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POPULATION SYNTHESIS OF X-RAY SOURCES AT THE GALACTIC CENTER

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ABSTRACT

We are exploring the evolution of massive binary star populations for a nuclear starburst occurring in the conditions similar to the Milky Way Galaxy, in its central part, on a timescale of 10 Myr. A computer code is applied allowing for computing, by using Monte Carlo simulations, the evolution of a large ensemble of binary systems, with proper accounting for spin evolution of magnetized neutron stars (NSs). Our results include a number of X-ray transients (each consisting of a NS plus main-sequence star), superaccreting black holes (BHs), and binaries consisting of a BH plus a supergiant, all as functions of time.

We find that by 7 Myr after such a starburst one expects ≈ 1 X-ray source with a BH (Cyg X-1 type), ≈ 1 SS 433–like source (BH in the regime of superaccretion), and ≈ 37 transient sources with a NS, all to be within the central 1 kpc or so. An interesting result that can be considered a specific starburst feature is that the ratio of the number of systems like SS 433 to the number of X-ray transients is about 1:100, compared with 1:1000 characteristic of the average ratio in the Galactic field. The ratio of the total number of X-ray sources containing a BH (of Cyg X-1 plus SS 433 types) to the number of X-ray transients with NSs turns out to be a sensitive function of the age of the starburst, and its computed value ≈ 0.04 is consistent with observations.

Subject headings: Galaxy: center — stars: evolution — stars: formation — stars: neutron — stars: statistics — X-rays: stars

1. INTRODUCTION

Since IRS 7 at the Galactic center was identified as a luminous red supergiant (Lebofsky, Rieke, & Tokunaga 1982), a lasting debate has been initiated as to whether the nucleus of the Milky Way had experienced a recent star formation episode. For more than a decade, many arguments both *pro* and *contra* have been accumulated. One of the strongest arguments for the presence of a young stellar population was the finding of luminous He I/H I emission-line stars both in IRS 16 (Hall, Kleinmann, & Scoville 1982) and in the central stellar cluster (Krabbe et al. 1991). The spectroscopic study of the AF star, one of the most remarkable representatives of these stars, came up with the conclusion that they are probably related to luminous, blue supergiants in a short-lived phase of intense mass loss (Najarro et al. 1994). However, Morris (1993) proposed that the interpretation of the He I/H I emission-line stars in terms of young, massive stars is not the only possibility. The finding of a very high stellar density in the central star cluster (Eckart et al. 1993) is seemingly consistent with the other interpretations: the He I/H I stars either could be 10 $M_\odot$ black holes (BHs) that have collided with giants (Morris 1993) or could result from collisions and mergers of less massive stars in the cluster (for discussion of these possibilities, see Genzel, Hollenbach, & Townes 1994).

Until recently, these conflicting arguments have remained insufficient to resolve the issue. Ozernoy, Titarchuk, & Ramaty (1993) suggested a new approach by showing that the 10 keV gas in the central 200 pc of the Galaxy (Koyama et al. 1989) could be produced by multiple supernova explosions. Such supernovae, if sequential, might be associated with a starburst whose parameters are a scaled-down version of those of starburst galaxies (Ozernoy 1994a). Related evidence was suggested by Sofue (1994) using the North Polar Spur data; it remains to be seen, however, whether this spur is associated with the Galactic center rather than being a local feature. Tamblyn & Rieke (1993) and Schaerer (1994) proposed starburst models that would be able to account for a young stellar population at the Galactic center, although the origin of some peculiar hot stars still remains to be explained (Tamblyn et al. 1996). A recent finding of a possible W-R star at a projected distance of 0.5 pc (Blum, Sellgren, & DePoy 1995) seems to be one of the still missing links to massive stars produced during the starburst.

The purpose of this paper is to explore some of the consequences of the putative starburst at the Galactic center by elaborating on the population synthesis model for the late evolutionary stages of massive binary stars created in the starburst, with emphasis on X-ray source statistics. As is known, X-ray observations of the Galactic center have revealed a number of energetic X-ray sources located in the innermost regions of the Galaxy (Pavlinsky, Grebenev, & Sunyaev 1994; Churasov et al. 1994), with a part of them being attributed, by their spectral characteristics, to BH candidates. These observations demonstrate a substantially enhanced spatial density, compared with the average Galactic value, of X-ray binary systems in the central region of the Galaxy. In this paper, we show that such a situation can be a natural consequence of binary stellar evolution if a starburst occurred a few million years ago at the Galactic center. We apply Monte Carlo simulations to the evolution

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of a large ensemble of binary systems, with proper accounting for the spin evolution of magnetized compact stars (Lipunov 1992; Lipunov et al. 1994). This method has been shown to be a powerful tool for studying different products of stellar evolution both in spiral and elliptical galaxies under a wide range of initial conditions and star formation histories (see, e.g., Kornilov & Lipunov 1984; Lipunov & Postnov 1987; Lipunov et al. 1994 and references therein).

In this paper, we will focus on the most prominent representatives, from the observational point of view, of the late stages of massive binary evolution, such as X-ray transients (a neutron star [NS] in a highly eccentric orbit around a main-sequence star, like A0535+26), superaccreting BHs (observationally seen as SS 433 if in pair with a Roche lobe filling secondary component), and BH plus supergiant binaries (like Cyg X-1, with an evolved supergiant underfilling its Roche lobe). Different kinds of binary pulsars that appear after a star formation burst were considered previously (Lipunov, Postnov, & Prokhorov 1995). Here we calculate the numbers of the corresponding X-ray sources and discuss their spatial distribution. We include in our study only massive X-ray systems because, during the first 10 Myr, only massive stars ($M > 15$–$20\ M_\odot$) can leave the main sequence.

2. MODEL

The Monte Carlo method for statistical simulation of binary evolution was originally proposed by Kornilov & Lipunov (1983a, b) for massive binaries and developed later by Lipunov & Postnov (1987) for low-mass binaries. Dewey & Cordes (1987) applied an analogous method for analysis of radio pulsar statistics, and de Kool (1992), using the Monte Carlo method, investigated the formation of the galactic cataclysmic variables. Recently, Leitherer & Heckman (1995) have modeled star formation for elliptical and spiral galaxies, taking into consideration only the single stars.

Monte Carlo simulations of binary star evolution allows one to investigate the evolution of a large ensemble of binaries and to estimate the number of binaries at different evolutionary stages. Inevitable simplifications in the analytical description of the binary evolution, which we allow in our extensive numerical calculations, make those numbers approximate to a factor of 2–3. However, the inaccuracy of direct calculations giving the numbers of different binary types in the Galaxy (see, e.g., Iben & Tutukov 1984; Meurs & van den Heuvel 1989; van den Heuvel 1994) seems to be comparable to what follows from the simplifications in the binary evolution treatment. Moreover, no rotational evolution of magnetized compact stars has been properly considered in those papers.

In our analysis of binary evolution, we use the "scenario machine," a computer code that incorporates all current scenarios of binary evolution (for a review see van den Heuvel 1994) and takes into account the influence of the magnetic field of compact objects on their observational appearance. A detailed description of the computational techniques and input assumptions is summarized elsewhere (Lipunov, Postnov, & Prokhorov 1996a); here we list only principal parameters and initial distributions.

We trace the evolution of binary systems during the first 10 Myr after their formation in a starburst. Obviously, only massive enough stars (with masses ≥ 8–$10\ M_\odot$) can evolve off the main sequence during a time as short as this to yield compact remnants (NSs and BHs). Therefore, we consider only massive binaries, i.e., those having the mass of the primary (more massive) component in the range of 10–120 $M_\odot$.

2.1. *Initial Binary Parameters*

To start the calculations, we choose the distributions of initial binary parameters. They are the mass of the primary zero-age main-sequence (ZAMS) component M_1, the binary mass ratio $q = M_2/M_1 < 1$, and the orbital separation a. Initial eccentricity is assumed to be zero.

The distribution in orbital separations is taken as deduced from observations (Abt 1983):

$$f(\log a) = \text{const},\ \max\,[10\ R_\odot,\ \text{Roche lobe}\ (M_1)] < \log a < 10^4\ R_\odot\ . \quad (1)$$

As for the mass ratio distribution in binaries, the observational information is poor. Meanwhile, from the evolutionary point of view, the differences in the initial masses of the components are particularly important (see, e.g., Trimble 1983). A customary "zero assumption" is that the mass ratio distribution has a flat shape, i.e., the binaries with a high mass ratio occur as frequently as those with equal masses. Since one cannot reliably establish such a distribution directly from observations (due to a number of selection effects), we have parameterized it by a power law, assuming the primary mass distribution to obey the Salpeter mass function:

$$f(M_1) \propto M_1^{-2.35}\ , \quad 10\ M_\odot < M_1 < 120\ M_\odot\ ,$$
$$f(q) \propto q^{\alpha_q}\ , \quad q \equiv M_2/M_1 < 1\ . \quad (2)$$

A comparison of the observed X-ray source statistics with the predictions of the current evolutionary scenarios shows (Lipunov et al. 1996a) that the initial mass ratio should be strongly centered around unity, so that we assume $\alpha_q = 2$ in the present calculations.

2.2. *Initial Parameters of Compact Stars*

Since we only deal with initially massive binary systems (their primary mass is higher than 10 $M_\odot$), which are capable of evolving off the main sequence during less than 10^7 yr, the compact stars left behind stellar evolution are (in the case of the most massive stars) NSs and BHs.

We assume that a NS with a mass of 1.4 $M_\odot$ is formed as the result of the collapse of a star whose core mass prior to collapse was $M_* \sim 2.5$–$35\ M_\odot$. This corresponds to an initial mass range ~ 10–$60\ M_\odot$, taking into account that a massive star can lose more than $\sim 10\%$–20% of its initial mass during the evolution with a strong stellar wind (de Jager 1980).

We also take into account that the collapse of a massive star into a NS can be asymmetrical, so that an additional kick velocity, v_{kick}, presumably randomly oriented in space, should be imparted to the newborn NS. In the present calculations, the kick velocity was taken to be 75 km s^{-1} (for a more detailed study of kick velocity distributions see Lipunov, Postnov, & Prokhorov 1996b).

The magnetic field of a rotating NS largely defines the evolutionary stage the star would have in a binary system (Schwartzman 1970; Davidson & Ostriker 1973; Illarionov & Sunyaev 1975). Because of this, in our calculations we use a general classification scheme for magnetized objects elaborated by Lipunov (1992).

Briefly, the evolutionary stage that a rotating magnetized NS has in a binary system depends on the star's spin period P (or spin frequency $\omega = 2\pi/P$), its magnetic field strength B (or, equivalently, magnetic dipole moment $\mu = BR^3$, where R is the NS radius), and the physical parameters of the surrounding plasma (such as density ρ and sound velocity v_s) supplied by the secondary star. This secondary star, in turn, could be a normal optical main-sequence star or red giant (or another compact star). In terms of Lipunov's formalism, the NS evolutionary stage is determined by one or another inequality between the following characteristic radii: the light cylinder radius of the NS, $R_l = c/\omega$ (where c is the speed of light); the corotation radius, $R_c = (GM/\omega^2)^{1/3}$; the gravitational capture radius, $R_G = 2GM/v^2$ (where G is the Newtonian gravitational constant and v is the NS velocity relative to the surrounding plasma); and the stopping radius, $R_{\rm stop}$. That radius is a characteristic distance at which the ram pressure of the accreting matter matches either the NS magnetosphere pressure (this radius is called the Alfvén radius, R_A) or the pressure of relativistic particles ejected by the rotating magnetized NS (this radius is called the Schwartzman radius, $R_{\rm Sch}$). For instance, if $R_l > R_G$, then the NS is at the ejector stage (E-stage) and can be observed as a radio pulsar; if $R_c < R_A < R_G$, then the so-called propeller regime is established and the matter is expelled by the rotating magnetosphere; if $R_A < R_c < R_G$, we deal with an accreting NS (A-stage), etc. These inequalities can easily be translated into relationships between the spin period P and some critical period that depends on μ, the orbital parameters, and the accretion rate $\dot{M}$ (which relates v, v_s, ρ, and the binary's major semiaxis a via the continuity equation). Thus, the evolution of a NS in a binary system is essentially reduced to the NS spin evolution $\omega(t)$, which, in turn, is determined by the evolution of the secondary component and the orbital separation $a(t)$. Typically, a single NS embedded into the interstellar medium evolves like $E \rightarrow P \rightarrow A$ (for details, see Lipunov & Popov 1995). For a NS belonging to a binary, the evolution becomes complicated as the secondary star evolves: for example, $E \rightarrow P \rightarrow A \rightarrow E$ (recycling), etc.

When the secondary component in a binary overfills its Roche lobe, the rate of accretion onto the compact star can be high enough to reach the Eddington luminosity $L_{\rm Edd} \simeq 10^{38}(M/M_\odot)$ ergs s^{-1} at the $R_{\rm stop}$; then a supercritical regime sets in (it is worth noting that not only superaccretors but superpropellers and superejectors can exist as well; see Lipunov 1992).

If a BH is formed in due course of the evolution, it can only appear as an accreting or superaccreting X-ray source; other very interesting stages such as a BH plus radio pulsar, which may constitute a rather large fraction of all binary pulsars after a starburst, are considered in Lipunov et al. (1995).

The distribution of the newborn NSs in the initial magnetic dipole moment is taken to be

$$f(\log \mu) = \text{const}\,, \quad 10^{28} \le \mu \le 10^{32}\ \text{G cm}^3\,, \tag{3}$$

and the initial rotational period of the NS is assumed to be 1 ms.

It is not clear yet whether the NS magnetic field decays or not (for a comprehensive review, see Chanmugam 1992). Below, we assume that the magnetic fields of NSs decay exponentially on a timescale of 10^8 yr. A radio pulsar is assumed to be turned "on" until its period P has reached a "death-line" value, $P_{\rm death}$, defined from the relation $\mu_{30}/P^2_{\rm death} = 0.4$, where μ_{30} is the dipole magnetic moment in units of 10^{30} G cm^3 and $P_{\rm death}$ is taken in seconds.

The mass limit for a NS (the Oppenheimer-Volkoff limit) is taken to be $M_{\rm OV} = 2.5\ M_\odot$, which corresponds to a hard equation of state of the NS matter. The most massive stars are assumed to collapse into a BH once their mass before the collapse is $M > M_{\rm cr} = 35\ M_\odot$ (which would correspond to an initial mass of the ZAMS star as high as $\sim 60\ M_\odot$ since a substantial mass loss due to a strong stellar wind occurs for the most massive stars). The BH mass is calculated as $M_{\rm bh} = k_{\rm bh} M_{\rm cr}$, where the parameter $k_{\rm bh}$ is taken to be 0.3, as follows from the studies of binaries NS + BH (Lipunov et al. 1994).

2.3. *Other Parameters of the Evolutionary Scenario*

We consider stars with a constant (solar) chemical composition. The process of mass transfer between the binary components is treated, when appropriate, as a conservative one, i.e., the total angular momentum of the binary system is considered to be constant. The nonconservativeness of the mass transfer is treated via an "isotropic reemission" mode (Bhattacharya & van den Heuvel 1991). If the rate of accretion from one star to another is sufficiently high (e.g., the mass transfer occurs on a timescale a few times shorter than the thermal Kelvin-Helmholz time for the normal companion) or the compact object is engulfed by a giant companion, the common envelope (CE) stage of the binary evolution can set in (see Paczyński 1976; van den Heuvel 1983).

During the CE stage, an effective spiral-in of the binary components occurs. This complicated process is not fully understood yet, so we use the conventional energy consideration to find the binary system characteristics after the CE stage by introducing a parameter $\alpha_{\rm CE}$ that measures what fraction of the system's orbital energy goes, between the beginning and the end of the spiraling-in process, into the binding energy (gravitational minus thermal) of the ejected common envelope. Thus,

$$\alpha_{\rm CE}\left(\frac{GM_a M_c}{2a_f} - \frac{GM_a M_d}{2a_i}\right) = \frac{GM_d(M_d - M_c)}{R_d}\,, \tag{4}$$

where M_c is the mass of the core of the mass-losing star of initial mass M_d and radius R_d (which is simply a function of the initial separation a_i and the initial mass ratio M_a/M_d), and no substantial mass growth for the accretor is assumed (see, however, Chevalier 1993). The less $\alpha_{\rm CE}$, the closer becomes the binary after the CE stage. In the present calculations, we take $\alpha_{\rm CE} = 0.5$.

Other cases of nonconservative evolution (e.g., evolutionary stages with a strong stellar wind or those where the loss of the binary angular momentum occurs due to gravitational radiation or magnetic stellar wind) are treated using the well-known prescriptions (see, e.g., Verbunt & Zwaan 1981; Rappaport, Joss, & Webbink 1982; Lipunov & Postnov 1987).

2.4. *Parameters of the Starburst*

We assume that an instantaneous starburst occurred in the region of the Galactic center, with half of the stars (in number) being formed in binaries. The total mass of the stars formed during the starburst was taken to be $\sim 4 \times 10^5$ $M_\odot$, as indicated by the Tamblyn & Rieke (1993) analysis.

As for the size of the region that experienced the starburst, its particular value is of no importance for evaluating the numbers of various systems, and we address this issue in § 3.2 while discussing the spatial distribution of massive systems after the starburst.

In order to obtain statistically significant results, the evolution of 300,000 binary systems was computed. Then we normalized the figures so as to be in agreement with the Tamblyn & Rieke (1993) calculations of the number of massive OB stars (1900 stars with $M > 10\ M_\odot$) that survived $\sim$6–8 Myr after the starburst onset (this age is supported below by an additional argument). In fact, the number of stars in IRS 16 estimated by Tamblyn & Rieke (1993) is uncertain within a factor of 2, but this is actually of no importance as long as we only use relative numbers of different X-ray source species.

3. RESULTS

3.1. *Number of Accreting X-Ray Binaries of Selected Types*

The numbers of three types of compact binaries containing accreting NSs and BHs, which are most interesting from the point of view of their observational appearances, have been calculated as a function of time: (1) the X-ray transient source containing a NS in an eccentric orbit around a main-sequence Be star (the observed prototype: A0535+26), (2) the BH accreting at a highly supercritical rate from the Roche lobe filling component (the assumed prototype: SS 433), and (3) the BH accreting from the stellar wind of an OB supergiant (the observed prototype: Cyg X-1). The evolution of the selected types of X-ray binaries during the first 10 Myr after the starburst onset is presented in Figure 1.

Figure 1*a* shows the number of X-ray transient sources consisting of a NS in an eccentric orbit around a massive secondary that acquired enough angular momentum during the first mass exchange to become a rapidly rotating Be star. This occurs for the binaries whose components have comparable initial masses and are not too distantly separated to avoid the CE stage formation during the first mass exchange (the last condition is always satisfied for the massive binaries at the Galactic center). To become an X-ray transient, the NS must accrete matter from the secondary Be star, at least during the periastron passages. Since the duration of the accretion depends upon the orbital eccentricity, rotational period, and magnetic field of the NS, not all the transients are in the accretion stage at the same time, therefore the observed number of these sources can be a few times less compared with Figure 1*a*. Figure 1*b* shows the evolution of X-ray binaries with a BH, like Cyg X-1. The number of such sources depends strongly on time, giving ≈ 1 source by $t = 7$ Myr. The evolution of a superaccreting BH of SS 433 type is presented in Figure 1*c*.

It is tempting to speculate that the presence of a radio jet in the well-known X-ray source 1E 1740−2942 (Churasov

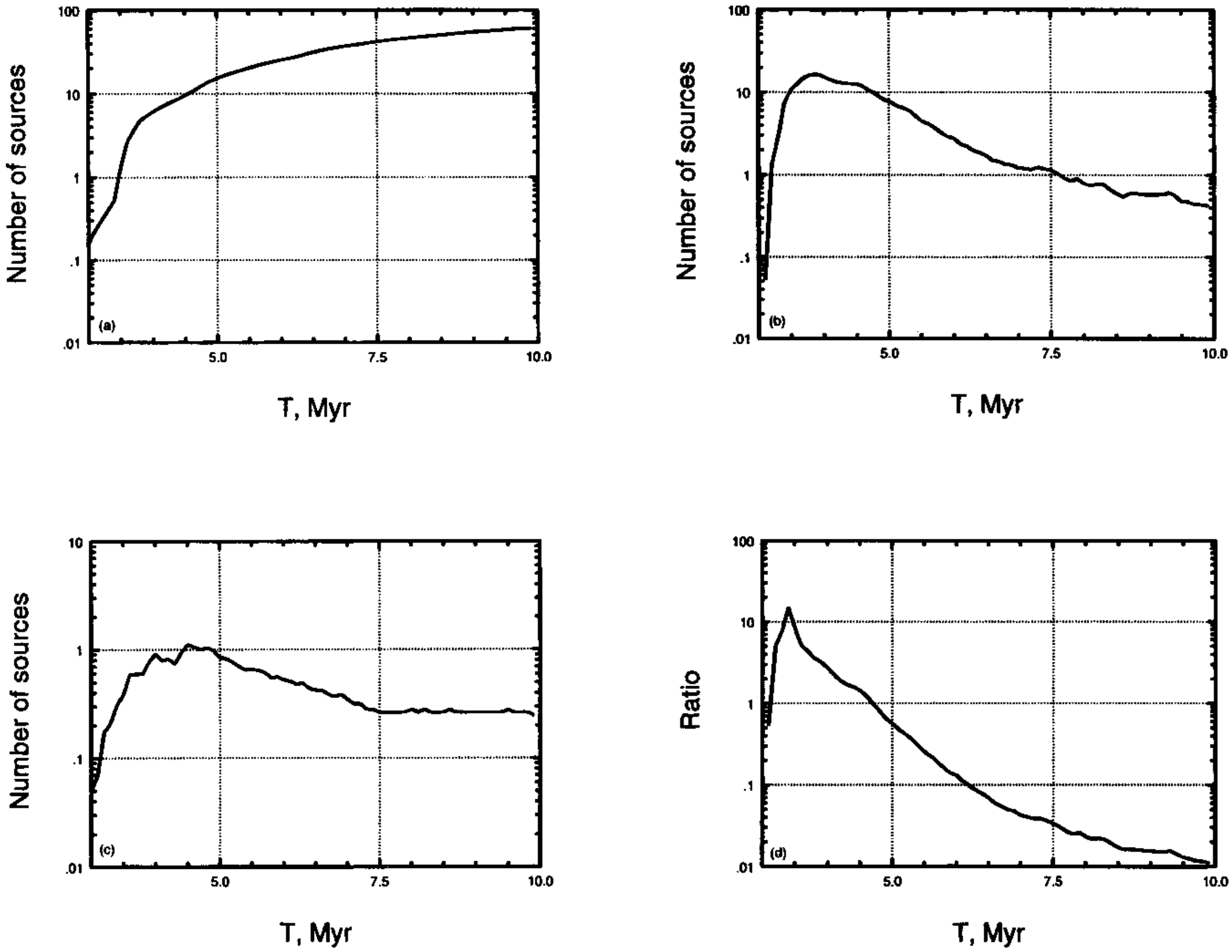

FIG. 1.—The evolution of X-ray binaries of selected types after the starburst at the Galactic center. (*a*) X-ray transients, (*b*) Cyg X-1–like sources, (*c*) SS 433–like sources, and (*d*) ratio BH/NS.

et al. 1994) may indicate that it belongs to superaccreting BH binaries. It was shown that this source can hardly be a system like Cyg X-1 (Heindl et al. 1993), and there are arguments (Mirabel et al. 1991) that it can be an isolated BH, accreting matter from the surrounding molecular cloud. At the moment, however, there are no direct observations that could prove that this object is an isolated BH.

The ratio of numbers of BHs containing binaries (of both SS 433 and Cyg X-1 type) to X-ray transients with Be stars is plotted in Figure 1*d*. This ratio is remarkably sensitive to the time elapsed after the starburst, and therefore it can be used for an independent estimation of the age of the X-ray binaries at the Galactic center. Absolute numbers of different systems seem to be worse age indicators since they are subjected to different, poorly known selection effects.

3.2. *Spatial Distribution of X-Ray Binaries at the Galactic Center after the Starburst*

As is known, the observed distribution of massive stars in the direction of the Galactic center looks very peculiar: the vast majority of all massive stars are concentrated toward the central 1 pc or so (Genzel et al. 1994). The observed X-ray sources demonstrate concentration toward the center, although significantly less pronounced: more than half of them are occupying a region of ≈ 750 pc $\times$ 750 pc in size (Fig. 2).

In order to compare the observed distribution of X-ray sources in the Galactic center with what would be expected from the population synthesis computations, we have considered two hypothetical scenarios for the location of the starburst. In scenario 1, the progenitors of X-ray binaries were formed in a region of ~ 1 pc in size. The resulting X-ray systems were ejected into and scattered within the central 1 kpc or so due to the "kick" that accompanied the formation of those systems. In scenario 2, the starburst happened on a scale $\gg 1$ pc.

3.2.1. *Scenario 1: Starburst Occurred in a Central Region of ~ 1 pc in Size*

The mass distribution at the Galactic center was taken in the form (Lacy, Achterman, & Serabyn 1991)

$$M(r) = 3.4 \times 10^6 \, M_\odot \left(1 + \frac{R}{1\ \mathrm{pc}}\right) . \qquad (5)$$

By integrating the motion of a star in the potential well produced by the above mass distribution, it is straightforward to show that the distance reached by the star and its velocity are related by

$$\ln \frac{r}{r_0} = \frac{1}{2.94} (v_0^2 - v^2) , \qquad (6)$$

where v_0 (in 100 km s^{-1}) is the initial ejection velocity at a radius r_0. This implies that, in order to reach $r = 1$ kpc from $r_0 = 1$ pc, even with a zero velocity, v_0 needs to be as high as 450 km s^{-1}. For $r_0 = 10$ pc, the required $v_0 = 368$ km s^{-1} is less, but not by a substantial factor. Such high velocities cannot be reached by imposing a "kick" onto an initial velocity dispersion of the newly formed stars without destroying binaries. This is supported by the absence of fast moving massive X-ray binary systems in our Galaxy (say, with $v > 50$ km s^{-1}). Therefore, explaining the observed wide distribution of X-ray binaries at the Galactic center within scenario 1 looks unlikely.

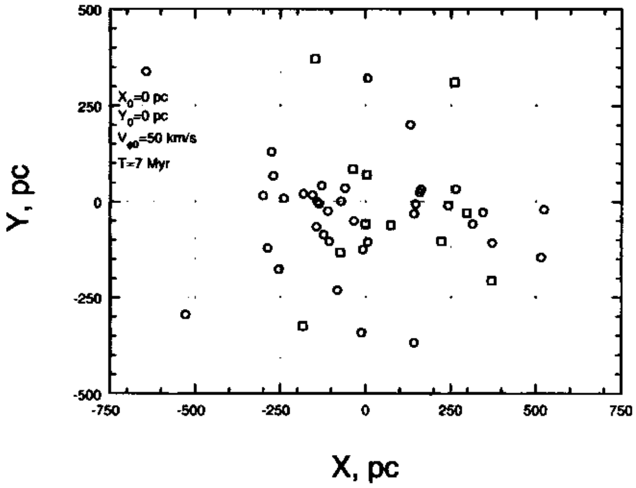

FIG. 2*a*

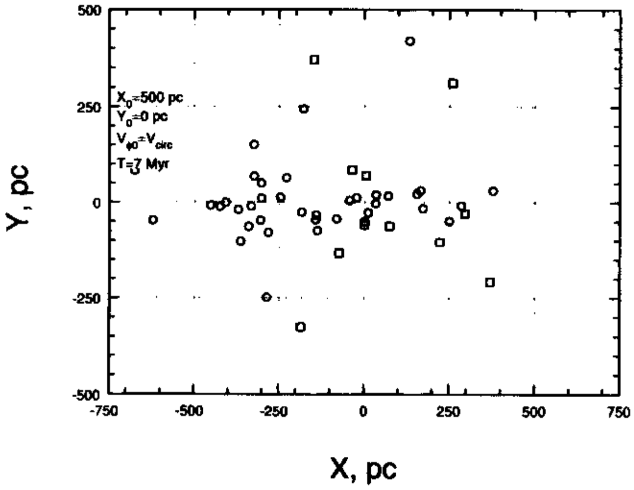

FIG. 2*b*

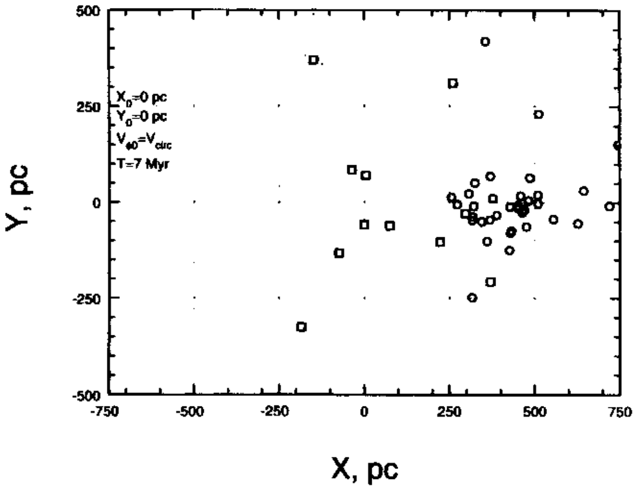

FIG. 2*c*

FIG. 2.—(*a*) Two-dimensional projection of the spatial distribution. *Circles*, X-ray transients; *squares*, *Granat* sources. The starburst occurred at the point with coordinates $X = 0$ pc, $Y = 0$ pc, i.e., on the line of sight (see the text); $v_{\phi_0} = 50$ km s^{-1}. (*b*) Same as (*a*), but the starburst occurred at the point with coordinates $X = 500$ pc, $Y = 0$ pc; $v_{\phi_0} = v_{\rm circ}$. (*c*) Same as (*a*), but the starburst occurred at the point with coordinates $X = 0$ pc, $Y = 0$ pc, i.e., on the line of sight; $v_{\phi_0} = v_{\rm circ}$.

3.2.2. *Scenario 2: Starburst Occurred in a Central Region on a Scale* $\gg 1$ pc

How could one explain the origin of a starburst well outside the central parsec, where no material appropriate for an extensive star formation is currently seen?

A feasible mechanism that might trigger (recurrent) starbursts in the central region of the Galaxy—collisions between giant molecular clouds (GMCs)—has been proposed by Ozernoy (1994b, 1996). Each collision between two GMCs, occurring with an average time interval of $\sim 2 \times 10^8$ yr, gives rise to the dissipation of a substantial part of the angular momentum of each of the clouds; as a result, they end up on much lower orbits. Besides, after the collision and dissipation of internal turbulent motions, the clouds become gravitationally unstable; they could fragment and experience star formation. Therefore, a "wave of star formation" could start at comparatively large distances from the Galactic center and gradually propagate toward the center, accompanied by the fall of the remnants of the clouds onto the center.

In order to quantify this scenario, let us assume that the collision between two molecular clouds occurs at a large distance (about 500–750 pc) from the center and produces a shock that initiates an instantaneous starburst. Suppose that the stars formed kept the initial internal velocity dispersion within the molecular clouds (say, 3 km s^{-1}). Since a substantial part of the transverse velocities of the clouds is lost in the collision, the remnant (stars plus gas) will be falling toward the Galactic center. Due to the conservation of angular momentum, the velocity dispersion of the stars will be growing as r^{-1} and will reach its maximum when the cloud passes at its minimum approach from the Galactic center. If this distance is ~ 10 pc (i.e., comparable to the initial radii of the clouds), the velocity dispersion of stars reaches ~ 150–225 km s^{-1}, while the systematic velocity of the cloud acquired at the central potential well turns out to be $v_0 \sim 300$–400 km s^{-1} as calculated above. A combination of these large systematic and chaotic velocities is expected to be the major factor leading to the scattering of the formed stars in the area of about 750 pc around the center.

For binary stars that are able to produce X-ray sources, two more factors could contribute to this scattering: (1) the ejection of mass during the supernova explosion, even if the ejection was spherically symmetric relative to the exploding star, and (2) a "kick" that the binary acquires as a result of an asymmetry of the supernova explosion. As for the first factor, an estimation for the acquired velocity ranges between 20 and 100 km s^{-1} (e.g., Shore, Livio, & van den Heuvel 1994). As for the second factor, even if we use a rather large estimate of 400 km s^{-1} for the "kick" velocity, which is currently under discussion in the literature (Lyne & Lorimer 1994), then a massive binary acquires a recoil velocity that is smaller by a factor of 10 unless it is disrupted. Therefore, both factors, while occurring for binaries during their infall onto the Galactic center, could even result in a larger scattering than that for the single stars.

Figures 2*a*–2*c* represent the results of some of our model simulations confronted with the distribution of the *Granat Observatory* sources and NS + Be systems (the latter are more numerous than BH sources both in the *Granat* observations and in our calculations). Initially, all the binaries have small, stochastically oriented peculiar velocities with a Maxwellian distribution and dispersion of 3 km s^{-1}. At the moment of the supernova explosion, they acquire, due to a "kick" and mass ejection from the system, an additional velocity of about 75 km s^{-1} (see § 2.2), also stochastically oriented in space. We have explored several variants of the resulting (by $T =$ 6–8 Myr) spatial distribution of the binaries formed in an instantaneous starburst for different initial locations of the starburst and different rotational velocities about the Galactic center, v_ϕ, ranging from zero to the circular velocity, $v_{\rm circ}$.

If the starburst's distance from the center is $r_0 \sim 500$ pc and $v_{\phi 0}$ is not too large, the resulting spatial distribution, as can be seen in Figure 2*a*, turns out to be quite extended and more or less symmetric, consistent with the observed distribution. Figure 2*a* shows the two-dimensional projection of a representative spatial distribution by $T = 7$ Myr. The starburst is assumed to occur at the distance of $r_0 = 500$ pc from the center on the line of sight, and its center's coordinates are projected to the point $X_0 = 0$ pc, $Y_0 = 0$ pc. The initial, after cloud-cloud collision, rotational velocity of the cloud about the Galactic center is taken to be $v_{\phi 0} = 50$ km s^{-1}. If the initial position of the starburst is not located on the line of sight, the results do not change appreciably unless the value of $v_{\phi 0}$ is large enough.

The larger $v_{\phi 0}$, the larger is the asymmetry of the spatial distribution, because the stars, under those circumstances, are not able to reach the center and thereby to increase substantially their velocity dispersion. Hence, those systems cannot move far enough from the rotation plane, and this results in a nonsphericity, representative examples of which are shown in Figures 2*b* and 2*c*. A rapid rotation about the center shifts those binaries in the direction of rotation (to the right on the figures) so as to make the distribution asymmetric relative to the Y-axis (which is perpendicular to the rotation plane). The asymmetry illustrated by Figure 2*b* is not well pronounced (and therefore might still be consistent with the observed distribution of X-ray sources). On the contrary, the asymmetry shown in Figure 2*c* is evidently at odds with what is observed. The asymmetry would be much weaker if we chose such initial conditions that, after 7 Myr from the starburst's onset, the center of the binaries' distribution would be situated on the line of sight: beyond the Galactic center or (as in Fig. 2*b*) in front of it. A large asymmetry, compared with what is observed, left by $T \sim 7$ Myr makes such cases, as in Figure 2*c*, unlikely, although available free parameters (age, $v_{\phi 0}$, r_0, X_0, and Y_0) could weaken the anisotropy relative to the Y-axis (but still leaving the nonsphericity). Another source of asymmetry is substantially larger r_0 (say, 700–900 pc), at which a value of $T =$ 6–8 Myr would not be enough for recently born stars to reach the central region.

In sum, Figures 2*a* and 2*b* indicate that, by $T \simeq 7$ Myr, a starburst would produce a quasi-isotropic–projected distribution of X-ray sources occupying a large region around the center with the size of several hundred parsecs, consistent with the data, for a rather wide range of initial conditions (initial distance from the Galactic center $r_0 \sim 500$ pc, not too large $v_{\phi 0}$).

4. DISCUSSION AND CONCLUSIONS

We compare our results with the *Granat* X-ray observations of the Galactic center (Churazov et al. 1994; Pavlinsky et al. 1994). Besides Sgr A*, 11 more X-ray sources have been reported to be observed in the central region of the Galaxy (5° × 5° across, which corresponds to the linear size of 750 pc × 750 pc, assuming the 8.5 kpc distance to the Galactic center). Two of these sources were classified as BH candidates by their hard power-law tails in the X-ray spectrum (similar to Cyg X-1), and the other nine sources are X-ray transients probably containing NSs.

As we noted above, the BH candidates/X-ray transients ratio is a good indicator of the time passed after the beginning of the starburst. The number of X-ray sources containing NSs increases with time and becomes approximately constant after 6 Myr. The number of binary systems with accreting BHs decreases approximately exponentially, with a characteristic timescale of ≈ 1.5 Myr. This is due to the fact that massive stars with $M > 35\ M_{\odot}$ as BH progenitors rapidly evolve and their number strongly decreases after several million years. The computed BH/NS ratio is ≈ 0.04 at the age of 7 Myr, which should be considered as a lower limit to the true ratio because we are not able to observe all the X-ray transients simultaneously.

Since only a few BH candidates have been found in the region so far (Churazov et al. 1994; Pavlinsky et al. 1994), some uncertainties in the estimated age of the starburst result from poor statistics, yet they are partially reduced as we use relative numbers of the systems. In our calculations employing the metallicity, we used the solar abundance. Since the metallicity at the Galactic center is, by a factor of 2, above the solar one, it also can slightly change our results. Still, given the adopted assumptions, our calculations of the absolute numbers of the systems of different types have an accuracy of $\approx 20\%$; relative numbers have even been calculated with better accuracy. Bearing in mind that not all of our assumptions are realistic, we feel that our absolute numbers are uncertain within a factor of 2–3 or so.

It is instructive to compare our results for the Galactic center starburst with what might be expected for a *continuous* star formation, with the average rate characteristic for the whole Galaxy. For this continuous star formation model, we would expect to observe in the region of $5° \times 5°$ around the Galactic center about 10% of the total number of X-ray sources in the Galaxy. Accounting for the projection effect, the fraction of the X-ray sources in the central 375 pc would be even smaller, $\sim 4\%$. Meanwhile, in the entire Galaxy, we currently observe only one SS 433–type source (SS 433 itself), one Cyg X-1–type source (Cyg X-1 itself), and about 10 X-ray transients are being discovered every year. Hence, for the Galactic center one would expect, after several years of observations with X-ray satellites, to reveal about five X-ray transients and, most likely, no SS 433–type or Cyg X-1–type sources at all (the probability of their appearance is very low). Therefore, the continuous star formation model is unable to explain the absolute or relative numbers of the X-ray sources actually observed in the Galactic center. In contrast, the starburst model presented above seems to be quite successful in this respect.

As for the size of the starburst region, the situation seems to be less certain. Still, as we have shown in § 3.2, the deepness of the central potential well does rule out a scenario in which the starburst occurs in the central 1 pc or so, and then a "kick" during the stage of NS formation ejects the binary system up to the distances of ~ 1 kpc, within which the observed X-ray sources are concentrated. We have discussed another scenario in which the starburst occurs on a scale $\gg 1$ pc as a result of a collision between two molecular clouds (Ozernoy 1996). In this approach, the high velocities acquired by the infalling gas in the Galactic potential well are inherited by the forming massive stars, and enable them to be scattered up to 1 kpc or so. A potential problem with this scenario is that, in contrast to the observed distribution of X-ray sources on a scale like this, the observed distribution of their progenitors, the massive stars, is apparently much more concentrated toward the central 1 pc. It is not excluded that accounting for the unknown selection effects might weaken/remove this problem. However, even in this case, the very presence of several dozens of hot, massive stars in the central 1 pc needs to be explained. In the frame of scenario 2 envisioned in § 3.2.2, which involves the scale $\gg 1$ pc for the starburst, a possible explanation would be as follows: For the newborn stars forming as a result of the collisions of two GMCs, the dispersion of their velocities increases, owing to the conservation of angular momentum, up to the free-fall velocity, in due course of the infall onto the center. A fraction of the material kept in the gaseous form after the dissipation might fall into the center and produce massive stars whose velocity dispersion would not exceed 100 km s^{-1}. Further numerical modeling to test this would be highly desirable. If successful, this scenario would combine formation of massive stars close to the center of the Galaxy with an opportunity to observe the massive binary successors, the X-ray systems, at very large distances from the center.

One may argue that the region of 750 × 750 pc in size around the Galactic center is broad enough so as to be contaminated by X-ray binaries originating in the adjacent regions. However, the fraction of X-ray binaries of such type among the "field" stars (i.e., not associated with the starburst of interest) is much lower. Yet, one could imagine in the Galactic center another starburst of a similar age but on a much larger scale, compared with what is considered above, which would of course somewhat change our results; however, no evidence for such a burst is known so far (for a comprehensive review of available evidence for, and constraints to, possible recurrent starbursts in the central regions of the Galaxy, see Hartmann 1995). We notice that the proposed scenario for the origin of X-ray sources in a comparatively compact starburst has a clear signature: the velocity of an X-ray source is (statistically) expected to be larger the closer the source is located to the Galactic center.

The results of our modeling also seem to be relevant for studying the star formation regions in other galaxies, including starburst galaxies. In the latter, short episodes of violent star formation with a timescale of ~ 10 Myr have been suggested to recur every some billion years (Coziol & Demers 1994). As follows from our modeling of the population synthesis of X-ray sources, the production of a few 10^5 stars in a starburst has to be accompanied by the formation of about 10 hard X-ray sources at the starburst age of 6–8 Myr (and a larger number of X-ray sources at earlier times).

To summarize, *the statistics of X-ray binaries, especially the ratio of the number of systems containing a BH to the number of X-ray transients with a NS, is a sensitive function of the starburst age on a timescale of 2–10 Myr*. As an application, a relatively large fraction of accreting BH candidates among the observed X-ray sources at the Galactic center could be naturally explained if a starburst indeed occurred ~ 6–8 Myr ago (Tamblyn & Rieke 1993).

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