Host Galaxy Effects in the Susy Model for Supernovae Ia

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Abstract

For more than forty years virtually all work on the theory of type Ia Supernovae (SN Ia) has assumed that these explosions were due to the transfer of mass to a degenerate star from a partner in a binary system. In these binary models, when the mass of one partner closely approaches the Chandrasekhar maximum for a stable degenerate system, fusion can be initiated and the star explodes. However, there are now a number of indications that fusion could instead be triggered by a phase transition in a sub-Chandrasekhar white dwarf star. Although these indications provide no clue as to what specific phase transition initiates the explosion, it is possible that remarkable and well established host galaxy effects as considered in the present work could point to a specific source of the energy deposition. These host galaxy correlations are, at first glance, surprising since the typical distance scale of white dwarf stars is the earth radius while the typical distance between stars is at the light year scale. Performing a least χ^2 fit to the delay time distribution to fix parameters, we give predictions from the susy phase transition model for the host galaxy effects. In addition we discuss a susy insight into the Phillips relation which is basic to the cosmological importance of the type Ia supernovae.

1 Introduction

An exhaustive review of the status of binary models for type Ia supernovae has been recently presented in ref. [1]. An essential feature of these models is that accumulation of matter from a partner star leads to an SN Ia explosion near the Chandrasekhar mass, M_C. In contradistinction to these models we have noted [2] that there are at least six indications

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that SN Ia are due not to mass growth to the Chandrasekhar maximum but, instead, to a phase transition in a possibly isolated white dwarf. An example of a latter such model is one [3][4] in which matter at extremely high density undergoes a tunneling phase transition to a background of exact supersymmetry (susy). The model assumes that the exactly supersymmetric universe is the ground state of the multiverse and that the transition rate to this ground state is enhanced at high density. In such a susy background, initial state fermion pairs would convert to boson pairs which, since they are unaffected by the Pauli Principle, would drop to the ground state emitting sufficient energy to trigger fusion in the surrounding matter. If the ground state of the universe is exactly supersymmetric and the current state is one of broken supersymmetry, the probability per unit space time volume of vacuum decay to the ground state in interstellar space is given by the Coleman-DeLuccia [5] formula:

$$\frac{d^2P}{dtd^3x} = Ae^{-B} \tag{1.1}$$

where the action takes the form

$$B = \frac{27\pi^2 S^4}{2\hbar c\overline{\epsilon}^3} \quad , \tag{1.2}$$

S is the surface tension of a critical bubble of true vacuum nucleated in the ambient false vacuum universe and $\overline{\epsilon}$ is the average energy density difference between the two vacua. Thus, given a knowledge of $\overline{\epsilon}$, the transition probability depends on the two parameters S with units of energy per unit area and A with units of an inverse space time volume. In the phase transition theory bubbles of all radii are constantly being nucleated in the false vacuum but most of them will be immediatey quenched in a competition between the volume energy, $4\pi r^3\overline{\epsilon}/3$, tending to expand the bubble and the surface energy, $4\pi r^2 S$, tending to collapse it. In a homogeneous vacuum, where the energy difference is equal to its average, bubbles with initial radius greater than a critical value

$$R_c = \frac{3S}{\overline{\epsilon}} \tag{1.3}$$

will grow at the speed of light to complete the vacuum transition. Presumably, the bubble growth speed and the speed of light in dense matter are also equal.

2 Density Enhancement of the Susy Phase Transition

Although it is proven only in lower dimensions [6][7], it is reasonable to assume that, in a dense medium, the phase transition is accelerated. This can be naturally implemented by assuming that, in the above formulae, the vacuum energy difference is replaced by the total energy difference.

Thus, in dense media, the lifetime τ for a white dwarf of mass M is given by

$$\frac{dP}{dt} = A\,V(M) \equiv \frac{1}{\tau(M)} \tag{2.4}$$

where

$$V(M) = \int d^3x\; e^{-B} \tag{2.5}$$

and the action now takes the form

$$B = \frac{13.5\pi^2 S^4}{\hbar c(\overline{\epsilon} + \overline{\Delta\rho(r)})^3} \quad . \tag{2.6}$$

The critical radius or minimum radius of a successful bubble nucleation is

$$R_c = \frac{3S}{\overline{\overline{\epsilon} + \overline{\Delta\rho}}} \quad . \tag{2.7}$$

Without loss of generality we can factor out of A the inverse of the maximum of $V(M)$ over all white dwarf masses leaving a free parameter with dimensions of inverse time.

$$\frac{dP}{dt} = \frac{1}{\tau_0}\frac{V(M)}{V_{\max}} \equiv \frac{1}{\tau(M)} \tag{2.8}$$

The free parameter τ_0 becomes then the minimum lifetime of the dwarfs in the sample.

If $\Delta\rho$ is simply and universally proportional to the density as assumed in earlier work we can define a critical density ρ_c such that, in dense matter where $\overline{\epsilon}$ is negligible,

$$B = (\frac{\rho_c}{\rho})^3 \quad . \tag{2.9}$$

In white dwarf physics the natural scale of energy is the solar mass, $M_\odot$, and the natural scale of distance is the Earth radius, R_E. In ref. [4], a good fit to the delay time distribution was found with $\rho_c = 7.42 \cdot 10^7 \mathrm{g/cm}^3 = 9.69 M_\odot / {R_E}^3$. With this parameter value, the surface tension is such that the critical radius in empty space is of the order of galactic size making our universe safe for billions of additional years.

In an inhomogeneous medium, the growth of a critically sized bubble will be halted if the critical radius of eq. 2.7 becomes greater than the current bubble radius. In an uncompactified superstring theory or one compactified on tori the ground state vacuum energy density vanishes so that the energy density difference is equal to the vacuum energy density in the broken susy phase which is currently measured to be

$$\epsilon = 3.35 GeV/m^3 \quad . \tag{2.10}$$

3 The White Dwarf Mass Distribution

In the phase transition model the rates are proportional to the white dwarf production rate. White dwarf binaries, in principle, are counted twice in this distribution. If there are large numbers of high mass binaries that are not included in the distribution due to systematic effects, the parameters of the susy model would be modified. On the other hand, the double degenerate model for SN Ia based on an assumed collision or coalescence of white dwarfs is crucially dependent on the existence of such as yet unobserved white dwarf binaries with total mass near the Chandrasekhar mass. Binaries with total mass below M_C would be expected to be even more numerous which might lead, once triggered, to many sub-luminous supernovae even in high metallicity environments.

The Salpeter initial mass function with a linear relation between the main sequence mass and the resulting white dwarf mass gives an excellent fit to the observed hot white dwarf mass distribution between the peak at 0.6 $M_\odot$ and 0.8 $M_\odot$. The hot white dwarf mass distribution is taken to approximate the birth mass distribution. However, It has been noted that the Salpeter initial mass function overpredicts the white dwarf mass distribution for masses above 0.8. It is also known, as discussed below, that white dwarfs of mass above 0.9 are primarily oxygen-neon-magnesium mixtures. Theoretically, white dwarfs in this mass range are produced preferentially in average to high metallicity environments while the observed white dwarfs belong to the low metallicity Milky Way galaxy and nearby satellite galaxies. We normalize the white dwarf production rate assuming a constant star production rate for 12.8 Gyr. There is, of course, some variation in this number and the rate would, of course, be greater in star-burst galaxies. We therefore take the Salpeter fit for $0.6 < M(0) < 1.35$, shown in ref. [4], as appropriate to the birth mass distribution in some average to high metallicity environment and, correspondingly, in some average to high galactic age t_g:

$$F(M(0)) = a_0((M(0) - 0.478)/0.09028)^{-2.35} \quad m(0) > 0.62 M_\odot \tag{3.11}$$

with

$$a_0 = 5.48\,\frac{12.8Gyr}{t_g} \mathrm{WD/yr/10^{10}WD} \quad . \tag{3.12}$$

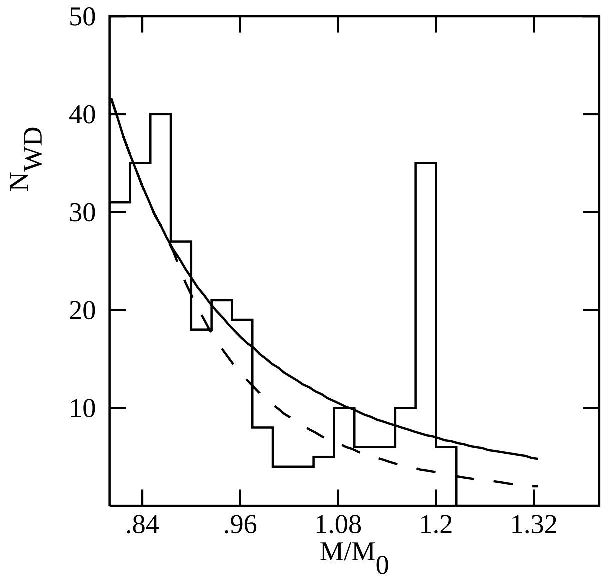

Figure 1: White Dwarf production rate for average to high metallicity environments (solid curve) and low metallicity environments (dashed curve) compared to white dwarf masses as observed in the (low metallicity) Milky Way. The solid curve is an expanded view of the high mass tail of the full Salpeter type fit to the white dwarf mass distribution shown in ref. [4] .

In the present fit we take a nominal age of $t_g = 12.8$ Gyr to fit the data in the delay time distribution (DTD). Good fits can also be found with ages ten to twenty percent lower. With future high statistics data it might be possible to give the DTD as a function of the host galaxy age.

In low metallicity environments such as the Milky Way it is suggested that $F(M(0))$ contains the extra factor

$$\frac{\theta(M(0) - 0.9)}{1 + 3.2\,(M(0) - 0.9)} \tag{3.13}$$

which comes from the crude fit of fig. 1 to the tail of the observed distribution of local white dwarfs. The spike at $M(0) = 1.2$ is known to be an artifact of the data treatment at high masses and should be ignored [8] or spread among higher masses. Other authors discussing the variation of the initial mass function are refs. [9] and [10].

4 Metallicity Dependence of the Susy Phase Transition

In the susy phase transition model the energy density difference in dense matter is the energy trapped in high energy levels due to the Pauli Principle. This energy is released in a transition to exact susy since Fermion pairs can convert to pairs of degenerate Bosons. The conversion takes place in nuclei on strong interaction time scales ($\approx 10^{-24}s$) via gluino exchange between quarks. On the electromagnetic time scale ($\approx 10^{-6}\,s$) electron pairs can convert into selectron pairs via photino exchange. The former conversion has a greater energy release but does not directly affect the electron degeneracy pressure which supports the star. The energy release per unit mass from electron to selectron conversion is equal to the electron internal energy that would be released as the star explodes. The electron to selectron conversion in a susy core, therefore, provides no additional energy release relative to the standard model once the explosion is triggered. Thus, the energy provided in the susy phase transition model comes entirely from the collapse of the Pauli towers in nuclei.

The first estimates based on the Fermi gas model indicated $\Delta\rho \approx 0.02\rho$ some twenty times greater than the fusion energy released in carbon. In the Fermi gas model, the Pauli energy is primarily a function only of the atomic number to atomic weight ratio, Z/A. Consequently the energy release would be the same for the all the low-lying stable nuclei carbon, oxygen, neon, and magnesium. This leads to a universal form for the action, B. However, the Fermi gas model fails to predict the magic numbers in nuclei which are naturally accommodated in the nuclear shell model. As we will discuss in this article, the nuclear shell model in combination with the phase transition model does predict atomic number dependence and allows for the correct sense of the SN Ia-host-galaxy correlation.

The primary host galaxy properties of interest in supernova physics are:
• 1. metallicity
• 2. galaxy age
• 3. galaxy mass
• 4. star formation rate

The galactic or stellar metallicity, Z_s, is a variously defined measure of the amount of higher atomic number elements in the system. A commonly used single parameter measure, normalized to zero for the sun, is

$$Z_s = \log_{10}(N_{Fe}/N_H) - \log_{10}(N_{Fe}/N_H)_{\odot} \tag{4.14}$$

A multi-parameter definition which takes into account the full complexity of galactic and stellar composition is

$$Z_s = \log_{10}(\sum_i Z_i f_i) - \log_{10}(\sum_i Z_i f_i)_\odot \tag{4.15}$$

where Z_i is the atomic number of element i and f_i is the fraction of that element in the galaxy or star of interest. An elevated abundance of iron is ordinarily accompanied by increased abundances of other high Z elements. The itemized galactic properties are strongly interrelated. Since elements of high atomic number are produced in supernovae, older galaxies with a longer history of supernovae are expected to have higher metallicity. These higher metallicities are then preferentially passed on to new stars in those galaxies. Younger galaxies such as the Milky Way have a bias toward low metallicity and stars in such galaxies have preferentially low metallicities although the sun has higher metallicity than would be expected from other stars in the galaxy. In general, stars born early in a galaxy's history are expected to have low metallicity while stars born late are expected to have high metallicity. Of course, due to galactic inhomogeneities, not all stars in a galaxy of high metallicity will have high metalicity so the relation is statistical at best.

In the susy phase transition model each white dwarf has a mass dependent lifetime as given in eq. 2.4. In a star-burst galaxy, the supernova rate will preferentially come from stars with masses near the minimum lifetime. Only when the star formation rate slows will stars with other masses contribute proportionately to the supernova rate.

The above mentioned galactic properties have well established correlations with the SN Ia rate and the SN Ia peak brightness or Ni^{56} production.

Z		Fe^{56}	Si^{28}	mean
6	carbon fusion	0.00116	0.00081	0.00099
8	oxygen fusion	0.00085	0.00051	0.00068
10	neon fusion	0.00076	0.00042	0.00059
12	magnesium fusion	0.00054	0.00020	0.00037

Table 1: fraction of rest energy released in fusion reactions to the indicated final states. Iron group elements in the final state are represented by Fe^{56} and intermediate mass elements (IME) are represented by Si^{28} . The last column gives the mean energy release per unit mass assuming equal production of Fe^{56} and IME.

It is commonly thought that the progenitors of normal type Ia supernovae are carbon-oxygen mixtures not because of any direct evidence [11] but because such mixtures lead to more successful standard model simulations once fusion is somehow triggered. As seen for example in [2], a roughly fifty-fifty mixture of carbon/oxygen fusing to a roughly fifty-fifty mixture of iron group elements and intermediate mass elements will produce enough fusion energy to match experiment. In this case the maximum amount of energy input from a source beyond the standard model is sharply limited although some such energy input is needed to trigger fusion. Typical white dwarfs will have maximum temperatures and pressures several orders of magnitude below that at which nuclei will touch and ignite fusion. Although, in [4], no assumption was made as to the atomic composition of the white dwarfs undergoing supernova, the progenitor (and ejected) mass was found to be in the range of O-Ne-Mg white dwarfs.

In fact, an energy deficit in the standard model begins to open up if there are unburned remnants or if the initial carbon composition falls below about 0.5. Such low carbon content of at least some white dwarf stars is suggested by recent astroseimological analyses [12]. It is also suggested [13] that among carbon-oxygen white dwarfs the oxygen content near the center is nearly 80% with the carbon content increasing toward the outer strata. However, unburned oxygen is observed in SN Ia but, normally, no unburned carbon. This might be the first reason to doubt the progenitor identification as a C-O mixture. The lighter elements in a mixture, preferentially found in the low density outer regions of the star, are the most likely unburned ejecta. Any significant amount of unburned elements, of course, reduces the fusion energy output and causes additional strain on the standard model. However, in spite of the oxygen observations, for the present we neglect any significant amounts of unburned fuel.

The fact that the fusion energy available is maximized in carbon has suggested that white dwarfs with a higher percentage of carbon, as would be obtained in low metallicity environments, would have an increased production of nickel and, therefore, a greater luminosity. There are counter-arguments to this [16] and, in fact, the opposite is true in observations: White dwarfs in high metallicity environments have been shown to produce more nickel and therefore higher peak luminosity [17].

In the phase transition model [4] the progenitor mass ranges roughly from $M_\odot$ to $1.4\,M_\odot$ which, neglecting a small surviving compact remnant, roughtly agrees with observations on the range of ejected mass [18]. White dwarfs in this mass range are known to be primarily oxygen-neon-magnesium mixtures or, at least, to have an oxygen-neon core [8]. Although not conclusive, the above considerations support the hypothesis that the progenitors are primarily O-Ne-Mg. Very close to the Chandrasekhar mass, it is additionally expected that the white dwarfs have an iron core [14], [15] which, of course, produces no energy output from fusion but would produce a large amount of energy if there is degeneracy breakdown.

Table 1 in connection with the energy sufficiency of carbon-oxygen dwarfs indicates that, if the progenitor nucleus has atomic number 8 or higher, the energy release from fusion alone is inadequate to explain observations and appreciable energy deposition is required from a source beyond the standard model. From table 1, allowing for 5% of the white dwarf mass to remain unburned, it can be seen that the mean fusion energy produced as a function of atomic number, Z, below $Z = 12$ is appoximately

$$E_{fusion} \approx 0.95\,(16 - Z) \cdot 10^{-4} \cdot M \tag{4.16}$$

where M is the Chandrasekhar mass in the binary models and is both the progenitor mass and, approximately, the ejected mass in the phase transition model. This could lead to a problem in the binary models with understanding the homogeneity of SN Ia namely the total fusion energy available is sensitive to the composition of the white dwarf; dwarfs with a higher metallicity would produce a significantly smaller amount of Ni^{56} and/or a significantly lower amount of ejecta kinetic energy contrary to observations. On the other hand, if SN Ia come from a very limited range of white dwarf masses near M_C , there is also a problem in producing a sufficient rate of supernovae.

As we show below, the phase transition model provides an extra energy input increasing with atomic number. For example, the energies released if the protons in carbon or oxygen convert to scalars dropping into the susy ground state are

$$\Delta E(C) = 4(E_{1p} - E_{1s}) + 6(E_{1s} - \tilde{E}_{1s}) \tag{4.17}$$
$$\Delta E(O) = 6(E_{1p} - E_{1s}) + 8(E_{1s} - \tilde{E}_{1s}) \tag{4.18}$$

where $\tilde{E}_{1s}$ is the energy of the susy $1s$ state which may or may not be the same as that in normal carbon or oxygen.

Figure 2 from Bakken et al. [19] illustrates the nuclear energy states of the modified harmonic oscillator model showing the approximately equally spaced shells and the prediction of the nuclear magic numbers shown in square brackets.

The harmonic oscillator parameters of the low lying elements, $6 < Z < 12$, depend on the atomic number but preserve the equal spacing so the excitation energies are scaled relative to those of carbon. From a digitization of Fig. 2 we can measure the excitation energies in pixels which can be converted to MeV using the empirical relation between the $1s$ ground state to the first excited state in carbon and oxygen [20]:

$$\begin{aligned} E_{1d5/2}(C) - E_{1s}(C) &= 4.44\,\mathrm{MeV} \\ E_{2s}(O) - E_{1s}(O) &= 6.05\,\mathrm{MeV} \quad . \end{aligned} \tag{4.19}$$

The $2s$ state and the $1d5/2$ are nearly degenerate being part of the same shell model energy level. The total internal energies of carbon and oxygen relative to the $1s$ ground state, multiplying by a factor of 2 to include neutrons, are then as an example

$$\begin{aligned} E_C &= 2 \cdot 4 \cdot E_{1p3/2}(C) = 12.008\,\mathrm{MeV} \\ E_O &= 2 \cdot (4 \cdot E_{1p3/2}(C) + 2 \cdot E_{1p1/2}(C)) \cdot 6.05/4.44 = 26.5\,\mathrm{MeV} \quad . \end{aligned} \tag{4.20}$$

In this article, given the present state of observations, we are interested primarily in the sense of the metallicity effects and only roughly in the magnitude of the effects. With this

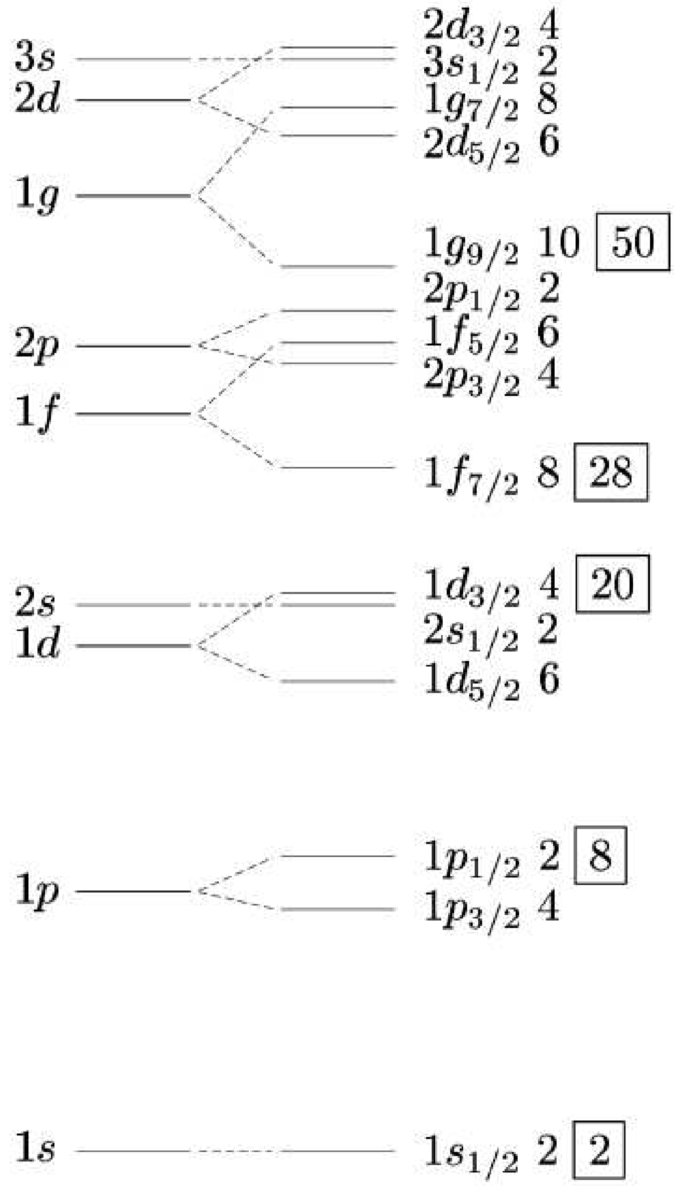

Figure 2: Nuclear shell model

in mind we will assume

$$E_{n,l}(Z+1) - E_{1s}(Z+1) \approx (E_{n,l}(Z) - E_{1s}(Z)) \cdot 6.05/4.44 \quad . \tag{4.21}$$

We can then construct table 2 for the energies of the low lying elements relative to the 1s ground states.

The main point of table 2 is that the susy energy release increases with atomic number

Z	element	$\Delta\rho/\rho$
6	carbon	$0.0467 = 0.0078 \cdot Z$
8	oxygen	$0.0562 = 0.0070 \cdot Z$
10	neon	$0.0719 = 0.0072 \cdot Z$
12	magnesium	$0.0824 = 0.0069 \cdot Z$
26	iron	$0.204 = 0.0079 \cdot Z$

Table 2: The fractional change in mass or density of the indicated element on giving up its excitation energy due to degeneracy breakdown as in the susy phase transition. The values for $\Delta\rho/\rho$ include an equal contribution from neutrons. If there is an extra contribution coming from the second terms in eq. 4.18, this would also be proportional to the atomic number. We neglect the possible suggestion of quadratic Z dependence.

while the energy from fusion shown in table 1 decreases with Z. This complementarity is the beginning of the susy model explanation for the uniformity of the supernovae Ia.

In earlier work on the phase transition model based on the Fermi gas model for even-even nuclei, the Pauli energy was taken to be simply and universally proportional to the density, $\Delta\rho \approx 0.02\rho$ and a term proportional to a power of ρ/ρ_c was added to the action to allow for the possibility of a transition-inhibiting effect analogous to the inhibiting of the liquid to gaseous transition at high pressure. In the absence of such a term the action would go to zero as the white dwarf mass approaches M_C in which limit the Coleman-DeLuccia model provides no guidance. However, the white dwarf lifetime defined by eq. 2.4 would in any case approach infinity as one approaches the Chandrasekhar mass from below.

In the nuclear shell model as tabulated in table 2, the Pauli excitation energies, neglecting a possible quadratic term, are proportional to the atomic number:

$$\Delta\rho \approx 0.007\, Z\, \rho \quad . \tag{4.22}$$

Thus in the Shell Model the critical density would be expected to be inversely proportional to the atomic number. We would define a new critical density, ρ_c, and minimum lifetime, τ_0, as free parameters in the fit to the delay time distribution. The action is parameterized as

$$B = (\frac{\rho_c}{Z_c \rho})^3 + b_0 (\frac{Z_c\, \rho}{\rho_c})^{4/3} \quad . \tag{4.23}$$

Since white dwarf masses in the range above 0.9 are expected to be progressively O-Ne-Mg mixtures with an increasingly important iron core, we write for the bulk composition

$$\overline{Z} = 7.5 + 9\,(M - 0.9) \quad . \tag{4.24}$$

We would interpret this as the average atomic number in a white dwarf of mass M. The calculations, for simplicity, treat a star of fixed atomic number constituents assuming that interpolating between integer Z is a reasonable approximation to a mixture of constituents. In addition, white dwarf theory suggests a small core of higher atomic number, Z_{core}. We would take

$$Z_c = 7.5 + 9\,(M - 0.9) + 56\,(M - 0.9)^2 \quad . \tag{4.25}$$

With this form, the core atomic number approaches that of iron as M approaches the Chandrasekhar mass. The fusion energy release is dependent on the bulk metallicity, $\overline{Z}$, while the fusion trigger is governed by the larger core metallicity, Z_c. Obviously, these equations are merely qualitative estimates of the bulk and core composition which may be refined as knowledge of white dwarf compostion increases. In the phase transition model a dwarf with a high Z core would be expected to combine an enhanced phase transition rate with a larger fusion energy deposition due to the lighter elements in the bulk.

With this Z dependent action the inverse lifetime for a white dwarf of mass M is

$$\tau(M)^{-1} = \frac{1}{\tau_0}\frac{V(M)}{V_{\max}} \tag{4.26}$$

with

$$V(M) = \int d^3r\, e^{-(\rho_c/(Z_c\rho(r))^3 - b_0\,(Z_c\rho(r)/\rho_c)^{4/3}} \quad . \tag{4.27}$$

Relying on the observational evidence ref. [21] and the indications from ref. [4] that accretion is statistically not a major factor in white dwarfs undergoing SN Ia, we can neglect accretion and identify the ejected mass with the progenitor mass at birth. Multiplying by the white dwarf birth mass distribution from section 2 we can write the combined distribution in delay time and progenitor mass.

$$\frac{d^2N}{dtdM} = a_0 F(M) e^{-t/\tau(M)}\,/\tau(M) \quad . \tag{4.28}$$

From eq. 4.28 we can derive the SN Ia rates as functions of delay time and ejected mass (or birth mass since we neglect any residual accretion). These are

$$\frac{dN}{dt} = a_0 \int dM\, F(M)\, e^{-t/\tau(M)}/\tau(M) \tag{4.29}$$

and

$$\frac{dN}{dM} = a_0 F(M) \cdot (1 - e^{-t_g/\tau(M)}) \quad . \tag{4.30}$$

5 The Delay Time and Ejected Mass Distributions

The distribution in delay times between white dwarf birth and SN Ia explosion has been measured with several techniques, the most accurate of which is illustrated in the red points of figure 1 of [22]. We do a χ^2 minimization of eq. 4.29 to these three large bin data points leading to the fit shown in figure 3

The resulting best fit parameters are

$$\begin{aligned} \rho_c &= 58.8\, M_\odot / {R_E}^3 \\ \tau_0 &= 0.418\, Gyr \\ b_0 &= 0 \quad . \end{aligned} \tag{5.31}$$

If desired the ρ_c value can be written in more familiar cgs units by noting that

$$\frac{M_\odot}{{R_E}^3} = 7.661 \cdot 10^6 \frac{g}{cm^3} \tag{5.32}$$

Some discussion is warranted here. First of all the best fit is not sharply determined. Good fits with χ^2 values less than 1 per degree of freedom are found with ρ_c varying by up to 30% and b_0 values as large as 1.5. Correlated values of τ_0 are found varying by as much as ten percent from the best fit. With respect to the b_0 values one should note that the Coleman-DeLuccia theory, while not specifying non-leading behavior in the action, is derived for large action. With $b_0 = 0$, the action approaches zero near the center of high mass white dwarfs. With $b_0 \approx 0.5$ or larger, the action is everywhere greater than unity. However, since the volume integral for $V(M)$ suppresses the behavior near $r = 0$, the theory might be acceptable even for $b_0 = 0$ especially since the predicted supernova progenitor mass distribution shown in figure 4 is suppressed at high mass.

The white dwarf lifetime as a function of its mass is not greatly changed from the plot shown in ref. [4] where there is no explicit Z dependence in the action.

The delay time distributions, DTD, have a shape that are nearly independent of the host galaxy metallicity although the integrated supernova rate is significantly lower in low metallicity environments. Moreover, supernovae in star-burst galaxies would be expected

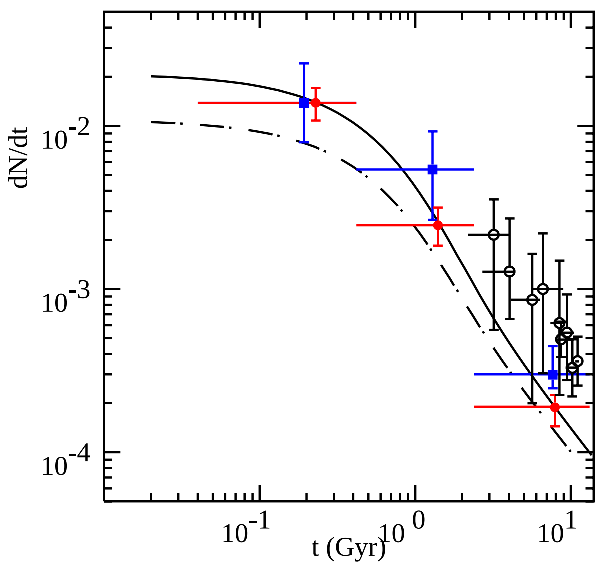

Figure 3: SN Ia delay time distributions. The solid curve shows the DTD for average to high metallicity environments. For low metallicity environments the DTD is reduced as shown in the dot-dashed curve due to the factor 3.13. Data is taken from [22] neglecting earlier data with larger errors.

to have an enhanced rate especially at small delay times. The shape and magnitude of the DTD is well reproduced by the phase transition model which also gives a prediction for the behavior at small delay times. The fact that, over a restricted range, the observed DTD plotted on a log-log scale is approximately linear with a slope near -1 has been widely cited as supporting the double degenerate model [1]. However, the binary models as reviewed there underpredict the DTD and vary among themselves by a factor of 3 to 10 in the low delay time region.

In the phase transition model the ejected mass should be the same as the progenitor mass since the surviving susy core has a negligible mass. One sees from fig. 4 that the progenitor mass is strongly peaked near one solar mass.

In the double degenerate model for SN Ia it has been suggested that the presence of a third star might be needed to throw two white dwarfs into each other with a short delay time. This possibility has now been ruled out as a major source of SN Ia [23].

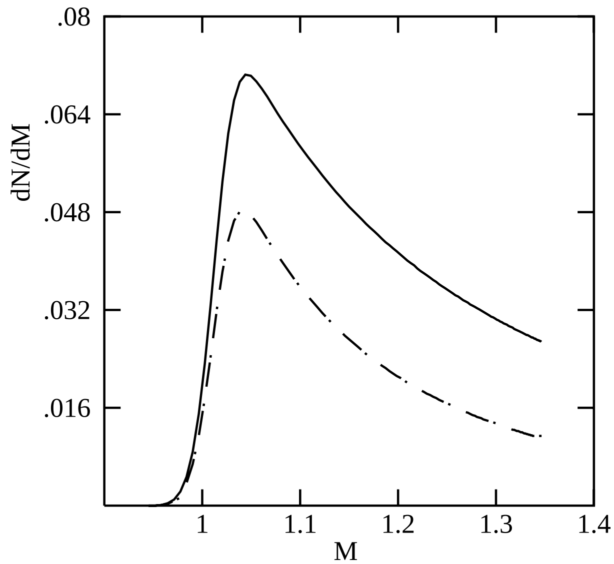

Figure 4: Progenitor mass distribution in high to average metallicity environments (solid curve) and in low metallicity environments (dot-dashed curve). Neglecting the compact surviving remnant these curves represent also the ejected mass distribution predictions.

The white dwarf lifetime as a function of its mass is shown in fig. 5. the phase transition model predicts no old white dwarfs in the quasi parabolic region except for exceptional, rapidly accreting stars as discussed in ref. [4]. It should be noted that the best fit parameters from the delay time distribution also correctly predict the edge of the white dwarf age vs mass plot as well as the lower edge of the ejected mass distribution as measured in [18].

In terms of the gravitational binding energy, B, the fusion energy release, E_{fus}, the electron internal energy released when the star explodes, U, and the kinetic energy of the ejecta, E_{kin}, we can write the total standard model energy input

$$E_{std} = E_{fus} + U \tag{5.33}$$

and the standard model energy deficit:

$$E_x = B + E_{kin} - E_{std} \quad . \tag{5.34}$$

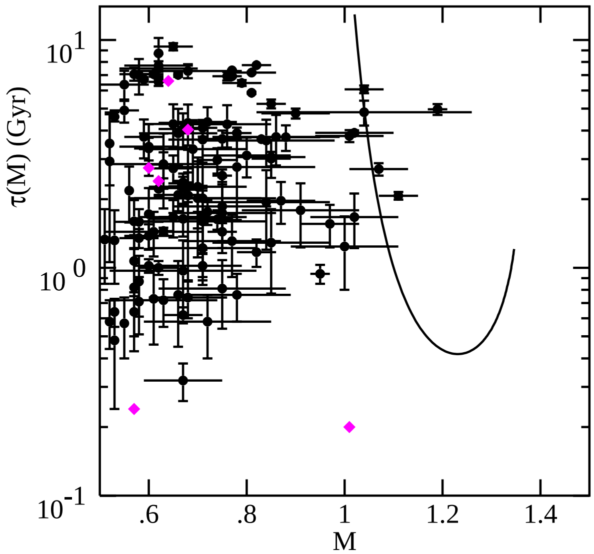

Figure 5: White Dwarf lifetime vs stellar mass in the susy phase transition model. The 95 cool DA white dwarfs with measured ages in the data of [24] are shown in black. Also shown in magenta are the six nearest white dwarfs. The plot is not signifcantly different from the corresponding plot with different parameter choices in the Z-independent model [4]

These separate energies are calculated in ref. [2] and elsewhere.

As alluded to above, the standard model energy deficit is consistent with zero in the case of a roughly fifty-fifty mixture of carbon and oxygen. However, since no compact remnants are observed and the ejected mass distribution ranges from $0.9\,M_\odot$ to $1.4\,M_\odot$ in which mass range stars are expected to be oxygen-neon-magnesium mixtures, there is a substantial energy deficit in the standard model which we propose is compensated by the susy energy release:

$$E_{susy} = E_x \quad . \tag{5.35}$$

The total energy released beyond that required to unbind the star is

$$E_t = E_{susy} + E_{fus} + U - B \quad . \tag{5.36}$$

Although the fusion energy release in the full star and the susy energy release in a

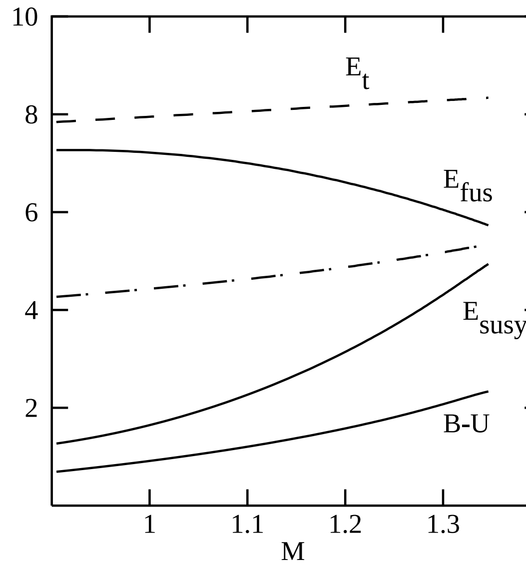

Figure 6: Various energies in SN Ia events in units of $10^{-4}\,M_\odot$ versus ejected mass, M, in solar mass units. The curves label the gravitational binding energy minus internal electron energy, $B-U$, the total fusion energy released, E_{fus}, and the nuclear degeneracy energy released in the small core, E_{susy}. The mean of the fusion energy and released susy energy is shown in the dot-dashed curve. The total released energy beyond that required to unbind the star is shown in the dashed curve.

small core vary rapidly with progenitor mass, the sum of the two grows only slowly, closely tracking the total energy release beyond unbinding. We propose that this is the basis for the uniformity of SN Ia events. The susy core which should shrink to a black hole after cooling has a mass near 0.1% of the progenitor mass:

$$m_{core} = \frac{E_{susy}}{0.007 \cdot Z_c} \quad . \tag{5.37}$$

Roughly half of the slow growth of released energy with progenitor mass is due to iron production through Ni^{56} so that the supernova brightness can be standardized by measuring the nickel production through its characteristic half life (the Phillips relation [25]). In the binary models the released energy tracks the more rapidly varying fusion energy making the

Phillips relation and the SN Ia uniformity a long-standing mystery. This, of course, assumes the supernovae proceeds through a sub-Chandrasekhar trigger.

6 Summary

Some forty five years since the binary models for SN Ia were proposed, a review of all the binary models [26] has still not been able to identify a unique progenitor system nor explain how a mixture of widely different progenitor systems can produce the observed homogeneity. We have argued that the possibility of a phase transition mechanism should not be ignored. Going beyond the six earlier indications of radical new physics in SN Ia [2], the host galaxy effects treated here could be taken as supporting the idea that the phase transition responsible for SN Ia is a transition to an exact susy phase. This is due to the indication that the standard model energy deficit grows with progenitor mass and metallicity as does the degeneracy energy.

With regard to the single degenerate model for SN Ia, continuing research on this model is based on the possibility of somehow avoiding the counter-indications from the X ray data of [21]. The Gilfanov-Bogdan limit is based on the inconsistency, given X ray constraints, of $1.2M_{\odot}$ white dwarfs accreting to the Chandrasekhar mass. The conflict is exacerbated if the progenitors are initially below one solar mass, as required if they are C-O dwarfs, since then an even higher accretion rate would be required.

In the double degenerate model, continuing research requires the expectation that a substantial population of high mass white dwarf binaries will be discovered above that suggested by the Salpeter initial mass function.

Some years ago, Sim et al. [27] showed that, if a suitable trigger could be found, the detonation of an isolated C-O white dwarf with mass between 0.97 and 1.15 would lead to good agreement with observed SN Ia properties. The model of [3] provides such a trigger. In the models of Sim et al. the trigger is assumed to provide negligible energy release to supplement the available fusion energy. We have argued that the actual composition should be O-Ne-Mg with the reduction in available fusion energy being compensated by the degeneracy energy released in a small but non-negligible core. The peak in the progenitor mass distribution is in reasonable agreement with one of the Sim et al. models and the range of progenitor masses roughly agrees with observations [18]. The delay time distribution is also well reproduced as in fig. 4.29. Although we have found in ref. [4] that accretion, in the susy model, is generally not important in supernova production, a small accretion rate onto high mass white dwarfs could be effective in producing the 1% of super-Chandrasekhar events and the second peak in the ejected mass distribution possibly suggested in ref. [18].

In the ejected mass distribution and the delay time distribution, the metallicity dependence should be visible in the future high statistics supernova data expected from the Gaia collaboration which should also settle the question as to the possible existence of high mass double degenerate systems [28]. Gaia has already succeeded in identifying binary companions among the progenitors of core collapse supernovae [29] but has not yet reported observations of binary progenitors of SN Ia.

The minimum energy released in the nucleation of a critically sized bubble is

$$E_{susy}(min) = \overline{\Delta\rho} \cdot \frac{4\pi}{3} {R_c}^3 = 36\pi^3 S^3 / \overline{\Delta\rho}^2 \tag{6.38}$$

where R_c is the critical radius of eq. 2.7. The fit to the critical density implies that the surface tension is

$$S \approx 2 \cdot 10^{-21} M_\odot / {R_E}^2 \quad . \tag{6.39}$$

The minimum bubble size from eq. 2.7 is then microscopic but significantly greater than nuclear size. In the susy phase transition model, the explosion can be efficiently catalyzed if there is an accumulation of high metallicity elements in the stellar center. The much larger full susy energy released depends on the final radius of the susy bubble which is critically dependent on its composition as a function of radius before the explosion and on the rapid change in the density profile as the star explodes. This is a difficult problem for future study but, if a phase transition model is realized, the extra energy input should be shown theoretically to match the standard model energy deficit as we have assumed in the current work.

The growth of the susy bubble is halted when the critical radius becomes greater than its current radius as could happen due to a sharp falloff of density or to its entrance into a region of lower atomic number. The supernova explosion is expected to create a cavity of density significantly lower than that of interstellar space. The extent of an iron core, if any, could also be critical since iron is inert to fusion but would provide a large energy release if there is degeneracy breakdown.

Prior to consideration of the host galaxy correlations, indications of the need for radical new physics could be satisfied by other types of phase transitions such as transitions to a quark-gluon plasma although no such model has as yet been worked out for SN Ia. The observation that the nickel production increases with metallicity as does the degeneracy energy is in line with exact susy being the phase transtion final state. Finally, it must be noted that the hypothesis of a phase transition to an exact susy phase implies that the broken susy phase must also exist and susy particles must be found at sufficiently high accelerator energies if the model suggested here is to be viable.

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