GRB: A Signature of Phase Transition to QGP?*

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Abstract. It is suggested that the inner energetic engine of Gamma ray burst (GRB) may be the result of the transition of normal hadron to quark-gluon plasma (QGP) in rapidly-rotating and spin-down newborn neutron star. When such a nascent neutron star slows down through dipole electromagnetic and quadruple gravitational radiation, the increasing center density may reach the QCD transition density, i.e., 5-10 nuclear density. Such kind of energy release from the phase transition would be responsible for GRB and its possible beaming effect. The relative dense gaseous environment of GRB location and the iron line observed in the X-ray afterglow support this idea. Some predictions in this model are given.

Keywords: Gamma-ray Bursts, Supernova, Quark-gluon plasma

Quark gluon plasma, supernova, and Gamma-ray burst are essential puzzles in particle physics, stellar physics and high-energy astrophysics, respectively. However, there might be an unusual conjunction of them, from which the three problems originated. Here we propose a possible way to settle the puzzles.

Quark Gluon Plasma (QGP) From 1960s to 1990s in this century, one of the most important progresses is the establishment of the standard model in particle physics. In the model, there are four kinds of fundamental interactions between elementary particles, namely, the gravitational interaction, the electro-weak interaction, the strong interaction, and the Yukawa interaction between Higgs particles. However, the knowledge of strong interaction is much less than that of gravity or electro-weak interaction. It is believed that the quantum chromodynamics (QCD) developed in 1970s could be the successful dynamical theory of the strong interaction, but the non-perturbation effect in QCD can hardly be settled. According to lattice QCD, where discrete points represent space-time, a new state of strong interaction matter, the so-called quark-gluon plasma (QGP), appears when the temperature (up to \( \sim 150 - 200 \) MeV) or density (up to \( 5 - 10 \rho_0 \), \( \rho_0 \sim 3 \times 10^{14} \text{g/cm}^3 \) is the nuclear density) is large enough.

One of the QGP might be simply the lumps of up, down, and strange quarks (also a few electrons for electric neutrality), which is known as

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strange quark matter (SQM). Unfortunately, we can not tell whether SQM is the lowest state of hadronic matter, but can only say that the energy of strange matter is lower than that of matter composed by nucleus for QCD parameters within rather wide range (Bodner 1971, Witten, 1984, Farhi & Jaffe 1984). Assuming SQM is absolutely stable, the most possible QGP in nature may be strange stars (Alcock et al. 1986) which might be the survivors in supernova explosions. The assumption is very strong, but does not be impossible.

While, in the terrestrial physics, it is the primary goal of relativistic heavy-ion laboratory to search QGP (Muller 1995). Many proposed QGP signatures have been put forward in theory and analyzed in experimental data, but the conclusion about the discovery of QGP are ambiguities. More likely, it is suggested in theory that the so-called strange hadron cluster (Schaffner et al. 1993) and strangelet (Benvenuto & Lugones 1995) may possibly exist in the nature, however, no experiment has affirmed or rejected the suggestion.

As will be suggested below, GRB might also be a signature of phase transition from neutron matter to QGP composed of \( u, d, s, e \) (i.e., SQM). If this can be confirmed by future astrophysical observations, people can study the transition as well as the plasma itself at a much longer timescale than those relevant to terrestrial laboratory.

**Supernova Explosion (SNE)** In the 20th century, one of the prominence successes in astrophysics is the development of the theory of stellar structure and evolution. However, there are still some challenges in understanding stars’ life, such as the core-collapse supernova paradigm, which begins with the collapse of the iron core of an massive star at the end of its thermonuclear evolution (Bethe 1990, and references therein). It is currently believed that the prompt shock, which is the result of the inner core’s rebound after implosion has compressed the inner core to supranuclear density, can not propagate directly outward and expel the entire envelope, but stalls and turns into an accretion shock at a radius of \( 100 \sim 200 \) km because of nuclear dissociation and neutrino cooling. One way to rescue an explosion may be through the Wilson mechanism (Wilson 1985, Wilson & Bethe 1985), in which the neutrino from the core can be absorbed by the material at \( 100 \sim 200 \) km and can heat this material sufficiently to revive the shock to expel the envelope. Generally, the simulations based on this mechanism give rather low energy, 0.3-0.4 foe (1 foe = \( 10^{51} \) ergs), while the observed energy in SN 1987A is at least 1.0 foe. Further, the supernova simulations that do not incorporate fluid instabilities might fail to explode (Bruenn 1993, Cooperstein 1993, Wilson & Mayle 1993). Thus, much of current research on the core collapse supernova mechanism is
focussed on the role of convection in the unstable regions that develop below and above the neutrinosphere. Whereas, Mezzacapa et al. (1998a, 1998b) found that the convection overturn and its associate effects are not strong enough to revive the stalled prompt shock, although the outward motion of the shock is enhanced.

Therefore, the key criterion for a successful explosion and its enough energy may be the sufficient power of neutrino energy deposition behind the stalled shock. The phase transitions from nuclear matter to two-flavor quark matter and from two-flavor quark matter to strange quark matter (SQM) might be one possible way to increase the neutrino power (Gentile et al. 1993, Dai et al. 1995). Because each nucleon contributes about 30 MeV energy (Cheng et al. 1998), the total energy $E_{pt}$ of the phase transitions is about $E_{pt} = M c^2 \times \frac{30}{931} \sim 5.8 \times 10^{52} \frac{M}{M_\odot}$ ergs, where $M$ is the mass of the inner core. Because the time scale of phase transition is much smaller (below $10^{-7}$ s, see Dai et al. 1995) than that of neutrino diffusion ($\sim 0.5$ s, see e.g., Bethe 1990), the neutrino luminosity $L$ caused by such conversion is about $E_{pt}/0.5 \sim 10^{53}$ erg/s. In Wilson’s computations, the typical value of $L$ is $5 \times 10^{52}$ erg/s without considering phase transition to SQM, hence, the total $L$ could be $15 \times 10^{52}$ erg/s (three times that of Wilson value). Thus, the simulated explosion energy should be about $0.3 - 0.4$ foe $\times 3$, which can explain the observed value from SN 1987A. The residual strange stars should be expected to be bare (Usov 1998) because of high rate of mass ejection. These bare strange stars being chosen as the counterpoints of pulsars have some advantages (Xu & Qiao 1998, Xu et al. 1999).

Another possible way favorable for a successful explosion might be rapid rotation. A nascent neutron star can be rapidly rotating even the initial precollapse core is not (Lai & Shapiro 1995), for the radius of a typical white dwarf near the Chandrasekhar mass ($\sim 1.5 \times 10^3$ km) is about $10^2$ times that of a neutron star ($\sim 10$ km). There may already be some indirect observational evidences for an asymmetric core collapse (Lai & Shapiro 1995 and references therein), which may result in a rapidly rotating core. Unfortunately, we have very little knowledge observationally and theoretically about how fast a nascent neutron star rotates. Further, rapid rotation has not been treated extensively in the simulated models. The existence of centrifugal force in a rotating core might have at least two effects (Monchmeyer 1990): (1), to increase the mass of inner core; (2), to enhance the prompt shock, thus favor a successful explosion. The third effect, especially for the case of rapid rotation, may be that the center density could be much lower than the QCD transition density (Fig. 6.4 in Glendenning 1997) and therefore a neutron star (rather than a strange star) is left after the explosion.
Gamma Ray Burst (GRB)  Gamma-ray burst is one of the most challenges for physicists in this and very possibly the next century. Although it is believed currently that GRBs are at cosmological distances and the observed afterglow can be well explained in the relativistic fireball models, the central energetic engines responsible for these extraordinary events are still poorly understood (e.g. Piran 1999, Meszaros 1999). Three main classes of models are generally considered: the NS$^2$ merger model (Eichler et al. 1989), the hypernova model (Paczynski 1998), and the supernova model (Vietri & Stella 1998).

The accumulating observations of afterglows have shown a close relationship between GRBs and supernovae, which are both the most energetic events in the universe. Supernovae typically have explosion energy of 1 foe, while the assumption of isotropic emission of GRB implies burst energies in excess of 100 foe. There are evidences, which may be suggestive of the hypernova or supernova models, that some detected afterglows are in relatively dense gaseous environments which may suggest that GRBs might be directly associated with star-forming regions (Meszaros 1999, Piran 1999). Piro et al. (1999) reported the possible detection (99.3% of statistical significance) of redshifted Fe ion line emission in the X-ray afterglow of GRB970508. Having discussed possible mechanisms for the production of strong iron line, Lazzati et al. (1999) found that a large amount of iron might be in a compact region where a supernova exploded a few months before the $\gamma$-ray burst. This result is favorable for the supernova model.

We propose an alternative scenario of supernova model for GRBs. In the Vietri-Stella one, a fast spinning neutron star, with a mass that would be supercritical in the absence of rotation, is formed after a supernova explosion. As it spins down, the neutron star inevitably collapses to a Kerr black hole when its center density increases to infinity. Since SQM might be absolutely stable, the nascent neutron star will undergo a transition of QGP to form a strange star when the central density increases to the critical density for QCD phase transition before collapsing to a Kerr black hole. Because of the huge energy release in the transition ($\sim 10$ foe), mass ejection is inevitable in the process, then it may be impossible to form a Kerr black hole. In fact, this kind of phase transition has been chosen as the energy source for GRB for a long time (e.g., Cheng & Dai, 1996, Ma & Xie 1996). The obvious advantage in Cheng & Dai’s model is that the baryon contamination is very small. The total burst energy could be upto $\sim 10^3$ foe if the beaming effect is included since a rapid spin neutron star or strange star is extremely non-spherical-symmetric (see discussion below).

Gravitational radiation induces a generic instability in rapidly rotating stars: a configuration with too much rotational energy will radiate...
away its excess angular momentum until a stable configuration is attained (Chandrasekhar 1970, Friedman & Schutz 1975). A nascent neutron star could be secularly unstable when the ratio \( \beta = T/|W| \) of the kinetic to potential energy is greater than \( \beta_{\text{sec}} \sim 0.14 \), while, the star should be dynamically unstable when \( \beta > \beta_{\text{dyn}} \sim 0.27 \). Gravitational radiation will destabilize some modes when \( \beta > \beta_{\text{sec}} \). For \( 0 < \beta - \beta_{\text{sec}} < 1 \) (i.e., secularly unstable but dynamically stable), the growth time \( \tau_{\text{GW}} \) for the secular instability is given by (Lai & Shapiro 1995)

\[
\tau_{\text{GW}} \sim 2 \times 10^{-5} M_{1.4}^{-3} R_{10}^{4} (\beta - \beta_{\text{sec}})^{-5} \text{ s},
\]

where \( M_{1.4} \) is the neutron star mass in unit of \( 1.4 \, M_{\odot} \), \( R_{10} \) the neutron star radius in unit of 10 km. For typical neutron stars, \( \tau_{\text{GW}} \sim 20 \) s for \( \beta \sim 0.20 \), \( \tau_{\text{GW}} \sim 7 \times 10^{4} \) s for \( \beta \sim 0.15 \), and \( \tau_{\text{GW}} \) could be very long for a very small \( \beta - \beta_{\text{sec}} > 0 \) (Fig. 1 in Lai & Shapiro 1995). For causal equation of state, Hasensel et al. (1999) found the minimum periods of uniformly rotating neutron stars can be as low as 0.288 ms.

If \( \tau_{\text{GW}} > 0.1 \) yr, the usual magnetic dipole radiation might become un-neglectable. The time scale \( \tau_{\text{EM}} \) for such spin-down is (Vietri & Stella 1998) \( \tau_{\text{EM}} \sim 0.1 \) yr \( \omega_{4}^{-4} B_{13}^{-2} \) for typical neutron stars, where \( \omega \) and \( B \) are the angular frequency and the polar cap magnetic field of a neutron star, respectively, and \( \omega_{4} = \omega/(10^{4} \text{s}^{-1}) \), \( B_{13} = B/(10^{13} \text{G}) \). The magnetic field for nascent neutron stars can be as strong as \( 3 \times 10^{15} \) G because of convection and amplification of their magnetic field (Thompson & Duncan 1993, Janka 1998). Therefore \( \tau_{\text{EM}} \) can range from hours to months. Obviously, the time scale for substantial angular momentum loss can be much shorter than the star’s lifetime.

A newborn neutron star will be converted into a strange star when spinning down enough that the central density increases to \( 5-10 \rho_{0} \). For neutron stars, \textit{only those very close to the mass limit can rotate rapidly} because there the radius is the least and the mass the greatest (i.e., the fine tune in mass, see Glendenning 1997), therefore, the time between supernova and conversion may be smaller than \( \tau_{\text{GW}} \) or \( \tau_{\text{EM}} \).

When a conversion takes place, a large amount of energy (\( E_{\text{pt}} \sim 58 \) foe) is released. Also the rotational and the magnetic energy would have important results in the burst of a nascent neutron star into a strange star. In fact, dumping huge energy into a small spatial volume in a short time inevitably leads to an opaque “fireball” (Meszaros & Rees, 1993) because of large possibility for the production of photon-photon pairs and electron-positron pairs. Because of multiple or dipole magnetic field around a nascent neutron star, the burst fireball might be significantly anisotropic; thus one could have a sense of the GRB’s \textit{beaming effect}, which is very essentail for explaining the great burst luminosities. The fireball could preferably expand in weaker field regions with the open...
fields. Furthermore, there might be a super-giant glitch (Ma & Xie 1996) accompanying the conversion since the equation of state of quark matter is much softer than that of neutron star. This possible glitch could results in strong electric field $E_{gl}$ in the open field line regions,

$$E_{gl} \sim R \nabla \cdot E_{gl} \sim \frac{RB}{2\pi c} \frac{\delta \omega}{\omega} \sim 1.6 \times 10^{16} V m^{-1} \frac{\delta \omega}{\omega} R_1 B_{13} \omega_4,$$

which can help charged leptons expanding in the region. Where $\delta \omega$ is the change of $\omega$ when glitch, $R$ is the radius of neutron star. $E_{gl} \sim 10^{15}$ V/m if $\frac{\delta \omega}{\omega} \sim 0.3$ (Ma & Xie 1996). In fact, Janka (1998) has found that such beaming effect might be important for an anisotropic supernova explosion to produce kicks in excess of 1000 km/s as long as an internal magnetic field could be $\sim 10^{14}$ G. In addition, the magnetic annihilation above a nascent neutron star and strange star may also be effective for the variety of afterglows (Dai & Lu 1999). In a conclusion, the energy sources responsible for GRB might be in four parts: phase transition, gravitational, rotation, and magnetic energy, although the magnetic energy may be originated from rotation according to Thomson & Duncan (1993).

**Conclusion** We have suggested a model that GRBs might be originated from the QCD phase transition of rapidly-rotating and spin-down nascent neutron stars to strange stars. The beaming effect, as well as the correlation between GRBs and supernovae explosions, can be understood in the model. Also the suggestion clarify the remain objects after later evolution of massive stars: 1. White dwarfs (for less massive stars), 2. neutron stars (for the case of highly rotating) or strange stars (for the case that rotation is not important), 3. black holes (for very massive stars). The neutron stars in case 2 should undertake a phase transition to SQM, thus produce fireballs of BRBs. Finally, the suggestion might be meaningful in laboratory physics.

**How can we distinguish this model from other models observationally?** According to Vietri-Stella model and our model, there is a supernova before a GRB. Hence, we can monitor some sampled regions with supernovae. There is possibility that a few of these samples can appear GRBs. As the remnants after GRBs in Vietri-Stella model are black holes, while those in our model are strange stars, we can differentiate these models by further observations. As strange stars can act as pulsars (Xu & Qiao 1998, Xu et al. 1999), we may find radio pulsars in GRB regions according to our model.

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