Gamma Ray Bursts and the transition to Quark Matter in Compact Stars

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We discuss a model for long Gamma-Ray-Bursts in which the central engine is associated with the conversion process of a metastable hadronic star into a star containing quark matter. We analyze also the observational signatures of the model, i.e. the Supernova-GRB temporal connection and the existence of long quiescent times in the temporal structure of Gamma-Ray-Bursts.

Several observations indicate that long Gamma Ray Bursts (GRBs) are connected to the final stage of massive stars. In a few cases a direct association between a Supernova and a GRB has been found but it has not yet been clarified if the two explosions are always simultaneous or if a time delay can exist, with the SN preceding the GRB.

In one of the most popular models, the Collapsar model [1], GRBs are generated by relativistic jets from massive helium stars whose cores have collapsed to a black hole and an accretion disk. In the Collapsar model the beaming of GRBs is naturally explained by the "funnel mechanism". The crucial ingredient of the model is a huge initial angular momentum of the star. One of the predictions of the Collapsar model is the SN-GRB connection with a short time delay (< 100 s) between the two explosions.

Here we discuss a quark deconfinement model [2,3] in which the energy source of the GRB emission is the process of conversion from a metastable, purely hadronic star into a more compact star in which deconfined quark matter is present. In our scenario, we assume a finite value of the surface tension between hadronic and quark matter. Therefore the hadronic star can become metastable and its mean-life time is related to the time needed to nucleate a drop of quark matter. The time delay between the birth of the hadronic star and the subsequent conversion into an hybrid or quark star corresponds to the delay between the SN explosion and the GRB. Temperature has no effect in our scheme because we assume that when quark matter forms the temperature is so low [4] that only quantum tunneling is a practicable mechanism [5]. The central density of a pure hadronic star can then increase, due to spin down or mass accretion, until its value

Hadronic Model	$B^{1/4}$ [MeV]	σ [MeV/fm^2]	$M_{cr}/M_\odot$	ΔE $\Delta=0$	ΔE Δ_1	ΔE Δ_2	ΔE Δ_3	ΔE Δ_4
GM3	170	10	1.12	18	52	57	86	178$^\bullet$
GM3	170	20	1.25	30	66	72	106	205$^\bullet$
GM3	170	30	1.33	34	75	81	120	221$^\bullet$
GM3	170	40	1.39	38	82	88	131	234$^\bullet$
GM3	180	10	1.47	BH	35	38	BH	–
GM3	180	20	1.50	BH	38	40	BH	–
GM3	180	30	1.52	BH	40	42	BH	–

Table 1
Energy released ΔE in the conversion to a hybrid or a quark star, for various sets of model parameters. M_{cr} is the gravitational mass of the hadronic star at which the transition takes place, for fixed values of the surface tension σ and of the mean life-time τ (here we have assumed $\tau = 1$ year).

approaches the deconfinement critical density. At this point a virtual drop of quark matter can form but its nucleation time can be extremely long.

By continuing mass accretion, the nucleation time can then be reduced from values of the order of the age of the universe down to a value of the order of days or years. We can therefore determine the critical mass M_{cr} of the metastable HS for which the nucleation time corresponds to a fixed small value (1 year in Tab. 1).

In Table 1 we show the value of M_{cr} for various sets of model parameters. In particular GM3 refers to the hadronic equation of state [6], $B^{1/4}$ is the value of the MIT bag constant which is included in the equation of state of quark matter and Δ_i are four different superconducting gaps of the Color-Flavor Locked (CFL) phase taken from Ref. [3]. In the conversion process from a metastable hadronic star into an hybrid or a quark star a huge amount of energy ΔE is released. We see in Table 1 that the formation of a CFL phase allows to obtain values for ΔE which can be much larger than the corresponding ΔE of the unpaired quark matter case ($\Delta = 0$).

In the model we are presenting, the GRB is due to the cooling of the justly formed hybrid or quark star via neutrino - antineutrino emission. The subsequent neutrino-antineutrino annihilation generates the GRB. As shown in Ref. [7], near the surface of a compact star, due to general relativity effects, the efficiency of the neutrino-antineutrino annihilation is strongly enhanced with respect to the Newtonian case. In our scenario the duration of the prompt emission of the GRB is therefore regulated by two mechanisms: 1) the time needed for the conversion of the hadronic star into a hybrid or quark star, once a critical-size droplet is formed and 2) the cooling time of the justly formed hybrid or quark star. Concerning the time needed for the conversion into quark matter of at least a fraction of the star, it is possible to show that the stellar conversion is a very fast process, having a duration much shorter than 1s [8]. On the other hand, the neutrino trapping time, which provides the cooling time of a compact star, is of the order of ~ 10 s [9], and it gives the typical duration of the GRB prompt emission in our model.

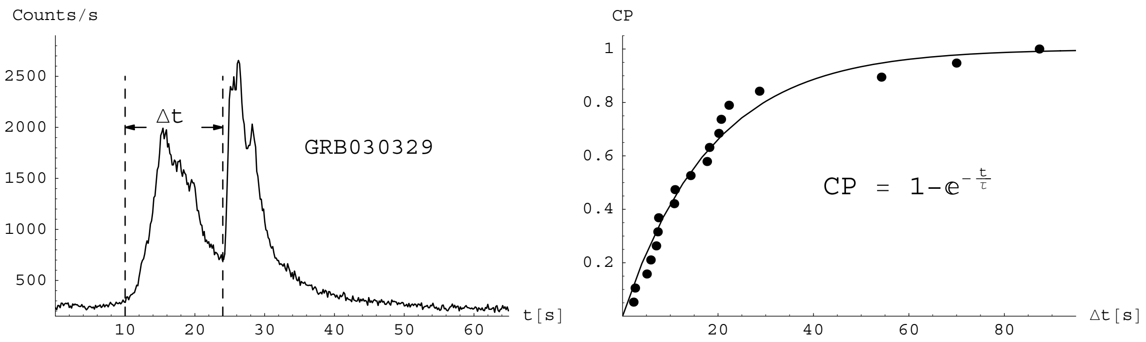

Figure 1. Left panel: Light curve of GRB030329 from HETE catalogue. The two active periods of the GRB are separated by a time interval $\Delta t \sim 14$ s. Right panel: cumulative probability of Δt from the GRBs of the HETE catalogue (dots) and the exponential cumulative distribution (solid line).

Temporal structure of GRBs

The time structure of long GRBs is usually very complex [1]. In the light curves it is in fact possible to distinguish several short pulses separated by time intervals lasting from fractions of second to several ten of seconds. From a statistical analysis performed by Nakar and Piran [12] it turns out that the distribution of intervals between the peaks of the light curves is well described by a log-normal distribution function up to delays of roughly three seconds while for longer intervals a noticeable deviation from the log-normal distribution is present. According to Nakar and Piran, such a deviation occurs because a different mechanism governs the high end tail of the distribution and it suggests that the long quiescent times reflect periods in which the “inner engine” of the GRB is not active, while the log-normal distribution correspond to delays having a stochastic origin.

In our model long periods of quiescence of the “inner engine” are possible. In the calculations presented in Table 1, we assumed a direct first order transition from hadronic matter to the CFL phase. Actually, recent results on the QCD phase diagram [13–16] suggest that the transition from hadronic to CFL phase can proceed in two steps, first with a transition from hadronic matter to a 2SC phase (or to unpaired quark matter, depending on the model parameters) and then from 2SC to CFL. In the scheme we are proposing, the first transition takes place due to the increase of the baryonic density (due to mass accretion), while the second transition is associated with the deleptonization (and the cooling) of the newly formed star containing the 2SC phase. These two transitions can both be first order [17] and therefore the newly formed hybrid or quark star containing 2SC quark matter can become metastable and then decay into a star containing CFL phase with a characteristic time delay which corresponds to the nucleation time of a drop

[1]In a sizable fraction of cases there is also evidence of a precursor activity before the GRB prompt emission, with time delays up to 200 s [10]. In Ref. [11] it has been speculated that the existence of precursors can help in shedding light on the inner engine.

of CFL phase inside the 2SC phase. In our model these time delays are connected with the time intervals Δt separating the active periods of long GRBs and therefore the delays Δt should follow an exponential distribution. Active periods correspond to emission periods during which the signal is about 4σ above the background [18]. It is important to notice that the first transition takes place when the central density of the star reaches a "critical" density, whose numerical value depends on the model parameters but, for a specific choice of the parameters value this density is determined to be in a very narrow range. From this viewpoint, the first transition acts as a "mass filter" and therefore the second transition takes place in a star which, in all bursts, has essentially always the same mass.

We tested our model performing a very simple statistical analysis on the small sample of GRBs detected by HETE. In the right panel of Fig.1, the cumulative distribution of Δt extracted from the analysis of the observations is shown together with an exponential distribution $1 - \exp(-t/\tau)$, with $\tau \sim 20$ s. It is clear that the theoretical distribution is compatible with the data (as it also results from the Kolmogorov-Smirnov test). Unfortunately the HETE catalogue contains only a very small number of GRBs, insufficient to reach a clear conclusion and therefore a statistical investigation based on the huge BATSE catalogue is now in progress.

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