Gamma–ray emission from Type Ia Supernovae

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Abstract

The explosion mechanism associated with thermonuclear supernovae is still a matter of debate. Since huge amounts of radioactive elements are synthesized during such explosions, it is possible to use the associated γ–ray emission as a diagnostic tool. In this paper we show, however, that for some values of the parameters that characterize the burning front propagation, the signatures overlap, thus avoiding a clear distinction among them. We also display some preliminary results obtained from 3–D simulations showing the influence of inhomogeneities in the γ–ray spectrum.

Key words: Supernovae, nucleosynthesis, γ–rays
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1 Introduction

It is commonly accepted that Type Ia supernovae are the result of the thermonuclear explosion of a mass–accreting CO white dwarf. Several models have been advanced to account for the observations. Some of them assume that the white dwarf is close to the Chandrasekhar mass and that the thermonuclear runaway starts at the centre. According to the properties of the burning front (Hillebrandt & Niemeyer , 2000), four cases can be considered: the detonation model (DET), the deflagration model (DEF), the delayed detonation model (DDT) and the pulsating detonation model (PDD). Another class of models assume a sub–Chandrasekhar mass white dwarf that explodes as a consequence of the ignition of a freshly accreted He mantle. Since the density and velocity profiles of the radioactive material synthesized are different for each model, the evolution of the total intensity of the γ–ray lines, their relative ratios, their widths and shapes as well as the importance and extension of the continuum component of the spectrum will be different and could be used for diagnostic purposes (Gómez–Gomar et al. , 1998; Isern, et al. , 1999).

2 One dimensional models

Except in the case of a Chapman–Jouguet detonation, there is not a self–consistent theory describing the propagation of the nuclear flames under stellar degenerate conditions. Consequently, different parametrizations of the velocity of the burning front have appeared for each burning regime. The necessary condition to discriminate among the different burning regimes (DEF, DDT or PDD) is that the diagnostic criteria (line shapes and light curves, continuum features and so forth) obtained from each family of models should not overlap for a given subset of the allowed values of the parameters that characterizes these models.

In order to check this condition we have computed the following series of models (Bravo et al. , 1996; Badenes et al. , 2003):

(1) Pure detonation model (DET). The speed of the flame is determined by the thermodynamic properties of the star. It is incompatible with the observations but it can be used as a reference.
(2) Deflagration model (DEF). The velocity of the flame is $v_{\rm def} = \max(v_{\rm l}, v_{\rm RT})$, where v_l is the laminar velocity and $v_{\rm RT} \propto r_{\rm fl}/\tau_{\rm RT}$, where $r_{\rm fl}$ is the maximum radius of the flame and τ_{RT} is the characteristic time for a Rayleigh–Taylor instability. Here, the constant of proportionality takes values from 0.06 (case 'a') to 0.16 (case 'f').
(3) Delayed detonation (DDT). The flame initially propagates as a deflagration, $v_{\rm def} = \alpha c_{\rm s}$, where $c_{\rm s}$ is the sound velocity. When the density drops below a critical value, $\rho_{\rm tr}$ the flame is artificially accelerated until a detonation occurs. Cases 'a' and 'e' correspond to $\rho_{\rm tr} = 3.9 \times 10^7$ and 1.3×10^7 g/cm^3 respectively. The parameter α was taken as 0.03.
(4) The pulsating delayed detonation (PDD) is treated in the same way, but after a bounce. Cases 'a' and 'e' correspond to $\rho_{\rm tr} = 4.4 \times 10^7$ and 7.7×10^6 g/cm^3 respectively. The parameter α was taken as 0.03.

Figure 1 displays the temporal behavior of the 847 keV line for these models. The light curve has been built taking into account the width of the line. As it can be seen, the degree of overlapping is noticeable and, consequently, it can introduce a high degree of uncertainty in the interpretation of the data.

3 Three dimensional models

Although the attempts to analyse the observations of SNIa looking for three dimensional signatures are still scarce, they suggest that the departures from sphericity are small (Wang et al. , 2001) except, perhaps, for the subluminous

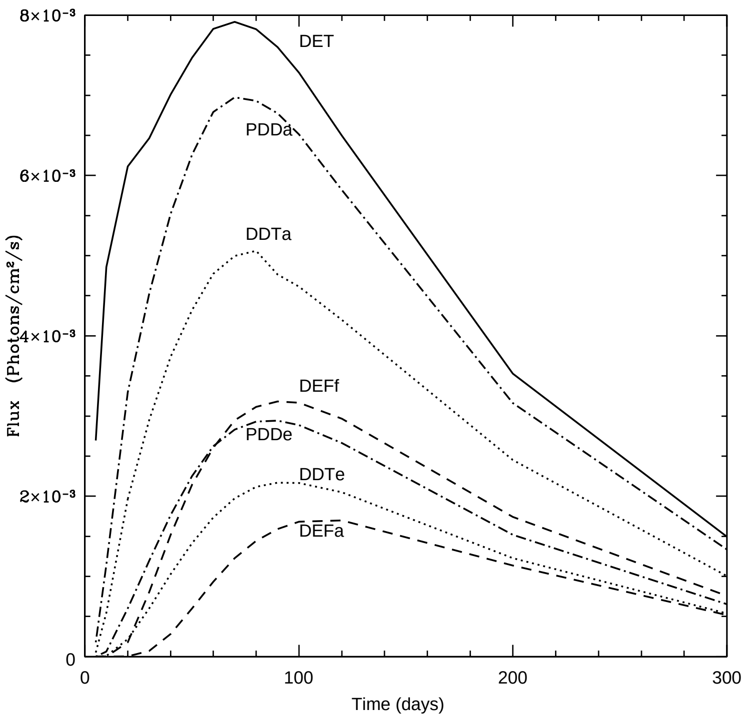

Fig. 1. Light curve for the 847 keV line obtained from different burning propagation mechanisms and for the most extreme values of the characteristic parameters of each family

events (Howell et al. , 2001). However, it is well known from the physics of the flames that, even when these propagate within an envelope which evolves spherically, the front structure is extremely unstable and, as a consequence, large pockets of unburned matter are left behind. These pockets introduce irregularities in the γ-ray lines which, in principle, can be detected. An important issue is that if the deflagration turns into a detonation these pockets can either be incinerated or be destroyed by the shock waves and disappear (Höflich , 2002).

To check these ideas, we have computed a series of 3D SNIa models using an SPH code (Bravo & García-Senz , 2003; García-Senz & Bravo , 2003). The ejecta profiles where afterwards mapped into a 3D version of our Monte Carlo gamma-ray code. The computed 3D models are representative of the deflagration and the delayed detonation classes, although here we only present results for the later one. The white dwarf was initially ignited in a central spherical volume, and the velocity of the points inside the flame was perturbed. The perturbation was the seed for the Rayleigh-Taylor instabilities which, after about half a second, started to develop several mushroom-like structures. A second later, the mean density at the flame had dropped to 2×10^7 g/cm^3, and the Rayleigh-Taylor fingers had grown were extended over nearly the whole white dwarf volume, giving rise to a corrugated flame surface. At this time, a

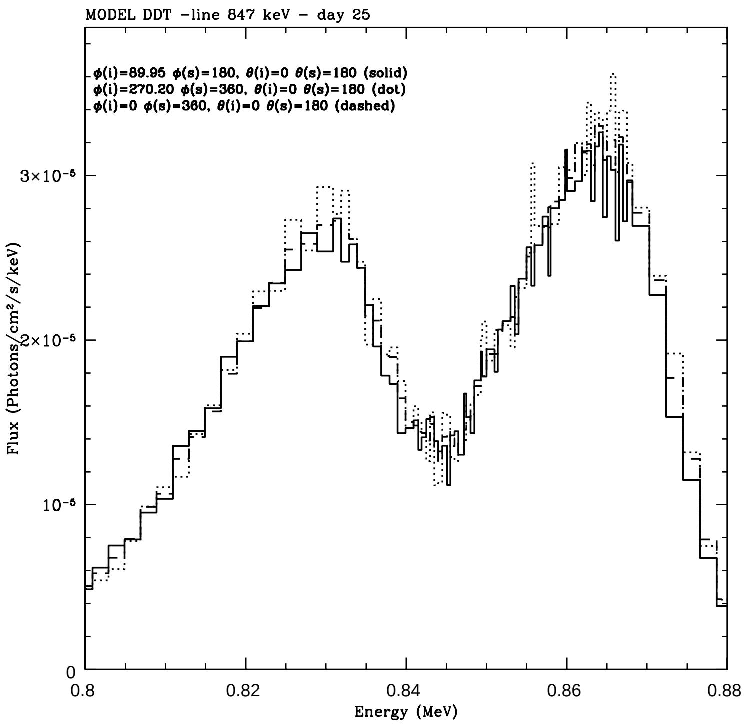

Fig. 2. Line profiles at 812 and 847 keV obtained averaging over different solid angles for the 3D-model discussed in the text 25 days after the explosion

detonation was initiated artificially.

As it can be seen from Figure 2, departures from sphericity introduce changes in the spectrum, but they are of the order of 10% and will not be detectable by INTEGRAL unless a supernova occurs at less than 1 Mpc. Similar conclusions apply in the case of pure deflagration simulations in 3D. However, if the internal structure clearly departs from sphericity, as is the case of the sub–Chandrasekhar's models, important variations in the line profile should appear, to the point where, in some extreme cases, they could even induce a misclassification of the explosion model (for a discussion of these models see Isern, et al. (1999)).

4 Conclusions

One dimensional simulations show clear differences between the γ–ray spectra of different SNIa models. These differences are more important at early times. An important issue is that the allowed values in the parameter space of each model overlap preventing a unique diagnostic based on γ–ray spectra. A combination of data from optics and γ will be necessary to determine the explosion model.

Three dimensional simulations indicate that appreciable asymmetries could be present in the γ-ray emission of sub-Chandrasekhar mass supernovae, particularly if the initial ignition starts at a single point. This translates into peculiar line profiles and non smoothly varying light curves. In the case of central ignitions, the differences between the different models are much smaller, $\sim 10\%$.

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