The Influence of the Initial Mass Function on Populations of X-ray Binaries After a Burst of Star Formation

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In this article we use "Scenario Machine" - the population synthesis simulator- to calculate the evolution of the populations of the selected types of X-ray sources after the starformation burst with the total mass in binaries $1.5 \cdot 10^6 M_\odot$ during the first 20 Myr after the burst. Sources of the four types were calculated: transient sources- accreting neutron stars with Be- stars; accreting neutron stars in pair with supergiants; Cyg X-1-like sources- black holes with supergiants; superaccreting black holes. We used two values of the $\alpha$ - coefficient in the mass-function: 2.35 (Salpeter’s function) and 1.01 ("flat spectrum"). The calculations were made for two values of the upper limit of the mass-function: 120 and 30 $M_\odot$. For the flat spectrum the number of sources of all types significantly increased. Decreasing of the upper mass limit below the critical mass of a black hole formation increase (for the "flat spectrum") the number of transient sources with neutron stars up to $\approx 300$. We give approximating formulae for the time dependence of source numbers.
1 Introduction

From the point of view of stellar evolution, objects undergoing bursts of star formation are of special interest. One example of such objects are Wolf-Rayet galaxies [1]. Considering the only evolution of single stars, Contini et al. [2] suggested that some observational properties of the galaxy Mrk 712 could be understood if the initial mass function were substantially different from the standard value. Specifically, they proposed a “flat” mass spectrum with index $\alpha = 1$ in place of a Salpeter mass spectrum with index $\alpha = 2.35$, with an upper mass limit of $120 M_\odot$. Later, Schaerer [3], also studying the evolution only of single stars, showed that the observations can also be explained using a Salpeter initial mass function.

In [4], we investigated a burst of star formation under the conditions at the center of the Galaxy, and showed that massive X-ray binary systems are sometimes better indicators of the presence and age of starbursts than the optical properties of populations of single stars (color indices, etc.). One of our goals here is to draw attentionof population-synthesis specialists to the necessity of taking into account the possible effects of synthesis parameters on the evolution of populations of binary stars. We consider the evolution of binary systems after burst of star formation with two initial mass functions and two upper mass limits.

2 The Model

Our “Scenario Machine” population synthesis simulator was first described in [5], and recently, a detailed description was given in the review [6] (see also [4]). Therefore, here, we will only make note of the parameters used in the calculations.

We considered two power-law initial mass functions, with indices $\alpha = 2.35$ and $1.01$.

$$\frac{dN}{dM} \propto M^{-\alpha} \quad (1)$$

We calculated $10^7$ binary systems in each run of the program. The lower mass limit for the more massive component was taken to be $0.1 M_\odot$ in the normalization and $10 M_\odot$ in the computations. Less massive stars do not evolve sufficiently over a time $< 2 \cdot 10^7$ years to produce neutron stars and black holes (unless their mass is appreciably increased by accretion). The results were normalized to a total mass of binary stars in the starburst of $1.5 \cdot 10^6 M_\odot$. We present here calculations for upper mass limits of $120 M_\odot$ and $30 M_\odot$. We chose the rather exotic upper mass limit of $30 M_\odot$ for the following reasons. In population synthesis modeling, usually two parameters are varied – the slope and upper mass limit of the initial mass function (see [11], where, in fact, an
upper limit of $30 M_\odot$ is used). We chose our smaller value for the upper mass limit to be less than the critical mass for the formation of a black hole so that it would be possible to study this situation. We took the relative mass distribution for the binary components to be flat, i.e., systems with components with similar and with very different masses were equally probable.

We took the major axes of the systems to be in the interval from $10$ to $10^7 R_\odot$, with a logarithmically uniform distribution. The magnetic fields of neutron stars were assumed not to decay; this is natural, given the relatively short evolution period investigated (see [10] for a discussion of the field decay). A black hole was formed when the mass of the pre-supernova star was more than $35 M_\odot$, 70% of the initial mass became part of the black hole. The Oppenheimer-Volkov limit was chosen to be $2.5 M_\odot$. We did not use the “enhanced” mass loss rate proposed by the Geneva group (see, for example, [3,9]). We will take this possibility into account in future papers.

In anisotropic supernovae explosions, the compact object (neutron star or black hole) acquired an additional velocity. These velocities had random directions and a distribution of amplitudes corresponding to that observed for radiopulsars [7], with a characteristic value of 200 km/s (see [8] for a discussion of our choice of a lower characteristic velocity than proposed in [7]).

3 Results

We present our results for four types of sources: (1) X-ray transients associated with neutron star – Be star systems; (2) accreting neutron star – supergiant systems (one of the types of binary systems that give birth to X-ray pulsars); (3) systems with a black hole accreting at a rate above the Eddington limit (SS 433 may be such an object); and (4) accreting black hole – supergiant systems (one example of this type of objects is Cyg X-1).

The calculated evolution of the number of sources for the two values of the initial mass function index are presented in Figs.1 (upper mass limit $30 M_\odot$) and 2 ((upper mass limit $120 M_\odot$). We have not smoothed the curves, and their “noisiness” is due to statistical fluctuations (we calculated $10^7$ binary systems for each mass interval and then normalized the results). X-ray transients were the most numerous type of source because of the long lifetimes of these systems at this stage (the figures show the observable number of systems at each time). It stands to reason that we have no information about whether a transient is in an active stage at any given moment in time.

When the upper mass limit is lowered, the number of sources with black holes decreases and the number with neutron stars increases. As we decrease the upper mass limit below the critical mass for the formation of black holes, sources with black holes may not disappear entirely, since they can form if the masses of neutron stars are increased to the Oppenheimer-Volkov limit by accretion. This is most likely when the accretion is supercritical (and depends
on the assumptions about the supercritical accretion stage), as was clear from our calculations. For this reason, the number of sources such as SS 433 rose with time when the upper mass limit was $30M_\odot$, rather than undergoing the sharp decrease observed for the upper mass limit of $120M_\odot$, when the vast majority of black holes are formed from massive stars in the first 3-4 million years after the starburst. Systems such as Cyg X-1 are not shown for the upper mass limit of $30M_\odot$, since not a single system of this type formed over the calculation time.

We present approximation formulas for the convenience in determining the number of various types of sources formed in starbursts with arbitrary masses. In these expressions, the time $t$ is in million of years. In the case of a Salpeter ($\alpha = 2.35$) initial mass function with an upper limit $M_{up} = 120M_\odot$, we find for X-ray transients at times from 5 to 20 million years after the starburst

$$N(t) = -0.14 \cdot t^2 + 5.47 \cdot t - 14.64. \quad (2)$$

For superaccreting black holes at times from 4 to 20 million years

$$N(t) = \frac{2.2}{t - 3.05}. \quad (3)$$

For sources such as Cyg X-1, we have at times from 4 to 20 million years

$$N(t) = \frac{4.63}{t - 2.9}. \quad (4)$$

We find for binary systems consisting of an accreting neutron star and a supergiant at times from 5 to 20 million years

$$N(t) = 2.12 \cdot 10^{-4} \cdot t^3 - 9.6 \cdot 10^{-3} \cdot t^2 + 0.13 \cdot t - 0.47. \quad (5)$$

For a flat initial mass function with an upper mass limit $M_{up} = 120M_\odot$, we obtain for X-ray transients at times from 3 to 7 million years

$$N(t) = -8.9 \cdot t^2 + 1.2 \cdot 10^2 \cdot t - 3 \cdot 10^2, \quad (6)$$

and at times from 7 to 20 million years

$$N(t) = -2.8 \cdot t + 1.2 \cdot 10^2. \quad (7)$$

For superaccreting black holes at times from 4 to 20 million years, we have

$$N(t) = \frac{39.97}{t - 3.17}. \quad (8)$$

For sources such as Cyg X-1 at times from 4 to 20 million years,

$$N(t) = \frac{58.44}{t - 3.08}. \quad (9)$$
Finally, for accreting neutron star - supergiant binaries, we find for times from 5 to 20 million years

\[ N(t) = 1.45 \cdot 10^{-3} \cdot t^3 - 5.96 \cdot 10^{-2} \cdot t^2 + 0.74 \cdot t - 2.41. \]  \hspace{1cm} (10)

4 Conclusion

In [4], we showed that the absolute and relative number of massive binary systems with black holes and neutron stars can serve as a good indicator of the age of a burst of star formation. Here, we considered the evolution of four populations of close binary systems with neutron stars or black holes after a starburst with a total mass of $1.5 \cdot 10^6 M_\odot$ in binary systems for the cases of Salpeter ($\alpha=2.35$) and flat ($\alpha=1.01$) initial mass functions, following the evolution for $2 \cdot 10^7$ years after the starburst. We included the exotic upper mass limit of $30 M_\odot$ in our study in order to model populations with a strongly reduced number of black holes (note that this situation could also come about in the presence of a strong stellar wind associated with a high mass loss rate).

The transition to the initial mass function index $\alpha = 1.01$ proposed in [2] leads to a significant increase in the number of X-ray sources. We expect the number of single accreting neutron stars and black holes, and also the number of other binary systems, to increase as well, but we have not considered these objects here.

Lowering the upper mass limit below the critical mass for the formation of black holes leads to the virtually complete disappearance of sources with black holes, but increases the number of transient sources with neutron stars (this increase is especially strong for a flat initial mass function, to $\approx 300$ neutron star systems). Thus, this change of the initial mass spectrum brings about a substantial change in the luminosity of the galaxy at standard and hard X-ray energies. In other words, a burst of star formation with a flat initial mass function should be accompanied by a large X-ray flux. The absence of a large X-ray luminosity suggests that the initial mass spectrum for the given starburst was not flat.

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