Gamma-ray bursts as the birth-cries of black holes

Pankaj S. Joshi\textsuperscript{1}, Naresh K. Dadhich\textsuperscript{2} and Roy Maartens\textsuperscript{3}

\textsuperscript{1}Tata Institute of Fundamental Research, Mumbai 400 005, India
\textsuperscript{2}Inter-University Centre for Astronomy and Astrophysics, Ganeshkand, Pune 411 007, India
\textsuperscript{3}Relativity and Cosmology Group, School of Computer Science and Mathematics, Portsmouth University, Portsmouth PO1 2EG, Britain

The origin of cosmic gamma-ray bursts remains one of the most intriguing puzzles in astronomy. We suggest that purely general relativistic effects in the collapse of massive stars could account for these bursts. The late formation of closed trapped surfaces can occur naturally, allowing the escape of huge energy from curvature-generated fireballs, before these are hidden within a black hole.

Gamma-ray bursts (GRBs) are the fireworks display of the cosmos. They originate from super-high energy events ($10^{51} - 10^{54}$ ergs), probably in star-forming regions, and appear to be isotropically distributed and of cosmological origin\textsuperscript{[1]}. According to the fireball model\textsuperscript{[2]}, GRBs are produced in shocks (probably internal) in a relativistically expanding fireball. Causality restricts the progenitor size to $\lesssim 3000$ km (up to $10^{12}$ cm in the fireball frame).

Speculations on the origin of GRBs include the capture of neutron stars by black holes, the merger of binary neutron stars\textsuperscript{[3]} and the hypernova model\textsuperscript{[4]}. In both the latter models, an accretion torus or disc forms around a rotating black hole, with energy coming via a $10^{15}$ G magnetic field, or the gravitational binding energy of the torus. Challenges for these models include explaining the required stability of the torus, and the required low baryon loading.

Considering the extreme nature of the energetics and durations, and severe problems faced by almost all current models, we should be open-minded about the possible nature of the progenitor. We point out that gravitational collapse of a massive star, which has exhausted its nuclear fuel, offers a rather natural GRB mechanism. Our model is very much within the standard framework of general relativity, based on certain very fundamental aspects, and less speculative than some other proposals.

As stellar collapse progresses, gravity becomes so strong that closed trapped surfaces start developing within the interior of the star. These are surfaces from which both outgoing and ingoing wave fronts converge to the centre of the cloud, and no light escapes. The well-known singularity theorems then predict that a spacetime singularity must develop. These theorems, however, do not provide any information on the nature of such a singularity, its physical properties and its possible interaction with outside observers.

To address these questions, one needs to study the dynamics of collapse of matter clouds as governed by the Einstein equations. This has been done in considerable detail in the past decade or so\textsuperscript{[5]}, for type I matter fields, which include all physically reasonable observed matter. The generic conclusions emerging from these studies are most striking: \textit{while the collapse always produces diverging curvature and density, trapped surfaces may not develop early enough to shield the whole process from outside.}

To be specific, consider a spherically symmetric matter cloud. The interior is governed by Einstein’s equations, and the exterior is matched to Schwarzschild or Vaidya spacetime. The interior metric in comoving coordinates is

$$ds^2 = -c^2\nu(t,r)dt^2 + c^2\psi(t,r)dr^2 + R^2(t,r)d\Omega^2,$$

and the type I stress-energy tensor is

$$T^t_t = -\rho, \ T^r_r = p_r, \ T^\theta_\theta = T^\phi_\phi = p_\theta, \ T^t_r = T^r_t = 0,$$ \hspace{1cm}

where $\rho, p_r, \text{ and } p_\theta$ are the density, radial and tangential pressures.

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\textsuperscript{1}psj@tifr.res.in
\textsuperscript{2}nkd@iucaa.ernet.in
\textsuperscript{3}roy.maartens@port.ac.uk
Initial data are the $t = 0$ values of the three metric functions, the density and the pressures (see [6]). Integrating Einstein’s equations produces a free function $F(t,r)$, the total mass within the shell of comoving radius $r$ at epoch $t$. Most studies so far on gravitational collapse, involving dust, perfect fluids, self-similar collapse, and so on, are part of this general scenario, and form special subcases. As collapse proceeds, the mass-energy density grows without bound. The development of trapped surfaces can be traced explicitly via outgoing null geodesics, and the equation for the trapped surface or apparent horizon is given by

$$F = R(t,r).$$

Within a finite time $t = t_s$, general relativity predicts that the density and curvature scalars such as $R^{abcd}R_{abcd}$ diverge to infinity. However, at the Planck scale $10^{-33}$ cm, quantum gravity effects should take over, smearing out the classical singularity. Hence, based on our current theoretical understanding of gravity, we conclude that the end-product of collapse of a massive star will be a super-dense region with extremely high spacetime curvature and density—a curvature-generated fireball. The key question is: what is the possible interaction of this object with outside observers?

If the apparent horizon as governed by Eq. (1) starts developing earlier than the epoch of formation of the fireball, then the event horizon will fully cover the fireball, which will thus be hidden within a black hole. On the other hand, if trapped surfaces form later, then it is possible for the fireball to communicate with far-away observers (see Fig. 1). This means that the physical effects caused by the fireball, and those created within the immediately surrounding medium, will be able to propagate into the universe. While a fireball always develops in gravitational collapse, its communication properties depend on the nature of the (regular) initial data. The properties of the initial data determine whether the apparent horizon starts developing early enough to shield the fireball, or develops at or later than the fireball epoch.

![FIG. 1. Formation of black hole (left) versus a visible fireball (right) in gravitational collapse.](image)

To take a specific example, consider the collapse of a dust ball [7]. When the dust is homogeneous, the apparent horizon starts developing early enough, and the fireball is fully hidden within a black hole. Now consider inhomogeneous dust with a generic mass profile.
\[ F(r) = F_0 r^3 + F_1 r^5 + F_2 r^6 + \cdots , \]
and with a peak at the centre, where the density gradient is \( \rho_n = (n + 3)! F_n \), decreasing outwards (which would be a physically more realistic situation for any star). Then trapped surface development is delayed, and given by

\[ t_{ab}(r) = \frac{2}{3} F_0^{-1/2} - \frac{F_n r^n}{3 F_0^{3/2}} - \frac{2}{3} F_0 r^3. \]

Thus the fireball (where \( \rho \to \infty, \ R^{abcd}R_{abcd} \to \infty \)), together with its surrounding medium, is able to communicate with far-away observers.

This meets the necessary basic criteria of the fireball proposal [2]. GRBs are created by the shocks formed in the surrounding medium by the fireball. The important point is that we have a natural and robust mechanism for the creation of the fireball, within the standard and familiar framework of general relativity, without invoking additional or exotic mechanisms.

Our mechanism is dominated by classical astrophysical effects and does not rely on quantum particle production (see [8]), although this will enhance the process. Also, our conclusions do not depend on any specific equation of state. This allows for the surrounding medium to become radiation-dominated, which is expected, so that it expands relativistically (there are no static solutions available to confine such a fluid). This will again create relativistic expansion and shocks, which will generate the GRBs as in the currently available mechanisms.

The really crucial step is the creation of a relativistic fireball, and its communicability with far-away observers, which depends on the initial data parameters from which the collapse evolves. The advantage of such a model is that we do not really need to see the rays coming from the fireball itself, which need not be visible. The actual role of the fireball, which is an envelope with a Planck-size super-strong curvature core and surrounding medium, is to create shocks in the matter outside via its relativistic expansion, which in turn gives rise to GRBs, before the fireball disappears within the black hole forever. For the collapse scenario with general matter fields as considered above, it can be established rigorously that the fireball will disappear within a black hole eventually. This feature naturally accounts for finite-duration bursts. In this sense, we may describe GRBs as birth cries of black holes.

From a physical viewpoint, the essential difference from a black hole model for GRBs (which has many difficulties), is that in our case, regions of arbitrarily high curvature are visible to a distant observer, in principle. Physical processes, including quantum particle creation, in these high-curvature regions then cause the star to appear very different from a black hole, and generate GRBs. In the black hole model, the inner part of the star must necessarily form a black hole first, followed at later stages by the infall of outer regions into the black hole. The required energy for the burst is extracted during this infall, by a suitable mechanism. In our model, the collapsing star develops regions of very high curvature which are not hidden behind a horizon. The key point is that a ‘window’ becomes available for escape of matter and energy from the extremely strong gravity regions to far-away regions.

We have already emphasized that the conclusions on the development of the fireball remain invariant, independent of the form of the matter and equation of state used in collapse. One could also inquire about stability and non-spherical perturbations. There have been some studies on this [9], and the indications are that departures from spherical symmetry will not necessarily change these conclusions, and may in fact preserve them.

The duration of GRBs can also be explained naturally within our framework. The development of the fireball initiates just before \( t = t_s \). For a collapsing star of a few solar masses, the collapse time-scale will be a few milliseconds in the comoving frame. As soon as the fireball is created, it generates shocks in the surrounding medium, and because of the causal connection available, the rays proceed outwards, coming out at \( r = 2m + \delta \) at the boundary of the star, where \( \delta \) is a small positive quantity (assuming a Schwarzschild exterior). This is the beginning of the GRB for an outside observer. Very soon the fireball disappears within the black hole, and the later part of radiation starts coming from closer to the event horizon, eventually being infinitely redshifted. Thus the outside observer sees a GRB coming out, with a peak, and then a dying intensity.
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