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Supersymmetric model of gamma ray bursts

L. Clavelli* and G. Karatheodoris†

Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA

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We propose a model for gamma ray bursts in which a star subject to a high level of fermion degeneracy undergoes a phase transition to a supersymmetric state. The burst is initiated by the transition of fermion pairs to sfermion pairs which, uninhibited by the Pauli exclusion principle, can drop to the ground state of minimum momentum through photon emission. The jet structure is attributed to the Bose statistics of sfermions whereby subsequent sfermion pairs are preferentially emitted into the same state (sfermion amplification by stimulated emission). Bremsstrahlung gamma rays tend to preserve the directional information of the sfermion momenta and are themselves enhanced by stimulated emission.

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Within the past five years well over a hundred articles have discussed the possibility of transitions between various local minima of the effective potential of string theory stimulated by work by Bousso and Polchinski [1], Susskind [2], and Kachru *et al.* [3]. In particular the phase transition between a vacuum similar to ours with positive vacuum energy and the vacuum of exact supersymmetry (SUSY) with vanishing vacuum energy has been treated in string theory [3]. In this article, we discuss possible phenomenological manifestations of such a transition in a dense star.

We take as a starting point the three experimental-theoretical indications:

(1) We live in a world of broken supersymmetry (SUSY) where most of the supersymmetric particle masses are at the weak scale (several hundred GeV) or above. Indications for this come from successful SUSY grand unification predications for the b/τ mass ratio and the $\alpha_s - sin^2(\theta)$ relationship as well as the astrophysical indications for nonbaryonic dark matter.

(2) In our world there is a positive vacuum energy density (dark energy) and a negative vacuum pressure $p_{\rm vac} = -\rho_{\rm vac}$ leading to an acceleration in the expansion of the universe [4].

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho_{\rm vac} + 3p_{\rm vac}) > 0 \qquad (1)$$

(3) The true ground state of the universe is a state of exact SUSY where particles and their supersymmetric partners have the same mass. This seems to be a persistent prediction of string theory. We choose to consider a transition to a flat space exact SUSY where the vacuum energy vanishes as opposed to a possible transition to an anti-de Sitter minimum which could also be explored and would probably be qualitatively similar.

A strict consequence of accepting these three indications and the string theory prediction that all parameters of the theory are dynamically determined is that the universe will ultimately undergo a phase transition to the true ground state of exact SUSY. In such a situation, only the probability per unit time for this transition to occur is, at present, unknown and subject to speculation. Such decays of the false vacuum were discussed in some generality by Coleman and collaborators several decades ago [5]. In a homogeneous medium, once a critical bubble of true vacuum is nucleated, it will grow without limit. Thus, in particular, if a bubble of critical size forms in dilute matter it will rapidly take over the universe [5] with the immediate extermination of all life.

Plausible suggestions have been made that the phase transition to the true vacuum might be catalyzed in dense matter [6,7] and we argue that a bubble of true (SUSY) vacuum, once formed, would be confined to the region of high matter density. Details are presented in another article [8]; the argument is outlined below. Such a situation would be in line with string theory arguments suggesting that the universe might have a domain structure in which different regions in space-time might have different physical constants, different particle masses, and even different gauge groups.

While superstring theory is struggling to find some experimental confirmation beyond the (already impressive) automatic incorporation of gravity and gauge forces, the field of gamma ray bursts, on the other hand, is one in which rapidly expanding observational data is, most astronomers admit, in need of additional theoretical insight. The sheer enormity of the energy release in these bursts together with their short lifetime and pronounced jet structure make it possible that a full explanation will not be found without some type of startling "new physics". One example of such speculative "new physics" proposals is the quark star model of Ouyed and Sannino [9].

Although the long duration gamma ray bursts (lifetimes greater than about two seconds) have been observationally associated with supernovae, the existence of the required

*Email address: lclavell@bama.ua.edu
†Email address: karat002@bama.ua.edu

explosion has not as yet been successfully modeled in standard astrophysical monte carlos of supernova collapse [10]. An additional energy release mechanism such as that proposed here could, therefore, be helpful. Conceptual gaps in conventional approaches to the theory of gamma ray bursts based on accretion disks and hydrodynamic shock waves are, at present, temporarily filled by the terminology of a "central engine" and "firecone production". It is not clear that the standard model has within it an adequate energy release mechanism nor a mechanism for the sufficient collimation of the burst. Models for the narrow collimation of the bursts typically involve the acceleration away from incipient black holes of large neutral bodies of matter to Lorentz parameters near 100. The physical basis for the requisite strong forces is not firmly established although some speculative ideas have been put forward. Most workers in the field would admit that the mechanism for launching such a jet is unclear. Another problem in the conventional approaches is the lack of "baryon loading". Namely, the accelerated body of matter must be largely leptonic in order for the energy deposition to be primarily in the gamma ray range with relatively little converted to kinetic energy of heavy particles or to low energy photons. [11,12].

In addition to not having a conceptually complete energy release mechanism or collimation mechanism, the conventional astrophysical approaches do not predict the primary quantitative characteristics of the bursts except as related to free parameters in the theory. These primary quantitative observations are

(1) burst energies in a narrow range near 10^{50} ergs. This assumes burst collimation, otherwise the burst energies are much greater and widely varying [12].
(2) typical photon energies in the 100 KeV to 1 MeV range [11].
(3) Burst durations of from some 20 milliseconds to 200 seconds with the duration distribution having a pronounced dip at about 2 s [13].

This, however, is not to say that no progress is being made in exploring conventional astrophysical possibilities. For instance, several models have been proposed in [14]. 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 [15] which involves the acceleration of a relativistic fireball away from a progenitor star but the nature of the central engine and jet launching mechanism are still uncertain.

Given the magnitude of the long-standing challenge posed by gamma ray bursts, we would hope that, while the feasibility of mechanisms such as the above is being investigated, broad latitude is also given to the discussion of ideas beyond the standard model even if they are necessarily less fully developed and seemingly more speculative.

In the current paper we propose as a model for the "central engine" the lifting of Pauli blocking due to a SUSY phase transition. The resulting energy release could be utilized in a subsequently conventional astrophysical model for the gamma ray bursts. However, we note that the transition to a largely bosonic final state also suggests a natural mechanism for the burst collimation.

Our proposal is based on the following scenario.

(1) In a region of space with a high level of fermion degeneracy there is a phase transition to a supersymmetric ground state. In the SUSY phase, electrons and their SUSY partners (selectrons) are degenerate in mass as are the nucleons and snucleons, photons and photinos etc. A critical assumption for the current work is that the common mass of electrons and selectrons in the exact SUSY phase is no greater than the electron mass in our broken-SUSY universe. This assumption is supported by string theory which predicts massless ground state supermultiplets in the true-vacuum, exact SUSY phase. In addition, one can note that, in the popular model of radiative breaking of the electroweak (EW) symmetry, SUSY breaking and EW breaking are linked so that in the absence of susy breaking, the ground state supermultiplets are massless. We know of no calculation in the literature requiring a necessarily higher common ground state mass. We assume for definiteness and simplicity an equality of the common mass in the exact SUSY phase and the particle mass in the broken phase.
(2) In the SUSY phase, electron pairs undergo quasi-elastic scattering to selectron pairs which, uninhibited by the Pauli principle, can fall into the lowest energy state via photon emission. These photons are radiated into the outside (non-SUSY) world. Other photons are emitted at the boundary to conserve momentum as the selectrons are reflected by the domain wall not having sufficient energy to cross into the non-SUSY domain. A highly collimated jet structure could be produced by the stimulated emission of sfermions and photons.
(3) Simultaneous with electron conversion into selectrons, nucleons within heavy nuclei convert into snucleons. With no further support from the electron degeneracy, the star collapses to nuclear density under gravitational pressure.
(4) Remaining nucleon pairs then undergo the analogous conversion to snucleon pairs with the cross section mediated by the strong exchange of supersymmetric pions. This process can be temporarily interrupted by brief periods of fusion energy release but then continues until the star falls below the Schwarzschild radius and becomes a black hole, thus extinguishing the gamma ray burst if it has

not already ended. The exact behavior of a SUSY bubble in a dense star is, obviously, a complicated problem and only the simplest zeroth order calculations are within the scope of this initial paper.

In this model bursts could be due to the decay of isolated white dwarfs which are absolutely stable in standard astrophysics. We therefore predict the existence of low mass black holes below the Chandrasekhar limit. In the following we show, in outline form, that the mechanism produced here can quantitatively, though roughly, account for the observations of stellar explosion, total energy release, minimum burst duration, average photon energy, and jet collimation. No other comparably parameter-free model predicting these primary quantitative features of the bursts exists at present. A more rigorous modeling of the burst in the SUSY phase transition framework, addressing some of the secondary characteristics, is deferred to a later paper and to future investigations.

Transitions between vacua of differing amounts of supersymmetry have been considered in string theory [16] and lie at the basis of string landscape models. In order for such phase transitions to occur, the effective potential must be dynamically determined as in string theory and some other models of spontaneous SUSY breaking. In a model such as the Minimal Supersymmetric Standard Model (MSSM) where the SUSY breaking is attributed to fixed parameters, one would not expect phase transitions between vacua with differing amounts of supersymmetry. Catalysis of vacuum decay by matter effects has been rigorously treated in two dimensions [6]. This catalysis is more difficult to treat in four dimensions but we adopt the idea that the SUSY transition will be much more likely to nucleate in a dense star than elsewhere in space. One likely manifestation of this catalysis might be that the critical radius above which a SUSY bubble will expand and below which be quenched is much greater in vacuum than in dense matter. From the expression of Ref. [5] for the vacuum case, we would expect a critical radius of

$$R_c = \frac{3S}{\epsilon + \Delta\rho} \tag{2}$$

where $\epsilon + \Delta\rho$ is the ground state energy density in the broken-SUSY phase minus the ground state energy density in the exact SUSY phase and S is the surface tension of the bubble. Here, ϵ is the observed vacuum energy density and ρ is the ground state matter density. The difference $\Delta\rho$ is the excitation energy density in the broken-SUSY phase. For the nominal white dwarf ignoring density inhomogeneity, the kinetic energy density of the degenerate electron gas is about

$$\Delta\rho \approx 6 \cdot 10^{34}\ \mathrm{MeV}/m^3. \tag{3}$$

Inhomogeneity effects are the subject of an article currently in preparation. It has been argued [17] that the current longevity of the universe requires that R_c in vacuum be greater than the galactic radius. Although he did not consider supersymmetry specifically, his analysis suggests a lower limit on S.

$$S > \frac{R_{\mathrm{galaxy}}\epsilon}{3} = 5.6 \cdot 10^{23}\ \mathrm{MeV}/m^3 \tag{4}$$

Extrapolating to a dense medium from the vacuum calculation of Ref. [5], the transition probability per unit time in a homogeneous body of volume V is expected to be of the form

$$\frac{1}{N}\frac{dN}{dt} = AVe^{-(\tilde{\rho}/\epsilon + \Delta\rho)^3} \tag{5}$$

where, in the vacuum, $\Delta\rho = 0$ [5]. In the simplest cases, $\tilde{\rho}$ is proportional to the 4/3 power of the surface tension which is usually treated as a constant but could be density dependent at high density. The exponential factor grows rapidly with $\Delta\rho$ up to $\tilde{\rho}$ and then saturates. For more dense systems the transition rate is proportional to the volume. The parameter A is at present undetermined. If $\tilde{\rho}$ is of order the nominal white dwarf electron kinetic energy density of Eq. (3), the other parameters can be reasonably chosen so that the transition probability in vacuum and the transition probability in a heavy nucleus are negligible while the rate in a dense star is appreciable. In this case we would predict bursts from isolated white dwarf stars and from more massive collapsing objects as they approach white dwarf density. Depending on the value of $\tilde{\rho}$, there could also be significant transitions in Neutron stars. Clearly, at present the rate of SUSY transtions is somewhat parameter dependent but, as we will show, the zeroth order manifestions of such a transition in a white dwarf star, once it occurs, are relatively unique.

If a SUSY bubble forms in an electron gas, electron pairs will convert to selectron pairs.

$$e^- e^- \rightarrow \tilde{e}^- \tilde{e}^- \tag{6}$$

The cross section for process (6) is, apart from logarithmic factors, [18]

$$\sigma_0 = \frac{\pi\alpha^2(\hbar c)^2}{4\langle E\rangle^2}. \tag{7}$$

Thus, the half life of a sample of electrons undergoing this process followed by bremstrahung is

$$\tau \approx \frac{1}{\alpha\sigma_0\rho v} \approx \frac{16\pi\langle E\rangle^3\hbar}{\alpha^3(cp_{\mathrm{max}})^4} \approx 3.3 \cdot 10^{-13}\ \mathrm{s} \tag{8}$$

where we have borrowed parameter values from considerations below. Once the radiated photons have left the bubble, the broken-SUSY phase can no longer quench the SUSY bubble since the sparticles are prohibitively massive in the normal world.

For the bremstrahlung to occur before the bubble collapses thus trapping the selectrons, the minimum size of the bubble must, therefore, be roughly of order

$$r > \frac{c}{\alpha \sigma_0 \rho v} \approx 10^{-4}\ \mathrm{m}. \tag{9}$$

The resulting constraint on the surface tension is well within that suggested by Eq. (4).

If we consider the transition as beginning with the strong transition from nucleons to snucleons, this minimum bubble size might be a few orders of magnitude smaller but still much greater than nuclear size. The volume factor in Eq. (5) makes it highly unlikely that the SUSY transition will take place in a terrestrial heavy nucleus but we postulate that the process occurs in fermi degenerate stars with a probability per unit time fixed by the rate of gamma ray bursts divided by the number of such stars. In the current state of the art with respect to vacuum decay we cannot calculate this probability nor do we need to know its value for our present considerations. Nevertheless, we can note that estimates of the number of white dwarfs in our (typical) galaxy are of order 10^9. The number of gamma ray bursts per year per galaxy is about $5 \cdot 10^{-7}$ assuming a 5° burst opening angle. Thus, if the SUSY phase transition model for the bursts is correct, the probability for a given white dwarf star to explode in a given year is less than 10^{-15}. Until the phase transition takes place, the white dwarf will cool according to standard physics. Thus, even if the estimate of white dwarf numbers or burst rates are off by some orders of magnitude, the present model is clearly not in conflict with current observations of white dwarf cooling. It is also possible that many, or even most, of the SUSY phase transitions result only in a neutrino burst with the gamma rays being swallowed by the subsequent black hole. Even then, it is still highly improbable that a particular white dwarf would be observed to suddenly disappear. In this connection one could note that there is, in fact, a long-standing shortage of cool white dwarfs [19] and, perhaps, a surplus of dark objects of white dwarf mass [20]. The MACHO experiment has also detected a surprisingly large number of dark objects of low mass [21] which, in the SUSY model, could be interpreted as SUSY black holes of mass below the Chandrasekhar limit. A repeat of these observations with increased sensitivity is highly desirable.

We consider the case of a typical white dwarf of solar mass ($M = 1.2 \cdot 10^{60}$ Mev$/c^2$) and earth radius ($R = 6.4 \cdot 10^6$ m) supported as in the standard astrophysical model by electron degeneracy. That is the number of electrons with momentum between p and $p + dp$ is

$$dN = \frac{8\pi p^2 dp V}{(2\pi\hbar)^3} \tag{10}$$

with

$$p_{\max} = \left(\frac{3N}{8\pi V}\right)^{1/3} 2\pi\hbar = 0.498\ \mathrm{MeV}/c. \tag{11}$$

Here, N is the total number of electrons in the white dwarf

$$N = 6 \cdot 10^{56} \tag{12}$$

where we have assumed equal numbers of electrons, protons and neutrons. The average squared three-momentum of the electrons is

$$\langle p^2 \rangle = \frac{3}{5} p_{\max}^2 \tag{13}$$

and the average electron energy is

$$\langle E \rangle = mc^2 (\sqrt{(1 + <p^2>/(mc)^2)} + g). \tag{14}$$

g is a small correction term given by

$$g = \sum_{l=0}^{\infty} \left(\frac{p_{\max}}{mc}\right)^{2l+4} \frac{\Gamma(3/2)}{(l+2)!\Gamma(-1/2 - l)} \times \left(\frac{3}{7+2l} - (3/5)^{l+2}\right). \tag{15}$$

When the final state selectron comes to rest after bremstrahlung or reflection at the boundary the energy release per electron is

$$\Delta E = \langle E \rangle - mc^2 = .11\ \mathrm{MeV}. \tag{16}$$

This photon energy is in the gamma ray range as observed in the bursts. The total energy release from all electrons is

$$N \cdot \Delta E = 1.2 \cdot 10^{50}\ \mathrm{ergs}. \tag{17}$$

The half life of a sample of electrons undergoing process (6) is

$$\tau \approx \frac{1}{\sigma_0 \rho v} \approx 2.4 \cdot 10^{-15}\ \mathrm{s}. \tag{18}$$

Since this is essentially instantaneous, the time scale of the selectron burst is fixed by the time it takes for the SUSY phase to spread across the star and for the photons from the far side of the star to traverse the star. The speed of light gives a lower limit to the duration of a burst from the nominal white dwarf.

$$\tau \approx \frac{R}{c} \approx 0.02\ \mathrm{s}. \tag{19}$$

This is roughly the observed minimum duration of the gamma ray bursts. However, this prediction is complicated by the fact that the bubble expansion speed in dense matter might be significantly slower than the speed of light. Using the average density, the speed of sound in the nominal white dwarf would lead to a bubble growth time of 2 s. We have, however, not taken into account the variations in radii among white dwarfs. In addition, one needs to consider the varying free collapse time discussed below of a star relieved of Pauli blocking. The investigation of these and many other possible effects relevant to the duration distribution of the bursts in the phase transition model is at an early stage. In the standard astrophysical approaches to gamma ray bursts, the duration distribution is also in early stages of understanding. Similarly, the rapid time variability or ''spikey'' nature of the bursts presents challenges to both the phase transition and conventional approaches. In the phase transition model these spikes could be due to emission from different momentum levels in the degenerate electron sea or to other quantum decoherence effects. In the conventional approach, the spikes are often attributed to ''subjets'' within the burst although their physical origin cannot be determined without a full theory of the central engine.

During the conversion of electrons, the lifting of electron degeneracy causes the star to collapse rapidly under the gravitational forces until nuclear density is reached. Until then, however, separated nuclei are outside the range of strong interactions so nucleon conversion proceeds only within individual nuclei. Initially SUSY conversion within nuclei occurs via the strong reactions

$$p + p \rightarrow \tilde{p} + \tilde{p} \qquad n + n \rightarrow \tilde{n} + \tilde{n} \qquad p + n \rightarrow \tilde{p} + \tilde{n}. \tag{20}$$

These processes are mediated by pioninos (the SUSY partners of the pions). In a white dwarf the dominant nuclei are Carbon and Oxygen. We can estimate the energy release in the processes (20) using a simple three dimensional square well model. After SUSY conversion to bosonic particles, the shell model excitation energy will be released. Using a Carbon radius of 2.3 fm [22] , we estimate that there will be 3.0 MeV released per Carbon nucleus for a total energy release in the nominal white dwarf of $4.9 \cdot 10^{50}$ ergs. This is slightly greater than that found from the electron sea.

If there are appreciable amounts of odd isotopes, the SUSY transition will not go completely within separated nuclei and, relieved of the electron degeneracy, the star will collapse under gravitational pressure until the remaining protons and neutrons achieve fermion degeneracy at, we assume, nuclear densities ($(\frac{N}{V})^{1/3} = 0.47\ \mathrm{fm}^{-1}$ [23]). At nuclear densities, the remaining nucleons will undergo SUSY conversion to scalar particles with further release of energy after which time the star will collapse to a black hole. Thus the SUSY phase transition model is a multicomponent model. Because of the high mass of nucleons and their nonrelativistic velocities, the nuclear energy release may not contribute significantly to the collimated burst but may contribute to the afterglows.

Classically, if a piece of a star of mass Δm implodes from a radius r_0 to a radius r, its final kinetic energy will be

$$\frac{1}{2}\Delta m\left(\frac{dr}{dt}\right)^2 = \Delta m\left(\frac{GM}{r} - \frac{GM}{r_0}\right). \tag{21}$$

A freely imploding star of initial radius r_0 at time $t = 0$ will have at time t a radius r given by

$$\theta + \frac{\sin(2\theta)}{2} = t \quad \sqrt{\frac{2GM}{r_0^3}} \tag{22}$$

where

$$\theta = \tan^{-1}\left(\frac{r_0}{r} - 1\right)^{1/2}. \tag{23}$$

If, as will always be the case, the initial radius is far greater than the final radius, the collapse time, assuming complete lifting of the Pauli blocking, will be

$$t = \frac{\pi}{2}\left(\frac{8\pi G\rho}{3}\right)^{-1/2} \tag{24}$$

where ρ is the initial density. This can be written

$$t = 1.53\ \mathrm{s}\left(\frac{\rho}{\rho_{WD}}\right)^{-1/2} \tag{25}$$

where ρ_{WD} is the typical white dwarf density (solar mass, earth radius).

Although further study is needed, it is tempting to suspect that this time is related to the observed dip at 2 s in the burst duration distribution. Objects with a natural burst duration near 2 s might have only a partial SUSY conversion before gravitational collapse thus resulting in a build-up of events at lower burst times. As can be seen from Eq. (25), a transition in a star of lower density will have a longer collapse time. In addition, as the star approaches the Schwarzschild radius, general relativistic effects are expected to stretch out the collapse time and redshift the final stages of afterglow. Other sources of afterglow are irradiated circumstellar material.

In conventional astrophysical models for the bursts, the duration distribution is often assumed to come from a viewing angle dependence although the existence and location of the dip is not easily predicted [11,24].

Next we explore 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 (6) in the presence of a bath of previously emitted pairs is proportional to

$$\mathcal{M} \sim \langle n(\vec{p}_3) + 1, n(\vec{p}_4) + 1 \mid a^\dagger(\vec{p}_3)a^\dagger(\vec{p}_4) \mid n(\vec{p}_3), n(\vec{p}_4)\rangle \sim \sqrt{(n(\vec{p}_3) + 1)}\sqrt{(n(\vec{p}_4) + 1)}. \tag{26}$$

The cross section is, therefore, proportional to $(n(\vec{p}_3) + 1)(n(\vec{p}_4) + 1)$. The full modeling of this enhancement requires a multi- dimensional monte carlo (three integrations for each initial state electron plus two angular integrals for one of the final state selectrons although two of these integrals can be done trivially). We would also need the cross section for process (6) without neglecting the electron mass. This complete calculation has been recently published [8]. Here we content ourselves with the following statistical model which has no dynamical input but provides a simplified demonstration of the principle of stimulated emission of Bosons.

We generate events in the three dimensional space of one of the selectrons momentum magnitude, p_3, polar angle cosine, $\cos(\theta_3)$, and azimuthal angle, ϕ_3, assuming that each event takes place in the *CM* system. Then $\vec{p}_4 = -\vec{p}_3$ and $n(\vec{p}_4) = n(\vec{p}_3)$. 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 4 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 decay down to the ground state via bremstrahlung photons which are also Bose enhanced leading to a narrow jet of photons which can penetrate the transparent domain wall and proceed into the non-SUSY phase.

We model this simplified process by standard monte carlo techniques. To deal with the three dimensional space we define a composite integer variable, k, defined as

$$k = n_{\rm bin}^2 n_1 + n_{\rm bin} n_2 + n_3 \tag{27}$$

where $n_{\rm bin}$ is the number of bins in each of the three variables, p_3, $\cos(\theta_3)$, and ϕ_3. The n_i are integers running from 0 to $n_{\rm bin} - 1$ and are related to the three variables by

$$\begin{aligned} p_3 &= p_{3,\max}(n_1 + 1/2)/n_{\rm bin} \\ \cos(\theta_3) &= (2n_2 + 1)/n_{\rm bin} - 1 \\ \phi_3 &= \pi(n_3 + 1/2)/n_{\rm bin}. \end{aligned} \tag{28}$$

k runs from 0 to $n_k = n_{\rm bin}^3 - 1$ and each value of k corresponds to a unique value of the three variables, p_3, $\cos(\theta_3)$, and ϕ. At each stage in which there are some occupation numbers $n(j)$ we calculate the normalized sum

$$R(k) = \frac{\sum_{j=0}^{k}(n(j)+1)^2}{\sum_{j=0}^{n_k}(n(j)+1)^2}. \tag{29}$$

$R(k)$ is a monotonically increasing function of bin number k, varying between 0 and 1.

Then choosing a random number r between 0 and 1, if $r < R(0)$ we add an event to the first bin and repeat the process. If $r > R(k)$ and $r \le R(k+1)$ we add an event to bin $k+1$ and repeat the process. After 10^5 events (still a tiny fraction of the available 10^{56}) we arrive at the distribution shown in Table I with $n_{\rm bin} = 10$ and $p_{\max} = 0.498$ MeV/c as in Eq. (11).

TABLE I. Development of jet structure in a simplified statistical model. The first column gives the photon energy, the third gives the polar angle cosine, and the fifth gives the azimuthal angle. The second, fourth, and sixth columns give the number of photons in the first 100 000 with those values of p, $\cos(\theta)$, and ϕ.

p_3(MeV)	N	$\cos(\theta_3)$	N	ϕ_3	N
0.02	52	−0.900	50	0.157	33
0.07	99608	−0.700	60	0.471	23
0.12	32	−0.500	34	0.785	49
0.17	35	−0.300	71	1.100	49
0.22	58	−0.100	45	1.414	44
0.27	52	0.100	99598	1.728	48
0.32	31	0.300	22	2.042	46
0.37	49	0.500	33	2.356	99604
0.42	30	0.700	49	2.670	65
0.47	54	0.900	39	2.985	40

This toy model gives, of course, no insight into the actual width of the jets since no dynamics is incorporated. In addition, the photon energy is here taken to be the full kinetic energy of the produced sparticle neglecting multiple bremstrahlung effects etc. A more physical picture of the jet distributions should come out of the more complete dynamical monte carlo to be treated in the near future.

We have presented a physical picture that, accepting its premise, does lead to an explosion into a burst of gamma rays of near MeV energies, with a pulse duration ranging down to a small fraction of a second, highly collimated in angle, and containing a total burst energy of about 10^{50} ergs. The SUSY phase transition takes place preferentially at high density. It is not clear whether isolated stars have sufficiently high density over sufficiently large volumes or whether accretion plays an important role in providing these necessary conditions. In the latter case the SUSY star model could be incorporated into the standard astrophysical approaches as a model for the central engine.

Although many details of the SUSY phase transition model remain to be explored, the gross features of the observed bursts are relatively easily understood with one radical, though not unwarranted, assumption but no free parameters. Given the existing physical basis for our assumption we do not regard the present hypothesis as overly speculative. The model leaves open the question whether evidence for similar SUSY phase transitions can be observed elsewhere in astrophysics or in terrestrial experiments such in heavy ion collisions.

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