Population Synthesis of the GRB Progenitors and their Brightness and Redshift Distribution

I. Panchenko[1]

Department of Physics, Moscow State University, Moscow, Russia

Sternberg Astronomical Institute, Moscow, Russia

Abstract.
We estimate the relativistic binaries merger rate and redshift distribution population synthesis of an ensemble of evolving close binaries. Results of such simulations definitely depend on the cosmic star formation rate history, which is different in galaxies of different types. This leads to a difference in merger rate in spiral and elliptical galaxies, which in principle can be an observational test for GRB models. Also a fit of BATSE long bursts $\log N$-$\log P$ is performed, showing that only a wide $(2-3$ orders of magnitude) luminosity function provides a good fit.

1. Introduction

For many years the binary relativistic star merger remains one of the most valuable models of gamma ray bursts (Blinnikov et al, 1984, Paczyński , 1991). Some recent alternative models, involving a collapse of massive rotating star (Paczyński , 1998), possibly easier fit the energy requirements for GRB, and are in nice agreement with the discoveries of GRB optical counterparts in actively star forming galaxies (Bloom et al, 1998).

Nevertheless, the old merger model is not excluded, as the observed binary radiopulsars display the examples of definite merger precursors.

This paper is devoted to the studies of close binary evolution which leads to the mergers of binary neutron star and black hole systems (NS+NS and NS+BH) which are suspected to be able to produce a GRB.

The collapsar GRB and the merger GRB can have similar physical mechanisms for energy extraction (Lee, 1999) and production of radiation (Piran, 1999, Usov, 1999). Nevertheless, they can be discriminated by evolutionary considerations.

2. The model of evolution

We use the "Scenario Machine", initiated by Kornilov and Lipunov (1995), and later developed by Lipunov et al (1996), as a stellar evolution engine. The basic

[1]ivan@sai.msu.su

evolution model is similar to one of Vanbeveren et al (1998), which are the best to reproduce the galactic population of massive binaries.

During the evolution of a binary its orbital separation changes in various modes of mass and angular momentum transfer. The most dramatic change of the orbit takes place during a supernova explosion, or a collapse into a black hole. It is usually supposed that a newly formed compact object obtains a kick velocity due to some asymmetry in the collapse. To explain the observed velocities of radio pulsars, one should assume the kick velocity to be of the order of $200 - 600$ km/s (Lyne, Lorimer, 1994).

As the observations suffer from many selection effects, the exact shape of the distribution is not precisely known. So we perform the calculations for several values of the kick velocity, in the range from 0 to 600 km/s, to show the influence of this parameter on the results.

3. The event age distribution

The life of the merging system consists of two important phases: first, the nuclear powered evolution of the normal stars, and second, the gravity wave powered orbit shrinking phase. The characteristic time scale of the first phase occupies the range from $3 \cdot 10^6$ years for the most massive stars to $\sim 10^8$years for the least massive stars being able to produce a neutron star. The gravitational inspiral time is determined by the parameters of the orbit after the formation of second compact object, and can be much greater than nuclear lifetime, being on average of the order of a billion years.

The age of a merging binary is a sum of the nuclear lifetime and the gravitational inspiral duration, The distribution of the ages of merging binaries is a direct output of the population synthesis procedure. Another sense of this distribution is the merger rate time history after a simultaneous (δ-like) star formation. It is shown in fig.1 for both NS+NS and NS+BH mergers.

The merger age distribution shows a power-law behavior with a slope ≈ -1. For NS+NS mergers, there is a strong dependency of the sharpness of the age distribution on the kick velocity. High kicks make the mergers on average younger. Without a kick, there are no mergers with ages less than 10^8 years.

For NS+BH mergers, the presence of a kick velocity is very important: without a kick, all the binaries are very wide and have very long inspiral times, usually greater than the Hubble time.

The power law distribution has a “heavy tail”: though a half of the mergers take place before several hundred million years after the star formation, there is also a significant part of mergers that take part after billions of years.

4. The distribution of merger redshifts

The distribution of merger redshifts can be obtained by a convolution of the star formation rate history and the merger age distribution. The present knowledge of the star formation rate (SFR) history is based on the works of Madau (1996). Earlier (Jørgensen et al, 1995) we assumed a simple two-parametric model of

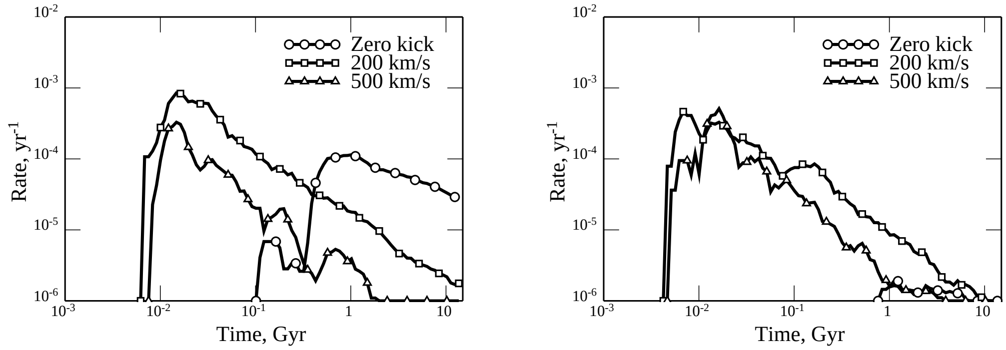

Figure 1. The binary merger age distribution. Shown as the event rate after a simultaneous formation of a typical galaxy ($10^{11} M_\odot$). Left: NS+NS, Right: NS+BH.

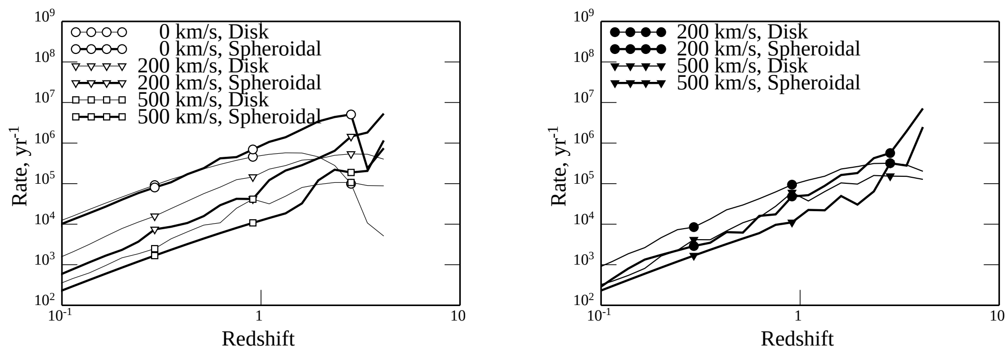

Figure 2. The merger redshift distributions (rate per unit z). Left: NS+NS; Right: NS+BH.

SFR, containing an initial star formation burst (where ϵ of all the stars were formed) at $z \sim 5$, and a subsequent constant SFR.

In this work we base on the Madau observational SFR, but still introduce an initial star formation burst, which should be responsible for the formation of the elliptical galaxies and spheroidal components of the spiral galaxies. Then, according to Fukugita et al (1998), the value of ϵ should be $\sim 2/3$. The adopted cosmological model was ($H_0 = 75$ km/s/Mpc, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$).

The obtained NS+NS and NS+BH merger redshift distributions are displayed in fig. 2 for spiral and elliptical galaxies (Madau and burst-like SFR, respectively) and different values of mean kick velocity.

Obviously, these event redshift distributions are different for spirals and ellipticals. This allows to propose a new observational test for the GRB progenitor. If we detect a GRB in an elliptical galaxy, it should be most likely a NS+NS and NS+BH merger and not a collapsar, because the population of the ellipticals is very old and does not contain massive normal stars.

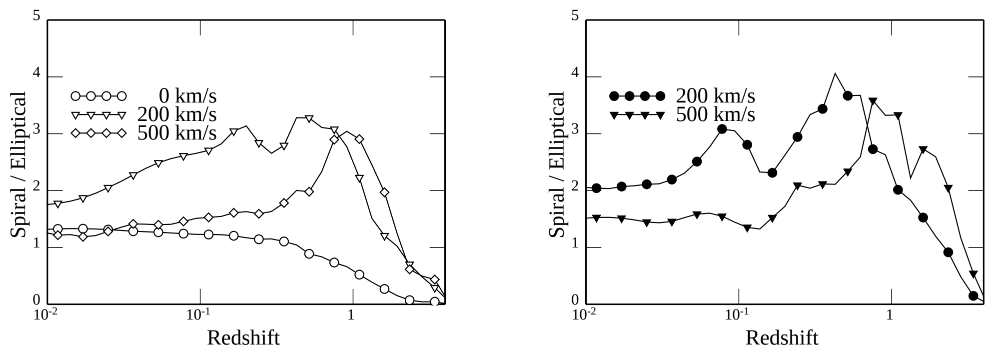

Figure 3. The evolution of the ratio of merger rates in spiral and elliptical galaxies. Left: NS+NS; Right: NS+BH.

Thus, future identifications of GRB host galaxies can solve the collapsar/merger dilemma.

5. The GRB brightness distribution – $\log N$-$\log P$

Another implication of the merger age distributions is an attempt to construct a GRB brightness distribution ($\log N$-$\log P$). This is done by a classic procedure (Weinberg, 1972) on the basis of the redshift distribution (fig. 2) and a luminosity function. Observations do not evidence directly for the spread of the GRB intrinsic luminosities, though some techniques allow to estimate it roughly (Petrosian, 1999). We assumed a power-law luminosity function characterized by the slope and range.

For comparison with the observations, we have chosen the long ($T_{90} > 1.5$s) and relatively bright (> 1 photon/cm^2) bursts from 4th BATSE GRB catalog (Meegan et al, 1998). Realistic GRB spectra were taken to estimate the spectral K-correction (Oke, Sandage, 1968).

The best fits are displayed in fig. 4. The $\log N$-$\log P$ distribution is shown in a differential form multiplied by $P^{5/2}$ in order to outline the difference from the euclidean case, in which the distribution should look as a horizontal line.

No acceptable fit can be obtained if luminosity spread is less than 2 orders of magnitude. In the best fit, the luminosity function spread is ≈ 2.5 orders of magnitude, and the most distant observed GRB are at redshift ≈ 4.5.

6. Conclusions

The computer simulations of the evolution of the possible GRB progenitors provide useful information which facilitates interpretation of the GRB statistics. In the present paper, we would like to outline two main conclusions:

A new interesting method which can help to determine the nature of GRB progenitors is the determination of the ratio of the rates of bursts in spiral and elliptical hosts. For GRB produced by mergers, the rate in ellipticals should be

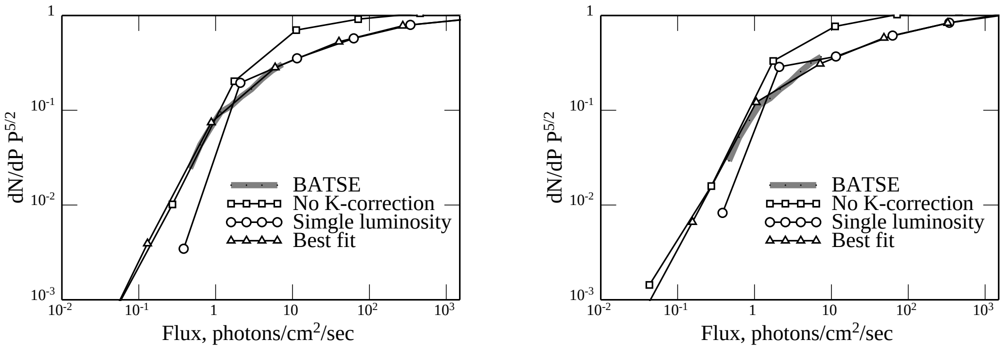

Figure 4. The best fits of the BATSE long bursts $\log N$-$\log P$. Left: NS+NS; Right: NS+BH. Triangles: The best fit. Circles: Without a luminosity spread. Boxes: Without the spectral K-correction. Thick line represents the BATSE observations.

only several times less than one in spirals, and increase with the redshift. For the massive collapsar GRB it is practically impossible to occur in an elliptical galaxy.

The analysis of the observed BATSE $\log N$-$\log P$ distribution with taking into account the evolutionary effects shows that the the spread of GRB intrinsic luminosity function can not be less than two orders of magnitude.

Acknowledgments. Author is grateful to the conference organizers, Dr Roland Svensson and Dr Juri Poutannen for their hospitality. This work was performed under supported of the INTAS project No. 96-0315, the "Universities of Russia" project No. 5559 and RFBR grant No. 98-02-16801.

References

Blinnikov, S.I., Novikov, I.D., Perevodchikova, T.V., Polnarev, A.G., 1984, PAZh, 10, 422; Sov. Astronomy Let., 10, 177

Bloom, J.S., Djorgovski, S.G., Kulkarni, S.R., Frail, D.A., 1998, ApJ, 507, 25

Fukugita, M., Hogan, C.J., Peebles, P.J.E., 1998, ApJ, 501, 518

Jørgensen , H.E., Lipunov, V.M., Postnov, K.A., Prokhorov, M.E., Panchenko, I.E., 1995, ApJ, 454, 593

Kornilov, V.G., Lipunov, V.M., 1983, AZh, 60, 574

Lee, 1999, this volume

Lipunov, V.M., Postnov, K.A., Prokhorov, M.E., 1996, A&A, 310, 489

Lyne, A.G., Lorimer, D.R., 1994, Nature, 369, 127

Madau, P. et al, 1996, MNRAS, 283, 1388

Meegan, C.A. et al, 1998 In: Gamma-Ray Bursts : 4th Huntsville Symposium, Edited by Charles A. Meegan, Robert D. Preece, and Thomas M. Koshut. Woodbury, New York : American Institute of Physics (AIP conference proceedings ; 428), 3

Oke, J.B. Sandage, A., 1968, ApJ, 154, 21
Paczyński , B., 1991, Acta Astr., 41, 257
Paczyński , B., 1998, ApJ, 494, L45
Petrosian, V., 1999, this volume
Usov, V.V., 1999, this volume
Vanbeveren, D., et al 1998, New Astronomy, 3, 443
Weinberg, S., 1972 Gravitation and cosmology. Whiley & Sons, NY