

Gamma-Ray Bursts and Quantum Cosmic Censorship

T. P. Singh

Tata Institute of Fundamental Research

Homi Bhabha Road

Mumbai 400 005, INDIA

Abstract

Gamma-ray bursts are believed to result from the coalescence of binary neutron stars. However, the standard proposals for conversion of the gravitational energy to thermal energy have difficulties. We show that if the merger of the two neutron stars results in a naked singularity, instead of a black hole, the ensuing quantum particle creation can provide the requisite thermal energy in a straightforward way. The back-reaction of the created particles can avoid the formation of the naked singularity predicted by the classical theory. Hence cosmic censorship holds in the quantum theory, even if it were to be violated in classical general relativity.

Gamma-ray bursts (GRBs) are non-thermal bursts of low energy γ -rays. The detection of isotropy in their distribution by the BATSE detector on COMPTON-GRO, together with the recent detection of afterglows following some bursts, strongly supports their cosmological origin. A burst takes place about once every million years in a galaxy, and an energy of about $10^{51} - 10^{52}$ ergs is released in every burst, making GRBs the most luminous objects in the Universe. Causality requirements restrict the size of the initial source that triggers a burst to about 10^7 cm. The time profile of a burst is very intricate, and there is great diversity in the temporal structure of bursts. It is hence a fascinating challenge for theoretical astrophysicists to construct a model which can correctly explain these observations.

The deposition of such a large amount of energy by the progenitor inside a small volume gives rise to photon energy densities which result in an optically thick, thermal, γe^\pm fireball. Such a compact energy deposition results in a highly relativistic expansion, and a Γ factor of $100 - 1000$ can be achieved. This is the standard fireball model, which to a good degree is independent of the nature of the progenitor. The expanding fireball becomes optically thin at a later stage, and the kinetic energy of expansion is converted into the observed non-thermal γ -ray photons by a dissipative mechanism like shocks. These could be external shocks, resulting from the interaction of the outflow with an external medium like the ISM, or internal shocks which take place in the outflow itself. It has recently been argued [1] that the external shock model is not viable, as these shocks cannot produce the complex, irregular temporal structure. The shocks, if assumed to be internal, carry information about the progenitor of the burst.

The most attractive model for the progenitor is the coalescence of binary neutron stars, which can release an energy of the order of 10^{53} ergs. Observations of pulsars suggest that such neutron star mergers take place about once every million years in a galaxy, which is in remarkable agreement with the observed GRB rate. However, a key problem with the neutron star merger model is: how is the gravitational energy available from the merger

converted into a fireball? Two solutions have been proposed. The first is that some of the energy released as neutrinos is reconverted, by the collision of these neutrinos, into e^+e^- pairs, or into photons. However, simulations suggest that this process is inefficient [2] and hence unlikely. The second solution is that strong magnetic fields ($\sim 10^{15}$ Gauss) convert the rotational energy of the system into a relativistic outflow. Though this solution cannot be ruled out, it remains an open issue as to how such large magnetic fields could be generated.

While considering the above two options for energy generation, one tacitly assumes that the merger of two neutron stars eventually leads to the formation of a black hole. The purpose of the present essay is to propose an alternative mechanism for energy generation from the merger, by questioning the assumption that the merger results in a black hole. It is customary in astrophysics to assume that continual gravitational collapse results in black hole formation. However, it is known to general relativists that this depends very crucially on the cosmic censorship hypothesis being valid. The hypothesis states that generic singularities resulting from gravitational collapse are hidden behind horizons and are not naked. As we explain below, a naked singularity has observational properties that are extremely different from those of a black hole.

In this essay, we assume that the coalescence of the two neutron stars results in the formation of a naked singularity, and not a black hole. We then show that such an assumption can successfully solve the energy generation problem in a natural manner. Striking evidence that the merger might actually result in a naked singularity comes from a recent work [3], where it is found that the ratio of the angular momentum to mass can be greater than one for the collapsed object. As is well known, in this range the collapse results in a naked singularity, and not a Kerr black hole. While we cannot rule out the possibility that the system can still lose enough angular momentum (say via gravitational radiation) before the completion of collapse, we find it quite attractive to consider the implications for a GRB if a naked singularity were indeed to form.

Before considering these implications we would like to make contact with what is known

about naked singularities in classical general relativity. Till today, the cosmic censorship hypothesis remains unproven. However, a few examples of naked singularity formation have been found over the last few years, in general relativistic studies of gravitational collapse. Most of these examples have been found in studies of spherical collapse using equations of state corresponding to dust, perfect and imperfect fluids [4]. It is typically found that for a given equation of state, both black-hole and naked singularity solutions result, depending on the choice of initial data. But perhaps the most striking evidence for censorship violation comes from studies of spherical collapse of a massless scalar field [5]. It has been found that regions of arbitrarily high curvature resulting in collapse are visible from infinity. While the actual naked singularity in this model is non-generic, regions of unbounded curvature (i.e. the black holes of arbitrarily small mass) result from generic initial data. The small mass black holes violate the spirit of cosmic censorship, because one can see as close to the singularity as one desires.

It is only fair to say at this stage that the censorship hypothesis has not been disproved, because the examples studied so far involve one or the other special form of matter. Nonetheless, the very fact that some examples have been discovered is sufficient cause for enquiring if there are any known astrophysical phenomena which can be modelled after naked singularities. Moreover, even if the censorship hypothesis were to be disproved some day, naked singularities will remain abstract curiosities unless some observational evidence is found in their favour. After all, black holes themselves became acceptable only after excellent evidence in their favour was found in systems like X-ray binaries and the centres of galaxies.

What will a naked singularity look like to an observer who is watching the collapse from far away? There is good theoretical evidence that even when a singularity forming in collapse is naked, the outgoing light rays starting from the singularity are infinitely redshifted. Similarly, even if regions of unbounded high curvature are in principle visible, like in Choptuik's study, light leaving these regions will be extremely redshifted. Naked singularities are thus effectively black, making them indistinguishable from black holes, so long as only classical processes are considered.

However, quantum effects will be of fundamental importance prior to the onset of a naked singularity. This is so even before the quantum gravitational regime is approached, because the development of high spacetime curvatures will give rise to intense quantum particle creation. The nature of this particle creation in a naked singular spacetime is fundamentally different from the Hawking radiation that accompanies a quantum black hole, and this difference serves to distinguish a naked singularity from a black hole, observationally. We explain this using an example developed in [6], where quantum effects were studied in the naked singular spacetime resulting from spherical null dust collapse. It is found that the outgoing flux of quantum radiation diverges on the Cauchy horizon, as seen by a far away observer. (This is in spite of the infinite classical redshift referred to above). Most of the quantum particle creation takes place during a very short period prior to the formation of the Cauchy horizon. Similar features have been observed in other studies [7] [8], and these features are expected to be generic to naked singularities.

Thus, a quantum naked singularity is a burst like phenomenon, unlike the black hole which evaporates slowly because of the Hawking radiation. Further, the divergence of the stress tensor on the Cauchy horizon represents a quantum blue shift instability, and strongly suggests that back-reaction will avoid formation of the naked singularity. Hence, even if censorship is violated in classical general relativity, it will hold in quantum theory - this is the quantum cosmic censorship [7] alluded to in the title.

We see that a quantum naked singularity bears resemblance to a gamma-ray burst. If the neutron star merger results in a naked singularity, quantum particle creation can convert a good fraction of the original infalling material into outgoing radiation. In fact, for every solar mass of matter, the equivalent energy is $M_{sun}c^2 \approx 10^{54}$ ergs, which will be available via quantum pair production. Besides, photons and neutrinos will be produced with equal probability, hence the required energy deposit will be available as electromagnetic radiation. This offers a natural solution to the energy conversion problem. While a good deal of work will have to be done to test the naked singularity - GRB model, it is an avenue that appears worth pursuing further (see also [9]).

The coalescing binary neutron star system is an excellent testing laboratory for the cosmic censorship hypothesis. If the merger results in a naked singularity, the gravitational wave signal will be significantly different from what would be seen by LIGO and VIRGO if a black hole forms. The gravity wave emission from a naked singularity will be much more copious and long lasting, because now regions of very high curvature will participate in producing the waves. If gamma-ray bursts indeed result from the formation of a naked singularity at the end of the merger, they are also ideal testing grounds for the quantum gravitational effects that become important in the approach to a naked singularity. These bursts are perhaps the only system nature has offered us in which candidate quantum gravity theories like string theory and quantum general relativity can be tested experimentally.

I acknowledge partial support of the *Junta Nacional de Investigação Científica e Tecnológica* (JNICT) Portugal, under contract number CERN/S/FAE/1172/97.

References

- [1] R. Sari and T. Piran, *Ap. J.* 485 (1997) 270.
- [2] M. Ruffert, H.-Th. Janka, K. Takahashi and G. Schafer, *A&A* 319 (1997) 122.
- [3] T. W. Baumgart and S. L. Shapiro, *astro-ph/9801294*.
- [4] for a review, see e.g. T. P. Singh, *gr-qc/9606016*.
- [5] M. Choptuik, *Phys. Rev. Lett.* 70 (1993) 9.
- [6] W. A. Hiscock, L. G. Williams and D. M. Eardley, *Phys. Rev. D* 26 (1982) 751.
- [7] C. Vaz and L. Witten, *Nucl. Phys.* B487 (1997) 409.
- [8] L. H. Ford and L. Parker, *Phys. Rev. D* 17 (1978) 1485; S. Barve, T. P. Singh, C. Vaz and L. Witten, *gr-qc/9802035*.
- [9] E. Witten in *Quantum gravity and beyond* Eds. F. Mansouri and J. J. Sciano (1992); S. K. Chakrabarti and P. S. Joshi, *Int. J. Mod. Phys. D* 3 (1994) 647.