

Gamma-Ray Bursts from Primordial Quark Objects in Space *

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Abstract

We investigate the possibility that gamma-ray bursts originate in a concentric spherical shell with a given average redshift and find that this is indeed compatible with the data from the third BATSE (3B) catalog. It is also shown that there is enough freedom in the choice of unknown burst properties to allow even for extremely large distances to the majority of bursts. Therefore, we speculate about an early, and very energetic, origin of bursts, and suggest that they come from phase transitions in massive objects of pure quark matter, left over from the Big Bang.

*To be published in the Proceedings of the Joint Meeting of the Networks 'The Fundamental Structure of Matter' and 'Tests of the Electroweak Symmetry Breaking', Ouranopolis, Greece, May 1997.

The bursts of intense gamma rays (GRB), first observed in the 1960s by the Vela military satellites designed to monitor breaches of the nuclear test ban treaty of 1963, but disclosed to the civilian research community only in 1973 [1], have confounded physicists and astronomers ever since. Although the outbursts must be very energetic, the actual value of the total energy depends on their distance from the earth. The time-span of the bursts lie between around 0.01 and 1000 seconds, and no characteristic features, such as spectral lines have been detected, with one exception. The burst named GRB970508 has been related to an object that appeared as an optical transient shortly after the burst, revealing clear spectral absorption lines. The absorbing body, which can be either a host-galaxy of the GRB, or an intervening foreground body, has been shown to have a redshift parameter $z \approx 0.835$. Hence the GRB source itself has $z \geq 0.835$. There is also some indirect evidence for an upper limit, $z \leq 2.3$ [2]. There are still no clues to whether this GRB is "average" in any sense, which means that detection of future optical GRB transients with spectral lines are certainly needed before a distance-scale can be confirmed. Only after such a scale has been determined, will it be possible to discriminate between the many dozen published theoretical models of the origin of bursts. It should be noted that all other efforts by authors of GRB publications to pinpoint an absolute distance to a particular GRB, or a well-chosen class of GRBs, are model-dependent, and therefore less reliable. Such estimates seem to cluster around z values of $1 \div 2$.

In the 1980s, the consensus among researchers was that the bursts originate within our own galaxy [3]. When the Burst and Transient Source Experiment (BATSE) [4], aboard the Compton Gamma Ray Observatory (CGRO), began to produce much more data it became evident that the gamma-ray bursts are distributed isotropically in the sky, not following the visible outlines of the Milky Way (nor of the Andromeda). The opinion among astrophysicists then swayed to models assuming a cosmological origin. A few thousand gamma-ray bursts have been detected to date, and there have been roughly as many different publications on the subject.

The most popular GRB model seems to be that they originate from the binary collapse of two very compact star remnants; neutron stars, black holes, or a combination thereof. Such models take it for granted that these events occur at random in all normal galaxies, typically once per a million years per galaxy. The rarity of such mergers would explain why none of the detected bursts has yet occurred close to a visible galaxy, and why there has been no repetition of events from the same locations. The low frequency is

also in line with estimates of the number of neutron stars in galaxies, and even the energy release seems to fit what would be expected if two neutron stars merge. If the GRBs are evenly distributed among galaxies, the bursts seem to release $10^{51} - 10^{53}$ erg of gamma rays.

Here we would like to test a completely different idea, namely that GRBs are not at all evenly distributed in space, with a universal frequency per galaxy, but instead strongly biased toward large distances, *i.e.*, the early Universe and high redshifts. Since very distant GRBs must be more energetic than in conventional models, we will also speculate about their origin, although we will leave the detailed work on a new model to a forthcoming publication [5].

Lacking an absolute distance-scale, it is, in fact, almost trivial to fit a distribution of GRB distances, with any chosen average distance, to the observations of gamma-ray fluxes. We will demonstrate how this works, with a simple choice of such a distribution.

We restrict ourselves to an Einstein-de Sitter universe with vanishing cosmological constant and global curvature. This choice seems, by comparison to observational data, to be a reasonably good approximation of the Universe. We also assume that the individual bursts can be treated as "standard candles", *i.e.*, that the characteristics of a typical ("average") burst stays the same during the full burst epoch.

Each burst is assumed to emit the radiation uniformly in all directions (*i.e.*, not in beams). Relaxing this condition would, of course, require more bursts, and a lower energy release per burst.

There seems to be no general agreement regarding possible time-dilation effects in GRB spectra, nor regarding an intrinsic duration-luminosity correlation (incompatible with the standard candle assumption), with strong bursts having shorter duration and *vice versa*. We simply ignore such (presumably weak) effects in the following analysis, and concentrate on the number/peak-flux relation.

Taking one or more of these complications into account would not change our general observation that a wide range of GRB space distributions can be fitted to the flux data.

The flux of a particular gamma-ray burst can, if the conditions mentioned above are satisfied, be given as a function of its redshift, z , [6]

$$P(z) = \frac{L(z)}{4\pi r(z)^2(1+z)^2}, \quad (1)$$

where $L(z)$ is the luminosity of the burst. The present distance to the source, $r(z)$, depends on the cosmological model. In our case (flat Einstein-de Sitter space), this relation reads

$$r(z) = \frac{2c}{H_0} \left(1 - \frac{1}{\sqrt{1+z}}\right), \quad (2)$$

where H_0 is the Hubble constant (taken as 75 km/s/Mpc).

The source luminosity detectable by an instrument near the earth, with an effective energy detection window between E_{min} and E_{max} , is given by

$$L(z) = \int_{E_{min}(1+z)}^{E_{max}(1+z)} \phi(E) dE, \quad (3)$$

where

$$\phi(E) = A_0 \frac{e^{-E/kT}}{E} \quad (4)$$

is the spectral form (thermal bremsstrahlung) conventionally chosen for modelling the burst [7, 8, 9]. kT is a characteristic energy for a typical burst, chosen to be 350 keV. For BATSE, $E_{min} = 50$ keV and $E_{max} = 300$ keV.

For simplicity, we assume that the number density, $\rho(r)$, of the bursts is a gaussian,

$$\rho = C \frac{1}{\sqrt{2\pi}\sigma} e^{-(r-r_0)^2/2\sigma^2}, \quad (5)$$

centred around $r_0 = r(z_0)$, and with variance σ . The normalising constant C is fitted to the data. A homogeneous distribution in Euclidean (fairly nearby) space, within a spherical shell with nothing outside, is also compatible with the BATSE data within observational errors, although such an abrupt cut-off seems unphysical. A smoothed-out version of such a distribution, or some completely different distribution altogether, could equally well be fitted to the data. For brevity, we only consider a gaussian distribution here.

In a given concentric spherical shell, there will be a differential number of bursts given by

$$n = 4\pi \rho r^2. \quad (6)$$

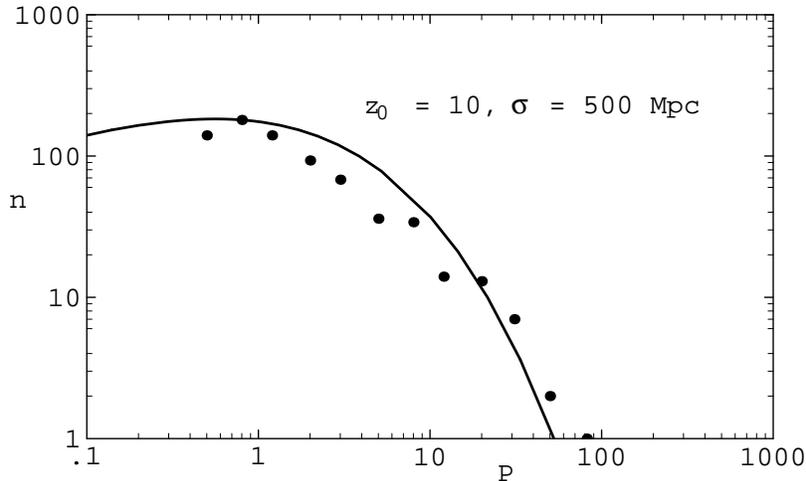


Figure 1: A generic example of the differential distribution of bursts (n), *versus* the peak flux of registered photons (P) computed in 256 ms time-intervals. The data points are from the BATSE 3B catalog, and the solid line is the fit using a normal distribution peaked at a redshift of $z_0 = 10$, with variance $\sigma = 500$ Mpc.

Equations (2) and (5) then directly give the parametric dependence, $n(z)$.

A typical fit to the BATSE data of $\log(n) - \log(P)$ is presented in Fig. 1, and the corresponding form of n as a function of z in Fig. 2. It is possible to fit the data reasonably well with any choice of z_0 , while σ would be derived by the fit (being smaller for higher z_0 value).

The data points are uncorrected for trigger efficiency, as such a correction would overestimate the true burst rate for fluxes near threshold (due to not including atmospheric scattering), while the data points with higher fluxes would be practically unchanged.

Suppose now that the bursts actually originate at redshifts that, in the mean, are considerably higher than the values $1 \div 2$, conventionally discussed. As can be seen from Fig. 3, standard GRBs would then release more than 10^{54} erg of energy (reaching, typically, 10^{59} erg at average redshifts of $z_0 = 1000$). We then have to consider mechanisms that would radiate considerably more energy than expected from, *e.g.*, neutron star mergers, and, in addition, would be connected to very young galaxies, or maybe even to the pregalactic era. It is tempting to speculate that the bursts are intimately related to the very creation of galaxies, or of the normal visible matter in

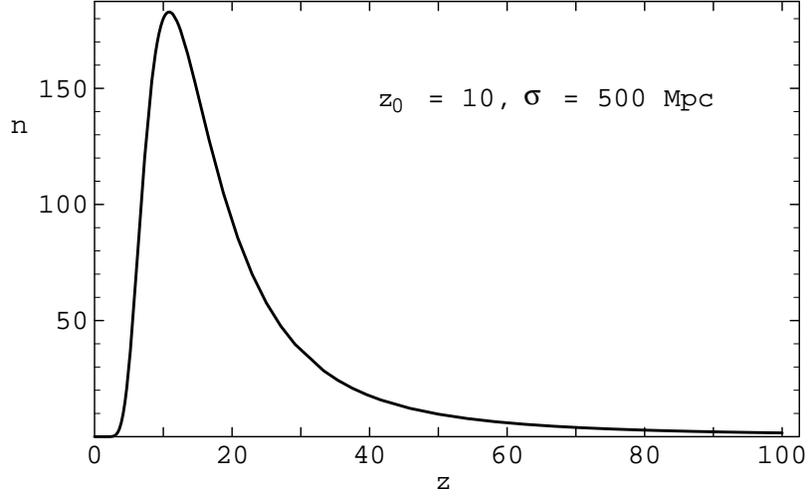


Figure 2: The differential number of gamma-ray bursts as a function of redshift in flat Einstein-de Sitter space for a gaussian distribution with the quoted values of z_0 and σ .

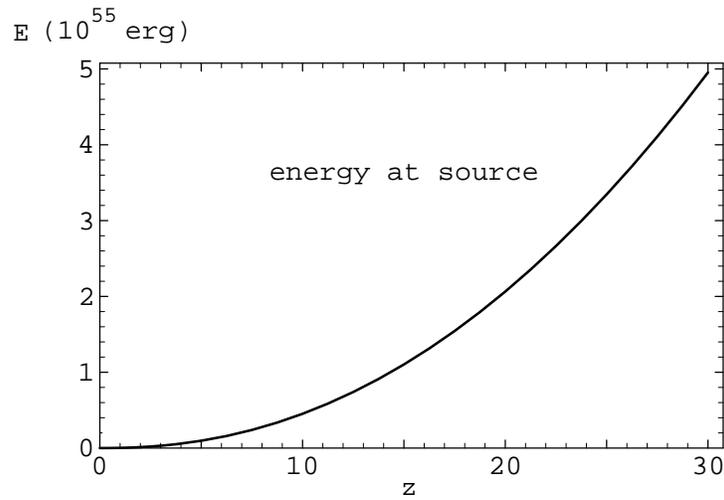


Figure 3: The total gamma-ray energy emitted by the source, given a flat Einstein-de Sitter space, and a typical detected energy flow of 10^{-5} erg/cm^2 . The Hubble constant, H_0 , is taken as 75 km/s/Mpc .

galaxies. Since GRBs most probably come, directly or indirectly, from detonations, we suggest that these detonations are *phase transitions* in large volumes of *quark matter* in the early Universe.

In the conventional Big Bang scenario, the phase transition from quark to normal nuclear matter took place at a very early stage, as either a huge detonation (second-order transition), or via a multitude of rapidly growing hadronic bubbles (first-order transition), once the global temperature fell below some critical value. All this occurred while the Universe was still one enormous quark-gluon plasma.

In 1984 Witten [10], as well as Fahri and Jaffe [11], suggested that quark matter might actually be the absolute ground state of matter also at low temperatures, and that chunks of such matter therefore could have escaped the overall hadronisation after the Big Bang. Eventually, these chunks could still be frequent enough to make up the celebrated cosmic dark matter.

Strangely enough, this simple dark-matter candidate has not gained the same popularity among astro- and particle physicists as the exotic ideas about neutralinos, axions, heavy neutrinos and the like, or the more down-to-earth brown dwarfs and "jupiters". Maybe this is due to some rather involved and model dependent counter arguments, like the one in [12], where it is claimed that abundant quark "nuggets" should have catalysed practically all neutron stars into quark stars, which, in turn, is claimed to be inconsistent with some observational data.

Consequently, most theoretical work on "quarks in space" now centres on the possible creation of quark matter out of normal matter in the cores of extremely dense objects, such as neutron stars, or collapsing supernovas. The engine for this phase transition would then be external gravitational pressure, which does not require the pure quark matter to be the absolute ground state of matter. Neither does it require any virgin quark matter that has escaped the universal phase transition. There is, in fact, a model built on the idea that the phase transition *from* normal matter *to* quark matter inside neutron stars is the true source of gamma-ray bursts [13]. An excellent review of the present understanding of quark matter inside neutron stars has been published recently by Glendenning [14].

Leaving the discussion of the dark-matter problem to a forthcoming work [5], we will now discuss the possibility that a phase transition inside leftover objects of pure quark matter is indeed the source of gamma-ray bursts.

Our two crucial assumptions are that

(i) quark matter represents the absolute ground state of "baryonic" matter (at least above a certain mass),

(ii) the early, and rapidly expanding, Universe split up into such quark-matter objects of different sizes *before* the hadronisation into normal matter.

Hence, we would like to "revive" the original idea by Witten, Fahri and Jaffe in a new version, combined with a suggestion of a new ordering of events after the Big Bang.

First, we note, however, that a sphere of pure quark matter (being the ground-state of matter or not) can be stable only if its radius is less than around 14 km. A heavier object would simply collapse into a black hole. Assume that the radius is R_{qm} , the density is ρ_{qm} and the mass is M_{qm} . The condition for collapse is then that the radius does not exceed the Schwarzschild radius, given by

$$r_s = 2M_{qm}G/c^2, \quad (7)$$

leading to a critical radius

$$R_c = \sqrt{\frac{3c^2}{8\pi\rho_{qm}G}}. \quad (8)$$

Setting $\rho_{qm} = \rho_{proton}$, where the proton is assumed to have a radius of 0.8 fm, we get $R_c \approx 14$ km and $M_c \approx 5M_{sun}$.

This means that the virgin quark-matter objects with $R_{qm} \geq 14$ km could not have survived for long. When their internal expansion did no longer match the overall expansion of the Universe, their cores must have collapsed into black holes, leaving the outer, and still expanding, layers relatively intact. The exact moment for the creation of the black hole is determined by the balance between the speed of light, the speed of sound (detonation wave) and the speed of internal expansion.

Naturally, also lighter objects might be unstable, and collapse after an initial expansion, followed by a slower gravitational contraction, in much the same way as the development of a heavy star into a supernova. We will analyse such a slower collapse in a forthcoming work [5], where the balance between gravitation and QCD forces will be considered.

The quark-matter layers close to the central black hole must, however, have experienced a sudden, enforced, drop of pressure and density, which should have triggered a phase transition to normal hadrons, running from inside out. (This is *not* equivalent to having the outermost layer of a quark-matter sphere facing an empty surrounding. An unlimited expansion outwards, and a phase transition running from outside in, is, in our model, prevented by gravity and strong quark forces, *i.e.*, confinement.)

If the original quark-matter object was big enough, it is likely that the phase transition, in the form of a central detonation, did not embrace the whole object. Rather, the outgoing particles (gammas, mesons,...), expected from the hadronisation, should have ripped the outer layers apart into smaller objects, before they had time to experience the right macroscopic conditions for a total phase transition. This is again similar to a supernova detonation, where the outermost parts are ripped apart by neutrinos, while the interior is pushed into a black hole or neutron star.

Such first-generation detonations most likely occurred too early to be of interest as an explanation of GRBs. The Universe was probably still too dense to let out those gamma rays in such a virgin shape that they can still be observed as pointlike events. Typically, an exploding object giving rise to the visible matter in a normal galaxy, say the Milky Way, would have radiated around 10^{64} erg of energy, assuming that hadronisation gives 100 MeV of excess energy per produced nucleon (give or take little-known beaming effects due to rotating plasmas, black-hole Kerr dynamics and the like, being the origin, or not, of disc-like galaxies). Assuming a spherical quark object, the inner part that hadronised should have had an original radius of around 40,000 km.

Nevertheless, each galaxy, or proto-galaxy, should have a surrounding cloud of stable quark-matter objects with radii less than 14 km (or whatever value a finer analysis will suggest). Would they indeed make up the dark matter, our galaxy would home at least 20 billion of them. Therefore, two such objects might merge at any time, say after a random collision, or after a slower spiralling within a binary quark-matter system. Would the new object become overcritical, the chain of events, with a central black hole and a detonating phase transition, would repeat. The maximal mass of such an object would then be twice the mass of a 14 km sphere, and the maximal release of excess energy would be around 10^{54} erg, under the idealised conditions that half of the mass goes into the black hole and the other half hadronises (radiating 100 MeV per final nucleon).

In this way, a galaxy continues to create its own nuclear matter through mergers of quark objects, giving off gamma-ray bursts. We believe that this process was more common in the distant past, when quark matter was more abundant, and when the merging of smaller proto-galaxies might have been an important mechanism for creating the galaxies we observe today. An obvious advantage of such a scenario is that we get gammas for free, without relying on rare neutrino annihilation processes, and subsequent interactions between charged particles and the intergalactic medium. Such processes

are often claimed to be too inefficient for producing the enormous energy outbreaks that are observed.

In conclusion, we have shown that the gamma-ray bursts might well come from very distant sources. We suggest that these sources are connected to phase transitions of big objects of pure quark matter into normal nuclear matter, taking place in young galaxies, during the merging of smaller proto-galaxies, or maybe even at the very moment of the creation of a whole galaxy. The phase transitions are triggered by black holes, formed when two quark-matter objects merge into an overcritical system, or inside an object that was overcritical all from the Big Bang. If so, the gamma-ray bursts are indeed the ultimate cosmic fireworks, announcing the birth of matter as we know it!

One of us (S.F.) would like to thank the organisers of this meeting for kind hospitality and for creating a most inspiring atmosphere. This project is supported by the European Commission under contract CHRX-CT94-0450, within the network "The Fundamental Structure of Matter".

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