

# A Susy Phase Transition as Central Engine\*

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## Abstract

For several decades the energy source powering supernovae and gamma ray bursts has been a troubling mystery. Many articles on these phenomena have been content to model the consequences of an unknown “central engine” depositing a large amount of energy in a small region. In the case of supernovae this is somewhat unsettling since the type Ia supernovae are assumed to be “standardizable candles” from which important information concerning the dark energy can be derived. It should be expected that a more detailed understanding of supernovae dynamics could lead to a reduction of the errors in this relationship. Similarly, the current state of the standard model theory of gamma ray bursts, which in some cases have been associated with supernovae, has conceptual gaps not only in the central engine but also in the mechanism for jet collimation and the lack of baryon loading. We discuss here the Supersymmetric (susy) phase transition model for the central engine.

## 1 Introduction

The “central engine” puzzle of violent astrophysical events has been evident [1] for decades. For a period, it was assumed that the neutrinos released from nuclear fusion could provide the energy needed to blow off the stellar mantle in a supernova but detailed monte-carlos

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never succeeded in demonstrating the required explosion. The neutrinos were too few and too weakly interacting. More recently, strong magnetic fields of unknown origin have been discussed as a possible part of the solution [2]. The situation is such that new physics input may be needed. One is reminded of the nineteenth century mystery of the sun’s “central engine” and of the long ignored mid-twentieth century prediction of neutron stars. In the last few decades new physics proposals for the enormous energy release in gamma ray bursts such as, for example, the quark star model of ref.[3] have, perhaps, not received the full discussion that they may deserve.

In recent years it has become increasingly likely that the expansion of the universe is accelerating in a way consistent with an interpretation in terms of a positive vacuum energy density of approximate magnitude

$$\epsilon = 3560 \text{MeV}/m^3. \tag{1.1}$$

A natural value that might have been expected for this quantity would be some 124 orders of magnitude greater:

$$M_{Planck}^4 = 10^{127} \text{MeV}/m^3. \tag{1.2}$$

A popular attitude towards this huge mismatch is the string landscape picture in which the effective potential as a function of the myriad scalar fields of string theory has a huge number of local minima most of which are of order of  $M_{Planck}^4$ . However, about one in  $10^{124}$  of these minima would be expected to have vacuum energy density comparable to  $\epsilon$ . If the vacuum energy were much larger than eq.1.1 the universe would be torn apart by the large acceleration[4] before galaxies and life would have had time to evolve. If there were such a huge number of universes, either temporally or spatially separated, it would not be surprising that we find ourselves in one with at most a mild acceleration. We could never be conscious of any other.

Furthermore, if all the parameters of the effective potential were dynamically determined as in superstring theory, one would expect quantum transitions between the various minima. Such transitions between string vacua with differing amounts of supersymmetry have already received some attention [5]. The basic string theories and, most likely, those with the absolute minimum of the effective potential have exactly supersymmetric (susy) vacua with vanishing vacuum energy. Unfortunately, these vacua are also inhospitable to life.

A key difference between a supersymmetric universe and our broken susy world is the reduced importance of the Pauli principle in the former. This is due to the fact that, in a susy universe, whenever fermions are forced into higher energy levels, it becomes energetically favorable for them to convert in pairs into scalars which can drop into the ground state in arbitrary numbers. Thus heavy nuclei and atoms would consist mostly of scalar nucleons and selectrons. Without the need to put additional particles into ever higher energy levels, fusion would occur at a greatly increased rate thus greatly reducing the lifetime of main sequence stars probably below the time required for planets to form and life to evolve. Furthermore, most nuclei that are stable with fermionic constituents would be highly beta unstable in a susy vacuum due to the absence of an effective Pauli principle. In addition scalar electrons

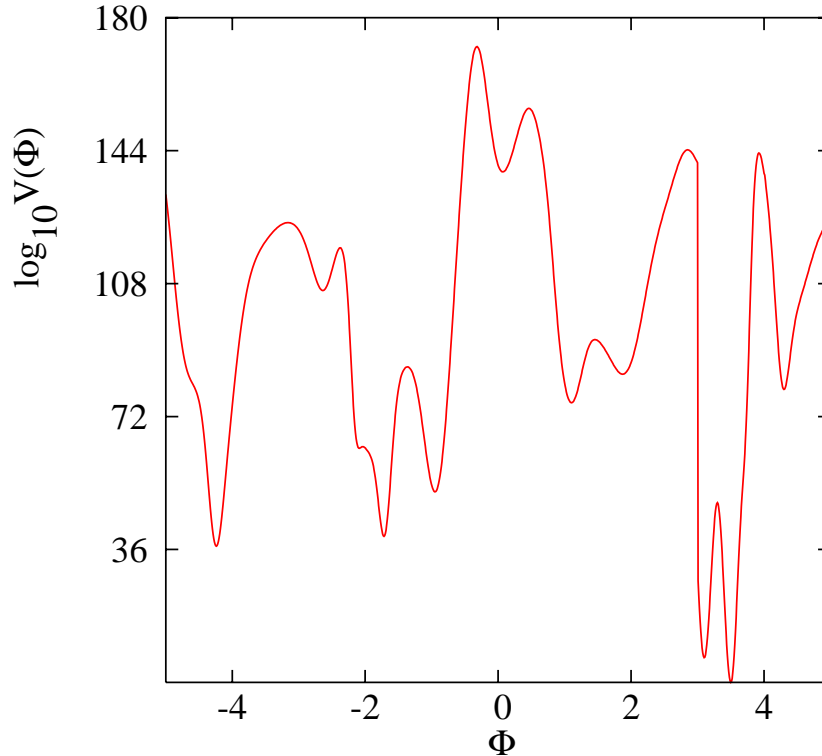


Figure 1: A schematic representation of the effective potential in the string landscape picture. The potential is measured in units of  $\text{MeV}/\text{m}^3$  and the y axis has a broken scale taken to be linear in  $V$  at low values of the potential. The exact susy phase has zero vacuum energy.

would all drop into ground state s wave states where they would have an increased probability of being K captured. Thus an exactly supersymmetric universe would be an impossibly toxic environment for human evolution.

Evidently, because of statistics, luck, or some other reason, there exists a local minimum which is not supersymmetric but also does not have too high a vacuum energy. We do not consider here the possibility that there might be other local minima with negative vacuum energy leading to other unpleasant vacuum decays.

Such an effective potential, the so called string landscape [6], can be schematically represented as in figure 1. The horizontal axis represents the space of scalar fields projected onto one dimension. The absolute minimum is supersymmetric and has vanishing vacuum energy while a second local minimum of broken susy and near vanishing vacuum energy is available. In such a broken susy world life has evolved on earth. This is not to imply that we understand the fine tuning required to make the susy breaking scale of 100 GeV, perhaps in conjunction with another dark energy component, consistent with the low vacuum energy of eq. 1.1. Furthermore, unlike the simplified picture of figure 1, the broken susy minimum may be separated from the susy minimum by a great distance in  $\phi$  and there may be many

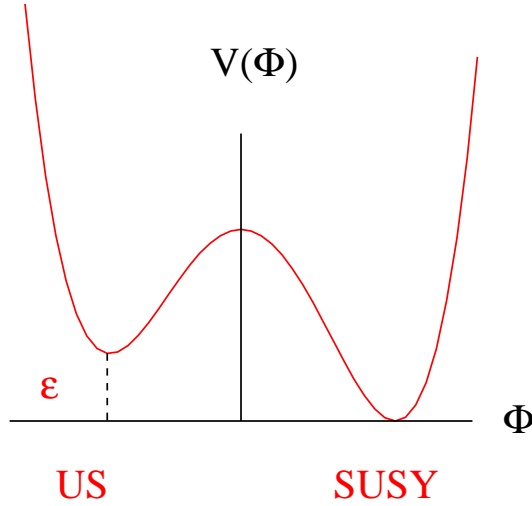


Figure 2: Double well potential in vacuo with a susy minimum

other intervening local minima. This would quantitatively affect the probability per unit time of vacuum decay but would not qualitatively change the ultimate outcome.

If we zoom in on the region near the potential minimum, it might look in vacuo, like the double well potential of figure 2 treated for the decay of the false vacuum by Coleman [7] and others several decades ago. It has been shown in lower dimensional theories that the transition rate is enhanced in the presence of matter [8] and it has been speculated that the same enhancement would occur in dense matter in any space-time dimension [9]. A new ingredient, which may be key to proving this enhancement and which has not been considered in previous years, is the role of the Pauli principle in dense matter. If a system of fermions in its ground state has energy density  $\rho$ , the ground state energy density of the corresponding susy system with the same baryon and lepton numbers would be  $\rho_s$ . The difference between the ground state energy densities in the two phases is the excitation energy density of the fermions in the normal phase. This assumes that the common mass of particles and sparticles in the exact susy phase is equal to that of the particles in the broken susy phase. In superstring theory the ground state supermultiplets are massless so it is reasonable that the common mass is light. If the common mass were lighter than that of the fermions in the broken susy phase the energy release in the phase transition would be increased above that of our current studies. If the common mass were heavier than that of the fermions in the broken susy phase the broken susy phase in figure 3 would be the stable minimum and there would be no transition to exact susy.

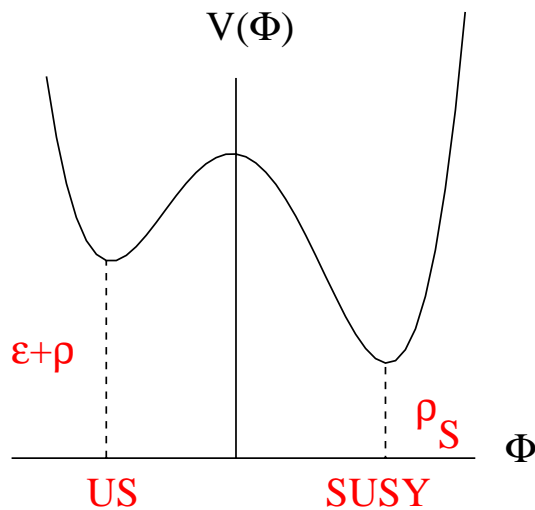


Figure 3: Susy double well in the presence of dense matter

In a region of dense matter, the effective potential may take the form of figure 3. If one is in the false vacuum of broken susy, bubbles of true vacuum (exact susy) are constantly being produced with a steeply falling distribution in bubble radius,  $r$ . At creation, or at any later stage in its development, a bubble of radius  $r$  will expand or contract depending on which behavior is energetically favorable. The condition for expansion depends on the surface tension,  $S$ , of the bubble and the energy density in the region immediately outside the bubble. Consider, for example, a bubble of exact susy in a larger region of broken susy. Outside the bubble the energy density will be  $\epsilon + \rho$  where  $\epsilon$  is the vacuum energy and  $\rho$  is the outside ground state matter density if any. If the susy bubble were to make a virtual expansion into an infinitesimally larger spherical shell, its ground state energy density would be  $\rho_s$ . Classically, the ground state energy after such a virtual expansion minus the previous ground state energy is

$$\Delta E = \frac{4\pi}{3} ((r + \delta r)^3 - r^3) (\rho_s - \rho - \epsilon) + 4\pi S ((r + \delta r)^2 - r^2) \quad (1.3)$$

or

$$\Delta E = -4\pi r \delta r (r(\epsilon + \Delta\rho) - 2S) \quad (1.4)$$

where we have put

$$\Delta\rho = \rho - \rho_s \quad (1.5)$$

Classically therefore, the system will find it energetically advantageous to expand if  $r > \frac{2S}{\epsilon + \Delta\rho}$ . Similarly, the bubble will contract if its radius is below this density dependent critical value. A more exact instanton calculation [7] in vacuo ( $\rho = \rho_s = 0$ ) replaces  $2S$  by  $3S$  in eq.1.4. One would, therefore, expect the critical radius for a susy bubble to be

$$R_c = \frac{3S}{\epsilon + \Delta\rho} \quad (1.6)$$

There is an implicit assumption here that the surface tension,  $S$ , is not significantly density dependent as in the low density limit. A more careful treatment of the surface tension is in the process of being explored. In regions of high density, and therefore high  $\Delta\rho$ , the critical radius will be much reduced from its vacuum value thus enhancing the phase transition rate. At creation or at any later stage, a bubble will expand if  $r > R_c$ . In vacuo or ignoring the effect of the Pauli principle,  $\Delta\rho = 0$ . In a homogeneous region, if a bubble is created at greater than the critical radius, it will expand indefinitely. If however, the bubble comes to the boundary of a dense region outside of which  $\rho$  and  $\Delta\rho$  are zero, the critical radius jumps discontinuously to its vacuum value, effectively confining the bubble to the high density region. In vacuo, the probability per unit time per unit volume of nucleating a bubble of true vacuum of critical radius or greater has been given [7] in the thin wall approximation as  $Ae^{-B}$  where  $B \approx R_c^4 \epsilon$ . If we naively carry this formula over to the case of a susy phase transition in a homogeneous body of volume  $V$ , we would have

$$\frac{1}{N} \frac{dN}{dt} = AVe^{-(\frac{\rho_1}{\epsilon + \Delta\rho})^3}$$

where  $\rho_1$  is an undetermined parameter of dimension  $[E^4]$ . We expect the important features of this expression to survive the extension to a body of non-uniform density with a density dependent surface tension and a non-negligible wall thickness between the normal and susy phases. These important features are that the phase transition rate per unit volume increases rapidly with  $\Delta\rho$  up to some density  $\rho_1$  and then saturates. At higher  $\Delta\rho$ , the transition rate is proportional to the volume of the body.

In a recent article [10], we have proposed that such a phase transition between our normal phase of broken susy and a phase of exact susy is the central engine of gamma ray bursts. Many of the zeroth order characteristics of the bursts can be readily understood in this model. Our current thinking is that  $\rho_1$  should be of order of the  $\Delta\rho$  that would be expected in a white dwarf star. Then, in less dense matter the phase transition rate would be exponentially suppressed while in more dense matter such as neutron stars or ordinary heavy nuclei the phase transition rate would be greatly suppressed by the volume factor. In the present state of the model, the constant  $A$  is a free parameter fit to the observed rate of gamma ray bursts.

The susy phase is a rich new world of phenomenology which has only just begun to be explored. Unlike our world which is dominated by the Pauli principle, the susy world would have a strikingly different particle, nuclear, and atomic physics. Ignoring the nuclear effects, which were discussed in outline form in [10], the key features of the susy phase transition model of grb's are

1. A white dwarf star with a high level of fermion degeneracy makes a phase transition to a state of exact supersymmetry where particles and their susy partners (sparticles) have equal masses.
2. Electron pairs undergo quasi elastic scattering to selectron pairs via photino exchange.

$$e^- e^- \rightarrow \tilde{e}^- \tilde{e}^- \quad (1.7)$$

3. Uninhibited by the Pauli principle, the selectrons fall into the ground state emitting photons which can penetrate into the broken-susy world.
4. Since selectrons and photons are Bosons, at least some amount of jet structure is produced by stimulated emission.
5. With no further support from electron degeneracy, The star collapses below the Schwarzschild radius and becomes a black hole.

We can briefly elaborate somewhat on each of these items as follows:

1. Our current thinking is that  $\rho_1$  is such that the vast majority of susy phase transitions take place in white dwarf stars. We have also considered the possibility that neutron stars are the progenitors of the gamma ray bursts.
2. The pair conversion process has been recently calculated [11] in the susy phase where electrons and selectrons have the same mass. Amplitudes in the normal phase where the electron mass is negligible compared to the selectron mass were calculated earlier by Keung and Littenberg [12]. At the same time in the susy phase, quarks will convert to scalar quarks via gluino exchange. A full conversion to scalar nucleons will be third order in the strong fine structure constant although a significant enhancement is to be expected from low lying quark-squark bound states (pioninos). Since, even at white dwarf densities, separate nuclei are outside the range of strong interactions, strong conversion takes place at first only within nuclei.
3. The photons can penetrate the bubble wall since they are light in both phases. The selectrons, however, being extremely massive in the broken susy phase are confined to the interior of the bubble. The resulting enormous energy release due to the relief from Pauli blocking can re-ignite fusion in the cold star and provide the energy to accelerate outward any circumstellar material which may be present. Thus the susy phase transition may provide a fundamental explanation for the “central engine” powering gamma ray bursts in the “collapsar” and “cannonball” models. However, in the current model, the gamma ray bursts can erupt even in the absence of significant circumstellar matter.
4. Beam collimation due to stimulated emission of bosonic particles is familiar from laser physics. The fundamental enhancement mechanism derives from the behavior of bosonic creation and annihilation operators discussed below.

5. In standard model astrophysics, isolated white dwarfs are totally stable due to the Pauli principle and there should be no black holes below the Chandrasekhar limit of 1.44 solar masses. In the current model however, once the Pauli blocking has been lifted, the typical white dwarf of solar mass and earth radius will collapse to a black hole in (classically) about 1.5 s. This free collapse time is tantalizingly close to the 2 s dip in the duration distribution of gamma ray bursts. We are currently investigating this as well as other mechanisms for the dip.

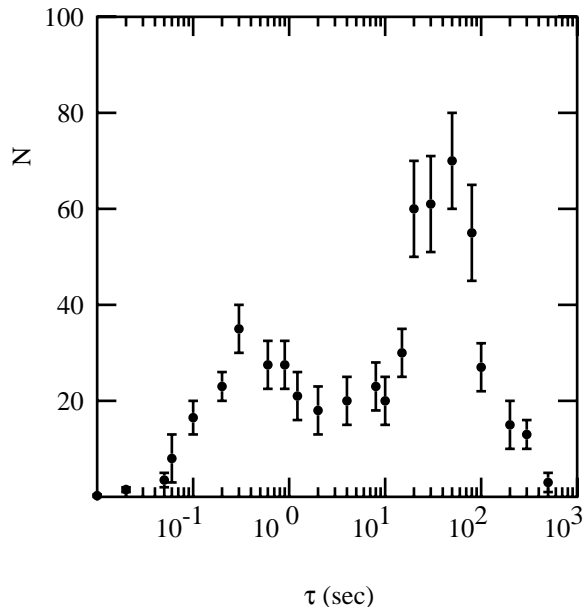


Figure 4: duration distribution of gamma ray bursts after ref.[15]

In conventional astrophysical models for the bursts, the duration distribution shown in figure 4 is sometimes assumed to come from a viewing angle dependence although the existence and location of the dip is not easily predicted [13, 14].

In ref.[10] we were able to easily show that the energy release from a susy phase transition in a white dwarf star would result in an at least partially collimated burst of MeV level gamma rays (the average kinetic energy in the degenerate electron sea) with a total energy from electrons of about  $10^{50}$  MeV (the total kinetic energy in the electron sea). The minimum time scale of the event would be about 0.02 s, the time for a light ray to traverse the radius of the typical white dwarf star (solar mass, earth radius). The predicted numbers are in

agreement with observations making the common assumption that the burst has about a  $5^\circ$  opening angle.

One would expect that any new idea for the central engine would be welcomed in astrophysics but it is also fair to critically compare the susy phase transition model with more conventional models for the gamma ray bursts to see which is more speculative. The long duration bursts ( $> 2$  s) have been extensively investigated in terms of the “collapsar” model [16]. In this model one begins with a “failed supernova” that has left a large amount of matter in one or more shells surrounding a collapsed core. The shells fall onto the dense core reigniting fusion the energy release from which is transferred to the infalling material causing them to rebound at relativistic speeds colliding repeatedly with the core and with each other to produce the observed gamma rays. The collapsar model has evolved to incorporate some features of the “cannonball” model of Dar and DeRujula [17]. In this latter model a large amount of stellar material is ejected from a star and the gamma rays are produced externally when this relativistic material collides with circumstellar matter.

Perhaps conventional astrophysical scenarios can be constructed in which the zeroth order quantitative observations mentioned above can be fit to reasonably valued parameters but, in these scenarios, several questions remain to be resolved:

1. What is the “central engine” (energy release mechanism)? Newtonian gravity by itself does not provide more energy to a falling object than its original potential energy. In Einsteinian gravity we are familiar with black holes continually pulling in surrounding matter but is there a mechanism for a black hole, or incipient black hole, to emit near stellar sized objects at relativistic speeds? Does conventional fusion provide a sufficient energy release mechanism? In an “evolved” core consisting of the nuclear ash of earlier burning, the remaining nuclei are relatively heavy and relatively little energy is available even from fusion reignition at elevated temperatures. Iron is the endpoint of conventional fusion and further fusion reactions absorb rather than release energy.
2. What is the collimation mechanism? In the cannonball model the collimation is produced by the large Lorentz parameters of the ejected matter ( $\gamma \approx 100 - 1000$ ). This would explain a collimated nature of the gamma ray bursts but what force can outwardly accelerate a macroscopic body to such speeds? Perhaps the susy phase transition photons in the presence of circumstellar material could produce the proposed cannonball acceleration. In the collapsar model, if the infalling shells are spherical or disk-like, it is difficult to construct a monte carlo that would transfer a huge amount of momentum into any one direction, even if there is a preferred axis such as the normal to an accretion disk. Here also, some combination of accretion disk models with a susy central engine could be productive.
3. What causes the lack of “baryon loading”? In conventional astrophysical models, even if a large amount of energy is available, it is difficult to deposit a large fraction of this energy into a limited range of the gamma ray spectrum as is observed. In a supernova for example most of the energy goes initially into kinetic energy of baryons and heavy nuclei and from there into a broad range of photons mostly well below the gamma ray

region. In heavy ion colliders where nuclei are given Lorentz parameters of up to 100, no events are observed where the energy is largely deposited into gamma rays.

4. What are the short duration bursts ( $< 2$  s)? The collapsar model seems incapable of incorporating the short duration bursts suggesting that they may be due to a totally different mechanism. Recently, several ideas [18] have been put forward to understand these short bursts. In one of these it is suggested that about  $10^{50}$  ergs (depending on accretion disk viscosities and an assumed efficiency of 1%) could be converted from  $\nu\bar{\nu}$  into an  $e^+e^-$  plasma which could then be made available for the production of a relativistic fireball. This model could be in line with the ‘‘cannonball’’ model of Dar and DeRujula [17] which involves the acceleration of a relativistic fireball away from a progenitor star. However, it still leaves open some major questions. The central engine is still unidentified and, even if a huge electron-positron cloud is available, what force can accelerate it outward and why don’t the electrons and positrons annihilate long before they produce gammas from a collision with circumstellar material? Annihilation gammas would not have collimation if the cloud annihilates at rest and would not have the observed spectrum if the cloud is first accelerated to a large Lorentz parameter. The idea that the fireball consists of electrons and positrons does, however, seem to deal with the absence of baryon loading so the model deserves further study. The current situation calls for an open-minded, non-dogmatic attitude.

Next we review the suggestion that the strongly collimated jet structure is due to a bose enhancement of the emitted selectrons, sprotons, and bremstrahlung photons, i.e. a stimulated emission. The matrix element for the emission of a selectron pair with momenta  $\vec{p}_3$  and  $\vec{p}_4$  in process 1.7 in the presence of a bath of previously emitted pairs is proportional to

$$\begin{aligned} \mathcal{M} &\approx \langle n(\vec{p}_3) + 1, n(\vec{p}_4) + 1 | a^\dagger(\vec{p}_3) a^\dagger(\vec{p}_4) | n(\vec{p}_3), n(\vec{p}_4) \rangle \\ &\approx \sqrt{(n(\vec{p}_3) + 1)} \sqrt{(n(\vec{p}_4) + 1)} \end{aligned} \quad (1.8)$$

Thus in a bath of previously emitted bosons, the cross section is enhanced by the factor  $(n(\vec{p}_3) + 1)(n(\vec{p}_4) + 1)$ . We have constructed both a primitive and a less primitive monte carlo for this enhancement as discussed below.

In ref. [10], we considered a purely statistical model where events were generated according to this changing enhancement factor in the three dimensional space of  $\vec{p}_3$  assuming  $\vec{p}_4 = -\vec{p}_3$ . One should consult ref.[10] for technical details. This simplified statistical model has no dynamical input but serves as a demonstration in principle of the stimulated emission. Initially all the  $n$ 's are zero but once the first transition has been made populating a chosen  $\vec{p}_3$ , the next transition is four times as likely to be into the same state as into any other state. Because of the huge number of available states, the second transition is still not likely

to be into the same  $\vec{p}_3$  state, but as soon as some moderate number of selectrons have been created with a common  $\vec{p}_3$ , the number in that state escalates rapidly, producing a narrow jet of selectrons. These selectrons would be expected to decay down to the ground state via bremsstrahlung photons which are also Bose enhanced leading to a narrow jet of photons which can either be reflected at the domain wall or transmitted into the broken susy phase.

| p<br>MeV | N     | $\cos \theta$ | N     | $\phi$ | N     |
|----------|-------|---------------|-------|--------|-------|
| 0.02     | 52    | -0.9          | 50    | 0.16   | 33    |
| 0.07     | 99608 | -0.7          | 60    | 0.47   | 23    |
| 0.12     | 32    | -0.5          | 34    | 0.79   | 49    |
| 0.17     | 35    | -0.3          | 71    | 1.10   | 49    |
| 0.22     | 58    | -0.1          | 45    | 1.41   | 44    |
| 0.27     | 52    | 0.1           | 99598 | 1.73   | 48    |
| 0.32     | 31    | 0.3           | 22    | 2.04   | 46    |
| 0.37     | 49    | 0.5           | 33    | 2.36   | 99604 |
| 0.42     | 30    | 0.7           | 49    | 2.67   | 65    |
| 0.47     | 54    | 0.9           | 39    | 2.99   | 40    |

Table 1. Distribution of events generated according to the changing number of pre-existing selectrons in each momentum space bin. Initially, all bins are equally likely but, after some fluctuation has given an enhancement in one bin, that bin is efficiently locked in for subsequent events.

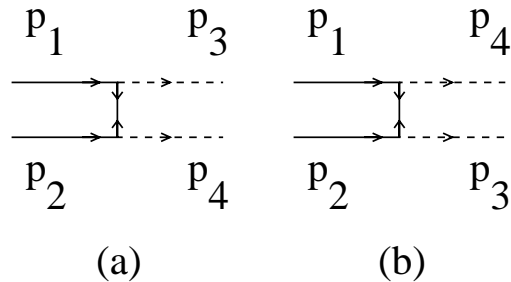


Figure 5:  $ee \rightarrow \tilde{e}\tilde{e}$  via photino exchange

More physical information can be put in by calculating the electron to selectron pair conversion process in the exact susy phase where particles and sparticles have degenerate masses. We have treated the Feynman diagrams of figure 5 to lowest order in the fine structure constant [11]. The helicity cross sections near threshold are plotted in figure 6.

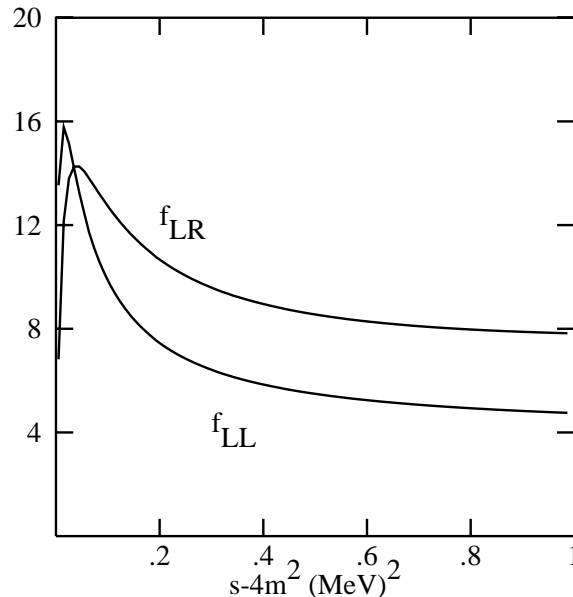


Figure 6: helicity cross sections as a function of CM energy squared

The indication that the annihilation of a left handed electron with a right handed electron is enhanced over that of two electrons of the same helicity suggests, in the context of stimulated emission, a possible mechanism for a spontaneous magnetization of a white dwarf star. A rapidly changing magnetic field could impact the long-standing mystery of cosmic ray generation.

We have also calculated the final state momentum distribution of the selectrons. In this paper, the photon energy is assumed to be the full kinetic energy of the produced selectron neglecting multiple bremsstrahlung effects etc. Incorporating the Bose enhancement factor, the angular distribution shows the jagged structure of figure 7. Due to computer memory limitations, the current simulations give only low resolution angular distributions. If there are secondary peaks as indicated in figure 7, an observer at one of the corresponding angles would interpret the event in terms of a significantly lower “isotropic energy”. The latter is defined as the energy that would be required if the observed burst were isotropic. Of

course, an actual burst in the susy model would involve many more pair conversions than present in the monte-carlo of ref.[11] and one would expect the primary peak to be further enhanced relative to that shown in figure 7. Nevertheless, secondary peaks might explain the anomalously weak bursts grb980425 and grb031203.

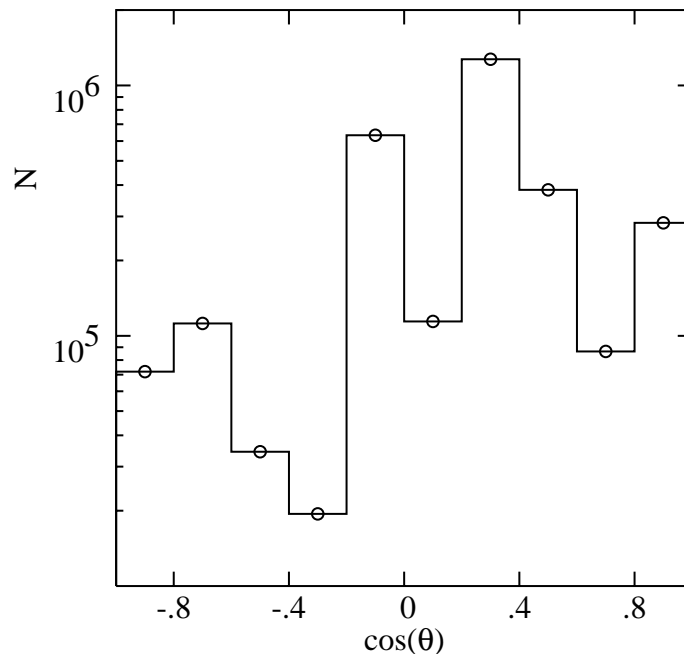


Figure 7: (low resolution) angular distribution after  $1.6 \cdot 10^6$  events, showing effect of Bose enhancement

The burst duration depends on the time taken by the susy bubble to expand to the edge of the star and on the time taken by the gamma rays to traverse the stellar diameter. The minimum burst duration is, therefore, the stellar diameter divided by the speed of light. In actuality, of course, nothing travels at the speed of light in dense matter. As a mechanical membrane, the susy bubble would more reasonably be expected to expand at the speed of sound. Treating the star as a monatomic gas of constant density, the speed of sound is

$$v_s(r) = \sqrt{\frac{10\pi}{9} G_N \rho (R^2 - r^2)}. \quad (1.9)$$

Near the center of the star the speed of sound can approach that of light; however, near the surface the speed of sound is low. Assuming a constant density, the nominal white dwarf of solar mass and earth radius would have a burst duration

$$\tau = \int_0^R \frac{dr}{v_s(r)} = \frac{\pi R_E}{2v_s(0)} \approx 2s. \quad (1.10)$$

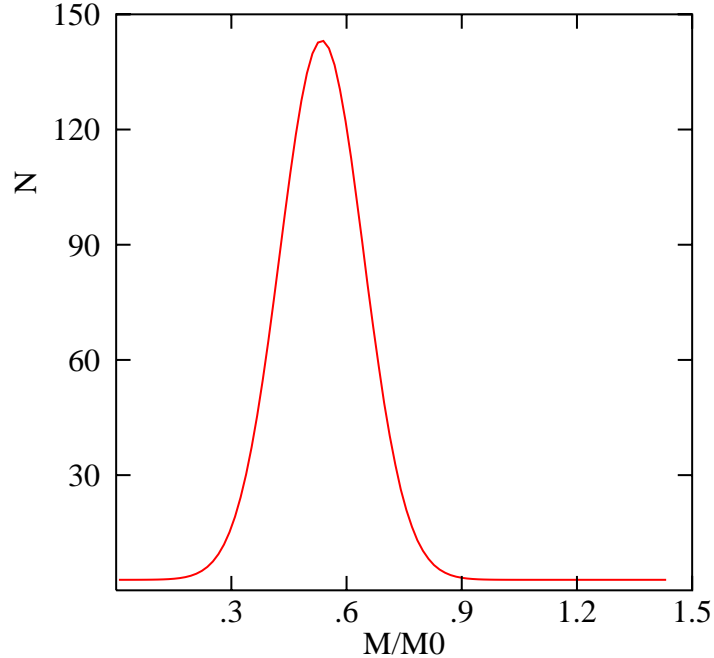


Figure 8: A rough representation of the white dwarf mass distribution

Up to now we have treated only the nominal white dwarf of solar mass and earth radius. In actuality, of course, there is a range of white dwarf masses and radii [19]. The mass distribution goes from about  $0.2M_{\odot}$  to nearly  $1.44M_{\odot}$ , (the Chandrasekhar limit) approximately as shown in figure 8. It is sharply peaked at  $0.56M_{\odot}$ , is asymmetric with some excess on the low side, and is characterized by a long tail on both the high and low sides. About eighty percent of all white dwarfs lie between  $0.42M_{\odot}$  and  $0.70M_{\odot}$ . The radius of zero temperature white dwarfs ranges from about 0.1 earth radius to about 2.5 earth radii. The theoretical radius decreases with increasing mass. Thus the observed white dwarfs have a wide range of densities. Based on average densities, the burst durations would then span the range from about 0.2s to 20s. This range coincides with the region between the two peaks in figure 4. Higher temperature white dwarfs have larger radii thus somewhat increasing the expected burst duration range. The dip in the duration distribution could be affected by the interplay of the mass distribution of figure 8 and the transition probability of eq. 1.7. This possible connection is currently under investigation.

Since the Fermi momentum of the degenerate electron gas is proportional to the  $\frac{1}{3}$  power of the density, the susy model allows a zeroth order understanding of the observation that the shorter bursts have higher average photon energy than the long bursts.

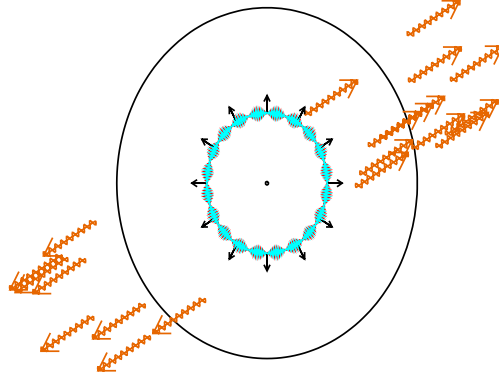


Figure 9: An idealized representation of a susy phase transition in a dense star

As the next refinement, not yet completed, one must take into account the inhomogeneity of the white dwarfs. The central density of such stars is some 50 times higher than the average density and the density near the surface is correspondingly lower than average. The susy bubble, therefore, most likely begins near the center and, most plausibly, expands at the speed of sound which is rapidly decreasing as the bubble approaches the stellar surface as indicated in the sketch of figure 9. The slowly expanding bubble of true vacuum therefore constitutes a spherical cavity inside of which photons and semi-relativistic selectrons resonate. Density inhomogeneity might, therefore, extend the burst duration distribution beyond the naive predictions given above. More quantitative predictions must await the results of current studies of the effect of stellar inhomogeneity.

Many issues remain to be examined. As a few examples one might consider:

1. **the grb-supernova connection.** The relative rates of supernovae  $SN_{1b,c}$  to gamma ray bursts depends on the burst opening angle  $\Delta\Omega$ .

$$\frac{R_{sn}}{R_{grb}} \approx 10^5 \frac{\Delta\Omega}{4\pi} \quad (1.11)$$

If the grb collimation is extremely narrow, these rates could be one-to-one. Presumably, only with a quantum collimation mechanism such as in the susy phase transition model

could such extreme collimation be contemplated. On the other hand, if the susy transition takes place in a large, less dense star, the average photon energies would be below the gamma ray range but perhaps still more effective than neutrinos in blowing off the stellar mantel. In this case the ratio of supernovae to grb's could be appreciably greater than one and one would expect a relatively broader burst.

2. **afterglows.** In the susy model, grb afterglows come from activated nuclei due to the passage of the gamma ray beam through circumstellar matter or due to fusion by-products within the star. The former should not be observed if there is no appreciable circumstellar matter or if the circumstellar matter is in a disk and the burst is perpendicular to the disk. Since the majority of white dwarfs are not in binary systems, there will be many cases where there is no afterglow of this type. Afterglows from within the transitioning white dwarf should not last longer than the free collapse time of a susy star which is a function of its density. Thus, in the susy model we would not expect the SWIFT experiment, which starts taking data soon, to see appreciable afterglows associated with every burst.

Comments on the present model at this and other conferences have centered on ways to examine the effects of the model on other systems and to refine the predictions for gamma ray bursts. In addition, it is sometimes useful to consider anonymous comments since these often give voice to critiques that their author might be ashamed to make in an open forum. Unfortunately, they usually have an obvious response. Typical of these latter comments and the obvious responses to them are the following:

1. "Given the large number of white dwarfs in the universe these very common astrophysical objects are among the best studied and better understood objects in the sky. Their equation of state can be tested to an high degree of accuracy and the stars monitored for long period of time. These observations exclude any exotic behaviour."

If the author of this comment were to consult an expert, he would immediately learn that the observed rate of grb's is very low compared to the number of white dwarfs. This rate is

$$R_{grb} \approx 5 \cdot 10^{-7} \frac{0.0239}{\Delta\Omega} yr^{-1} galaxy^{-1} \quad (1.12)$$

with 0.0239 being the solid angle corresponding to a  $5^\circ$  burst half opening angle. Even if the bursts are extremely collimated ( $\Delta\Omega \approx 4\pi \cdot 10^{-5}$ ), this corresponds to far fewer than one burst per century per galaxy. Given the enormous number of white dwarfs in a typical galaxy, many of which are quite dim, the probability that a given burst could be associated with the disappearance of a known white dwarf is negligible. The estimates are that 95% to 99% of the  $10^{11}$  stars in our galaxy are or will become white dwarfs with perhaps  $10^9$  already being white dwarfs. Until the phase transition occurs, the white dwarf star will cool according to standard model physics. Nevertheless, a surprising shortage of old white dwarfs has also been observed [20] leading to an

anomalously low estimate for the age of the universe. It is not clear whether this is due to low statistics or some other cause.

2. “Supersymmetry in nature is badly broken and the splitting among the supersymmetric partners is, at least, of the order of a TeV! So, there is no reason to expect the particles and the sparticles to be degenerate. Besides why are their common masses chosen, in the false vacuum, to be identical to the ones of the particles in the ordinary vacuum and not at the TeV scale?”.

At first, the author of this comment did not seem to realize that we are dealing with an exact susy phase where particles and sparticles are degenerate. Then, in mid-sentence so to speak, he seemed to realize this basic fact but he still did not realize that we viewed the exact susy phase as the true vacuum, not the “false vacuum”. Finally, he did not seem to remember that superstring theory predicts light (even massless) ground state supermultiplets. Ultimately, of course, there is an assumption in our work that the common mass is not greater than the particle mass in the broken phase. Even without the string theory bias, however, this assumption is no worse than any other and does not make our proposal unworthy of consideration.

3. “the vacuum structure of SUSY extensions of the standard model usually does \*not\* have a vacuum with unbroken supersymmetry.”

Even if this were “usually” true, it would never be used to discourage discussion of a model except behind the mask of anonymity. The author of this comment had in mind the highly restricted minimal supersymmetric standard models (MSSM) with two higgs and fixed susy breaking parameters. Obviously, such models have no dynamical mechanism for a phase transition to exact susy. In fact, of course, the five basic string theories are supersymmetric and string models have been constructed with standard-model-like broken supersymmetry (e.g. [21] and references therein). In string theory all the parameters of the theory are dynamically determined. A formal string theory study of the transition we consider (from an unstable de Sitter vacuum with positive vacuum energy to a stable susy vacuum) has already been undertaken [22] and well over a hundred articles have been written in the past two years on string landscape ideas. Our work differs from these only in that we suggest immediate experimental consequences.

In summary, we feel that the field of gamma ray bursts may still be in its infancy despite more than three decades of intense study. Therefore, some tolerance of new physics proposals may be in order. The mystery is there to be solved and not just to be savoured and protected from radical new ideas.

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