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TYPE I SUPERNOVA MODELS

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RESUMEN. Tras presentar las características de las explosiones de supernova del tipo I, describimos los modelos teóricos elaborados para dar cuenta de las mismas. Pese a la reciente subdivisión en los subtipos Ia y Ib, seguimos haciendo hincapié en los modelos basados en la explosión de una enana blanca en un sistema estelar doble. Junto a los modelos que suponen combustión termonuclear explosiva en un interior estelar fluido, consideramos con algún detalle los correspondientes a interiores parcialmente sólidos. Discutimos finalmente los basados en aportes de energía distintos del termonuclear, sugeridos para explicar las explosiones del subtipo Ib.

ABSTRACT. We briefly describe the characteristics of Type I supernova outbursts and we present the theoretical models so far advanced to explain them. We especially insist on models based on the thermonuclear explosion of a white dwarf in a close binary system, even regarding the recent division of Type I supernovae into the Ia and Ib subtypes. Together with models assuming explosive thermonuclear burning in a fluid interior, we consider in some detail those based on partially solid interiors. We finally discuss models that incorporate nonthermonuclear energy contributions, suggested in order to explain Type Ib outbursts.

Key words: STARS-STRUCTURE -- STARS-SUPERNOVAE -- STARS-WHITE DWARFS

I. INTRODUCTION

Type I supernovae (SNI) have always been characterized by the absence of hydrogen lines in their spectra, in contrast with Type II supernovae (SNII), that show Balmer lines. In Table 1 (taken from Panagia et al. 1986) are summarized the main features "classically" thought to define both classes of supernovae.

Light curves of SNI were explained by the radioactive decays

$$^{56}Ni(e^+,\gamma)\,^{56}Co(e^+,\gamma)\,^{56}Fe$$

the "peak" of the light curves corresponding to the decay of ^{56}Ni into ^{56}Co, and the exponential "tail" to that of ^{56}Co into ^{56}Fe (Pankey 1962; Colgate and McKee 1969; Colgate et al. 1980; Arnett 1982).

It has recently been realized, however, that there is a rather well- defined subclass of outbursts sharing with all SNI the lack of hydrogen lines in their spectra but showing significant differences with the "classical" ones. They have been termed SNIb, to distinguish them from the "classical" or SNIa subclass. SNIb have light curves similar to those of SNIa in the optical, but clearly different in the infrared (Elias et al. 1985). They are about 1.5 mag dimmer at maximum light and helium is present in their spectra. Two of them, SN1983n and SN1984l, have been detected in radio (Sramek et al. 1984; Panagia et al. 1986), in contrast with the SNIa. SN1985f (Filippenko and Sargent 1985) was first thought to represent a new, third subclass, but it has later been shown to be also a SNIb (Gaskell et al. 1986).

TABLE 1. "Old" Facts about Supernovae (Optical)

	Type I	Type II
Where	Elliptical, Spiral and Irregular Gal.	Only in Spiral Galaxies, associated to the Spiral Arms
How Bright	$M_B(max) \sim -20$	$M_B(max) \lesssim -16$
	$(L \sim 10^{10} L_\odot)$	$(L \gtrsim 3 \times 10^8 L_\odot)$
Light Curve	Decay Rate ~ 0.1 mag/day; $(t \lesssim 30$ d) ~ 0.01 mag/day; $(t \gtrsim 30$ d)	All kinds of behaviour
Optical Spectrum	Broad, unidentified features, more prominent with time $v \approx (10-20) \times 10^3$ km s^{-1}	Balmer lines HeI, NaI(?), etc. $v \approx (5-10) \times 10^3$ km s^{-1}
Behaviour	Very Homogeneous	Heterogeneous
Progenitors	Low-Mass Stars	High-Mass Stars

The SNIa or "classical" subclass appear to show some range of variability in their light curves (Barbon et al. 1973; Pskovskii 1977; Branch 1982). The "breadth" of the peaks around maximum light can be characterized by a parameter:

$$\beta = 100 \frac{\Delta m}{\Delta t} \qquad (6 \lesssim \beta \lesssim 14) \tag{1}$$

where Δm is the magnitude difference between maximum and the beginning of the exponential "tail", and Δt is the time (in days) elapsed between those two events. Lower β-values correspond to "slow" SNIa and larger β-values to "fast" ones. There seems also to be a correlation between β-values, expansion velocities at maximum light, and absolute magnitudes at maximum:

$$v_9 = 1.2 + 0.05\ (7 - \beta) \tag{2}$$

$$M_B = -21.03 + 0.11\ \beta \tag{3}$$

where v_9 is the expansion velocity in units of 10^9 cm s^{-1} and M_B is the absolute blue magnitude. "Slow" SNIa are thus brighter than "fast" ones and they also show larger expansion velocities.

As for the spectra of SNIa, lines of Ca, Si, S, Mg, and O have been identified around maximum light (Branch et al. 1982), and those of Fe and Co in late-time spectra (Axelrod 1980).

II. THEORETICAL MODELS

The most widely accepted scenario for SNI outbursts (with, now, the possible exception of the SNIb ones) is the explosion of a mass-accreting white dwarf in a close binary system (Mestel 1952; Schatzman 1963; Whelan and Iben 1973). Mass accretion by the white dwarf from its companion would progressively increase its internal densities and temperatures up to the point of thermonuclear ignition of its material. The electron component of the stellar plasma being strongly degenerate, a thermonuclear runaway should start, its propagation leading to the explosion of the star.

The outcome of the stellar explosion depends on the mode of propagation of the thermonuclear burning. Supersonic burning (detonation), induced by the shock wave started by the ignition, was first postulated (Arnett 1969; Wheeler and Hansen 1971). The material ahead of the burning front having no dynamical connection with that already burnt, its ignition happens at the same density as before the explosion. This leads to complete incineration of the stellar material to nuclear statistical equilibrium (NSE). . The star is totally disrupted and $\sim 1.4\ M_\odot$ of Fe-Ni isotopes are ejected.

Subsonic burning propagation has later been assumed (Mazurek *et al.* 1974; Nomoto *et al.* 1976). Arguments based on shock-tube analogy and consideration of shock-wave damping due to the spherical geometry make it unlikely that the initial shock wave might start a self-sustained detonation (for central carbon ignition at least). Thermal conduction and mixing of unburnt with burnt layers due to Rayleigh-Taylor instability would thus be the main mechanisms for burning propagation. Subsonic burning allows the material ahead of the burning front to expand before being ignited. For central ignitions, the material in the deeper layers is incinerated to NSE. The outer layers are only partially burnt. Hydrodynamic burning is fast enough, however, so that electron captures (that would remove pressure) cannot compete with it and the star is finally disrupted. The chemical composition of the ejected matter will be a mixture of NSE nuclei and intermediate-mass ones, with possibly some light, unburnt material.

The chemical composition of the mass-accreting white dwarf also enters in determining the relevant mode of explosive burning propagation.

1. In helium white dwarfs, the ignition densities being lower and the specific energy release being larger (as compared to carbon), detonation is still likely, even for central ignitions. Models based on helium detonation give approximatively correct light curves, but excessive expansion velocities at maximum light. Besides, intermediate-mass elements would be absent from the spectra.

2. In carbon-oxygen white dwarfs, there is dependence on the chemical composition of the accreted material, on the mass-accretion rate, on the mass, and on the initial temperature of the white dwarf.

a) Accretion of hydrogen-rich material.

- Accretion at $\dot{M} \lesssim 10^{-9}\ M_\odot\ yr^{-1}$ would lead to nova outbursts, with ejection of material in amounts roughly equivalent to those previously accumulated (that for initial masses $M_i \gtrsim 1.1\text{-}1.2\ M_\odot$) (MacDonald 1983).
- Accretion at $10^{-9} M_\odot\ yr^{-1} \lesssim \dot{M} \lesssim 4\times10^{-8} M_\odot\ yr^{-1}$ would allow processing of the material into He, but finally inducing detonation at the bottom of the accreted layer (Fujimoto 1980).
- Accretion at $4\times10^{-8} M_\odot\ yr^{-1} \lesssim \dot{M} \lesssim 1.3\times10^{-7} (M/M_\odot)^{3.57}\ M_\odot\ yr^{-1}$ would allow processing the material first into He and later into C+O. The mass increase would induce central carbon ignition.

b) Accretion of helium-rich material.

- Accretion at $\dot{M} \lesssim 10^{-9} M_\odot\ yr^{-1}$ would either lead to mass increase up to central carbon ignition (for $M_i \gtrsim 1.15\ M_\odot$) or to helium detonation (for $M_i \lesssim 1.15\ M_\odot$).

-Accretion at $10^{-9} M_\odot\ yr^{-1} \lesssim \dot{M} \lesssim 4x10^{-8} M_\odot\ yr^{-1}$ would lead to double detonation, propagating both into the He and into the C+O layers (Nomoto 1982; Woosley et al. 1983).

-Accretion at $4x10^{-8} M_\odot\ yr^{-1} \lesssim \dot{M} \lesssim 10^{-6} M_\odot\ yr^{-1}$ would lead to mass increase up to central carbon ignition.

c) Accretion of C+O material.

-Accretion at $\dot{M} \lesssim 10^{-6} M_\odot\ yr^{-1}$ should lead to mass increase up to central carbon ignition (Iben and Tutukov 1984).

-Accretion at $\dot{M} \gtrsim 10^{-6} M_\odot\ yr^{-1}$ should lead to off-center ignition followed by quasi-hydrostatic burning of C+O into O+Ne+Mg (Nomoto and Iben 1985).

All the preceding classification is almost solely based on one-dimensional calculations. Some predictions, such as that of the double detonation, should thus be taken with extreme care (imploding shock waves, for instance, are always stable in one dimension, but not in the real world!).

III. HYDRODYNAMICS

1) In models assuming a completely fluid white dwarf interior, ignition always happens for $\rho_c \simeq 2\text{-}4x10^9\ g\ cm^{-3}$.

a) One-dimensional models. The outstanding problem in those models is that of the speed of the burning front. Different approaches have been used:

-To treat the burning front as if it were the outer edge of a time-dependent convective zone. The speed is parametrized with respect to $\alpha \equiv l/H_p$, where l is the mixing-length and H_p is the pressure scale height (Nomoto et al. 1984).

-To take the speed of the burning front as a variable fraction of the local sound speed (Woosley et al. 1984).

-To consider the burning front as a laminar flame in an incompressible fluid first and later to parametrize the speed of the turbulent flame front (Zeldovich et al. 1985; Woosley et al. 1986).

b) Two-dimensional models. Numerical experiments on C+O burning have been performed by Müller and Arnett (1982, 1985). They show the strongly asymmetrical structure of the (probably turbulent) burning front. The front accelerates as the ignited layers encompass increasing fractions of the star's mass, and complete disruption is predicted.

Results can be summarized as follows:

Synthetic spectra based on those fluid models give fairly good fittings to the observed ones near maximum light (Branch et al. 1985). Complete models for the emerging radiation are currently being calculated (Harkness 1986; Pinto and Axelrod 1986).

The predicted light curves are in broad agreement with those observed, but the correlation between peak luminosities, expansion velocities, and the "fast" or "slow" character are just the opposite to the "Pskovskii-Branch effect" (Nomoto et al. 1984).

Detailed nucleosynthesis calculations (Thielemann et al. 1986) show excess production of neutron-rich isotopes. The abundances of ^{54}Fe and ^{58}Ni, namely, are significantly larger than the solar-system ones.

IV. SOLID LAYERS

Partially solid models have also been considered (Canal and Isern 1979; Canal, Isern, and Labay 1980; Isern et al. 1983; Labay et al. 1985; Canal et al. 1986). Partial solidification of the white dwarf prior to the mass-accretion stage is generally to be expected. One of the effects of mass accretion will be to melt again the star's interior, in a variable extent, but central solid cores of different sizes are predicted for a broad range of initial conditions plus accretion rates (Canal et al. 1986; Hernanz et al. 1986). Concerning solidificaton, three hypotheses are possible:

a) Solidification produces a random C+O alloy (Loumos and Hubbard 1976). In those models central ignitions in the range $3\text{-}4\times10^{9}$ g cm^{-3} $\leq \rho_c \leq 10^{10}$ g cm^{-3} are found. Burning propagates by conduction as the solid layers are successively melted. Given the relatively low speeds and the high densities, electron captures can successfully compete with the expansion induced by burning and collapses to neutron star densities are obtained (Canal and Isern 1979; Labay et al. 1985). There is also a possibility of off-center ignitions inducing partial explosions and leaving white dwarf remnants (Isern, Labay, and Canal 1984).

b) An ordered alloy, with carbon ions preferentially having oxygen neighbours, should be energetically favoured (Schatzman 1983). Thus, if C/O $\leq$ 1 (by number), ^{12}C+^{12}C reactions should not be relevant to ignition in the solid phase. Recent reestimates of the ^{12}C(α,γ)^{16}O cross-section point towards carbon being less abundant than oxygen at the end of helium burning. Those models can also give off-center explosions.

c) Carbon and oxygen are not miscible in the solid phase (Stevenson 1980). A long enough cooling period would lead to partial (and even total) C/O separation, carbon being in the outer layers and oxygen in the central ones (Mochkovitch 1983). Models based on this hypothesis give either collapses (to neutron stars) or off-center ignitions (leaving white dwarf remnants), that depending on the sizes of the central oxygen cores.

The main results can be so summarized:

Partially solid models reproduce well the "Pskovskii-Branch effect" in their light curves (López et al. 1986a,b). This is true for models c) and might also be the case for models b) and a).

^{54}Fe and ^{58}Ni excesses can be eliminated by the previous diffusion of ^{22}Ne (the main source of neutron excess before electron captures) towards the star's center. This would also be true for models c) and perhaps also for b) and a).

Neutron star formation is predicted in models a) and c).

White dwarf remnants are predicted by models c) and b), and in some cases also by a).

Calculations of collapse to nuclear matter densities, two-dimensional models, detailed nucleosynthesis, and spectra are also currently being performed for those models.

V. SNIb SUPERNOVAE

The origin of SNIb outbursts remains unclear. Similarity in shape of the light curve with SNIa, together with fainter peak luminosities but roughly the same expansion velocities at maximum light, have suggested that another energy source besides the thermonuclear one is involved in the explosions (Wheeler and Levreault 1985). Since hydrogen is absent from the spectra, Wolf-Rayet stars might be good progenitor candidates. This massive star hypothesis is also supported by the apparent association of SNIb with spiral arms.

SNIb spectra, however, can be interpreted as iron-peak material moving at high speeds, followed by intermediate-mass elements moving at lower speeds (Branch and Nomoto 1986). Those last authors suggest helium detonation in the outer layers of a mass-accreting white dwarf.

Nothing really quantitative has been done in either way, so the issue of the origin of SNIb remains an open question.

VI. CONCLUDING REMARKS

Significant progress is to be expected in the next few years, concerning the origin and explosion mechanism (or mechanisms) of Type I supernovae: improvement of the numerical models and increase in the numbers and accuracy of the observations. Three-dimensional simulations with acceptable resolution should be possible with the next generation of supercomputers. Space telescope observations should, on the other hand, provide enough constraints on the theoretical models so as to enable us to decide among the different hypotheses. It will thus be possible, for instance, to use SNI as reliable standard candles for extragalactic distance measurements, or to ascertain their role in the chemical evolution of galaxies and that of the intergalactic, intracluster medium. The relationship beween SNI and the origin of galactic X-ray and γ-ray sources (and that of a fraction of pulsars as well) is another outstanding problem still awaiting its solution.

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DISCUSSION

PEIMBERT: ¿Cuál ha sido el efecto del cambio en la eficiencia de la reacción $C^{12} \rightarrow O^{16}$ en los modelos y en el posible enriquecimiento del carbono en el medio interestelar?

CANAL: Es un tema todavía controvertido, pues diferentes modelos de evolución estelar dan respuestas también distintas. Así, Arnett y Thielemann encuentran que C/O < 1 sólo para estrellas relativamente masivas ($M > 15\ M_\odot$). En cambio Tomambi y colaboradores incluyen "overshooting" en las zonas convectivas de sus modelos y encuentran C/O < 1 para masas mucho menores (4-10 $M_\odot$).

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