A NEW KIND OF TYPE I SUPERNOVAE?

J. ISERN\textsuperscript{1}, E. BRAVO\textsuperscript{1,2}, I. DOMÍNGUEZ\textsuperscript{3}

\textsuperscript{1}Institute for Space Studies of Catalonia (IEEC/CSIC/UPC), Barcelona, Spain
\textsuperscript{2}Departament de Física i Enginyeria Nuclear (UPC), Barcelona, Spain
\textsuperscript{3}Departamento de Física Teórica y del Cosmos(UGR), Granada, Spain

ABSTRACT. In this paper we examine the consequences of the propagation of a slow deflagration front through a C–O white dwarf that leads to the formation of a marginally bound remnant. This situation corresponds to the transition between the Delayed Detonation models and the Pulsating Delayed Detonation ones. The radioactive decay of the freshly formed $^{56}\text{Ni}$ not only powers the light curve but also produces an ablative front that finally disrupts the star. The light curve is characterized by its low luminosity (~16.8 m)–as compared with a normal SNIa– and its broad peak (~ 100 days).

1. Introduction

The high luminosity and the relative homogeneity of Type Ia supernovae (SNIa) make these events one of the most valuable tools for cosmological research. Nevertheless, despite their homogeneity, a number of SNIa display differences in expansion velocity, spectrum and shape of the light curve. Therefore it is of the highest interest to be able to distinguish among "normal" and "peculiar" events or, what is equivalent, to understand which physical mechanisms and astronomical scenarios are responsible of such a behavior.

From the observational point of view, there is a wide consensus that SNIa split into two gross classes: "normal" which are very homogeneous both photometrically and spectroscopically, and "subluminous" which display some scatter in their properties. From the theoretical point of view there is also consensus that "normal" SNIa are the result of the central deflagration of a white dwarf near the Chandrasekhar limit, while the subluminous ones can be produced either by the detonation of a freshly accreted layer on the top of a C–O white dwarf of any mass (this is why they are called sub–Chandrasekhar supernovae, see e.g. Ruiz–Lapuente et al 1993, Woosley & Weaver 1994), or by a deflagration that is so slow that fails to produce the explosion, then the star collapses again, and finally detonates when the density is $\sim 10^7$ g/cm$^3$ (this is why they are called Pulsating Delayed Detonation models: Khokhlov 1991; Höflich, Khokhlov and Wheeler 1994).

In the case of the Pulsating Delayed Detonation models, the burning front must reach a density lower than $3 \times 10^7$ g/cm$^3$ during the expansion phase to get the right mixture of fuel and hot ashes to ensure a detonation during the recontraction phase. This condition requires pulsations of very large amplitude that, however, are not able to unbind the star. Thus, the question is why pulsations barely disrupting the star do not
occur or are not observed (Niemeyer & Woosley 1997)? In other words, the identification of astronomical objects with an intermediate behavior between normal deflagrations and pulsating delayed detonations should be a major argument in favor of the last models.

2. Model and Results

In order to explore this possibility, barely exploding models have been constructed using an explicit hydrodynamical code that successfully reproduces the typical properties (both qualitatively and quantitatively) of SNIa (Bravo et al 1993). The velocity of the burning front was given by the maximum between the conductive velocity (Timmes & Woosley 1992) and the turbulent velocity parametrized as (Woosley 1986):

\[ \nu_{\text{turb}} = F \nu_s (1 - e^{-r/r_0}) \]

where \( F \) and \( r_0 \) are free parameters and \( \nu_s \) is the sound velocity. In the present work \( F \) was set equal to 0.3 leading \( r_0 \) as the unique parameter controlling the deflagration velocity.

For a white dwarf made of half and half by mass of \(^{12}\)C and \(^{16}\)O igniting at \(3.55 \times 10^8 \) g/cm\(^3\), direct explosions were obtained for \( r_0 \leq 4.0 \times 10^8 \) cm, and pulsations for \( r_0 \geq 4.5 \times 10^8 \) cm, while for \( r_0 = 4.2 \times 10^8 \) cm, the burning front just incinerated 0.33 M\(_\odot\) to Fe-peak elements. This quantity is so close to the minimum necessary to unbind the white dwarf that the bulk of matter remained at low densities during a long time but with a negative total energy. The explosion developed in two phases. Up to \( \sim 10^8 \) s the energy deposited by the central combustion front produced the expansion of the star to a large radius (\( \sim 10^{12} \) cm). While the external layers (0.13M\(_\odot\)) immediately reached a velocity larger than the escape velocity, the rest of the star remained gravitationally bound and, shortly after, started to collapse. The second phase started at \( \sim 3 \times 10^8 \) s when the energy input from radioactive decay of freshly produced \(^{56}\)Ni (mass 0.0044M\(_\odot\), half-life 2.88 \times 10^5 s) and \(^{56}\)Ni (mass 0.162M\(_\odot\), half-life 8.80 days) started to increase the temperature and the pressure in the layers containing them. At \( 3.45 \times 10^4 \) s the radiation pressure was already \( \sim 50 - 80\% \) of the total pressure in that layers, and gave rise to an ablative shock front when they reached the surrounding material. Ten hours after the beginning of the explosion, the central layers, rich in \(^{56}\)Ni, expanded and collided with the layers rich in stable Fe-peak elements and swept them off. Shortly before the upward \(^{56}\)Ni rich layers were caught, the photon density was high enough to induce a second ablative shock front at the interface with the outer, unprocessed, C-O layers. After one day, the full star expanded with a velocity slightly higher than the escape velocity. The kinetic energy at infinity was \( \sim 10^{49} \) erg, and the maximum velocity computed was \( \sim 6000 \) km/s, although the bulk of material was moving at less than 1000 km/s.

The nucleosynthesis produced in this model is not representative of normal thermonuclear supernovae. Due to the slow velocity of the flame, electron captures turned \( \sim 0.2M_\odot \) of incinerated matter into \(^{56}\)Fe and substantial amounts of neutronized Fe-peak nuclei. The main products were \(^{44}\)Ca, \(^{50}\)Ti, \(^{54}\)Cr, and \(^{60}\)Zn, all of them in proportions about two orders of magnitude larger than the corresponding Solar System values (Anders & Grevesse 1989). That, together with the distribution of nuclei through the
expanding star and the small abundances of Si put this model at odd with typical SNIa spectra. The most external layers, detached from the rest of the star at early times, became transparent to photons in the optical wavelengths just about 2–3 days after the beginning of the explosion, although the photosphere remained locked to the layers composed of unprocessed C–O for another ~ 95 days. Thus, the spectra at maximum magnitude, and several weeks after, would be dominated by C and O lines, instead of Si and Fe-peak elements as usual in thermonuclear supernovae. At ~ 150 days, the whole star was transparent to optical photons, and the supernova entered the nebular phase.

The bolometric light curve, obtained as in Bravo et al (1993), is displayed in Figure 1. The maximum is lower than those of "normal" as well as "sub–luminous" SNIa, which is in some sense surprising since the model computed here physically corresponds to the transition between both classes. Before and after the maximum there is a long epoch of sustained luminosity which makes it to look strange. Its comparison with the observations is not straightforward since observed bolometric light curves are still scarce. It is however reasonable to assume that the B–band and the bolometric magnitudes share most of their properties at least near the maximum and one has to wonder why, if explosions like the one described exist, they have never been observed.

There are at least two reasons why these peculiar supernovae would have not yet been observed. First, they must be scarce in nature since the range of allowed parameters ($r_0$) is very narrow as compared with the range of values that produce "normal" and "sub–luminous" SNIa. Furthermore, their abundant production of heavily neutronized isotopes, mainly $^{54}$Cr and $^{66}$Zn, is only compatible with a rate of the order of ~ 1/20–1/200 the total Type Ia Supernovae rate. Second, because of their very small luminosity, they are strongly selected against in magnitude limited samples. In this kind of samples, the available volume for detecting this class of supernovae is about a factor 16 smaller than for "normal" SNIa. This represents about 0–2 events of this kind in the whole observed supernova sample. Therefore, the detection of a single event matching the models described here would be a strong argument in favor of the models based in slow deflagrations.

SN1909A was discovered by Wolf in the galaxy M101 (NGC 5457) in 1909 and it was not recognized as a supernova until many years later when it was classified as a peculiar or Type IIP on the only basis of its light curve, since there are not spectra of this event (see Sandage & Tamman, 1974, for a detailed discussion). Its peak magnitude was 13.47 ± 0.08 and it displayed an extremely wide peak of ~ 100 days. Using the distance modulus to the galaxy, derived from HST measurements of cepheid variables present in M101 (Kelson et al 1996), 29.34 ± 0.17 mag, and the blue extinction estimated to be 0.5 mag (Young & Branch 1988), the peak absolute magnitude results to be −16.4, in close agreement with the results of this paper. Figure 1 shows the comparison between the theoretical bolometric light curve and the SN1909A observed blue curve. The fit is impressive over ~ 400 days and more than 4 mag range, despite the comparison is between bolometric and blue curves.

Sandage and Tamman (1974) did not find satisfactory classification of SN1909A neither as SNI nor SNII, although favored the type II alternative because of the faint maximum of the supernova as compared to "normal" type I, and also because of the widely spread idea of the homogeneity of SNIa light curves. Young and Branch (1988)
Fig. 1. The bolometric light curve of the model (continuous line) is characterized by a slow rise (68 days to reach the maximum), a low brightness at maximum (-16.8^m) as compared with normal SNIa, and a slow decline both just after the maximum (ΔM_15 = 0.15) and during the exponential tail (β_tail = 0.97). The observed blue magnitudes of SN1909A are displayed (open circles) at different instants of time (Sandage & Tammann 1974). Note that the first point is just an upper limit. For comparison, the blue light curve of the Type II SN1987A (crosses, from Whitelock et al 1988 and references therein), and of a typical SNIa (open triangles) are also displayed. The strong discrepancy between both of them and the light curve of SN1909A contrasts with the nice agreement between the last one and the computed light curve of the model.
proposed that SN1909A belongs to the same family as SN1987A (being therefore a SNII) given the similarity of shape of their light curve. However, despite they used the old distance modulus of 28.8 mag, SN1909A was too bright to be compared to SN1987A. With the new distance modulus, the difference in magnitude can be attributed to a $^{56}\text{Ni}$ mass 2.1 times bigger in SN1909A (0.15 $M_\odot$) than in SN1987A (0.07 $M_\odot$), giving a value very close to the model presented here. In addition, SN1909A was produced in the outskirts of M101, a place not completely disconnected from the arm structure but more characteristic of SNIAs than SNII.

3. Conclusions

Slow flames propagating through C–O white dwarfs near the Chandrasekhar’s limit can produce very dim outbursts with a very broad light curves. These light curves are completely different from the characteristic SNIa light curves and resemble peculiar SNII. SN1909A, classified as a peculiar SNII, provides an striking example. Unfortunately, it is not possible of discerning if it is no more an speculation or it is real due to the absence of spectral information. However, since SN1909A occurred once and the number of supernova discoveries steadily increases, it is natural to expect that SN1909A like events will be detected in a near future. In this case, the spectral information will play a critical role.

Acknowledgements

This work has been supported by CICYT (ESP98-1348),DGICYT (PB96–1428 and PB97–0983–C03–03), CIRIT (GRC & PIC) and Junta de Andalucía (7004) grants.

References


*Mem. S.A.It.,* 2000