A Supersymmetric model for triggering Supernova Ia in isolated white dwarfs

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In a two parameter phase transition model we fit the rate and several properties of type I supernovae and address the gap in the supermassive black hole mass distribution. One parameter is a critical density fit to about $3 \cdot 10^7$ g/cc while the other has the units of a space time volume. The model involves a phase transition to an exact supersymmetry in a small core of a dense star. In white dwarfs it is proposed to trigger an explosion. If this approach could be verified quantitatively, it would constitute observational support for the existence of two supersymmetric phases in nature.

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Supernova Ia explosions have been successfully used to provide strong evidence that the expansion of the universe is accelerating. Vital to the argument is the understanding of the calibration of the light curves, and for that we do need insight into the explosion mechanism. The white dwarf binary model for Supernova (SN) Ia is encountering serious difficulties [1]. We propose that the supersymmetric (SUSY) phase transition occurs in single white dwarfs of mass from about 0.9 to about 1.3 solar masses, starting a deflagration front, which then triggers the explosion as a supernova [2, 3]. Since the data clearly show that Supernovae Ia occur both in stellar systems, which are constituted out of mostly old stars (elliptical galaxies), and in stellar systems made of old and many new stars (late Hubble type spirals) [4], there has to be a very broad delay time distribution from making a white dwarf to its explosion. We emphasize that what we call here a delay time is more akin to the decay of a radioactive nucleus, so any particular white dwarf passing the threshold may still have a chance to go SUSY much earlier and also much later than the nominal delay time. For single stars a broad delay time distribution between creation and explosion constitutes a challenge, but a SUSY phase transition offers such a possibility.

Super-massive black holes have been observed over a wide mass range, from about $3 \cdot 10^6\, M_\odot$ to $3 \cdot 10^9\, M_\odot$, with some outliers to lower masses such as $3 \cdot 10^5\, M_\odot$ [5]. There is also strong evidence for stellar black holes, in the approximate mass range 3 - 5 $M_\odot$. However, there is currently no convincing evidence for a large number of black holes in the intermediate mass range [6]. These are either difficult to detect, or just may not exist. Observational arguments for the existence of a few do exist [7]; expected are many. Here we pursue the notion, that such black holes can derive from the agglomeration of very massive stars: we explore the concept that across the mass range of the gap the final collapse of the star leads to a SUSY phase transition in the core. This leads to an additional energy input possibly pushing these stars into an enhanced mass loss during collapse, and may result in a final compact object of much less than $10^5\, M_\odot$.

From many points of view, the theory of violent astrophysical events would be less problematic if there were a new source of energy release beyond the standard model. In earlier years it was thought that the energy required to blast off the outer shell of massive stars in a Type II supernova was provided by neutrinos but many detailed studies have found that such supernovae would stall because of insufficient numbers of neutrinos and the weakness of neutrino interactions [8]. In the case of the Type Ib/c supernovae of very massive stars magnetic fields may help cause the explosion [9, 10].

A phase transition to exact SUSY in dense stars could be nature's way to release the energy stored in a Pauli tower of fermions. Similarly, up until recently it was almost universally believed that Type Ia supernovae were caused by white dwarfs or neutron stars accreting matter from a companion star, getting pushed over the Chandrasekhar limit, and then exploding without remnant [2]. In the absence of a sufficient number of corresponding binary systems [1], an explanation for these supernovae in standard astrophysics must be sought in collisions of white dwarfs or neutron stars which may be problematic due to the small size of such dense objects and the surprising uniformity of the supernovae light curves. A SUSY phase transition in white dwarf stars (WD's) could eliminate the need for accretion and allow an isolated white dwarf to explode.

In the vacuum the probability per unit time per unit volume for the decay of the false vacuum is governed by the Coleman-DeLuccia formula [11].

$$\frac{d^2P}{dt d^3r} \;=\; A_C e^{-B(vac)} \tag{1}$$

with

$$B(vac) \;=\; \frac{27\pi^2 S^4}{2\,\hbar\, c\, \epsilon^3} \tag{2}$$

and $A_C = 1/(\tau_0\, V_0)$. S is the surface tension of the true

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vacuum bubble in the dominantly false vacuum background. In the case of a SUSY phase transition ϵ is the difference between the vacuum energy density of our universe and the zero vacuum energy density of an exactly supersymmetric background.

In dense matter it is expected that the transition is accelerated since the energy density difference between a broken SUSY ground state and that of an exact SUSY ground state with the same additive quantum numbers (baryon and lepton numbers) is dominated by the energy stored in the Pauli towers. Thus it is plausible that the phase transition formula could, to at least a first approximation, be given by replacing ϵ with $\epsilon+\Delta\rho\, c^2$. At present however, a rigorous proof of the acceleration exists only in lower dimensions [12]. In exact SUSY, the degeneracy of bosons and fermions plus the availability of a conversion mechanism [13, 14] from a pair of fermions to a pair of partner scalars implies that $\Delta\rho\, c^2$ is the Pauli excitation energy density of the fermions. The Fermi gas model predicts for this excitation energy in a heavy nucleus of N neutrons and Z protons $\Delta\rho \approx 0.02\,\rho$ (this requires only $N = Z = A/2$).

Thus the parameter controlling the exponential factor in the transition rate would then be

$$B = \frac{27\pi^2 S^4}{2\,\hbar\, c\,(\epsilon + \Delta\rho\, c^2)^3} \quad . \tag{3}$$

Here B replaces $B(vac)$ above. In dense matter ϵ is negligible compared to $\Delta\rho\, c^2$. The phase transition probability per unit time per unit volume, eq. 1, increases rapidly with $\Delta\rho\, c^2$ until it becomes of order $S^{4/3}$ at which point it saturates. For denser media, the transition rate is proportional to the volume. For present purposes we will ignore the additional Pauli energy stored in electronic states. The critical radius would be

$$R_c = \frac{3S}{\epsilon + \Delta\rho\, c^2} \quad . \tag{4}$$

Once nucleated a bubble of critical radius will grow as long as its radius exceeds the density dependent critical radius of eq. 4. In a medium of uniform density (such as the vacuum) the bubble will grow without limit.

It is important to work out the SUSY phase transition front growth: A phase transition with energy input can be seen as analogous to an HII region ionization front; the ionization injects energy and there is a shock front. Writing for the speed of sound ahead of the front, in the normal white dwarf matter, C_{wd}, and for the speed of sound behind it, in the SUSY matter C_{SUSY}, the advance speed U_D is ([15]) given by what is called a D-type front:

$$U_D \;\simeq\; \frac{C_{wd}^2}{2\, C_{SUSY}} \quad . \tag{5}$$

Since very likely $C_{wd}/C_{SUSY} < 1$, it is probable that the advance speed is below the speed of sound, and so the SUSY core grows only slowly.

Normal fusion reactions outside of the SUSY core produce the Nickel that determines the SN Ia light curves. Since, according to calculations (see [16]), the Nickel seems to be produced at intermediate r, it is important that the SUSY core is small compared to the radius of the star [14]. It is convenient to replace the S parameter by a critical density ρ_c so that

$$\frac{dP}{dt} = \frac{1}{\tau_0\, V_0} \int d^3 r\, e^{-(\rho_c/\rho(r))^3} = \frac{1}{\tau_0} \frac{V_c}{V_0} \; = \; \frac{1}{\tau} \quad . \tag{6}$$

It has been suggested [17] that the critical radius in vacuo should be the Galactic radius ($\approx 4.7 \cdot 10^{22}\, cm$). This would lead to a surface tension $S = 8.9 \cdot 10^{13}\, erg/cm^2$ and then to $\rho_c = 3 \cdot 10^5\, g/cc$. An independent estimate from applying the SUSY phase transition model to gamma ray bursts [13] leads to comparable values from $\rho_c \approx 10^6\, g/cc$ to $\rho_c \approx 3 \cdot 10^7\, g/cc$. Thus from two very different starting points a critical density near the white dwarf density is suggested. As we shall see, the edge of the high mass black hole distribution also suggests interesting new physics near this density.

Without loss of generality one can choose V_0 to be the maximum V_c for all white dwarf masses at a given ρ_c. Then the parameter τ_0 represents, for given ρ_c, the minimum half-life of white dwarfs against nucleation of a SUSY core. The half-life of any other star is inversely proportional to its critical volume, V_c. Ultimately, a star with such a SUSY core must either be totally disrupted by the SUSY energy release or collapse into a black hole due to the absence of degeneracy pressure. The time over which a star can survive with a SUSY core is dependent on the rate of SUSY energy release.

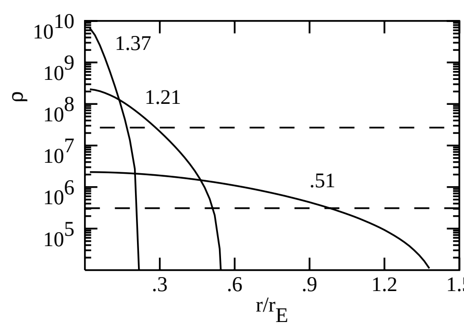

FIG. 1: The density of three white dwarfs as a function of radius relative to the Earth radius r_E. Dashed lines give the range of previously discussed critical densities. Masses of the three white dwarf examples are given in $M_\odot$.

In a single star model for SN Ia we obviously have no means to push a star's mass up with time via accretion from a binary partner; leaving aside the possibility that there could be quiescent partners, what we propose is commonly referred to as as a sub-Chandrasekhar model: the explosion of a white dwarf below the Chandrasekhar mass limit, in our model triggered by the phase transition to a SUSY phase inside a very small core of the white dwarf. Thus this model makes no distinction between

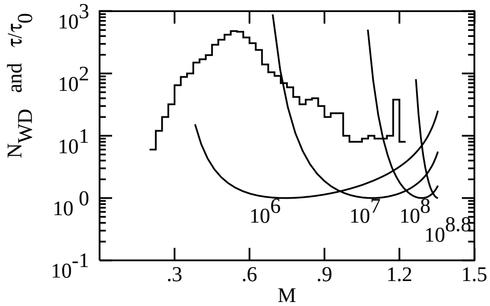

FIG. 2: The histogram of the observed mass distribution of white dwarfs above an observed temperature of 12,000 K [18]; we also give the τ/τ_0 as a function of mass for critical densities of 10^6, 10^7, 10^8, and $6.3 \cdot 10^8$ g/cc.

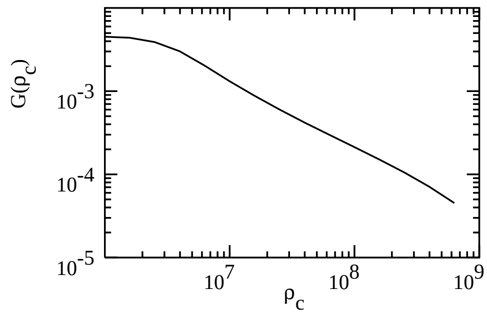

FIG. 4: The function $G(\rho_c)$ which gives via eq. 7 the supernova rate. ρ_c is given in g/cc.

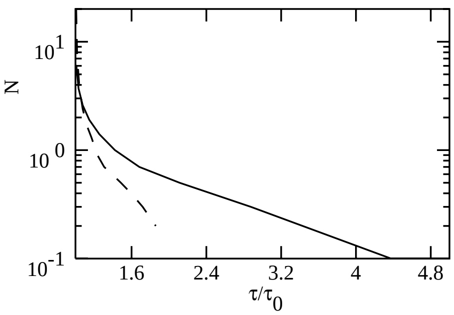

FIG. 3: The relative half life distributions for the critical density of $3.556 \cdot 10^7$ g/cc, as a function of τ/τ_0. The solid line is for the part of the curve with masses lower than the mass at the minimum of the delay time, and the dashed line for the part of the curve at masses above the minimum.

C+O white dwarfs and Ne-O white dwarfs, except in so far as they exist in different white dwarf mass ranges.

The explosion rate can then be written as

$$\frac{dN_{SNIa}}{dt} = N_{WD}\frac{G(\rho_c)}{\tau_0} \tag{7}$$

$$G(\rho_c) = \int dM \frac{1}{N_{WD}} \frac{dN_{WD}}{dM} \frac{V_c}{V_0} \quad . \tag{8}$$

Here the white dwarf mass distribution - which can be modelled over the relevant mass range using the Salpeter mass function and the lifetime of stars on the main sequence - is taken to follow the high mass tail of the Sloan white dwarf sample of 4621 stars with $T_{eff} > 12000K$ [18, 19], and N_{WD} is the total number of white dwarfs in the Galaxy, estimated at near 10^{10}.

Statistics suggest [20] that SN Ia are about as common as SNe from higher masses. Assuming that all white dwarfs above some particular zero age main sequence (ZAMS) mass and below 9 $M_\odot$ become SN Ia, and that all stars above ZAMS mass 9 $M_\odot$ become other kinds of SNe, suggests [21] that this critical mass is about 5.5 $M_\odot$, corresponding to a white dwarf mass of about 0.9 $M_\odot$ again, approximately. This is the mass at which the delay time approaches some large fraction of the Hubble time, so that we still can get a few white dwarfs exploding at that mass within the age of a Galaxy. These estimates suggest a critical density of order $3 \cdot 10^7$ g/cc, which we have used in fig. 3.

We can check how much energy is released by the phase transition of a very small part of the white dwarf: As a limit we consider blowing the white dwarf apart just from this energy release and obtain $M_{SUSY} << M_{wd}$. We have to remember that this is a strong upper limit to the real mass undergoing a SUSY phase transition in the model proposed since the deflagration wave triggers actually a detonation much earlier. For SN Ia cores we need less than $10^{-3.5}\, M_\odot$ ([3]) for an initiating phase transition. Since the SUSY phase transition provides more energy than even Hydrogen burning, even less matter than in normal models is required to initiate the deflagration.

We posit that this phase transition is what triggers the deflagration wave discussed in [3] and so might be the real cause for SN Ia. The time characteristic of this trigger is the main difference to other models.

One proof of our approach could be if these very small compact SUSY objects could be found that remain after the explosion. In some respects these objects might resemble black holes of anomalously small mass.

Folding the white dwarf mass function with the delay time distribution allows on the one hand to obtain the SN Ia progenitor mass distribution (see fig. 2), and also to obtain the SN Ia distribution as a function of delay time (fig. 3). Most SN Ia are produced after a lifetime near τ_0 although there is a tail extending to higher lifetimes (see fig. 3). Since our approach yields a very narrow mass distribution for those white dwarfs that explode as SN Ia, the energy distribution is also very tight and so a use as a calibrator is understandable.

Data also show [22] a relatively large number of SN Ia with a delay time of order $5 \cdot 10^8$ yrs. Combining these two points yields the critical density and the critical time scale. Therefore a clear prediction of this model is a relatively sharp sub-Chandrasekhar mass distribution (see, e.g., ref. [23]), peaking at the minimum of the delay time distribution. Thus our estimates for the key parameters are $\rho_c \simeq 3 \cdot 10^7$ g/cc, $\tau_0 \simeq 5 \cdot 10^8$ yrs, resulting in a typical progenitor mass close to $1.2\, M_\odot$, mostly an original Ne-O composition, and a SN Ia rate of about 1/100 yrs, see eq. 7. Considering the range of uncertainty in the observations ([20, 22]), the time scale could be yet shorter, implying a smaller value of $G(\rho_c)$ and so a higher critical density; similarly, the fraction of all SNe turning into SN Ia could also be smaller, pointing in the same direction. This should be verifiable with a few well observed SN Ia.

Applying the same idea to massive stars as they agglomerate [24] within a dark matter clump in the very early universe also leads to a phase transition that may be fast enough to slow the collapse and eject much of the mass of the star before it ultimately collapses as a black hole (BH) at much lower mass. This would then help to explain the BH mass distribution gap between about 30 and about a million solar masses, where we observe very few BHs. Going through the numbers [25] suggests 10^5 solar masses as the upper limit for this mechanism since this is the dividing line to achieve white dwarf density before collapsing into a BH at higher masses. This then leaves the range of about 10^5 to about 10^6 solar masses to make the first generation of super-massive BHs; these BHs can merge and then may help to explain the observed supermassive BH mass distribution [6].

A clear prediction is then the absolute rate of SN Ia, see eq. 7 and eq. 8 and the relative statistics in terms of mass, energetics, chemical composition, of which white dwarfs explode with what delay. A key prediction of our model is the shape of the delay time distribution, see fig. 3. Detailed observations and modelling should confirm that the total mass is below the Chandrasekhar limit, and that most of the original white dwarf was composed mostly of Neon and Oxygen, since these are the stars in the preferred mass range. A further prediction is the existence of very small mass compact SUSY objects, observable in their passage through the interstellar medium.

If confirmed, without any viable alternative, this would constitute the first observational evidence for the transition between two SUSY phases realized in Nature.

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