Star Wreck

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Abstract

Electroweak models with low-energy supersymmetry breaking predict the existence of stable non-topological solitons, Q-balls, that can be produced in the early universe. The relic Q-balls can accumulate inside a neutron star and gradually absorb the baryons into the scalar condensate. This causes a slow reduction in the mass of the star. When the mass reaches a critical value, the neutron star becomes unstable and explodes. The cataclysmic destruction of the distant neutron stars may be the origin of the gamma-ray bursts.

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The gravitational contraction transforms the low-density gaseous baryonic matter into the dense bodies, stars, which, in turn, burn out leaving behind the remnants of even higher density: white dwarfs, neutron stars, and black holes. Isolated cold white dwarfs and neutron stars do not evolve any further if the particle content of Nature comprises that of the Standard Model. As we shall see, however, supersymmetry can change the destiny of baryons in the universe.

In supersymmetric theories, the presence of squarks makes it possible for the baryon number to be carried by scalar particles. Since the squarks are supposed to be much heavier than the quarks to satisfy the present experimental limits, one might think that they cannot play a role in the late stellar evolution. However, it was recently shown [1, 2] that in a class of SUSY theories with low-energy supersymmetry breaking the lowest-energy state with a given (and sufficiently large) baryon number is a coherent state of squarks, Q-ball, rather than the ordinary nuclear matter. A large stable Q-ball, of the kind that may have been copiously produced in the early universe [1] and can presently exist as a form of dark matter [1], can grow by absorbing the matter nuclei and annexing their baryon number to its scalar condensate [2, 3]. It is of interest, therefore, whether the presence of the relic Q-balls can alter the ultimate fate of the baryonic astrophysical objects.

In this Letter we show that the relic Q-balls can accumulate in both the neutron stars and the white dwarfs, and cause their eventual destruction. While a Q-ball consumes the baryon number of a neutron star, the energy liberated in the process is emitted, predominantly, in neutrinos. The dramatic weight loss associated with this process brings the masses of both the neutron stars and the white dwarfs to their respective minimal values beyond which they are unstable. This leads to an explosion. The lifetime of a contaminated star is determined by the parameters of the underlying supersymmetric theory and can be in the Gyr range. The energy released from the cataclysmic death of a neutron star may be the origin of the observed gamma-ray bursts (GRB). Assuming a cosmological distance scale, and using the observational data on GRB, one can put a constraint on the Q-ball parameters and the mode of

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supersymmetry breaking. Another constraint, a lower limit on the neutron star lifetime, comes from the observation of pulsars, rotating magnetized neutron stars, with ages over 0.1 Gyr.

In general, Q-balls are non-topological solitons [4, 5, 6] that owe their stability to the conservation of some global charge. Regardless of the way supersymmetry is broken, the Minimal Supersymmetric Standard Model (MSSM) admits Q-balls [7], held together by the tri-linear couplings in the scalar potential that originate from the Yukawa couplings in the superpotential, and also from the soft supersymmetry-breaking terms. Such Q-balls, whose charges are arbitrary [8], could be produced in the early universe [9] but would have eventually decayed into the light fermions that carry the same global charges. Formation and subsequent decay of the unstable Q-balls could have various cosmological consequences, in particular, with respect to the baryogenesis [1, 10].

If, however, the scalar potential $U(\phi)$ has a flat direction[5] and $U(\phi) \sim m^4 = const$ for large ϕ, then the mass of a soliton with charge Q_B is $M_Q \propto Q_B^{3/4}$ for large Q_B [2, 1]. Therefore, for arbitrary m, the mass of a baryonic Q-ball with a sufficiently large charge Q_B is less than $m_p Q_B$. Such a Q-ball is stable because it cannot decay into the ordinary matter baryons. The natural values of the mass parameter m in theories with low-energy supersymmetry lie between 100 GeV and 100 TeV. Stable baryonic Q-balls can be produced in the early universe from the breakdown of a coherent scalar condensate [1] and can contribute to dark matter. The primordial scalar condensate is invoked in the Affleck–Dine scenario for baryogenesis [14]. It is possible, therefore, that the baryonic matter in the universe and the solitonic dark matter may share the same origin.

We assume the condensate inside a Q-ball to be a combination of squarks (and, possibly, some other, non-baryonic, scalar fields, like sleptons and the Higgs fields) that transforms as a singlet under the action of the gauge group. The latter is a

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[5]Flat potentials arise naturally in theories with low-energy supersymmetry breaking (see, *e. g.*, Refs. [11, 12]) and are generic for gauge-mediated scenarios (for a review see, *e. g.*, Ref. [13]).

necessary condition for the scalar field to be a flat direction of the potential in a supersymmetric theory. At the same time, this allows one to describe a Q-ball semi-classically as a field configuration in which all the gauge charges vanish [15]. Following Refs. [2, 1, 3], we will assume that the mass of a soliton with charge (baryon number) Q_B is $M_Q \simeq (4\pi\sqrt{2}/3)\, m\, Q_B^{3/4}$, its radius is $R_Q \simeq (1/\sqrt{2})\, m^{-1}\, Q_B^{1/4}$, and the maximal scalar VEV inside is $\phi_Q \simeq (1/\sqrt{2})\, m\, Q_B^{1/4}$.

The dark-matter Q-balls, with expected baryon charges over 10^{21} [3], are too heavy to stop in the Earth or the Sun. However, they do stop and accumulate inside a neutron star. The equation of motion for a small heavy object moving with friction inside a gravitating body is

$$\ddot{R} = -\Omega^2 R - \gamma \dot{R}, \tag{1}$$

where R is the distance to the center of the star. For simplicity, we work in the Newtonian approximation to gravity and neglect the effects of general relativity. Assuming that the Q-ball has a geometrical cross-section of scattering, we obtain

$$\Omega = \sqrt{\frac{4\pi}{3} \frac{\rho}{M_P^2}}, \tag{2}$$

$$\gamma \sim \frac{\rho v_n}{m^3 Q_B^{1/4}}, \tag{3}$$

where ρ is the matter density (assumed to be constant inside the star), v_n is the average nucleon velocity in matter, and M_P is the Planck mass. Depending on the matter density, the Q-ball can oscillate (if $\Omega \gg \gamma$), or it can wade to the center gradually (if $\Omega \ll \gamma$). For the neutron star density, the latter is the case because $\gamma/\Omega \sim 10^2 \, (10^{24}/Q_B)^{1/4} \gg 1$. The Q-balls settle in the center of the star in a matter of seconds.

The interactions of a large baryonic soliton with matter proceeds in two stages. First, an incoming nucleon (or a nucleus) collides with a Q-ball and dissociates into quarks. This is because QCD deconfinement takes place inside every baryonic Q-ball due to the spontaneous SU(3) breaking by the squark VEV's. This process is

accompanied by the emission of, roughly, 1 GeV in pions and is the basis for the experimental detection of the relic Q-balls discussed in Ref. [3]. Second, the quarks inside a Q-ball transfer their baryonic charge to the Q-ball. As a result, the Q-ball grows in baryon number and in size at the expense of the incoming baryons. The rate of "processing" of quarks inside a Q-ball is determined by the physics beyond the Standard Model, which we will assume to be described by the MSSM.

In the ordinary matter, the rate of nucleon collisions with a large Q-ball is much lower than the time scale associated with the conversion of quarks into the quanta of the scalar condensate [3]. In contrast, a Q-ball inside a neutron star receives nucleons at a much higher rate, which may exceed the rate of "processing". In this case, the growth of the baryonic condensate is determined by the cross-sections of the MSSM reactions that generally proceed through a gluino exchange. The VEV of squarks inside a Q-ball causes the mixing of quarks and gluinos, through which they gain masses. Therefore, the rate of a quark decay inside a Q-ball is suppressed by the magnitude of the VEV and takes place predominantly in the outer region of the soliton, where the scalar VEV is small. Hence, the rate of change in the soliton charge Q_B is proportional to the surface area $4\pi R_Q \propto Q_B^{1/2}$ of a Q-ball: $dQ_B/dt = \alpha' Q_B^{1/2}$. If the quarks can be absorbed into the condensate faster than the rate at which they enter the Q-ball, the growth of the soliton's baryon number is also proportional to the surface area: $dQ_B/dt = \alpha'' Q_B^{1/2}$, where α'' is determined by the flux of incoming baryons. Therefore, for an individual Q-ball in matter,

$$dQ_B/dt = \alpha Q_B^{1/2}, \tag{4}$$

where $\alpha = min(\alpha', \alpha'')$.

Unlike the Grand Unified monopoles, which catalyze the proton decay [16] but do not grow in size, Q-balls convert the baryon number of the nucleons into that of the condensate. As a result, their ability to absorb nuclei grows with their surface area, in accordance with equation (4). This makes the behavior of the Q-balls inside the star very different from that of the monopoles [17].

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Some Q-balls may be impervious for the electrons [3]. This causes an additional suppression of their interactions with the ordinary matter because, after the first proton is absorbed, the Coulomb barrier can prevent the other nuclei from approaching a Q-ball. Depending on their ability to retain the electric charge, Q-balls can be separated in two classes: Supersymmetric Electrically Neutral Solitons (SENS) and Supersymmetric Electrically Charged Solitons (SECS) [3]. In a neutron star, where all nucleons are electrically neutral, there is no difference between SENS and SECS. However, when we discuss the fate of the white dwarfs, we will have to make a distinction between the two types.

When a neutron star is born in a supernova explosion, the first relic Q-balls can be slowed down by the dense nuclear matter. They drift towards the center. As they grow in size at the expense of the ambient matter, they coalesce and consolidate into a single Q-ball with a very large baryon number. From that point on, the baryon number of a neutron star is consumed by the Q-balls at the rate

$$\frac{dQ_B}{dt} = \frac{q_*}{\tau} + \alpha Q_B^{1/2}, \tag{5}$$

where q_* is the average charge of a newly arriving Q-ball at the time it merges with the large central Q-ball, and τ is the time scale associated with the flux of Q-balls. If some Q-balls are already present in the neutron star at the time of its formation, this is accounted for by the appropriate initial conditions. (This may be relevant, in particular, to the Population III stars that may form prior to the formation of the galaxies and may be accompanied by a cloud of primordial Q-balls from the start.)

In the case of a neutron star, the very high matter density ensures a plentiful supply of nucleons. Parameter α depends, therefore, entirely on the rate of absorption of quarks into the condensate. This process can be thought of as a quark-quark annihilation in the external background scalar field $e^{i\omega t}\phi(x)$. The cross-section σ of this process depends on the parameters of the MSSM and the structure of a given Q-ball. We parameterize σ as $\sigma = \beta/m^2$. As was mentioned above, the absorption of quarks into the condensate can take place in the outer region of the soliton, where the gluino mass is

not too large. The effective volume of this region can be estimated using the form of $\phi(x)$ from Ref. [2] and is proportional to $\omega^{-3} \propto m^{-3}$. Therefore, $\alpha \propto \sigma\omega^{-3} \propto m^{-5}$. In what follows we will use α as a phenomenological parameter,

$$\alpha = 10^8 \left(\frac{m}{1\,\text{TeV}}\right)^{-5} \beta\,\text{s}^{-1}. \tag{6}$$

The fate of a neutron star is sealed when it captures the first Q-ball. In less than a second it reaches the central region of the star and begins to grow. In the process it may coalesce with the other solitons captured at later times. When the baryon number of the central Q-ball exceeds $\sim (q_*/\alpha\tau)^2$, the solution of equation (5) is $Q_B(t) \approx (\alpha t/2)^2$. The lifetime of a neutrons star depends on m and on the cross-section of qq annihilation,

$$t_s \sim \frac{1}{\beta} \times \left(\frac{m}{200\,\text{GeV}}\right)^5 \text{Gyr}, \tag{7}$$

and can be as low as 10^{-2} Gyr for $m \sim 100$ GeV, or can exceed 10 Gyr for $m \gtrsim 300$ GeV, if $\beta \sim 1$. Since the pulsars with ages around 0.1 Gyr are known to exist, there is a lower bound on t_s and, correspondingly, on m^5/β. If $\beta \ll 1$ and m is in the TeV region then the lifetime of a neutron star exceeds the age of the Universe and the relic Q-balls play no role in the stellar evolution at present time.

The lifetime of the star has little dependence on the flux of Q-balls in a wide range of parameters. If the baryonic solitons make up a substantial fraction of dark matter ($\Omega_Q \sim 1$), their flux is estimated to be $F = 1.2 \times 10^2 Q^{-3/4}(m/1\,\text{TeV})^{-1}$ cm^{-2} s^{-1} sr^{-1} [3]. If, however, $\Omega_Q \ll 1$, then it is possible that the probability for a neutron star to capture a Q-ball is very small. In this case, the average lifetime of a neutron star can be much greater than t_s in equation (7).

The energy released from the consumption of nuclear matter by the Q-balls is

$$\frac{dE}{dt} = m_n \frac{dQ_B}{dt} \sim m_n \alpha^2 t. \tag{8}$$

For $\alpha \sim 10^8$ s^{-1} and $t \sim 1$ Gyr, this yields $dE/dt \sim 10^{30}$ erg/s. This energy is radiated away in thermal neutrinos and photons, with no observational consequences.

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Meanwhile, the star slowly looses its mass.

Neutron stars are stable in a certain range of masses. Assuming Harrison–Wheeler equation of state, one obtains a lower limit on the mass $M_{min} \approx 0.18 M_\odot$ [18]. By the time the Q-balls annex 80% of the neutron star baryon number, a similar fraction of the star's mass is radiated away with thermal neutrinos. At this point the mass of the Q-ball inside the star, $M_Q \sim 10^{-11} M_\odot$, is still too small to affect the conditions of hydrostatic equilibrium. When the mass of a neutron star becomes less than M_{min}, its gravity is no longer sufficient to support the stability of nuclear matter. The result is an explosion, in which the nuclear matter undergoes a transformation into protons and electrons. The explosion is associated with the energy release $\sim 10^{52}...10^{53}$ erg, almost as grandiose as that of a supernova. As the gravity subsides at the onset of the explosion, the unleashed neutrons can decay into protons and electrons with an emission of neutrinos and gamma-rays.

The emission of gamma-rays may account for the observed gamma-ray bursts. The energy of the explosion corresponds to that inferred from the data on gamma-ray bursts under the assumption that they take place at the redshift $z = 1 - 2$ [19]. The lifetime of a neutron star we obtained in equation (7) depends sharply on the parameter m determined by the physics beyond the Standard Model. It seems natural for t_s to be of order a few billion years. If this is the case, there is a population of dying neutron stars at the redshift of a few that can be the source of gamma-ray bursts. An exploding neutron star with subcritical mass would produce a fireball of protons, electrons and decaying neutrons. The study of such explosion, to which some of the discussion in Ref. [19] may apply, lies outside the scope of the present work.

A similar analyses of white dwarfs shows that they can also capture the relic Q-balls. However, since $\Omega \gg \gamma$, equation (1) yields an oscillatory solution. After a number of oscillations, the Q-balls settle down in the center of a white dwarf. If they are of the SECS type, their effect is negligible. If, however, they are SENS, they consume the white dwarf from the inside, just like in the case of a neutron star. The white dwarfs also become unstable when their masses become less than $2.2 \times 10^{-3} M_\odot$, at which

point they also explode. However, the energy liberated by the explosion is, probably, too small to cause any significant observational consequences.

In summary, the relic Q-balls can accumulate inside a neutron star and cause a gradual reduction in the mass of the star until it reaches a critical value. At that point gravity can no longer support the stability of the nuclear matter, and an explosion follows. The lifetime of a neutron star depends on physics beyond the Standard Model, but can be in the Gyr range. If so, the explosions of distant neutron stars can be the origin of the gamma-ray bursts.

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