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OBSERVATIONAL CONSTRAINTS TO THEORETICAL MODELS FOR TYPE I SUPERNOVAE

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RESUMEN

Generalmente se cree que las supernovas de Tipo I son el resultado de la explosión de una enana blanca masiva, que forma parte de un sistema estelar doble. Las propiedades de las curvas de luz, así como la correlación propuesta por Pskovskii y Branch sugieren que tales explosiones deben dejar un residuo en algunos casos. Esta condición se cumple de forma natural si se toma en consideración que la enana blanca puede tener un núcleo sólido y que la ignición termonuclear comienza en el borde de éste.

En este trabajo se comparan las curvas de luz observadas con las teóricas obtenidas de la explosión de enanas blancas parcialmente sólidas para un amplio rango de los parámetros relevantes. Nuestros resultados muestran que el carácter "lento" y "rápido" de la curva de luz depende básicamente del material expulsado (M_{ej}) y de la fracción de este material que no ha sido procesado hasta el equilibrio estatístico nuclear (M_δ). Las observaciones limitan los valores de estos parámetros al rango $0.8\ M_\odot \leqslant M_{ej} \leqslant 1.4\ M_\odot$ y $0.2\ M_\odot \leqslant M_\delta \leqslant 0.4\ M_\odot$. El valor de la constante de Hubble $H_0 = 100$ km s^{-1} Mpc^{-1} parece estar excluido para cualquiera de los valores razonables de los parámetros de nuestros modelos.

ABSTRACT

It is generally thought that Type I supernovae are the outcome of the explosion of a massive white dwarf in a close binary system. The properties of the light curves as well as the Pskovskii-Branch effect suggest that such explosions should leave a bound remnant in some cases. This condition is naturally fulfilled by taking into account that the white dwarf may have a solid core and that the thermal runaway starts at the edge of this core.

In this paper, observed light curves are compared with the theoretical ones obtained from the explosion of partially solid white dwarfs for a wide range of the relevant parameters. Our results show that the "slow" and "fast" character of the light curve depends basically on the expelled material (M_{ej}) and on the fraction of this material that has not been processed to the nuclear statistical equilibrium (M_δ). The observations constrain these parameters to take values in the range $0.8\ M_\odot \leqslant M_{ej} \leqslant 1.4\ M_\odot$ and $0.2\ M_\odot \leqslant M_\delta \leqslant 0.4\ M_\odot$. A value of the Hubble constant $H_0 = 100$ km s^{-1} Mpc^{-1} seems to be excluded for any reasonable choice of the relevant parameters of our models.

Key words: **STARS-WHITE DWARFS – SUPERNOVAE**

I. INTRODUCTION

It is usually thought that Type I supernova explosions (SNI) originate from the thermonuclear deflagration of a carbon-oxygen white dwarf, member of a close binary system. Mass accretion on the white dwarf pushes it towards the Chandrasekhar limit and induces explosion. Wide acceptance of this scenario arises from the fact that it qualitatively reproduces the observed characteristics of SNI.

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Current models assume the explosion of massive white dwarfs ($M = 1.2$ to $1.4\ M_\odot$). Numerical simulations trying to reproduce SNI explosions predict incineration to ^{56}Ni of about $1\ M_\odot$ of the star. Most of the energy liberated by the explosion comes out as kinetic energy of the expanding material. The velocities calculated for the external layers (Sutherland and Wheeler 1984) are comparable to those actually observed (Kirshner 1982). Decays of ^{56}Ni to ^{56}Co and of ^{56}Co to ^{56}Fe give enough energy to power the light curve. The observed shape of the light curves agrees with the predicted behaviour (Barbon, Ciatti, and Rosino 1973; Barbon, Cappellaro,

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and Turatto 1984). Synthetic spectra calculated by Axelrod (1980) actually confirm those models by reproducing reasonably well the spectroscopic observations of SNI at late times. (See Trimble 1982 for a review).

It must be pointed out that there is a subclass of peculiar SNI (Panagia *et al.* 1985; Wheeler and Levreault 1985; Uomoto and Kirshner 1985). It cannot be ascertained, yet, whether the origin of this subclass of SNI is or not the same as that of "classical" SNI. Wheeler (1986) attributes the outburst to collapse and explosion of an intermediate mass star having lost its envelope either by binary mass transfer or by a strong stellar wind. If we leave this "peculiar" subclass aside, we see that the photometric and spectroscopic homogeneity predicted by the deflagration models of a C – O white dwarfs is confirmed by the observational data.

A more detailed analysis shows, nonetheless, a range of variation from one supernova to the other. Pskoskii (1977) and Branch (1982) have found a correlation between luminosity at maximum, expansion velocity, and the rate of decline of the light curve (previous to the exponential tail). The most luminous supernovae expand faster and their luminosity decay more slowly. In contrast, dimmer supernovae expand slower and their post-maximum decline is steeper. This can be quantitatively expressed as:

$$v_9 = 1.2 + 0.05\,(7 - \beta) \qquad (1)$$

(v_9 is the velocity expressed in units of 10^9 cm s^{-1})

$$M_B = -21.03 + 0.11\,\beta \qquad (2)$$

The dispersions being ±800 km s^{-1} and $\pm 0\overset{m}{.}5$, respectively. The parameter β is defined as the ratio of the magnitude difference between the magnitudes at maximum and at the beginning of the exponential tail to the corresponding time difference. It is expressed as magnitudes per 100 days. The observed values fall into the range $6 \leqslant \beta \leqslant 14$.

Thermonuclear deflagration models of C – O white dwarfs, predicting complete disruption of the star, do account for the general feature of "classical" SNI, but they are unable to reproduce the Pskovskii-Branch effect. López *et al.* (1986) show how this effect could be explained, with the explosion leaving a bound remnant. The possibility of leaving such a bound remnant arises from the fact that C – O white dwarfs in close binary systems are, in general, solid objects. The consequences of solidification have been largely explored by Isern *et al.* (1983) and references therein. Depending on the size of the solid core at the onset of the thermal runaway, these models predict either the total disruption or the formation of a bound remnant (a neutron star or a white dwarf) (Canal *et al.* 1986).

Numerical, self-consistent simulation of a white dwarf explosion is rather a complex, time-consuming calculation. It involves treatment of burning front propagation, the nuclear reaction network, shock wave formation, etc. In the present paper we only intend to explore the minimal requirements to be fulfilled by the theoretical models of SNI explosions in order to be compatible with the observational data.

II. RESULTS AND DISCUSSION

We have constructed models for SNI light curves following the procedure described in López *et al.* (1986). Those models assume thermonuclear explosion of a compact object. Both, the amount of material ejected and the mass of ^{56}Ni synthesized are variable. The explosion energy is spent on gas expansion, while radioactive decay of ^{56}Ni accounts for the light curve. The models only cover the stages previous to the exponential "tail".

a) *Models leaving no Bound Remnant*

The two basic parameters governing the shape of a SNI light curve are the amount of matter ejected and that of ^{56}Ni synthesized. Most models proposed so far give total disruption of the star. The ejected mass is approximately equal to the Chandrasekhar mass.

Those models treat the white dwarf's interior as being fluid. Burning front propagation through fluid layers is still an open problem (Wheeler 1982; Müller and Arnett 1985). This introduces a sizeable uncertainty as to the amount of ^{56}Ni synthesized. In order to analyze the implications of this uncertainty on the light curves, we have calculated a first series of models for different values of the ^{56}Ni mass. Their characteristics are shown in Table 1.

M_{Ni}, R_p, v_p, L_{43} and M_B are, respectively, the mass of ^{56}Ni sinthesized, and radius, expansion velocity of photospheric material, bolometric luminosity, and abso-

TABLE 1
MODELS THAT SUFFER TOTAL DISRUPTION

Model	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	E_{kin} (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
a	1.435	1.2	1.12	1.60	13118	2.26	−20.01
b′	1.435	0.9	0.70	1.69	10247	1.48	−19.44
c′	1.435	0.65	0.36	1.46	7615	0.91	−18.85

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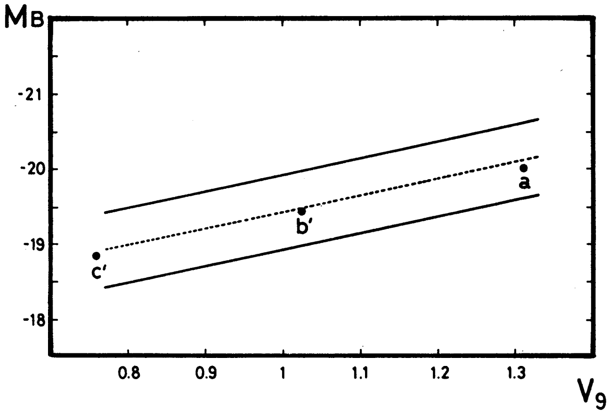

Fig. 1. B-magnitude versus ejection velocity diagram at maximum light for Type I supernovae ("v-M_B diagram" hereafter). The strip is the loci of the observations and the dashed line represents the best fit obtained by Pskovskii assuming $H_0 = 60$ km s^{-1} Mpc^{-1}. Dots correspond to models of Table 1.

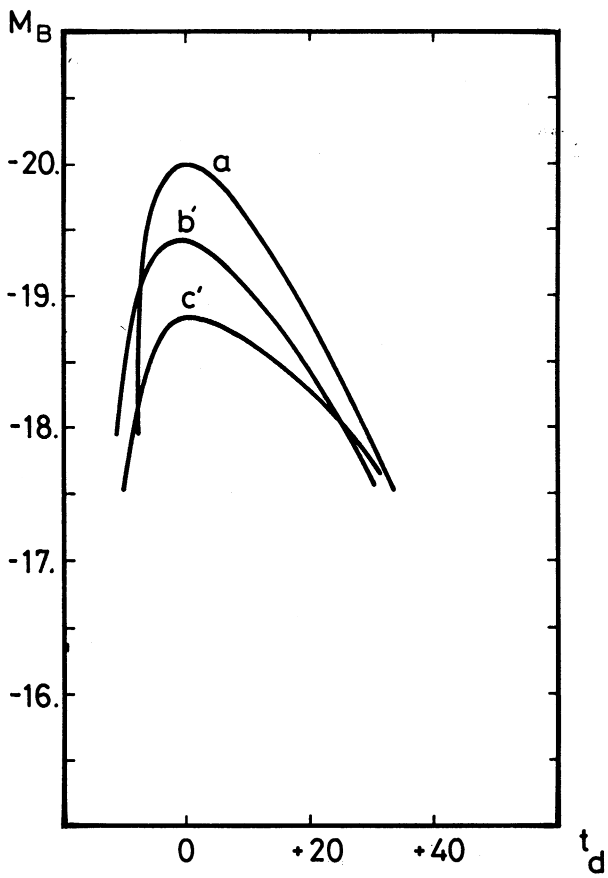

Fig. 2. Light curves for models of Table 1. In these models the white dwarf is completely disrupted.

lute magnitude in the B-band, all at maximum light. E_{kin} is the kinetic energy of the initial models. It is the difference between explosion energy and binding energy. The ejected mass is 1.435 $M_\odot$ in all models. A constant value for the opacity has been adopted $\kappa = 0.2$ cm^2 g^{-1} (Colgate and McKee 1969).

Figure 1 shows the position of the models on an expansion velocity-absolute B-magnitude at maximum diagram. Figure 2 shows the light curves. From both figures we see that the results are compatible with the observed luminosities and expansion velocities and also with the average shape of the light curves. However, changes in the amount of ^{56}Ni alone cannot reproduce the Pskovskii-Branch effect, since the light curves become broader when the maximum luminosity is lowered.

b) *Models with Bound Remnant*

Evolutionary models of mass-accreting white dwarfs have recently been constructed (Labay, Canal, and Isern 1983; Isern *et al.* 1983). Those models include the fact that the white dwarf interior's can be solid and even go through a chemical separation process (Stevenson 1980). In C – O white dwarfs, oxygen settles at the center and carbon is concentrated in the outer layers (Canal, Isern, and Labay 1980; Mochkovich 1983). Calculations show that when the thermonuclear runaway starts there is still a central solid core. Its size depends on the initial mass and the initial temperature of the white dwarf, and on the accretion rate. Outside the core there is a carbon-rich "mantle". The ignition takes place at the base of this mantle (Figure 3). Those models provide a natural way for variation of both the ejected mass and the amount of ^{56}Ni synthesized. The thermonuclear burning front propagates very slowly through the solid layers (Isern, Labay, and Canal 1984). In this case only a fraction of the mantle is burnt into ^{56}Ni and ejected by the explosion. Table 2 shows the characteristics of those models.

A total mass of 1.435 $M_\odot$ has been adopted for the white dwarf, and a value of 0.2 cm^2 g^{-1} for the opacity, the same as for models in Table 1. Figures 4 and 5 show that these models not only agree with the observational data as to expansion velocities, maximum luminosities, and light curve shape, but they also reproduce the Pskovskii-Branch effect. The behaviour of the models in Table 2 can be understood on the basis of the analytical models derived by Arnett (1982). According to them, peak luminosity width scales as $(\kappa\, M_{ej}^3/M_{Ni}^*)^{1/4}$, and the expansion velocity as $(M_{Ni}^*/M_{ej})^{1/2}$, where M_{Ni}^* is the effective amount of ^{56}Ni to be synthesized in order to eject the mantle. Peak luminosity is proportional to ^{56}Ni mass (López *et al.* 1986).

The mass of ^{56}Ni produced not only depends on the size of the oxygen core, but also on the outermost point reached by the burning front. In the fluid phase, the burning front propagates through Rayleigh-Taylor instability and its speed is of the order of the sound speed (Wheeler 1982). Detailed numerical calculations are very complex, given the difficulties arising when mixing NSE material with non-NSE material. For that reason, several authors have either adopted a propagation speed which

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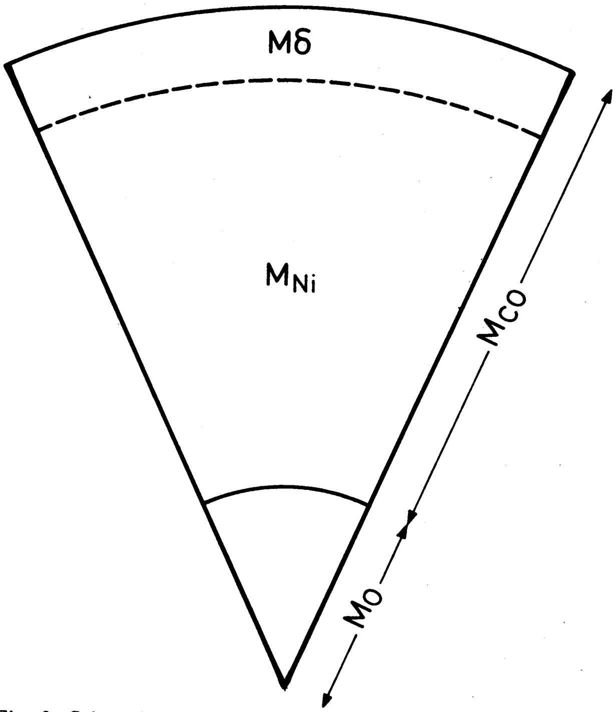

Fig. 3. Schematic structure of the progenitors of Type I supernovae. "M_O" is the solid oxygen core and "$M_{C\text{-}O}$" is the fluid carbon-oxygen mantel. "M_{Ni}" represents the incinerated material and "M_δ" the unburnt part of the star.

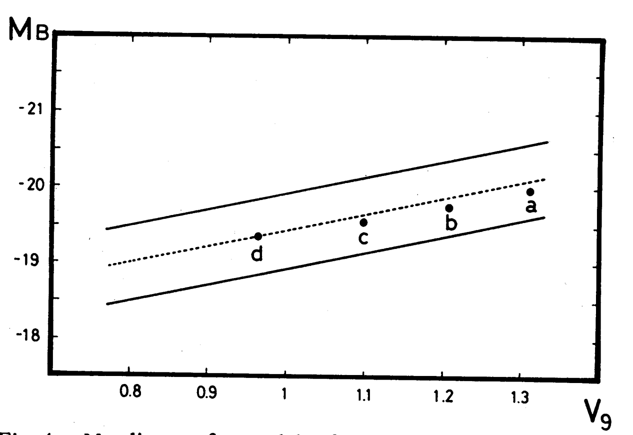

Fig. 4. v-M_B diagram for models of Table 2. (The best fit is also for $H_0 = 60$ km s^{-1} Mpc^{-1}).

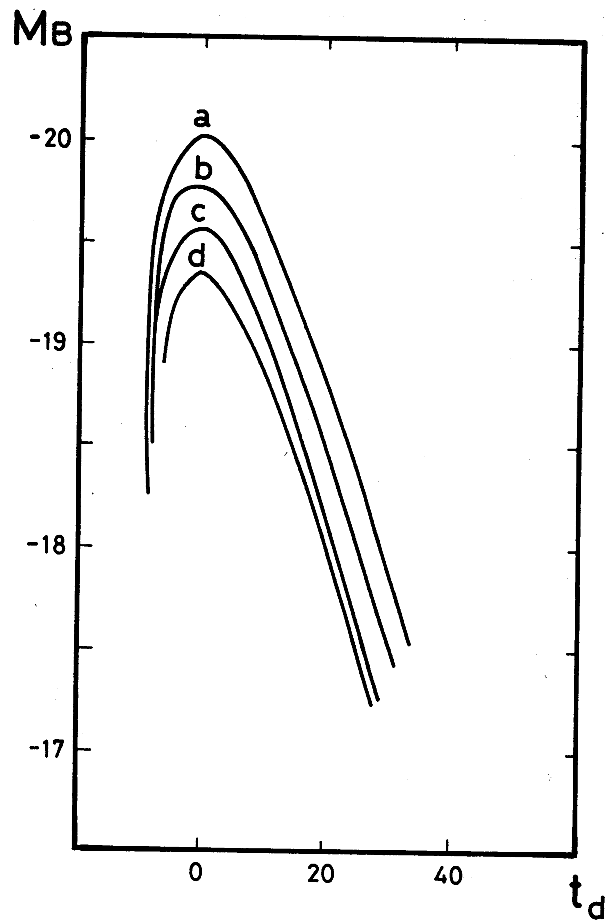

Fig. 5. Light curves for models of Table 2 (models that leave bound remnants).

is a constant fraction of the local sound speed (0.2-0.3), or velocity prescriptions derived from a time-dependent mixing-length theory, where the mixing length is left as a free parameter (Nomoto and Sugimoto 1977). For instance, for $\alpha = 1/H_p$ equal to 0.6, 0.8, 1, and 2, they obtain M_{Ni} equal to 0.49, 0.65, 0.8, and 1.15 $M_\odot$ respectively (Nomoto 1984; Jeffrey and Sutherland 1985). Given those uncertainties, one cannot accurately determine how much of the external mass left unburnt (M_δ). For every value of M_δ, different masses of the central oxygen core have been assumed. We have: $M_{Ni} = M_{tot} -$

TABLE 2

MODELS THAT LEAVE A BOUND REMNANT

Model	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	E_{kin} (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
a	1.435	1.2	1.12	1.60	13118	2.26	−20.01
b	1.2	1.0	0.81	1.52	12075	1.83	−19.76
c	0.9	0.7	0.50	1.30	10975	1.49	−19.55
d	0.8	0.6	0.34	1.18	9645	1.22	−19.34

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TABLE 3

INFLUENCE OF NON-INCINERATED EXTERNAL MASS

Model	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	E_{kin} (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
				M_δ = 0.2			
a_1	1.435	1.2	1.12	1.60	13118	2.26	−20.01
d_1	0.8	0.6	0.34	1.18	9645	1.22	−19.34
				M_δ = 0.3			
a_2	1.435	1.135	1.05	1.60	12726	2.05	−19.88
d_2	1.0	0.7	0.45	1.35	9958	1.29	−19.36
				M_δ = 0.4			
a_3	1.435	1.0	0.95	1.68	11914	1.87	−19.74
d_3	1.2	0.8	0.63	1.50	10677	1.47	−19.48

$M_\delta - M_{core}$, where $M_{tot} = 1.435\ M_\odot$. Table 3 shows the initial parameters and the characteristics of these models at the peak of the light curve. The quantity of ^{56}Ni in model *d* is the minimun value allowable to reproduce the Pskovskii-Branch effect as to the width of the light curve (López *et al.* 1986). Increasing M_δ reduces the possible combinations of M_{ej} and M_{Ni} which are able to simultaneously produce high luminosities, high velocities, and broad light curves. The corresponding ranges of variation for M_B and v_{ej} finally become narrower than those observed (see Figure 6).

The basic parameters that characterize the light curves are ejected mass and ^{56}Ni mass. There are, however, other physical parameters that can influence the results. Opacity is an important one. Since the gas is far from LTE, its opacity is uncertain. A lower bound to its value comes from the free electrons, whose number depends on the ionization degree of the material. The opacity due to scattering by free electrons in a gas composed by iron-peak elements is 0.007*s*, where *s* is the degree of ionization (Chevalier 1981). Since the spectra at times close to maximum light show multiply ionized elements, opacity values above 0.01 $cm^2\ g^{-1}$ are generally accepted. As the absorption opacities in those conditions are not reliably known, nor is the importance of the expansion effects on their values (Karp *et al.* 1977), usually adopted values for κ range from 0.08 to 0.2 $cm^2\ g^{-1}$ (Colgate and McKee 1969; Arnett 1982; Sutherland and Wheeler 1984). In order to evaluate the influence of the opacity on the light curves, we have recalculated models *a, b,* and *c* from Table 2, for $\kappa = 0.1\ cm^2\ g^{-1}$. The results obtained in this case are displayed in Table 4. Figure 7 shows the positions of the two series of models in the v-M_B diagram. The global effect is an increase by about $0^m\!.5$ of the maxima and a decrease in the velocities of the layers close to the photosphere by about 700 km s^{-1}. Both changes are of the same order as the observational dispersions of the corresponding values. In the last case ($\kappa = 0.1\ cm^2$

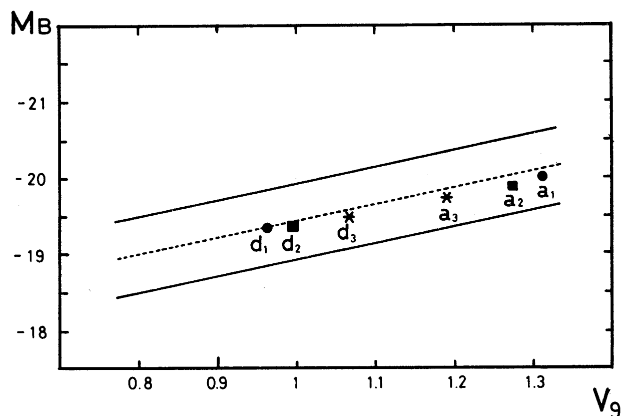

Fig. 6. Influence of the non-incinerated mass of the white dwarf (M_δ) on the position of Type I supernovae in the v-M_B diagram. Dots correspond to models with $M_\delta = 0.2\ M_\odot$, squares to models with $M_\delta = 0.3\ M_\odot$ and asterisks to models with $M_\delta = 0.4\ M_\odot$. In all cases, models labelled with "a" do not leave bound remnants, and the mass of ^{56}Ni synthesized in models "d" is the minimum that is required to reproduce the "Pskovskii-Branch" effect.

g^{-1}), the H_0 value giving the best fit to the models is 50 km s^{-1} Mpc^{-1}. In Figure 8 we show the light curves for models *a* and *a'*. As it should be expected, luminosity decreases with increasing opacity and, as shown by the scaling relationship above, light curves become broader. Also, the rise to maximum is steeper for lower opacities. Besides, since Ni is not observed at maximum light, were the opacity lower than 0.1 $cm^2\ g^{-1}$, one should exclude the models with M_δ, the non-incinerated mass, below 0.2 $M_\odot$.

In all the models considered so far the total mass of the white dwarf has the same value. But thermonuclear ignition can happen at slightly different central densities ($3 \times 10^9 \leqslant \rho_{ig} \leqslant 10^{10}$ g cm^{-3}), which also means slightly different total masses. That changes the binding energies and thus the amount of nuclear energy available for

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TABLE 4

INFLUENCE OF THE VALUE OF THE OPACITY

Model	Mej ($M_\odot$)	M_{Ni} ($M_\odot$)	Ekin (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
a	1.435	1.2	1.12	1.60	13118	2.26	−20.01
a′	1.435	1.2	1.12	1.26	12745	2.93	−20.41
b	1.2	1.0	0.81	1.52	12075	1.83	−19.76
b′	1.2	1.0	0.81	1.16	10788	2.37	−20.18
c	0.9	0.7	0.50	1.30	10975	1.49	−19.55
c′	0.9	0.7	0.50	0.99	10095	1.89	−19.94

Models a, b, and c: $\kappa = 0.2$ cm^2 g^{-1}. Models a′, b′, and c′: $\kappa = 0.1$ cm^2 g^{-1}.

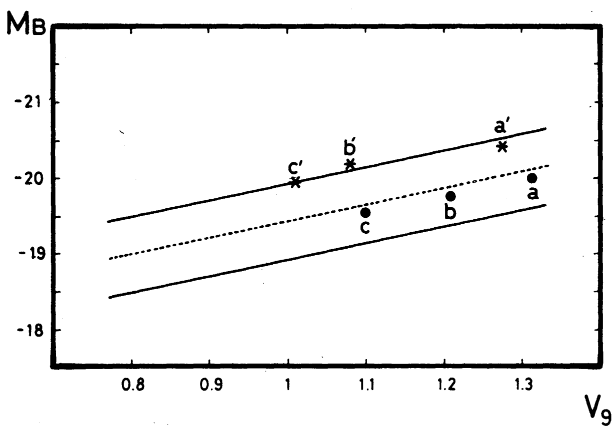

Fig. 7. v-M_B diagram for models of Table 4. Dots correspond to models with an opacity $\kappa = 0.2$ cm^2 g^{-1}. Asterisks to same models with $\kappa = 0.1$ cm^2 g^{-1}. In the last case, the best fit to the Pskovskii-Branch relationship is obtained assuming $H_0 = 50$ km s^{-1} Mpc^{-1}.

expanding the material, the so-called "effective Ni mass" (the total mass of Ni produced minus the equivalent to the binding energy). In order to evaluate the corresponding changes in the light curves, we have calculated three more models, for ignition densities 3×10^9, 7.55×10^9, and 1.05×10^{10} g cm^{-3}, in the case of total disruption of the white dwarf. Results show that luminosity and light curve shape are hardly affected and the expansion velocities alone are slightly modified. Their variations remain below 500 km s^{-1}, and thus are within the observed dispersion. The positions of those models in the v-M_B diagram indicate a better agreement with the Pskovskii-Branch effect for the models where ignition happens at higher densities (model *a*: $\rho_{ig} = 10^{10}$ g cm^{-3}).

We have always assumed that the whole nuclear energy available is converted into kinetic energy of expansion. There are, however, several factors that can modify this hypothesis. Electron captures on the incinerated material generate copious amounts of neutrinos, taking away a fraction of the available energy with them. Also, incineration may be incomplete in the outermost layers and thus the total energy released would be lower. In order to elucidate the importance of those effects, we have calculated another series of models where the energy yield

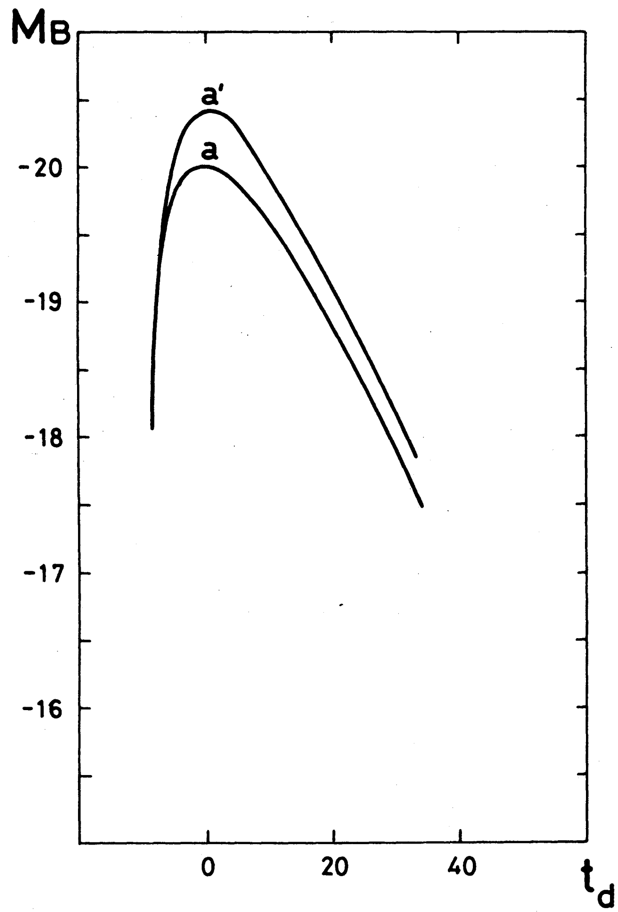

Fig. 8. Light curves for models "a" ($\kappa = 0.2$ cm^2 g^{-1}) and "a′" ($\kappa = 0.1$ cm^2 g^{-1}) of Table 4.

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has been parametrized through α, the fraction of the available energy that goes into kinetic energy. In Table 5 we give the characteristics of models calculated for $\alpha = 1$ (models *a*, *c*, and *d*), and for $\alpha = 0.8$ (models *a′*, *c′*, and *d′*). Maximum luminosities are practically unaffected. Expansion velocities are lowered by about 1000 km s^{-1}. Figure 9 shows these effects. Light curves shapes are only slightly broadened. When α lower than 0.8, the models with least ^{56}Ni synthesized would be hardly compatible with the observed velocities.

Calculations by Colgate and McKee (1969) showed that the explosion of a polytropic structure of index n = 3 produces an extended structure composed by an uniform density core which contains about 60% of the initical mass, surrounded by an envelope whose density decreases with the radius as $\sim r^{-p}$, where p takes the value of 6.5 for an initial structure of 1.4 $M_\odot$ and higher values for lower masses. Moreover, numerical models show that the envelopes are quite well fitted by the aforementioned relationship except for the outermost regions which show a steeper dependence (Branch *et al.* 1985). In order to know the influence of the density profile on the light curves, we have computed two models with p = 6.5 and p = 7. In both cases we have assumed that no bound remnant is left. Table 6 shows the characteristics of both

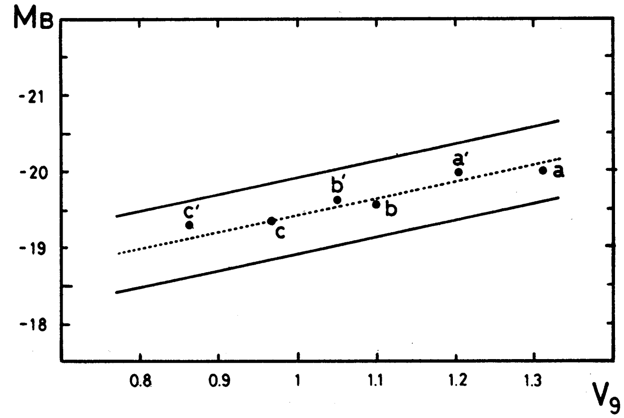

Fig. 9. v-M_B diagram for models of Table 5. Models marked with (′) have been calculated assuming $\alpha = 0.8$ (i.e., losses in the thermonuclear energy of about 20%). The ejection velocity is strongly affected by these losses as it can be seen from the figure.

models. The main results are the broadening of the light curve, even in the pre-maximum regime, and the reduction of the expansion velocity as p decreases. Steeper profiles than p = 7.5 give expansion velocities that do not agree with the observed ones.

TABLE 5

INFLUENCE OF THE PARAMETER α

Model	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	E_{kin} (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
a	1.435	1.2	1.12	1.60	13118	2.26	-20.01
a′	1.435	1.2	0.92	1.52	12017	2.20	−20.00
b	1.0	0.8	0.60	1.38	11408	1.61	−19.64
b′	1.0	0.8	0.49	1.29	10508	1.56	−19.62
c	0.8	0.6	0.34	1.18	9645	1.22	−19.34
c′	0.8	0.6	0.27	1.14	8655	1.18	−19.31

Models a, b, and c: $\alpha = 1$. Models a′, b′, and c′: $\alpha = 0.8$.

TABLE 6

INFLUENCE OF THE DENSITY PROFILE

Model	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	E_{kin} (10^{51} erg)	R_p (10^{15} cm)	V_p (km s^{-1})	L_{43} (erg s^{-1})	M_B
a	1.435	1.2	1.12	1.60	13118	2.26	−20.01
a′	1.435	1.2	0.80	1.50	11789	2.30	−20.05

Model a: p = 7. Model a′: p = 6.5.

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III. CONCLUSIONS

Generally speaking, thermonuclear deflagration of a white dwarf in a close binary system can reproduce the average characteristics of Type I supernovae. Ordinary models cannot, however, account for the Pskovskii-Branch effect. Attempts have been made to reproduce this effect by only varying the amount of ^{56}Ni generated. Besides being *ad hoc*, this produced an effect that is the opposite to the observed one.

If we take into account that a white dwarf can easily become solid and that in many cases it is still partially solid when thermonuclear ignition happens, the Pskovskii-Branch effect naturally results from this property, since both ejected mass and ^{56}Ni change from an explosion to another. It must be stressed that, in the framework of this last type of models it is not necessary to assume the star to be solid in every case. Only a fraction of the explosions leave bound remnants (when there is still a solid core at ignition). The expected frequency of the outburst is not changed by that (they do not generally have to be delayed until the star has become solid). The recent discovery of a subclass of "peculiar" SNI, whose progenitors might be intermediate-mass star, contributes to the agreement between observed frequencies and theoretical ones (those deduced from the proposed scenarios).

Observational data concerning SNI are still scarce and incomplete. There is still a sizeable dispersion in the values of the maximum luminosities and, specially, in the expansion velocities. In the same way, the criteria foı classifying SNI as either "slow" or "fast" still lack reliability and precision. All the uncertainties put together, we cannot determine the range of the basic parameters of our models in a clear-cut way. The most important one appears to be M_δ, the non-incinerated mass. Its value critically depends on the mode of propagation of the burning front through fluid layers, and this last problem is far from solved. Were M_δ larger than 0.4 $M_\odot$, models assuming off-center ignitions might hardly reproduce the Pskovskii-Branch effect. On the other hand, the presence of intermediate-mass elements moving at high speeds, together with the absence of Ni in the spectra at maximum luminosity, do suggest that the non-incinerated mass, for reasonable values of the opacity ($\kappa = 0.1 - 0.2$ cm^2 g^{-1}), cannot be much lower than 0.2 $M_\odot$. Also, the mass of the thermonuclearly inert core being between 0 and 0.6 $M_\odot$, the losses in the process of conversion of nuclear and internal energies into kinetic energy cannot be larger than about 20%, unless we assume a contribution from gravitational energy (bounce of the compact remnant).

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