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**Deflagrating White Dwarfs
and the
Statistical Properties of Type I Supernovae**

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ABSTRACT

It is generally supposed that the luminosity of a type I supernova (SN I) is powered by the decay of the radioactive isotope ^{56}Ni , which is synthesized and ejected when a white dwarf explodes. The class of models in which thermonuclear ignition leads to the formation of a turbulent burning front and total disruption of the white dwarf is well favored because of the excellent agreement between theory and observations. Despite the maturity of this model it can be criticized because it has not been shown to account for the intrinsic dispersion in the properties of SN I. A careful examination of the importance of the distribution of radioactive material near the center of the explosion suggests how deflagrations may encompass the variation encountered from event to event.

I Introduction

The radioactive decay model of type I supernovae (SNI) (Colgate & McKee 1966) has achieved a considerable degree of observational confirmation (Colgate Petschek & Kriese 1980; Meyerott 1980; Axelrod 1980; Graham *et al.* 1986). A specific astrophysical realization of this model invokes a C+O white dwarf which is provoked into thermonuclear explosion by accretion from a companion star (see Woosley and Weaver 1986 for a recent review). Nomoto, Thielemann and Yokoi (1984) have considered the evolution of a $1.38M_{\odot}$ white dwarf accreting He at $M = 4 \times 10^{-8} M_{\odot}/\text{yr}$, and simulated the propagation of the ensuing burning front using time-dependent mixing-length theory of convection. This carbon deflagration supernova (designated model W7) has achieved unprecedented success in reproducing the spectra and light curves of type I supernovae (Branch *et al.* 1985; Graham 1987). Nonetheless, it can be argued that a carbon deflagration cannot be a complete description of the SN I phenomenon because the model is too restrictive and does not admit the intrinsic dispersion in observed properties (Isern, Labay, and Canal 1984; Lopez *et al.* 1986). In an idealized form the carbon deflagration supernova is a single parameter model in which the observational consequences of the explosion depend upon what fraction of the white dwarf is converted to radioactive ^{56}Ni (*c.f.* Sutherland and Wheeler 1984). The white dwarf is completely disrupted by the explosion and the ejected mass is always close to the Chandrasekhar limit.

If one admits partial disruption of the white dwarf, so that a variable fraction of the initial mass is ejected, a broader range of behaviour can be expected. It has been pointed out that thermonuclear ignition and ensuing collapse and explosion inside a partially *solid* carbon-oxygen white dwarf (Canal, Isern, and Labay 1982) may lead to a range of outcomes leaving condensed remnants of various mass from practically the initial mass up to zero (Isern *et al.* 1984). This scenario could

account for a wide range of phenomena from the formation of low mass binary X-ray sources which contain neutron stars to the most energetic SN I.

Although it is often noted that SN I show a remarkable degree of spectral and photometric homogeneity - especially when a distinction is made between type Ia and Ib events (Elias *et al.* 1985; Branch 1986; Graham 1986), properties such as the rate of post-peak decline, the wavelength of absorption features, and the absolute magnitude at maximum do vary from supernova to supernova (Branch 1981). These properties are correlated in the sense that supernovae with the slowest post-peak decline rate are among the brightest events and have the highest photospheric velocities. The additional degree of freedom in the exploding solid white dwarf model not only accounts for the dispersion in supernova properties, but also explains why 'slow' supernovae are the most energetic (Isern *et al.* 1984; Lopez *et al.* 1986). This correlation is a source of difficulty for the carbon deflagration because total disruption models predicts that the most energetic supernovae will be the fastest events, *i.e.* it predicts a strong correlation in the opposite sense to the observations (Arnett 1982). Thus even though the observed correlations may not be established beyond doubt, the statistics do not seem to be consistent with the correlation which is expected for total disruption (Branch 1981).

The purpose of this *Letter* is to point out that it is an over simplification to treat a carbon deflagration as a one parameter white dwarf explosion, and to show how the rate of post-peak decline and the maximum luminosity may be varied in accordance with the data even though the ejected mass remains constant.

II Light Curves

Graham (1987) has recently calculated the bolometric light curve for the model carbon deflagration of Nomoto *et al.* (1984, model W7). An excellent fit to the data is obtained. However, it is found that the rate of decay of the light curve is very sensitive to the distribution of radioactive material near the center of the explosion. This is a consequence of the density distribution being approximately exponential in form. A good fit is found only when care is taken to describe accurately the internal structure of the deflagration in the light curve calculation.

A deflagration wave ensues when carbon is ignited under conditions of high density. When the density is sufficiently high, release of nuclear energy results in only a small change in the Fermi pressure, and a detonation wave cannot form, but explosive burning can propagate behind a deflagration wave which expands outward on the timescale for convective energy transport across the front. One important consequence of ignition at high density, which is characteristic of deflagrations, is a high electron capture rate (Woosley and Weaver 1986; Nomoto *et al.* 1984). In the absence of weak interactions during explosive processing of $Z = N$ material the most abundant isotope after freeze-out from nuclear statistical equilibrium is ^{56}Ni - the most tightly bound nucleus with equal numbers of proton and neutrons. When the energy of the electrons is sufficiently high inverse β -decay can occur and neutron rich isotopes are synthesised. In the carbon deflagration of Nomoto *et al.* sufficient electron capture occurs so that the central $\sim 0.25 M_{\odot}$ of the ejecta consist chiefly of non-radioactive ^{54}Fe and ^{58}Ni .

The presence of this small mass of stable isotopes near the center of the explosion plays a crucial rôle in determining the rate of post-peak decline (Graham 1987). If the mass of this non-radioactive material is increased, at the expense of the amount of ^{56}Ni synthesized, and the hole in the distribution of radioactive material is enlarged, then on average γ -rays, which carry the

decay energy, are more likely to escape and the light curve declines faster. Conversely, if ^{56}Ni extends closer to the center, because less electron capture occurred and fewer stable isotopes were synthesized, then the deposition efficiency of radioactive decay energy is increased, and the light curve decays more slowly. As the amount of electron capture is sensitive to the ignition density, which in turn is a function of the accretion rate, it is not unreasonable to expect that supernovae will ignite over a range of densities and eject a variable mass of non-radioactive iron group elements near the center of the explosion. Consequently, these explosions should exhibit a range of light curve decay rate.

In order to test whether or not deflagrations with variable mass stable-isotope cores could account for the spread in post-peak decline rate, light curves have been calculated using the techniques developed in Graham (1987) for models with masses of non-radioactive cores between 0 and $0.4 M_{\odot}$. (This range was chosen as it represents the limits of the 99.9% confidence interval on core mass determined from fitting observations of SN1981b and SN1972e). The outer mass coordinate of the ^{56}Ni zone is fixed by the propagation speed of the burning front (Nomoto *et al.* 1984), and consequently is set to its value in W7, $0.84 M_{\odot}$. Slightly more nuclear energy is available for conversion to kinetic energy if a more tightly bound neutron rich isotope is synthesized. However, for the sake of simplicity this small effect is ignored, and the velocity and density structure of W7 is assumed.

To allow comparison with observations the bolometric luminosity has to be converted into an inband flux. Bolometric corrections were calculated following Schurmann (1983) and Sutherland & Wheeler (1984) by locating the position of the photosphere at $\tau=2/3$ and then calculating the temperature of a truncated Planck function ($\lambda_t = 4000\text{\AA}$) which yields the appropriate flux. The results are displayed in Figure 1, where, for each model, the absolute magnitude at maximum is

plotted against the speed-class parameter β , which is defined as the post-peak decline rate, prior to the point of inflection in the light curve, in units of 0.01 magnitudes/day. The value of the optical opacity, which is important in determining the shape of the light curve near maximum, is not particularly well known, and so each model has been calculated for plausible values of $\kappa = 0.1$ and $0.3 \text{ cm}^2 \text{ g}^{-1}$.

Clearly, this family of models with variable core masses can account for the spread in the post-peak decline rate, β . But most importantly, these models reproduce the trend for slower supernovae to be brighter and fall remarkably close to the regression line defined by the data.

One might expect that tampering with W7 in the manner proposed could be ruled out by spectral constraints. However, J. C. Wheeler and R. P. Harkness (private communication, 1986) find that the theoretical spectrum of W7 with only $0.15M_{\odot}$ of ^{56}Ni remaining is still consistent with observations.

III Discussion

We have argued that the accretion rate onto the progenitor white dwarf determines the ignition density and consequently the luminosity and speed class of the resultant supernova, explaining the $\Delta M_{\text{B}} - \beta$ correlation. The amount of energy liberated in each explosion is virtually the same, and so these explosions do not show any dispersion in photospheric velocity at maximum light.

We have assumed that the burning-front propagates at the same speed in all explosions. Since the amount of energy released by a deflagration is a strong function of flame speed it is important to consider the consequences of a variable flame speed. A faster flame will travel further before expansion of the white dwarf quenches the explosion, extending the ^{56}Ni zone (Nomoto *et al.* 1984). A faster burning front will also reduce the time the central regions spend at high density

and thereby reduce the amount of electron capture (Nomoto *et al.* 1984). Thus the fastest deflagration waves synthesize the largest mass of ^{56}Ni and the smallest mass of stable iron-group elements, and as expected from observations the most energetic SN are the brightest, and have slow light curves.

Accordingly, a carbon deflagration explosion is a two parameter model in which the speed of the deflagration-wave, and the mass of the neutronized core are the two most important variables. There is good reason to expect that these parameters are not independent, but that they may be related in the correct sense to explain all the observed correlations. As argued above the outcome of the explosion is sensitive to the ignition density. But it is also plausible to expect that the propagation of a turbulent burning front will depend upon the density and temperature structure of the white dwarf, which will in turn depend upon the initial white dwarf mass and the accretion rate. Thus, the possible explosions which reflect a range of initial mass and accretion rate could occupy a finite area on Figure 1. If this is the case, then some of the dispersion in ΔM_B seen in each speed-class bin must be intrinsic. The strongest evidence for a range in brightness is found if type I events are classified spectroscopically into type Ia and type Ib (Branch 1986). The optical light curves of SNIa and SN Ib are similar, yet SN Ib are significantly dimmer (Panagia *et al.* 1987; Uomoto and Kirshner 1985). (Note the Ib events in fig. 1 lie on the lower edge of the envelope defined by SNIa)

Although it would be attractive to treat SNIa and SN Ib as extreme examples of a continuous sequence of events, there is evidence that SNIa and SN Ib are fundamentally different. SN Ib appear to be correlated with sites of massive star formation (Uomoto and Kirshner 1985) and late time spectra also favor a massive progenitor (Begelman and Sarazin 1986). However, it is difficult to reconcile this proposal with the observation that the optical light curves of SNIa and SN Ib are

indistinguishable, despite the fact that an order of magnitude more ejecta has been proposed to explain SNIb spectra.

If SNIb are exploding white dwarfs then the difference between them and classical events must be due to the different initial conditions - the dwarf mass and the accretion rate. These are of course both strong functions of mass of the parent population. Consequently, the ensuing explosion in high and low mass populations may be substantially different.

IV Conclusions

A physical explanation for the dispersion and correlations of SN I properties has been proposed within the framework of the carbon deflagration model. It is pointed out that the mass of the neutronized core plays a major rôle in determining the rate of post-peak decline, and it is argued that plausible explosion scenarios will lead to configurations such that the most energetic supernovae will have the smallest stable-isotope core masses, and thus exhibit the slowest light curves, as required by the data. It is clearly important to explore the the range of conditions over which thermonuclear ignition will lead to a carbon deflagration supernova and hence discover whether or not they can reproduce the diversity found in nature.

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Figure Caption

Figure 1:

Absolute magnitude plotted against post-peak decay speed, β . The are data from Branch (1981) where the zero point has been defined so that $\Delta M_B = 0$ for $\beta = 9$. Type Ia and Ib events are coded seperately. Five deflagration supernova models are shown with stable-isotope core masses from $0.0M_\odot$ to $0.4M_\odot$. Solid lines join models calculated with $\kappa = 0.1$ and $0.3 \text{ cm}^2 \text{ g}^{-1}$.

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