Astronomy Letters, Vol. 28, No. 8, 2002, pp. 536–542. Translated from Pis'ma v Astronomicheskiĭ Zhurnal, Vol. 28, No. 8, 2002, pp. 609–615.

Nearby Young Single Black Holes

M. E. Prokhorov and S. B. Popov*

Sternberg Astronomical Institute, Universitetskiĭ pr. 13, Moscow, 199992 Russia

Received February 15, 2002

Abstract—We consider nearby young black holes formed after supernova explosions in close binaries whose secondary components are currently observed as the so-called runaway stars. Using data on runaway stars and making reasonable assumptions about the mechanisms of supernova explosion and binary breakup, we estimate the present positions of nearby young black holes. For two objects, we obtained relatively small error regions (∼50–100 deg^2). The possibility of detecting these nearby young black holes is discussed. *© 2002 MAIK "Nauka/Interperiodica"*.

Key words: *pulsars, neutron stars, and black holes; X-ray and gamma-ray sources; supernovae and supernova remnants; star clusters and associations, stellar dynamics*

INTRODUCTION

To date, stellar-mass black holes (BHs) have been discovered in close binaries (Cherepashchuk 1996) and supermassive BHs have been discovered in galactic nuclei (Kormendy 2001). It would be of great interest to find a single stellar-mass BH, but this is technically very difficult to do. Therefore, nearby single BHs are of considerable interest. To detect such objects, it would be desirable to reduce the search area, i.e., to estimate the positions of possible sources in advance. Below, we suggest a method of such estimation and use specific examples to illustrate it.

Popov *et al.* (2002) briefly discussed nearby young compact objects (neutron stars and BHs) and assumed that radio-quiet neutron stars in the solar neighborhood were associated with recent supernova explosions that produced various structures in the local interstellar medium (Local Bubble, Loop I, etc.). Here, we analyze nearby young BHs in more detail.

The main idea of our study is as follows. We estimate the present positions of nearby ($r < 1$ kpc) young (<6 Myr) BHs formed in close binaries with massive secondary components that broke up after the first supernova explosion. The so-called runaway star (Blaau 1961) appears after binary breakup. Knowing the present position and velocity of the runaway star and specifying certain parameters for the binary and supernova explosion (see, e.g., Lipunov *et al.* (1996) about the evolution of binary stars), we can estimate the present-day position of a black hole.

*E-mail: polar@sai.msu.ru

YOUNG MASSIVE STARS IN THE SOLAR NEIGHBORHOOD

The Galactic region where the Sun is located has some peculiarities. The so-called Gould Belt (Pöppel 1997) dominates in the solar neighborhood. This is a disk-like structure, ∼750 − −1000 pc in size, whose center is at 150–250 pc from the Sun. The plane of the Gould Belt is inclined ∼18° with respect to the Galactic plane. The age of the Gould Belt is estimated to be 30–70 Myr; i.e., the life of the most numerous stars among those that can produce supernova explosions ($M \approx 8$–$10M_\odot$) has come to an end there. Single radio-quiet neutron stars discovered by the ROSAT satellite (Popov *et al.* 2002) and some of the unidentified EGRET sources (Grenier and Perrot 2001) are probably associated with the Gould Belt.

Fifty-six runaway stars are known within ∼700 pc of the Sun (Hoogerwerf *et al.* 2001). They were formed either during the dynamical evolution of the clusters and associations where they were born (the most likely cause is a close encounter of binaries) or through the binary breakup during a supernova explosion. Four stars from this group have masses larger than ∼$30M_\odot$ (since these stars are single and massive, the accuracy of determining their masses is not very high).

Table 1 gives data [parameters from Hoogerwerf *et al.* (2001)] on the runaway stars considered here. Hoogerwerf *et al.* (2001) investigated all 56 nearby runaway stars in detail. These are nearby stars in that they were studied by the HIPPARCOS satellite and their sky positions, proper motions, and parallaxes are known within milliarcsecond accuracy (here, we ignore the errors in the velocities and other parameters of the runaway stars). The authors traced the motion of these stars in the Galaxy and for most of them (including the four massive stars), they found when and from which association they escaped and which of the two possible ejection mechanisms operated for each particular star.

The four massive runaway stars are most likely to have acquired their high space velocities through binary breakups after supernova explosions (to all appearances, the fifth massive star, ι Ori, was ejected from its parent association through dynamical interaction; see Hoogerwerf *et al.* 2001). Several arguments may be advanced in support of this conclusion:

(1) These stars are very massive. To be ejected from the cluster (association), they had to pass near stars of comparable mass. Otherwise, according to the law of momentum conservation, less massive stars would be ejected from the cluster, whereas such massive stars are very few for any reasonable mass function. Close encounters of several massive stars turn out to be extremely rare events compared with rare close triple encounters of low-mass stars.

(2) Massive stars live only several Myr. This imposes an additional constraint on the rare events described above: the encounter must take place until the massive star explodes as a supernova.

(3) Finally, all these stars move at velocities that are several times higher than the velocity dispersion of their parent associations. This fact does not contradict anything; after a successful close encounter, the stars can acquire high velocities. However, this occurs only in rare cases; the mean velocity acquired in such processes is much lower.

More detailed arguments for each of the four stars from this group can be found in Hoogerwerf *et al.* (2001).

Thus, to all appearances, each of these four stars was a member of a binary in which its neighbor exploded some time ago. The exploded star traversed its entire evolutionary path faster; i.e., it was even more massive than the observed runaway star. Such massive stars ($M > 30{-}40 M_\odot$) are currently believed to collapse not into neutron stars but into BHs (White and van Paradijs 1996; Fryer 1999). Moreover, the cores in stars with slightly higher masses ($M \gtrsim 40{-}50 M_\odot$) are most likely to collapse directly into BHs without going through the intermediate stage of a hot neutron star (see, e.g., Bisnovatyĭ-Kogan 1968).

Table 1. Parameters of the four most massive runaway stars in the solar neighborhood (Hoogerwerf *et al.* 2001)

Star	Mass, $M_\odot$	Velocity, km s^{-1}	Kinematic age, Myr
ξ Per	33	65	1
HD 64760	25–35	31	6
ζ Pup	67	62	2
λ Cep	40–65	74	4.5

BINARY BREAKUP AFTER SUPERNOVA EXPLOSION

If a supernova explodes symmetrically in a binary with a circular orbit, then *at least half of the binary mass* must be ejected for the binary to break up [all aspects of binary breakup during mass ejection were considered in detail by Hills (1983)]. For example, if the mass of the runaway star is $M_{\rm opt} = 30 M_\odot$ and if it did not change significantly since the binary breakup, while the BH mass is $M_{\rm BH} = 10 M_\odot$, then the mass of the ejected envelope must be no less than $\Delta M \geq M_{\rm opt} + M_{\rm BH} = 40 M_\odot$ and the mass of the exploded presupernova is $M_{\rm SN} = M_{\rm BH} + \Delta M \geq 50 M_\odot$. Since the mass loss from such massive stars over their lifetimes is large (at least 30% of the initial mass), each of the stars under consideration was a member of an *extremely massive* binary. The presupernova mass for ζ Pup that follows from such reasoning is $87.5 M_\odot$; i.e., either this was a particularly massive star ($>100 M_\odot$ during its birth) or the mass loss was much lower than that expected.

We consider only binaries with two massive stars and assume that none of their components filled their Roche lobe before a supernova explosion. Note that it is unlikely that these systems passed through the stage of mass transfer. However, if such a process takes place, then for stable and unstable (with a common envelope) mass transfer, the primary component will lose part of its mass and the mass of the secondary component will be constant or increase. As a result, the binary-component mass ratio decreases and a symmetric supernova explosion will most likely be unable to tear the binary apart. Our second condition, a circular orbit, is guaranteed to be satisfied after the stage of mass transfer.

Since the binaries under consideration are close systems (the current velocities of the runaway stars are on the order of their orbital velocities in binaries), the assumption of circular orbits appears acceptable and the high presupernova mass makes probable the direct collapse of the supernova core into a BH (White

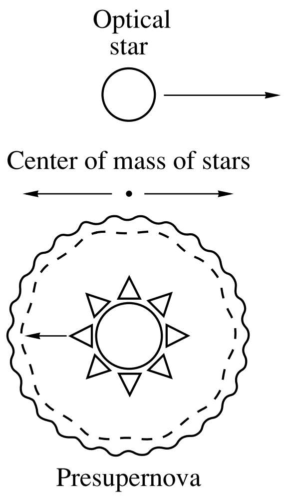

Fig. 1. A scheme for binary breakup after a supernova explosion.

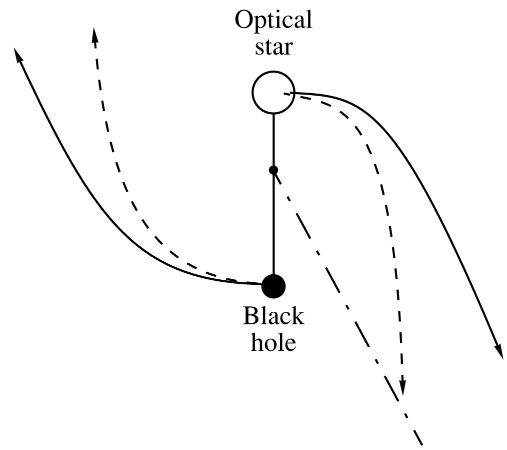

Fig. 2. Star separation after a supernova explosion in the presupernova center-of-mass frame of reference.

and van Paradijs 1996). Such collapse is generally believed to be symmetric and without recoil (i.e., the BH velocity is the same as that of the presupernova velocity before the explosion). This is in contrast to the formation of neutron stars, which are born with space velocities of several hundred kilometers per second (Lyne and Lorimer 1994).

Binary breakups through supernova explosions were considered by several authors (see, e.g., Tauris and Takens 1998; Hills 1983). However, since the above two conditions are most likely satisfied, the breakup proceeds in a simple way (see Fig. 1). The envelope is ejected symmetrically about the presupernova center and is carried away in a straight line in the direction and with the velocity of its orbital motion at the explosion time. The motion refers to the center of the envelope and is unaffected by its symmetric expansion. The center of mass of the two stars (the BH and the binary's secondary component, which became a runaway star) moves in the opposite direction but at a higher velocity, because the mass of the ejected envelope exceeds the total mass of the remaining stars.

In the center-of-mass frame of reference of the two stars (without the ejected envelope), the star velocities immediately after an explosion are directed perpendicularly to the line that connects them and the relative velocity of the star and the BH is equal to the relative orbital velocity of the stars before the explosion (see Fig. 2). The runaway star and the BH move along similar hyperbolas with the eccentricity $e = \Delta M/(M_{\rm opt} + M_{\rm BH}) \geq 1$. As the two stars move apart, the vectors of their velocities turn through angle φ: $\sin\varphi = 1/e$. In the limiting case where the ejected mass is exactly equal to half the binary mass, the stars move along parabolas ($e = 1$) and the direction of their velocities change by 90° in the separation time. The parabolic trajectories are indicated by the dashed lines in Fig. 2.

In the presupernova center-of-mass system (Fig. 3), the hyperbolic or parabolic star separation is supplemented with the uniform motion of their center of mass. As a result, both the runaway star and the BH move in the direction opposite to the motion of the ejected envelope.

CALCULATING THE BH POSITIONS

The errors in the proper motions and parallaxes of stars affect the *relative* positions of the BH and the runaway stars only slightly. The contribution of these errors to the BH localization is less significant than the uncertainties in the remaining parameters. Given the sky position of each of the stars, their distance, and velocity component, we can integrate a star's motion in the Galactic gravitational field back in time. We took the kinematic age (the time elapsed since the supernova explosion and binary breakup) from Hoogerwerf *et al.* (2001). Therefore, we can determine the relative velocity $v_{\rm opt}$ with which each of the runaway stars escaped from its parent association and its direction. The BH velocity $v_{\rm BH}$ must be determined from $v_{\rm opt}$. The problem has a unique solution if ΔM and $M_{\rm BH}$ are known, and we can find the velocity $v_{\rm BH}$ and the angle ψ that it makes with $v_{\rm opt}$: $\psi(v_{\rm BH}, v_{\rm opt}) = \widehat{\mathbf{v}_{\rm BH}\mathbf{v}_{\rm opt}}$. The center of mass of the envelope, the BH, and the runaway star moves in the orbital plane of the binary whose orientation is unknown. Thus, the velocity $\mathbf{v}_{\rm BH}$ is directed along the side surface of the cone whose axis coincides with $\mathbf{v}_{\rm opt}$ and whose half-angle is ψ. We characterize the specific position of vector $\mathbf{v}_{\rm BH}$ on the cone by an

Table 2. Parameters of the error regions for the BHs associated with massive runaway stars

Name	Distance, pc	Velocity, km s^{-1}	Error region	$N_{\rm EGRET}$
ξ Per	537–611	19–70	$\sim 7° \times 7°$	1
HD 64760	263–645	11–59	$\sim 45° \times 50°$	12
ζ Pup	404–519	33–58	$\sim 12° \times 12°$	1
λ Cep	223–534	19–70	$\sim 45° \times 45°$	6

azimuthal angle ϕ (ϕ is related to the orientation of the binary orbital plane; the choice of the zero point from which it is counted off is of no importance for subsequent analysis). Since we cannot determine the specific position of $\mathbf{v}_{\rm BH}$ on the cone surface (i.e., ϕ) from observations, this parameter must be varied.

After specifying the binary breakup parameters, we must integrate the motion of the BH from its birth and to the present time. To integrate the motion in the Galactic potential, we used the same code and constants specifying the Galactic potential as in our previous computations of the motion of single neutron stars (Popov *et al.* 2000).

Here, we make three simplifying assumptions, which are discussed below:

—the supernova explosion is symmetric, i.e., the space velocity of the remnant (BH) does not vary during the explosion;

—the association moves in a circular orbit in the Galactic disk;

—the binary velocity inside the association is disregarded.

These assumptions allow us to use the above relation between the velocities of the runaway star and BH at the point of binary breakup. For each set of parameters ϕ, ΔM, and $M_{\rm BH}$, we obtain the vector $v_{\rm BH}(\phi, \Delta M, M_{\rm BH})$. Integrating the BH motion from the supernova explosion to the present time, we find its sky position. When exhausting the admissible values of the parameters, these points sweep the sky region where the BH must be searched for.

Table 2 gives the following data on BHs: the heliocentric distance; the BH velocity relative to the interstellar medium (i.e., relative to the circular Galactic rotation at a given point); the size of the error region; and the number of unidentified EGRET sources in this region. Despite the simplifying assumptions, we obtained large regions in the sky for λ Cep and HD 64760 in which the search was not promising. Figure 4 shows the trajectory of the optical star and a number of possible BH trajectories for the binary that produced ζ Pup. Figure 5 shows the possible BH error region for this system (both figures are in Galactic coordinates). Figures 6 and 7 show the same results for ξ Per. Since we obtained large error regions for other stars, no similar figures are given here for them.

The mass of the ejected envelope ΔM, the presupernova mass $M_{\rm SN}$, and the BH velocity relative to the interstellar medium for the rings is shown in Figs. 5 and 7.

The largest masses are given for illustrative purposes. It should be noted, however, that a reduction in the upper limit of the presupernova mass to $100 M_\odot$ for ξ Per and to $120 M_\odot$ for ζ Pup changes the BH error regions only slightly.

DISCUSSION AND CONCLUSIONS

The errors in the proper motions and parallaxes affect only slightly the relative positions of the BHs and runaway stars. The contribution of these errors to the BH localization error is less significant than that of the uncertainty in other parameters (ΔM, $M_{\rm BH}$, ϕ).

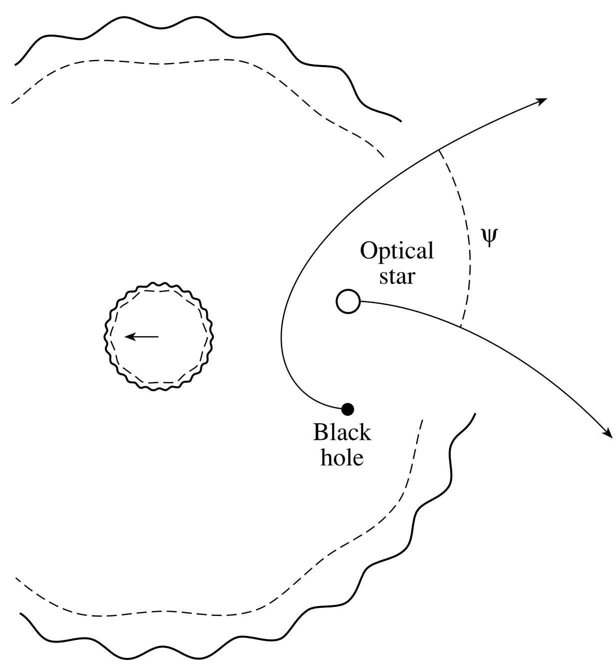

Fig. 3. Star separation after a supernova explosion in the presupernova center-of-mass system.

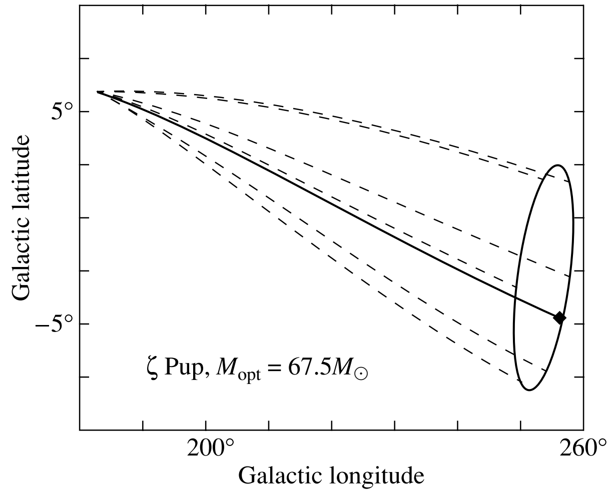

Fig. 4. The sky trajectory of the runaway star ζ Pup (solid line) and four possible BH trajectories (dashed lines). The BH mass was set equal to $M_{\rm BH} = 10M_{\odot}$.

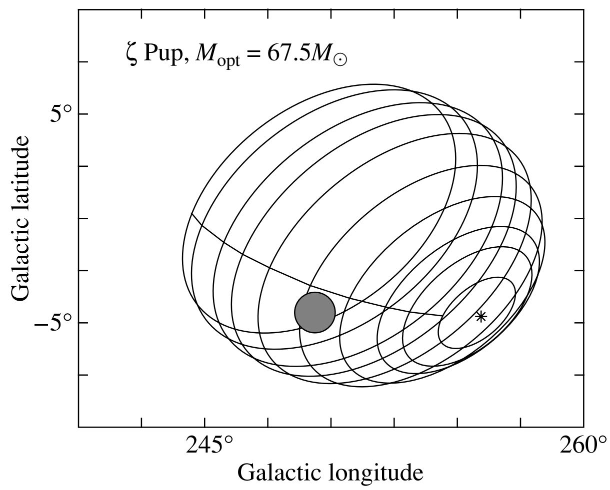

Fig. 5. The possible error region of the BH that originated from the same binary breakup as the runaway star ζ Pup. The rings correspond to different ejected masses ΔM and presupernova orbital orientations ϕ. The asterisk and the circle mark the positions of the runaway star and the unidentified EGRET source (3EG J0747−3412), respectively. The BH mass is set equal to $M_{\rm BH} = 10M_{\odot}$. The smallest ΔM corresponds to the ring nearest the runaway star.

ζ Pup

$\Delta M, M_{\odot}$	78	79	80	82	85	90	95	100	110	120
$M_{\rm SN}, M_{\odot}$	88	89	90	92	95	100	105	110	120	130
v, km s^{-1}	57–58	56–57	55–56	53–55	51–52	47–49	44–46	41–43	37–38	33–35

ξ Per

$\Delta M, M_{\odot}$	44	45	47	50	55	60	70	80	100	120
$M_{\rm SN}, M_{\odot}$	54	55	57	60	65	70	80	90	110	130
v, km s^{-1}	69–70	66–68	62–63	56–58	49–51	44–46	33–35	31–32	24–25	19–20

From our assumptions about the velocities, the first assumption (about zero recoil during the BH formation) seems most uncertain. If we draw an analogy with neutron stars (i.e., if we scale the velocity in ac-

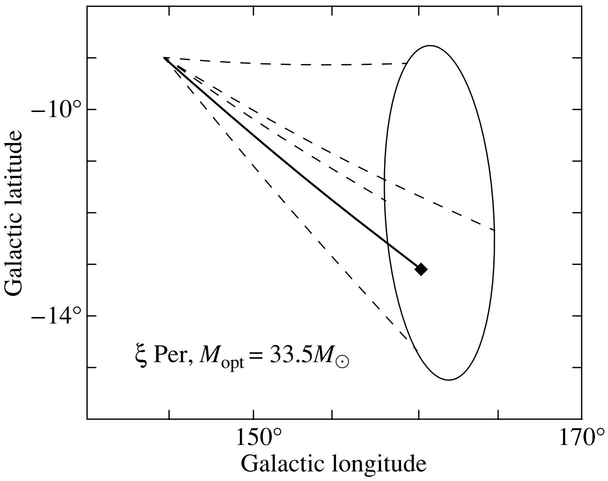

Fig. 6. Same as Fig. 4 for the runaway star ξ Per.

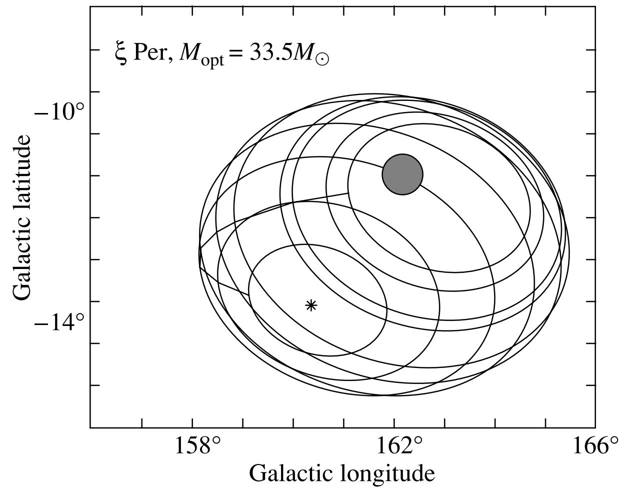

Fig. 7. Same as Fig. 5 for the runaway star ξ Per. The circle marks the position of the unidentified EGRET source (3EG J0416+3650).

cordance with an increase in the mass of the compact object and with changes in other parameters), then the BH could gain an additional velocity of up to several km s^{-1} during its birth, which would completely change the inferred error region. However, as yet, no compelling experimental evidence is available for a low or high BH recoil velocity.

The assumption about the circular motion of young stellar associations in the Galactic disk appears plausible enough. Moreover, this motion can, in principle, be measured. The motion of a binary inside an association can be taken into account in calculations (by adding a randomly oriented velocity on the order of the velocity dispersion inside the association to the velocity vector of its center). These velocities are low and their allowance causes a small increase in the error regions (by 15–20 %, according to our estimates). We ignore the small corrections here.

The probability of finding a BH increases as the corresponding runaway star is approached. This is because closer sky positions of the two components correspond to closer pre-explosion stellar masses. The close positions of the BH and the runaway star prove to be more probable for the mass functions that fall off toward more massive stars. However, the distribution function is wide enough and there is no sharp maximum at the current position of the runaway star. The situation is even more complicated observationally, because farther relative positions of the BH and the runaway star correspond to a lower BH space velocity, i.e., to a higher accretion rate at the same interstellar-gas density, which should facilitate the detection of such an object.

The BH activity in the hard energy band may result from the accretion of turbulized interstellar matter (Shvartsman 1971). Such matter has a nonzero angular momentum and cannot immediately fall to the BH. Instead, it forms an accretion ring near the latter, which, due to viscosity, transforms into an accretion disk. If the matter from such a ring does not fall completely to the BH in the time it takes for it to cross an interstellar turbulence cell, then a new ring of matter with a different orientation will begin to form near the BH. These rings "annihilate" (i.e., mutually destroy each other), thereby increasing the accretion rate. The accretion rate will vary greatly on the turbulent-cell crossing time scales (from several days to several years, depending on the BH velocity relative to the interstellar medium). The upper limits on the BH velocity (see Table 2) are large and no significant accretion rate should be expected in this case. However, the lower limits on the velocities make the $\dot{M}$ estimate optimistic.

Many authors considered the rate of accretion onto a single BH [see, e.g., Gruzinov (1998) and references therein]. However, of particular interest in our case is nonstationary BH activity (Gruzinov 1999). At a low mean luminosity and at relatively large heliocentric distances (hundreds of pc, see Table 2), the source can be open during a short-term increase in flux.

Since we obtained relatively small possible BH error regions for ξ Per and ζ Pup, only one candidate can be found in the third EGRET catalog for each of these stars. These sources are 3EG J0747−3412 (for ζ Pup) and 3EG J0416+3650 (for ξ Per). For λ Cep and HD 64760, for which our computations yielded large BH error regions, we found 6 and 12 sources, respectively, in the EGRET catalog. However, in the latter case, of particular interest may be the sources that are especially close to the observed runaway star. These are 3EG J2227+6122 for λ Cep and 3EG J0724−4713, 3EG J0725−5140, 3EG J0828−4954, and 3EG J0903−3531 for HD 64760.

Note that analysis of massive runaway stars can shed additional light on the explosion mechanism of massive stars. According to the currently most popular supernova explosion mechanism (Fryer 1999), the collapse of stars with masses $>40M_\odot$ proceeds with no mass ejection and gives rise to the most massive BHs. However, in this case, it is difficult to explain the breakups of binaries in which the secondary components are heavier than $\sim 30M_\odot$. Prokhorov and Postnov (2001) considered various supernova explosion mechanisms and concluded that the magnetorotational mechanism best explains the observed mass distribution of compact objects. In this mechanism, the recoil for BHs is much weaker than that for neutron stars and, furthermore, the envelope is ejected even if a BH is formed. The study of the breakup products of close binaries may give additional arguments for a particular supernova explosion mechanism.

Apart from the BHs formed in massive close binaries, there must be about 20 more BHs younger than 10 Myr in the solar neighborhood. This follows from the supernova rate in the Gould Belt, which is about 20–30 per Myr (Grenier 2000), and the ratio of the number of neutron stars to that of BHs (on the order of 10 : 1). In addition, one might expect a large number of old BHs to exist within 1 kpc of the Sun. However, these objects are difficult to identify without some a priori knowledge about their positions and other parameters (space velocity, heliocentric distance). That is why we attempted to show how these parameters can be determined from data on runaway stars.

ACKNOWLEDGMENTS

We are grateful to Profs. K.V. Kuimov and A.S. Rastorguev for their advice and to the referees for their remarks that improved this paper. S.B. Popov thanks Monica Colpi, Aldo Treves, Roberto Turolla, and Luca Zampieri. We are also grateful to the organizers and participants of the HEA-2001 conference (Space Research Institute of the Russian Academy of Sciences) for providing a forum for the presentation and fruitful discussion of this work. This work was supported by the Russian Foundation for Basic Research (project no. 00-02-17164).

REFERENCES

1. G. S. Bisnovatyĭ-Kogan, Astrofizika **4**, 221 (1968).
2. A. Blaauw, Bull. Astron. Inst. Netherlands **15**, 265 (1961).
3. A. M. Cherepashchuk, Usp. Fiz. Nauk **166**, 809 (1996) [Phys. Usp. **39**, 759 (1996)].
4. C. L. Fryer, Astrophys. J. **522**, 413 (1999).
5. I. A. Grenier, Astron. Astrophys. Lett. **364**, L93 (2000).
6. I. A. Grenier and C. A. Perrot, in *Gamma 2001,* Ed. by S. Ritz, N. Gehrels, and C. R. Shrader, AIP Conf. Proc. **587**, 649 (2001).
7. A. Gruzinov, Astrophys. J. **501**, 787 (1998).
8. A. Gruzinov, astro-ph/9908101 (1999).
9. J. G. Hills, Astrophys. J. **267**, 322 (1983).
10. R. Hoogerwerf, J. H. J. de Bruijne, and P. T. de Zeeuw, Astron. Astrophys. **365**, 49 (2001).
11. J. Kormendy, Rev. Mex. Astron. Astrofis. **10**, 69 (2001).
12. V. M. Lipunov, K. A. Postnov, and M. E. Prokhorov, Astrophys. Space Phys. Rev. **9**, part 4 (1996).
13. A. G. Lyne and D. R. Lorimer, Nature **369**, 127 (1994).
14. S. B. Popov, M. Colpi, A. Treves, *et al.*, Astrophys. J. **530**, 896 (2000).
15. S. B. Popov, M. E. Prokhorov, M. Colpi, *et al.*, Gravitation and Cosmology (in press); astro-ph/0201030 (2002).
16. W. Pöppel, Fundam. Cosm. Phys. **18**, 1 (1997).
17. M. E. Prokhorov and K. A. Postnov, Odessa Astron. Publ. **14**, 78 (2001); astro-ph/0110176.
18. V. F. Shvartsman, Astron. Zh. **48**, 479 (1971) [Sov. Astron. **15**, 377 (1971)].
19. T. M. Tauris and R. J. Takens, Astron. Astrophys. **330**, 1047 (1998).
20. N. E. White and J. van Paradijs, Astrophys. J. Lett. **473**, L25 (1996).

Translated by A. Dambis