a shockwave is driven into the carbon-oxygen core, triggers a detonation there, and disrupts the star. The spectra and lightcurves of such an explosion, however, are strongly affected by the burning products of the detonation in the helium shell [24, 25, 26]. Since these burning products can produce iron-group material at very high velocities which is not observed, this results in problems for spectra and lightcurves. As shown by [27], an artificial sub-Chandrasekhar-mass explosion without the helium shell agrees very well with observed normal SNe Ia. So the success of the model depends on whether the effects of the helium shell on the optical display can be avoided. A comparison of synthetic lightcurves of models with different shells is shown in Fig. 1.

An important advantage of this scenario is that population synthesis models predict frequent enough events to explain the observed SNe Ia rate [28, 29]. It also provides a nice explanation for the spread of ^{56}Ni-masses among normal SNe Ia, because more massive carbon-oxygen cores synthesize more iron group elements. On the opposite side it depends crucially on the ignition of the detonation in the helium shell. As in the other models, however, the circumstances under which the detonation forms are still debated.

5. Violent mergers

Mergers of two carbon-oxygen white dwarfs have long been speculated to be the progenitor system of SNe Ia. The main motivation is that a the large number of such systems is predicted by population synthesis [15] and they naturally explain the lack of hydrogen in SNe Ia. It has been shown, however, that mergers generally lead to an accretion-induced collapse instead of a thermonuclear explosion [30]. This was confirmed repeatedly by hydrodynamical simulations of white dwarf mergers in different configurations [31, 32, 33, 34, 35] and a special conditions may be needed to get a SN Ia [32].

Here we specifically investigate mergers of white dwarfs with a mass ratio close to one, which have not been studied in detail before. As shown in [36] these mergers evolve differently. Owing to a large mass ratio, the merger is much more violent. When the less massive white dwarf is destroyed and its material is accreted violently onto the primary, hot spots develop that reach the conditions required to form a detonation [37]. This detonation then burns most of the merged object and unbinds it. Synthetic lightcurves of such an explosion following the merger of two $0.9 M_\odot$ white dwarfs are shown in Fig. 2. They show good agreement with 1991bg-like SNe Ia [38], which were hitherto unexplained theoretically.

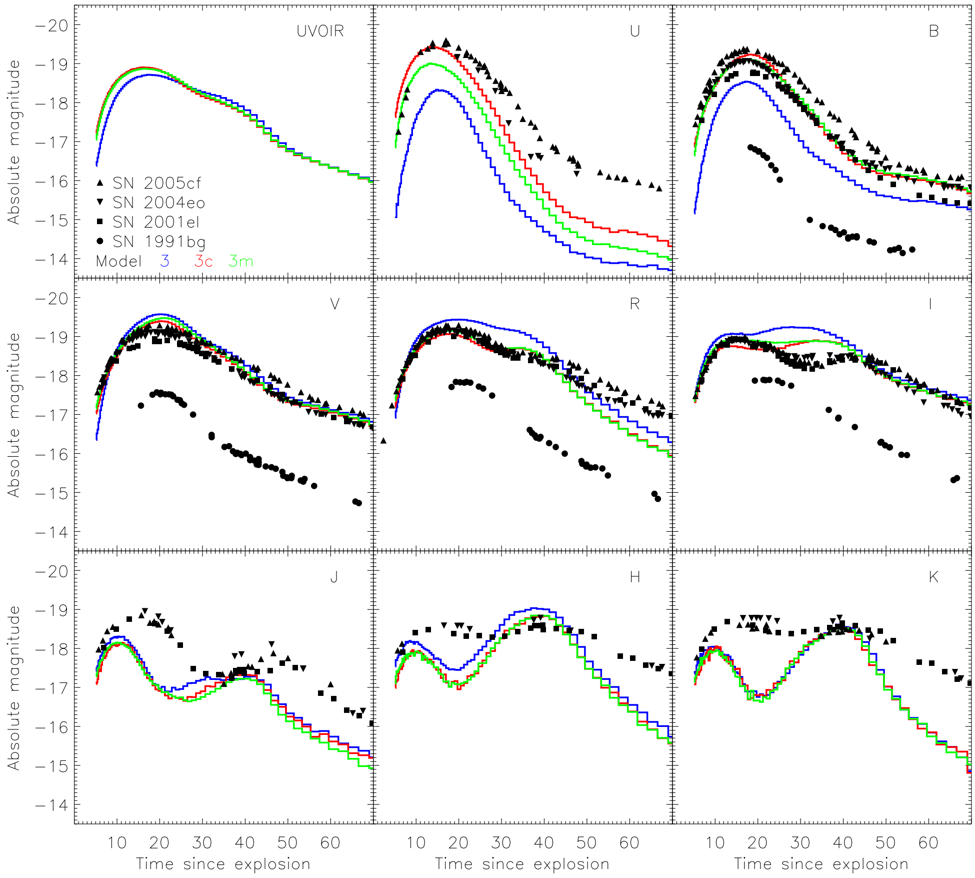

Figure 1: Synthetic lightcurves of sub-Chandrasekhar-mass double detonation explosions. Colored lines are different models with the same core mass and a helium shell that produces dominantly iron-group elements (3), no shell (3c), and a polluted helium shell that mainly produces intermediate-mass elements. Black symbols are observational data of four SNe Ia.

In contrast to the majority of white dwarf mergers, the violent merger scenario only works for mass ratios above ≈ 0.8 [39] for a $0.9\mathrm{M}_\odot$ primary white dwarf. Thus, also the rate of those mergers is significantly lower than the overall white dwarf merger rate. Consequently they will not be able to explain the dominant fraction of all SNe Ia. It also has yet to be explored, how more massive violent mergers look like and whether they resemble normal SNe Ia.

6. Conclusion

With recent advances we are finally able to seamlessly model a SN Ia consistently from the formation of the first thermonuclear flame all the way to synthetic lightcurves and spectra. This enables us to make predictions for the observational counterparts of different explosion models and different parameters within a given explosion model. All three scenarios discussed above show at least good agreement with observations within the uncertainties. Therefore, to decide which of these scenarios is really realized in Nature, we need to cover their whole parameter space and

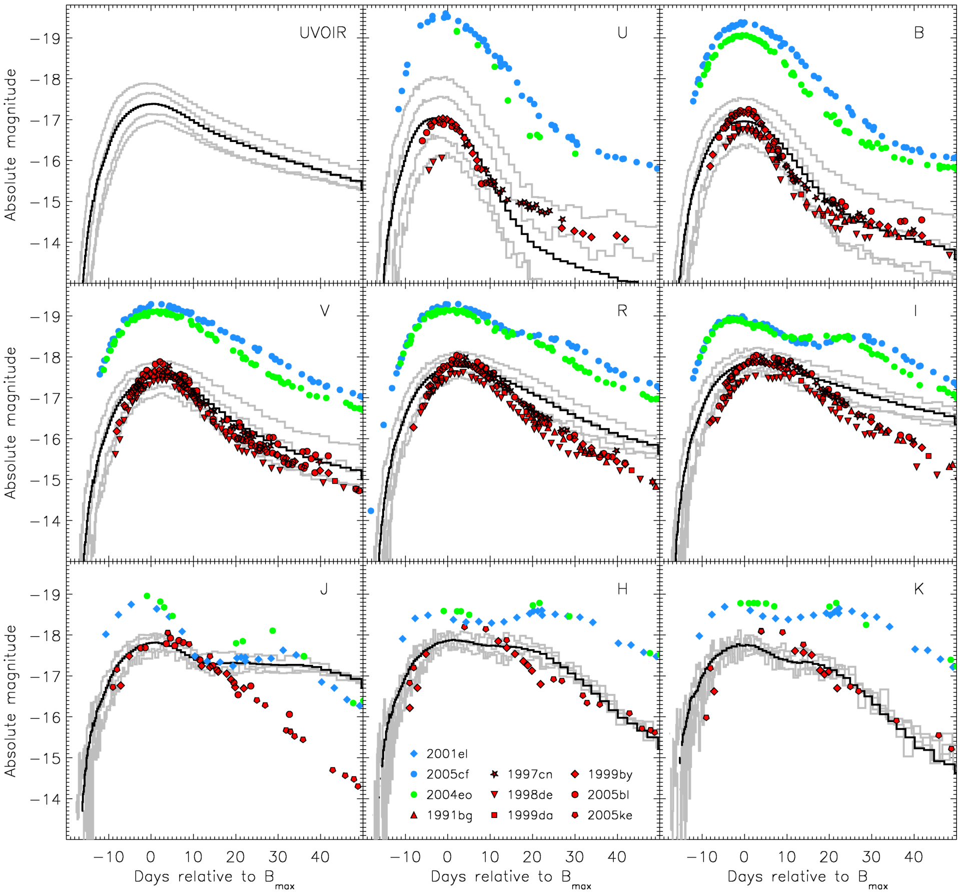

Figure 2: Synthetic lightcurves of the thermonuclear explosion following the merger of two 0.9$M_\odot$ white dwarfs. Black and gray lines are the angle-averaged and angle-dependent light curves of the model. The colored data symbols denote observational data of different SNe Ia.

further and to improve our modeling.

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