Long Gamma-Ray Bursts and the Morphology of their Host Galaxies

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We present the results of population syntheses for binary stars carried out using the “Scenario Machine” code with the aim of analyzing events that may result in long gamma-ray bursts. We show that the observed distribution of morphological types of the host galaxies of long gamma-ray bursts can be explained in a model in which long gamma-ray bursts result from the core collapse of massive Wolf-Rayet stars in close binaries. The dependence of the burst rate on galaxy type is associated with an increase in the rate of stellar-wind mass-loss with increasing stellar metallicity. The separation of binary components at the end of their evolution increases with the stellar-wind rate, resulting in a reduction of the number of binaries that produce gamma-bursts.

1 Introduction

Although cosmic gamma-ray bursts (GRBs) have been studied for four decades, the origin of this phenomenon is far from fully understood. At present, according to observational limitations, gamma-ray bursts are subdivided into short GRBs (durations less than $\approx 2$ s) and long GRBs (durations more than $\approx 2$ s). This likely reflects different natures of the precursors of the two types of GRBs [1].

Long GRBs, are probably associated with the core collapse of massive Wolf-Rayet stars in close binaries, accompanied by the formation of accretion disks around black holes [2]. These events may be associated with the formation of spinars [3, 4]. There exist two possible reasons for fast rotation of the presupernova core: acceleration of the rotation of the core of an evolving star if its angular momentum is conserved, or the presence of a close companion to the presupernova – a Wolf-Rayet star [2]. The second option seems more appropriate, since the rotation of the cores of massive stars most likely decelerates in the course of evolution [5, 6], while binary orbital motion enables fast rotation of the presupernova due to to tidal synchronization of its rotation [7, 8].

Below we will consider Kerr black holes, which we define as objects with effective Kerr parameters $a$ satisfying the condition

$$a = \frac{I\Omega}{GM_{BH}^2/c} \geq 1,$$

where $I$ is the black holes moment of inertia, $\Omega$ the angular frequency of its rotation, $M_{BH}$ its mass, $G$ the gravitational constant, and $c$ the velocity of light. This condition for the Kerr parameter is necessary for the formation of a massive accretion disk or a spinar, if a strong enough magnetic field is present. It is clear that (1) does not describe any real black hole, but provides a characteristic of the angular momentum of both the non-degenerate presupernova and the nascent black hole. In the absence of accurate estimates of the masses of collapsing cores and the fractions of the stellar mass falling inside the event horizon during the formation of black holes, we assume that the orbital period of a binary prior to the supernova explosion must be less than $\approx 1 - 3$ day [7, 8].

Sokolov et al. [9] published observations of host
galaxies of long GRBs obtained with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. They discovered that long GRBs occur in galaxies with very intense star formation and significant internal absorption, and with luminosities not exceeding the luminosity of the Milky Way.

Observational data on host galaxies of long GRBs and Type Ic supernovae (SN Ic) obtained with the Hubble Space Telescope are provided in [10]. It was assumed that SN Ic and long GRBs should occur in similar environments. However, the observational data show that this is not the case. First, core collapse supernovae (such as SN Ic) are located in blue regions of their host galaxies, while long GRBs are located in the brightest regions of the galaxies. Second, most long GRBs occur in dwarf irregular galaxies, while SN Ic happen in both dwarf irregulars and giant spirals [10, Fig. 1]. Only one of 42 long GRBs occurred in a giant spiral galaxy, with the others occurring in dwarf irregular galaxies; if the redshift of the host galaxies is restricted to 1.2, one in 18 long GRBs occurred in giant spirals.

The Galactic rates of events resulting in rotational collapse accompanied by the formation of rapidly spinning relativistic objects were analyzed in [11], where it was concluded that these rates are sufficient to explain the cosmic rate of observed GRBs. The aim of the present paper is to show that the observed correlation between host-galaxy and the rate of long GRBs can be explained in a model in which long GRBs result from core collapse in Wolf-Rayet stars in close binaries.

It is known that stellarmetallicity has a very strong effect on the stellar wind, and that the metallicity of galaxies grows with their mass and age. One example of a population-synthesis study of the effect of metallicity on stellar wind is [12], and a recent empirical study of the metallicities of star-forming galaxies can be found in [13] (see also, e.g., [14]).

In the first half of the 1990s, radio observations were made of the pulsar J0045-7319 in the Small Magellanic Cloud, which is in a close binary with a B1 main-sequence star [15]. The estimated mass-loss rate by the optical star does not exceed $10^{-10} M_\odot/yr$, two orders of magnitude lower than for stars in the Milky Way (see, e.g., [16]).

For our analysis, we introduce a luminous-mass limit separating low- and high-metallicity galaxies (in our model, galaxies with “strong” and “weak” stellar winds). This limit corresponds approximately to the observational data of [13][14]. Following [17] we assume a mass function for the galaxies (see, e.g., also [18][19])

$$\frac{dN}{d\log M} \approx \text{const}, \quad 10^5 M_\odot \leq M \leq 10^{11} M_\odot, \quad (2)$$

where $M$ is the mass of luminous matter in the galaxy and $N$ the number of galaxies.

In addition, we introduce a maximum mass for galaxies that can host long GRBs. Since the most massive galaxies usually have the highest metallicities, and hence the strongest stellar winds, the two components may be too far apart at the time of the supernova explosion to satisfy condition (1). For obvious reasons [see (2)], the input to the total rate of events calculated using this mass function will be the highest for the most massive galaxies in the range given above. Therefore, adopting an upper limit for the masses of galaxies that can host long GRBs can substantially affect the results.

2 Population synthesis

We used the “Scenario Machine” for our population synthesis, synthesizing $10^6$ binaries for each set of initial parameters.

Since the “Scenario Machine” has been described many times in previous publications, we will only note here the most important parameter for our study, which especially affects the results of numerical modeling of the objects under investigation. A detailed description of the “Scenario Machine” can be found in [20][21].

This critical parameter is the stellar wind, which strongly influences the semi-major axis of the binary orbit. We used the following stellar-wind models, which differ in the amount of matter lost by a massive star in the course of its evolution:

- **Wind model 1.** This model corresponds to scenario A in [11][21]. The amount of matter lost via the wind is small. The total fractional mass loss in the main-sequence, supergiant, and Wolf-Rayet stages does not exceed 30% of the initial stellar mass.
Figure 1: Dependence of the Galactic rate of core collapses of Wolf-Rayet stars in close binaries accompanied by the formation of black holes with large orbital angular momenta on the orbital period at the time of the supernova. Curve 1 is computed for stellar-wind model 1, curve 2 for stellar-wind model 2, and curve 3 for stellar-wind model 3.

- **Wind model 2.** This model corresponds approximately to scenario C in [11, 21], except that the star loses 70% of its envelope mass in each evolutionary stage.

- **Wind model 3.** This model corresponds to scenario C in [11, 21]. The star loses its entire envelope in each evolutionary stage. This means that, at the end of the evolution, the total mass loss can be more than half the initial mass of the star.

The assumed minimum initial mass of stars producing black holes is $25M_\odot$.

### Results

Figure 1 shows the dependence of the Galactic rate of core collapses of Wolf-Rayet stars in close binaries accompanied by the formation of black holes with large orbital angular momenta on the orbital period at the time of the supernova. Curves 1, 2, 3 were computed for stellar-wind models 1, 2, 3, respectively. The plot shows that this rate in close binaries (with orbital periods $P < 10$ day) varies very strongly with the mass outflow rate in

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3 If a star in the course of its evolution accretes mass from a companion, such that its final mass exceeds its initial mass, we consider the maximum mass of the star after the completion of accretion.
the course of the evolution of the normal star.

Figure 2 shows the ratio of the rates of GRBs in different types of galaxies computed using the galaxy mass function [see (2)]. This plot shows that, within the existing uncertainties in the observed relative rates of long GRBs and mass-loss scenarios by non-degenerate stars, the observed correlation of host galaxy morphology with the rate of long GRBs can be explained if long GRBs are produced in close binaries. If stellar-wind model 3 is assumed for strong stellar winds in giant spiral galaxies, this becomes true automatically, since the minimum orbital period of a binary in which collapse of a WolfRayet star can occur is then about 3.5 day, condition 4 is not fulfilled, and all long GRBs occur in dwarf irregular galaxies. If stellar-wind model 2 is adopted for strong winds and model 1 for weak winds, the ratio of GRB rates depends on the boundary between the dwarf and giant galaxies ($a$) and the upper limit for the mass of the host galaxies of long GRBs ($b$). If we assume that the latter is approximately 10% of the mass of the Milky Way and $a \approx 5 \cdot 10^9 M_\odot$ our model for long GRBs fits the observational data well, with enough leeway to allow for uncertainty in the critical orbital period for producing long GRBs. If $b/a$ (for the wind combination we just considered), a model in which long GRBs are products of the evolution of the closest binaries cannot explain the observed fractions of long GRBs in different types of host galaxies.

Thus, we conclude that the theoretical model for long GRBs proposed in (7, 8), fits the observations within current uncertainties in the observational data and theoretical models.

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