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SEARCHING FOR RUNAWAY OB STARS IN SUPERNOVA REMNANTS

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Searching for runaway stars in Supernova remnants gives us the possibility to estimate the mass ratio in binary systems in which there occur Supernova explosion. Such a method also gives information on portions of spectroscopic and close binaries among the stars on the main sequence with mass > 7 – 8 $M_\odot$. More importantly, we can learn more about space velocities and spin periods of pulsars by this way. We have searched for runaway OB stars in central parts of 48 Supernova remnants with distances less than about 3 kpc. In 16 of the remnants in our sample, there is no candidate O or B type star and we have shown that pulsars (point sources) might be born not only in spectroscopic and close binaries. We have represented a list of stars which are candidates for runaway B type stars located in Supernova remnants. Spectroscopic investigations on these candidates could provide solutions for the problems mentioned above.

Key words: *(stars:)supernovae:OB stars*

1. *Introduction.* After single neutron stars (NSs) are born they show very different properties; they show themselves as radio pulsars (PSRs), X-ray pulsars, dim radio quiet neutron stars (DRQNSs), dim isolated thermal neutron stars (DITNSs), anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) which have possibly different initial rotation periods,though there is no observational or theoretical confirmation of such a possibility.

For single NSs with such different physical properties, which have genetic connections with known supernova remnants (SNRs), there is no significant difference in the lower limit on the mass values of the progenitor stars [1]. Iben & Tutukov [2] claim that only the NSs born in close binary systems show PSR properties in which case they get high spin velocities. It must be noted that DRQNSs which are located in SNRs have P (spin period) and $\dot{P}$ (time derivative of spin period) values similar to PSRs (but on average DRQNSs have a bit larger values of P). Therefore, they also must be born in close binary systems. On the other hand, space velocities of NSs which are born in close binaries must be larger than the average space velocity of PSRs, because such neutron stars in binaries have probably more asymmetric supernova explosion.

Average space velocity of PSRs is ~250-300 km/s [3,4]. Such a high space velocity can only be due to asymmetric supernova (SN) explosion. In such a case, the companion star (including O-and B-type stars) of the close binary system can become a runaway star with its high space velocity. Of course, if the binary is a close one it may trigger an asymmetry for the explosion more easily which leads to disruption of the system.

Single stars and stars in wide binary systems, which have initial mass values $M > 7-8\,M_{\odot}$ [5,6], experience SN at the end of their evolution.This boundary mass value can be different in the case of close binaries because of differences in their evolution. If we take into account that most of the massive stars are members of binary systems, even without the idea of Iben & Tutukov [2], we can say that runaway OB stars may be located in central parts of some SNRs. Considering the work of Iben & Tutukov [2] we can say that if there is a PSR or another type of NS with a spin period less than 3-5 seconds in a SNR then there must also be a runaway star (not necessarily but mainly O-type or early B-type) in the SNR.

The main reason in failing to observe PSRs in SNRs is not the beaming fraction. Most of the newborn PSRs have radio luminosities, $L = S_{400} \times d^2$ mJy kpc^2, at least one order of magnitude less than the radio luminosity of the Crab PSR [7]. Therefore, it is difficult to observe PSRs in SNRs. In the Galaxy, the number of DRQNSs, which do not show PSR properties, with P and $\dot{P}$ values similar to PSRs is smaller than number of PSRs (see Table 1). DRQNSs may be PSRs with very low radio luminosity. This must be more probable compared to the possibility of existence of high luminosity PSRs which have beams not passing through the line of sight, because the SNRs in which DRQNSs have been observed belong to pure shell morphological type. If this is true, the birth rate of PSRs (including the part of

Table 1

VALUES OF $\beta \equiv \Delta\theta/\theta$ FOR THE SNR - POINT SOURCE PAIRS

SNR l, b	SNR type	Pt. Source	β ($\equiv \Delta\theta/\theta$)	References
34.7-0.4	C	PSR J1856+0113	0.51	[47]
69.0+2.7	?	PSR J1952+3252	0.14	[47,44,56]
78.2+2.1	S	DRQNS RX J2020.2+4026	0.03	[38]
109.1-1.0	S	AXP 1E 2259+586	0.2-0.3,0.2,<0.2	[43,53,48,41]
111.7-2.1	S	DRQNS CXO J2323+5848	~0	[38]
114.3+0.3	S	PSR J2337+6151	0.08	[47,40]
119.5+10.2	S	DRQNS RX J0007.0+7302	0.33	[38]
130.7+3.1	F	PSR J0205+6449	~0.14	[12,39]
180.0-1.7	S	PSR J0538+2817	~0.3	[12,55]
184.6-5.8	F	PSR J0534+2200	~0.1	[47]
189.1+3.0	C	CXOU J061705.3+222127	~0.6	[12,51]
260.4-3.4	S	DRQNS RX J0822-4300	0.28	[38,52]
263.9-3.3	C	PSR J0835-4510	0.29	[47]
266.2-1.2	S	DRQNS SAX J0852.0-4615	~0.1	[12,50]
5+10.0	S	DRQNS 1E 1207.4-5209	0.1-0.2	[38,46,54,49,42]

DITNSs which were PSRs with $B > 10^{13}$ G when they were young) must be about 60-70% of the total supernovae rate. On the other hand, in many nearby SNRs no X-ray point source nor PSR has been found [8].

In this work, we investigate the possibility for the existence of runaway stars in SNRs, which are earlier than B9 spectral type or with masses $> 2.5 M_{\odot}$. This problem is also related to the mass ratio of the components in close and spectroscopic binary systems. Also, if we find runaway stars genetically connected to SNRs, we can use the distance of the runaway star as the distance of the SNR, as the distance of stars can be more precisely determined. If the conclusion given by Iben & Tutukov [2] is correct and also if the mass ratio in close and spectroscopic binaries is in the range 1-0.25, then we expect to observe OB runaway stars in about 60% of the SNRs. If the mass ratio in these binaries is yet smaller, then only a small number of SNRs is expected to contain OB runaways. On the other hand, the idea of PSRs to be formed only in close binaries should be rejected, because low mass stars can not have considerable influence on PSR formation. The large number of PSRs with small values of rate of rotational energy loss ($\dot{E}$) also contradicts the idea that PSRs are born only in close binary systems.

2. *The Supernova Remnants Chosen for Examination.* In Table 2, some data of 48 SNRs [9] located up to about 3-4 kpc from the Sun are represented; names, morphological types, distances, coordinates and the angular region ($\theta/6$) around the geometrical center in which candidates of runaway OB stars were searched from various catalogs are given (where θ is the angular size of SNR, see Green [9]). In order to estimate the interstellar absorption values (A_V) for the stars located in SNRs, A_V values (which depend on distances and directions) given by Neckel & Klare [10] have been used. A_V and $m_V - M_V$ values are also shown in Table 2. The earliest possible spectral type for the candidate stars located within the $\theta/6$ regions, which we have

Table 2

SOME DATA OF NEARBY SUPERNOVA REMNANTS INCLUDING LIMITS ON THE TYPES OF POSSIBLY EXISTING B-TYPE STARS IN THESE SNRs

l, b	d (kpc)	RA (2000)	Dec (2000)	$\theta/6$ (')	A_V (mag)	$m_V - M_V$ (mag)	B-type candidates
1	2	3	4	5	6	7	8
6.4-0.1	2.5	18 00 33	-23 25 04	7	2.0	14.0	>B4
18.9-1.1	2.5	18 29 49	-12 57 56	5.5	2.0	14.0	>B3
32.0-4.9	2.7	19 05 37	-02 55 22	10	2.8	14.8	>B3
34.7-0.4	2.8	18 56 02	01 21 57	5.2	2.8	15.2	>B3
43.9+1.6	3.1	19 05 52	10 29 39	10	2.5	14.9	>B4
54.4-0.3	3.3	19 33 23	18 56 33	6.7	3.5	15.9	>B4

Table 2 (the end)

1	2	3	4	5	6	7	8
65.3+5.7	0.8	19 32 57	31 11 32	45.8	0.3	9.8	>B9
69.0+2.7	2	19 53 26	32 52 52	13.3	1.5	11.8	>B9
74.0-8.5	0.8	20 51 05	30 41 17	32.5	0.5	10.0	>B9
78.2+2.1	1.5	20 20 47	40 24 34	10	3	13.9	>B8
82.2+5.3	1.7	20 19 08	45 29 29	13.3	2.5	13.4	>B4
89.0+4.7	0.9	20 45 03	50 35 58	17.5	2.2	11.7	>B8
93.7-0.2	1.6	21 29 29	50 48 11	13.3	2	13.2	>B8
109.1-1.0	4	23 01 36	58 53 09	4.7	2.5	16.0	>B3
111.7-2.1	3.4	23 23 26	58 48 29	0.8	2.8	15.0	>B4
114.3+0.3	2.5	23 37 06	61 54 37	12.1	2.2	14.4	>B4
116.9+0.2	3.5	23 59 13	62 26 42	5.7	2.3	15.0	>B4
117.4+5.0	2.2	23 54 59	67 46 42	11.7	2	13.5	>B6
119.5+10.2	1.4	00 06 39	72 46 42	15	1	11.7	>B9
120.1+1.4	3.3	00 25 18	64 08 37	<1.3	3.3	15.8	>B4
126.2+1.6	2.5	01 21 51	64 15 41	12	3	14.9	>B3
127.1+0.5	2.5	01 28 22	63 10 31	7.5	2.5	14.5	>B4
130.7+3.1	3.2	02 05 42	64 49 19	1.7	1.8	14.3	>B5
132.7+1.3	2.3	02 17 46	62 43 51	13.3	2.6	14.4	>B7
152.2-1.2	1.8	04 09 10	48 31 53	18.3	2.3	13.5	>B9
156.2+5.7	2	04 58 35	51 51 34	18.3	2	13.5	>B8
160.9+2.6	1.2	05 00 42	46 40 24	21.7	0.8	11.7	>B9
166.0+4.3	3.8	05 26 35	42 54 33	9.2	2	14.9	>B9
179.0+2.6	2.9	05 53 44	31 05 34	11.7	1.5	13.7	>B8
180.0-1.7	1	05 39 09	27 51 38	30	1	11.0	>B9
184.6-5.8	2	05 34 31	22 00 58	1	1.5	13.0	>B9
189.1+3.0	1.5	06 17 01	22 34 52	7.5	3	13.9	>B7
192.8-1.1	2.3	06 09 25	17 19 25	13	1	12.7	>B8
201.1+8.3	0.5	06 58 50	13 55 52	170	0.1	8.1	>B9
205.5+0.5	1	06 38 41	06 27 17	36.7	0.2	9.6	>B9
206.9+2.3	3.4	06 48 41	06 26 35	8.3	0.5	13.3	>B4
211.7-1.1	2.4	06 45 44	00 20 47	11.7	1.2	12.7	>B8
240.9-0.9	1.8	07 42 35	-25 13 10	16	0.8	12.1	>B8
260.4-3.4	2	08 22 13	-42 59 40	9.2	1	12.5	>B9
261.9+5.5	3.3	09 04 17	-38 41 59	5.8	1	14.1	>B5
263.9-3.3	0.4	08 34 10	-45 45 22	42.5	0.5	9.0	>B9
266.2-1.2	1	08 52 00	-46 20	20	0.5	10.5	>B9
279.0+1.1	1.8	09 57 48	-53 14 21	15.8	1.7	12.9	>B8
296.5+10.0	1.8	12 09 37	-52 26 42	12.9	0.3	11.5	>B9
315.4-2.3	2.7	14 42 56	-62 29 45	7	1.8	13.8	>B8
326.3-1.8	2	15 52 58	-56 08 55	6.3	2.3	13.7	>B5
327.6+14.6	2	15 02 51	-41 55 45	5	0.5	12.0	>B9
330.0+15.0	0.8	15 08 14	-39 41 28	30	0	9.5	>B9

determined after analysing the existing data, are given in column 8. We may consider only the stars which are located within angular regions $\leq \theta/10$ around the geometrical centers of the SNRs, but it is also necessary to take into account the uncertainties in the geometrical centers of the SNRs. As seen from

Table 1, the largest distance and A_V values belong to SNR G109.1-1.0 (CTB 109) and a B9V type star in the direction and at the distance of this SNR must have $m_V = 16.5$. Practically, all the known data on most of the SNRs represented in Table 2 can be found in Guseinov et al [11-13].

Space velocity of runaway stars is roughly >30 - 40 km/s (Sayer et al [14]; Philp et al [15]). Most of them (~90%) have space velocities <80 km/s. If we take into account the changing character of values of the shock front velocities of SNRs (which are decelerated from ~10000 km/s down to ~300 km/s), then we can confidently say that almost all of the runaway stars can not go away more than 1/10 of the SNR's angular diameter (θ). Since the ages of SNRs practically are always $<5 \times 10^4$ years, runaway stars in SNRs can not go more than 4-6 pc in the plane perpendicular to the line of sight. In the case of SNRs which are young and/or expanding in low density environments (in particular inside HII regions created by the progenitor stars), the angular distance of runaway stars from the SN explosion points must be considerably smaller than $\theta/10$.

Far away SNRs in the Galactic center direction and the SNRs with large angular diameters are not considered in this work. For example, SNR G65.1+0.6 is at $d = 2.9$ kpc from the Sun and its diameter is ~70 arcmin. In the direction of this SNR the interstellar absorption, A_V, increases rapidly beyond 1.5 kpc and reaches a value of $3^m.3$ at distances close to the SNR's distance (Neckel & Klare [10]). A B9 type star in this SNR can be as dim as $m_V = 16$. Number of such dim stars in such a large area (with diameter ~11 arcmin) is very high that finding a B-type runaway star genetically connected to this SNR is difficult. Therefore, we did not include such SNRs in Table 2.

Some of the chosen SNRs (see Table 2) contain different types of point sources (single NSs). The data of these 14 point sources are represented in Table 1; names of the SNRs, morphological types of the SNRs, names of the point sources and ratio of the separation between the center of the SNR and the position of the point source connected to the SNR to the angular radius of the SNR are given in columns 1-4, respectively. The references are shown in the last column. As seen from Table 1, even the PSRs, which have space velocities on average 3-4 times larger than the space velocities of runaway stars, are located on the sky close to the centers of the SNRs, in general.

As mentioned above,for most of the possible OB runaway stars which we search in SNRs (more than 90% of the cases) the tangential velocity can be assumed as $V_t \leq 80$ km/s (Sayer et al [14], Philp et al [15]). Using this upper limit for V_t the maximum value of the proper motion is found to be (depending on the distance):

$$\mu \leq \frac{1}{50 \times d(\mathrm{kpc})} \text{ arcsecond/year} . \qquad (1)$$

The maximum proper motion values for possible OB runaways in the SNRs are represented in Table 3.

Table 3

POSSIBLE COLORS, VISUAL MAGNITUDES AND PROPER MOTIONS OF B9,B5, B0 TYPE STARS IN THE DIRECTIONS AND AT THE DISTANCES OF THE SNRs

l, *b*	B9V m_V	B9V-I B-V	B9V-I U-B	μ ("/yr)	B0V m_V	B5V m_V	B5V B-V	B0V B-V
1	2	3	4	5	6	7	8	9
6.4-0.1	14.5	0.61	0.63	0.008	9.9	12.9	0.45	0.31
18.9-1.1	14.5	0.61	0.63	0.007	10.0	13.0	0.45	0.31
32.0-4.9	15.3	0.85	0.92	0.008	10.7	13.7	0.79	0.55
34.7-0.4	15.7	0.85	0.92	0.007	11.1	14.1	0.79	0.55
43.9+1.6	15.4	0.76	0.81	0.007	10.8	13.8	0.60	0.46
54.4-0.3	16.4	1.06	1.17	0.006	11.8	14.8	0.90	0.76
65.3+5.7	10.3	0.09	0.008	0.025	5.7	8.7	-0.05	-0.21
69.0+2.7	12.3	0.37	0.188	0.015	7.6	10.6	0.11	-0.19
74.0-8.5	10.5	1.15	0.8	0.024	5.9	8.9	0.99	0.85
78.2+2.1	14.4	0.90	0.98	0.013	9.8	12.8	0.74	0.60
82.2+5.3	13.6	0.76	0.81	0.012	9.3	12.3	0.60	0.46
89.0+4.7	12.2	0.67	0.70	0.022	7.6	10.6	0.51	0.37
93.7-0.2	13.7	0.61	0.63	0.012	9.1	12.1	0.45	0.31
109.1-1.0	16.5	0.76	0.81	0.004	11.9	14.9	0.60	0.46
111.7-2.1	15.0	0.78	0.83	0.006	11.0	14.0	0.62	0.48
114.3+0.3	14.2	0.67	0.70	0.007	9.6	12.6	0.51	0.37
116.9+0.2	15.5	0.7	0.74	0.006	10.9	13.9	0.54	0.40
117.4+5.0	14.0	0.61	0.63	0.009	9.4	12.4	0.45	0.31
119.5+10.2	12.2	0.30	0.26	0.014	7.6	10.6	0.14	0.0
120.1+1.4	16.3	1.0	1.1	0.006	11.7	14.7	0.84	0.7
126.2+1.6	15.6	0.91	0.99	0.007	11.0	14.0	0.75	0.61
127.1+0.5	15.0	0.76	0.81	0.008	10.4	13.4	0.60	0.46
130.7+3.1	14.8	0.55	0.56	0.007	10.2	13.2	0.39	0.25
132.7+1.3	14.9	0.79	0.85	0.009	10.3	13.3	0.63	0.49
152.2-1.2	14.0	0.7	0.74	0.011	9.4	12.4	0.54	0.40
156.2+5.7	14.0	0.61	0.63	0.009	9.4	12.4	0.45	0.31
160.9+2.6	12.2	0.24	0.19	0.016	7.6	10.6	0.08	-0.06
166.0+4.3	15.4	0.61	0.63	0.005	10.8	13.8	0.45	0.31
179.0+2.6	14.2	0.45	0.44	0.007	9.6	12.6	0.29	0.15
180.0-1.7	11.5	0.30	0.26	0.02	6.9	9.9	0.14	0.00
184.6-5.8	13.5	0.45	0.44	0.01	8.9	11.9	0.29	0.15
189.1+3.0	14.4	0.91	0.99	0.013	9.8	12.8	0.75	0.61
192.8-1.1	13.2	0.30	0.26	0.009	8.6	11.6	0.14	0.00
201.1+8.3	8.6	0.03	-0.064	0.05	4.0	7.0	-0.13	-0.27
205.5+0.5	10.1	0.06	-0.028	0.025	5.5	8.5	-0.10	-0.24
206.9+2.3	13.8	0.15	0.08	0.005	9.3	12.3	-0.01	-0.15
211.7-1.1	13.4	0.36	0.33	0.008	8.8	11.8	0.20	0.06
240.9-0.9	12.6	0.24	0.19	0.011	8.0	10.9	0.08	-0.06
260.4-3.4	13.0	0.30	0.26	0.01	8.4	11.4	0.14	0.00
261.9+5.5	14.7	0.30	0.26	0.008	10.1	13.1	0.14	0.00

Table 3 (the end)

1	2	3	4	5	6	7	8	9
263.9-3.3	9.5	0.15	0.08	0.04	4.5	7.5	-0.01	-0.15
266.2-1.2	11.0	0.16	0.09	0.02	6.4	9.4	-0.10	-0.24
279.0+1.1	13.5	0.52	0.52	0.011	8.9	11.9	0.36	0.22
296.5+10.0	11.7	0.09	0.008	0.014	7.2	10.2	-0.07	-0.21
315.4-2.3	14.3	0.54	0.55	0.008	9.7	12.7	0.38	0.24
326.3-1.8	14.2	0.70	0.74	0.011	9.6	12.6	0.54	0.40
327.6+14.6	12.5	0.15	0.08	0.01	7.9	10.9	-0.01	-0.15
330.0+15.0	10.0	0.0	-0.1	0.064	5.4	8.4	-0.16	-0.3

Below, we use

$$E(U-B) = 1.27\,E(B-V) \tag{2}$$

and

$$E(V-R) = 0.72\,E(B-V) \tag{3}$$

given in Schlegel et al. [16] and the central wavelength values of 0.70μ, 0.55μ, 0.44μ and 0.36μ are used for R, V, B and U, respectively. So, for B9V-I type stars:

$$(U-B) = (U-B)_0 + E(U-B) = -0.1 + 1.27\,E(B-V) \tag{4}$$

and

$$(V-R) = (V-R)_0 + E(V-R) = 0.03 + 0.72\,E(B-V). \tag{5}$$

In order to find OB runaway stars in the regions of SNRs shown in Table 2, first of all, it must be searched if there are OB stars in these regions. For B9V-I type stars, $(B-V)$ and $(U-B)$ values are given in Table 3. To find these values the $E(B-V)$ values were used. The A_V and $E(B-V)$ values of the SNRs (or runaways) were found by using distance values of the SNRs and the dependences of A_V values on distances given in Neckel & Klare [10] for each small region on the sky. We have also used the values of $(B-V)_0$ and $(U-B)_0$ given in Gray [17].

In order to examine possible existence of OB stars located in the SNRs we have followed this method: first, we have analysed the characteristics of the stars which are in the directions within $\theta/6$ regions around the geometrical centers of the SNRs and which have m_V values up to 1 magnitude dimmer than the m_V values of the B9 type stars given in Table 3 (the data were taken from Guide 7 catalog [18]). Then, we have analysed the data on distances, proper motions, magnitudes, photometric and spectral characteristics and binarity. After this analysis, we have got a preliminary list of the candidate OB stars for which we continued to search for additional data which we have found in USNO catalog*. As seen from Table 2, there is no B9 or earlier type runaway

* *USNO A2/SA2.0 catalogue (www.projectpluto.com/datasets.htm)*

candidate star in many of the SNRs (in 16 and 26 of the 48 SNRs shown in Table 2, there is no candidate star with a spectral type equal to or earlier than B9 (≥ B9) and B8 (≥ B8), respectively). A list of 25 SNRs and possible candidates of runaway OB stars are represented in Table 4. The bright stars given in this table must be observed and examined to choose runaway candidates. In the other 7 SNRs it is difficult to search for runaway candidates, since there are large number of B-star candidates.

3. *Known Runaway Stars.* O and B-type runaway stars have space velocities >30 km/s. In some rare cases, a runaway star can have such a high velocity due to encounters between three or more stars in open clusters (Leonard & Duncan [19]), in other words, by some mechanisms other than the SN explosion in spectroscopic and close binary systems. On the other hand, it is known that it is not easy to observe low-mass companions of highly luminous OB stars. But it is also confidently known that binarity is very rare among runaway stars (Gies & Bolton [20]). This is an evidence that the dominant mechanism to form OB runaways is the SN explosion, so that, there must be genetic relations between runaway stars and SNe, in general. In most of the cases, lifetime of a SNR is only $<5 \times 10^4$ years. But the main sequence lifetime of O5V, B5V and B9V type stars are, respectively, 3×10^6 yr, 8.2×10^7 yr and 5.5×10^8 yr [21]. Therefore, the probability to find a known runaway star genetically connected to a SNR is very low, since the number of such stars is small.

There are a few lists of OB runaways given in the literature. In Sayer et al. [14], there are 40 runaway OB stars 22 of which are given also in Philp et al. [15] where a list of 44 runaway stars are given. None of these runaway stars are related to the SNRs given in Table 1, nor to other SNRs, with respect to both their coordinates and distances.Cruz-Gonzalez et al. [22] gives a list of 72 possible runaway O stars and none of them are within the SNRs, either.

Gies & Bolton [20] gives a list of 36 runaway stars 27 of which are also given in the lists mentioned above and the remaining 9 stars also do not have any genetic relations with the SNRs. In van Buren et al. [23], a list of 58 runaway stars with bow-shocks are given (22 of these stars are given also in the other lists). None of these 58 stars have genetic relation with the SNRs. It is necessary to note that X-ray binaries with high-mass optical companions (HMXBs) have high space velocities compared to ordinary O and B-type stars. O and B type companions of runaway HMXBs are not included in the number of ordinary (classical) OB runaways.

The total number of known runaway stars is 77, 36 and 41 of which are O and massive (high luminosity) B-type stars, respectively. In the region within 2 kpc from the Sun,there are about 55-60 OB runaways and most of these runaways might be formed due to Supernova explosions. The same region contains 9 HMXBs among which 4 of them have optical companions with masses $M > 12\,M_{\odot}$ and the other 5 HMXBs have optical companions with masses $M < 10\,M_{\odot}$ (Guseinov et al. [24]). All the 4 HMXBs with massive companions contain X-ray pulsars and 3 of them have optical companions with $M > 15.5\,M_{\odot}$. In the same region, there are 242 O-type stars given in the catalog of Cruz-Gonzalez et al. [22]. In the Galactic center region ($l = \pm 90^{\circ}$), there are 120 and 159 O-type stars up to 1 kpc and 2 kpc from the Sun, respectively. In the anti-center region up to 1 kpc and 2 kpc from the Sun, there are 27 and 83 O-type stars, respectively, in the catalogue of Cruz-Gonzalez et al. [22]. Naturally, these numbers of O-type stars can not be changed considerably in time, because O-type stars can easily be observed at such small distances.

According to Gies & Bolton [20] the fractions of runaway stars are: 10- 25% among O-type stars, ~2% among B-type stars and ~0.1-0.2% among A-type stars. In the region up to 2 kpc from the Sun, the ratio of the number of O-type runaways to the total number of O-type stars is 0.15 (36/242) and this is in accordance with the data given in Gies & Bolton [20]. According to Garmany et al. [25], number of O-type stars up to 1.8 kpc is 214 and within the region around the Sun between 1.8-2.5 kpc there are 192 O-type stars.Considering the difficulties related to searching for runaway O-type stars we may adopt the fraction of runaway O-type stars among all O-type stars to be close to 15%.

Under the supernova explosion in spectroscopic and close binaries with O-type or massive B-type components, not only single OB runaways, but also high mass X-ray binaries and several wide binaries with OB+NS components are formed which do not accrete enough to produce accretion based X-ray luminosity. OB +NS binaries are naturally included in the known OB runaway lists as single runaways because it is difficult to observe the orbital motion of OB stars in such systems and radio pulsar phenomenon must be supressed by the stellar wind. Many years after these ideas have been published (Zeldovich & Guseinov [26]) two binaries including runaway O-type star +NS have been observed (Boyajian et al. [27]).

4. *Discussion and Conclusions.* As mentioned above, average space velocity of PSRs is ~250-300 km/s and this corresponds to a kinetic energy of $\sim 10^{48}$ erg assuming the mass of the PSR to be $1.4\,M_{\odot}$. If we calculate the potential energy of a binary system (with a $10\,M_{\odot}$ companion and an orbital period of 5 days) just before the first SN explosion we find that the potential energy is also $\sim 10^{48}$ erg. SN explosion energy is $\sim 10^{49}$-10^{51} erg (Sollerman et al. [28]; Wright et al. [29]), so that, only a small part of the explosion energy is enough to disrupt even a massive binary system. This is well known

from the statistical investigations of optical and X-ray binaries [30,31]. Almost all of the radio pulsars are single NSs. Singleness and large space velocities of NSs and the ratio of runaway stars among O and B-type stars convincingly show that the dominant mechanism for the formation of runaway stars is the SN explosion. But naturally most of the NSs are formed from single O-type and massive B-type stars and from such stars in spectroscopic and wide binaries. Since the birth rate of radio pulsars is >50% of the supernova rate, most of them are not formed from close binary systems.

Table 4

SOME OB CANDIDATE STARS IN THE DIRECTIONS OF THE SNRs

SNR	GSC No.	m_V	Properties
1	2	3	4
G18.9-1.1	5698 1773	11.6, 12.0	$B-V$=0.4-0.6, $B-V$=0.3, $V-R$=0.2 μ = 0.0063, ~B0
	5698 2817	13.5, 13.4	$B-V$=0.4, $V-R$=0.2, ~B4
	5698 468	13.3, 13.7	$B-V$=0.7, $V-R$=0.4, farther, B5 - B0
	5698 963	13.2, 13.8	$B-V$=0.3, $V-R$=0.2, ~B5
G32.0-4.9	5132 7	9.82, 9.60-10.36	$B-V$=0.531, $B-V$=0.3, $V-R$=-0.1 μ = 0.005, Spect. B3, B0 - O9
G34.7-0.4	449 365	12.9, 13.3	$B-V$=0.6, $V-R$=0.4, B4 - B3
	449 273	12.9	$B-V$=0.6, $V-R$=0.3, B4 - B3
	449 137	12.9, 13.4	$B-V$=0.6, $V-R$=0.4, B4 - B3
G43.9+1.6	1044 734	13.3, 13.0	$B-V$=0.5, $V-R$=0.3, B4 - B5
	1044 1350	12.8, 13.8	$B-V$=1.1, $V-R$=0.6, B4 - B5
	1044 1408	13.8, 15.0	$B-V$=0.6, $V-R$=0.3, B9 - B8
	1044 256	12.9, 12.4	$B-V$=0.6, $V-R$=0.4, B5 - B3
G54.4-0.3	1609 1858	13.7, 14.0	$B-V$=0.9, $V-R$=0.6, B5 - B4
G78.2+2.1	3156 1420	12.9, 12.7	$B-V$=0.4, $V-R$=0.2
	3156 1955	13.7, 14.1	$B-V$=0.4, $V-R$=0.2
	3156 1430	12.4, 12.5	$B-V$=0.6, $V-R$=0.4
	3156 2093	13.7, 14.9	$B-V$=0.7, $V-R$=0.5
	3156 2154	13.9, 14.4	$B-V$=0.8, $V-R$=0.5
	3156 1974	13.9	$B-V$=0.5, $V-R$=0.4
G82.2+5.3	3572 372	11.2, 11.6	$B-V$=0.56, $B-V$=0.6, $V-R$=0.3 μ = 0.006, binary?
	3572 399	12.9, 13.1	$B-V$=0.6, $V-R$=0.4
	3572 604	12.5, 12.3	$B-V$=0.5, $V-R$=0.3
G89.0+4.7	3582 29	12.0, 12.5	$B-V$=0.5, $V-R$=0.3
G93.7-0.2	3602 449	12.9, 13.2	$B-V$=0.4, $V-R$=0.3
	3602 497	13.2, 13.6	$B-V$=0.6, $V-R$=0.3
	3602 586	11.8, 11.9	$B-V$=0.7, $V-R$=0.5
G109.1-1.0	3997 1897	13.4, 14.3	$B-V$=0.5, $V-R$=0.3
G114.3+0.3	4284 546	12.3, 12.5	$B-V$=0.7, $V-R$=0.4
	4284 884	12.4, 12.7	$B-V$=0.4, $V-R$=0.3

Table 4 (the end)

1	2	3	4
G116.9+0.2	4285 3110	13.3, 13.7	$B-V=0.4$, $V-R=0.2$
	4285 448	13.1	$B-V=0.5$, $V-R=0.3$
	4285 2960	13.7, 14.3	$B-V=0.4$, $V-R=0.3$
G126.2+1.6	4038 1950	11.6, 12.3	$B-V=0.66$, $B-V=0.3$, $V-R=0.2$
	4038 1594	12.7, 13.2	$B-V=0.6$, $V-R=0.3$
	4038 1089	12.4, 12.7	$B-V=0.6$, $V-R=0.3$
	4038 1949	13.5, 14.0	$B-V=0.5$, $V-R=0.3$
	4038 1388	12.7, 13.3	$B-V=0.6$, $V-R=0.4$
G127.1+0.5	4035 607	12.9, 13.3	$B-V=0.4$, $V-R=0.3$
G132.7+1.3	4050 2138	12.7, 12.9	$B-V=0.4$, $V-R=0.2$
	4050 1872	12.1, 12.6	$B-V=0.7$, $V-R=0.4$
	4050 2534	14.2, 14.1	$B-V=0.6$, $V-R=0.4$
	4050 2687	14.1, 14.6	$B-V=0.8$, $V-R=0.5$
	4050 1390	14.2, 14.6	$B-V=0.6$, $V-R=0.4$
	4050 2661	13.8, 14.0	$B-V=0.5$, $V-R=0.3$
	4050 2206	13.9, 14.1	$B-V=0.8$, $V-R=0.5$
G156.2+5.7	3356 425	13.4, 13.9	$B-V=0.6$, $V-R=0.4$
	3356 519	12.6, 12.7	$B-V=0.5$, $V-R=0.3$
	3356 147	13.8, 14.1	$B-V=0.6$, $V-R=0.4$
G179.0+2.6	2406 1616	12.6, 13.0	$B-V=0.4$, $V-R=0.2$
	2406 1722	13.8, 13.7	$B-V=0.1$, $V-R=0.0$
	2406 1041	14.0	$B-V=0.5$, $V-R=0.3$
	2406 819	12.6, 12.9	$B-V=0.3$, $V-R=0.2$
G189.1+3.0	1878 147	12.6, 13.2	$B-V=0.6$, $V-R=0.4$
G192.8-1.1	1318 5	12.4, 12.5	$B-V=0.4$, $V-R=0.2$
G206.9+2.3	160 2083	12.2	$B-V=1.1$, $V-R=0.6$
	160 2164	12.1	$B-V=0.7$, $V-R=0.5$
G211.7-1.1	148 1988	12.7	$B-V=0.31$, $B-V=0.3$, $V-R=0.2$, $\mu=0.012$
	148 2264	12.9, 13.3	$B-V=0.37$, $B-V=-0.3$, $V-R=0.2$ $\mu=0.006$, inside diffuse nebula
G240.9-0.9	6544 2319	11.9, 11.7	$B-V=0.1$, $V-R=0.0$
	6544 3996	11.3	
	6544 3995	10.97, 10.8	$B-V=0.213$, $B-V=0.1$, $V-R=0.0$
G279.0+1.1	8598 880	12.8, 11.3	$B-V=0.3$, $V-R=0.2$
	8598 1016	13.1, 12.3	$B-V=0.2$, $V-R=0.1$
	8598 1144	11.9, 11.4	$B-V=0.1$, $V-R=0.1$
	8598 794	13.1	
	8598 888	11.7, 11.2	$B-V=0.2$, $V-R=0.1$
	8598 848	13.3	
	8598 618	13.4, 12.5	$B-V=0.5$, $V-R=0.3$
	8598 1134	13.3, 12.6	$B-V=0.2$, $V-R=0.2$
G315.4-2.3	9011 4459	11.2	
	9011 4311	14.1, 13.8	$B-V=0.4$, $V-R=0.7$
	9011 4093	12.4, 12.0	$B-V=0.2$, $V-R=0.2$
	9011 4641	13.7	
G326.3-1.8	8701 1218	12.8, 12.7	$B-V=0.5$, $V-R=0.3$

Masses of O-type stars are $>16\,M_\odot$, whereas masses of B-type stars are in the interval $2.5\,M_\odot < M < 16\,M_\odot$ (see Table 4 and Gray [17]) and the mass function of stars has an exponential character with a large slope of about 2.3-3 (Schaerer [32]). On the other hand,masses of the progenitors of SNe on the main sequence are $>7\text{-}8\,M_\odot$ [5,6]. Therefore, the portion of runaways among O-type stars must be considerably larger than the one among B-type stars and this is also known from observational data [20]. But the number of stars with masses $7\,M_\odot < M < 16\,M_\odot$ is about one order of magnitude larger than the number of stars with masses $M > 16\,M_\odot$ and if we also take into consideration the lifetimes of O and B-type stars together with the mass ratio in binary systems (which have influences inversely proportional to each other), then we can conclude as follows: the number of runaway B-type stars is larger than the number of O-type runaways. In other words, SN explosions lead to birth of B-type runaways more often. Therefore, it is considerably more probable to observe B-type (rather than O-type) runaways in our sample of SNRs given in Table 2.

Depending on the value of slope of the mass function being 2.3 or 3 [32], the number of stars which must end their evolution by SN explosion in arbitrary unit time and which have initial masses in the interval $8\text{-}16\,M_\odot$ is 2-2.5 times larger than the stars with masses $>16\,M_\odot$. We can also assume that the mass ratio values of binary systems in these two intervals of mass (i.e. $8\text{-}16\,M_\odot$ and $>16\,M_\odot$) are similar to each other and most of the binary systems have mass ratio >1/4 [33-36]. Then, practically all the binary systems which are included in the former interval of mass and most of the binaries in the latter interval of mass must produce B-type runaways after the SN explosion. Therefore, we must search for B-type runaways in the SNRs. Of course, single stars and wide binaries do not form runaway stars after the explosion (in wide binaries the orbital velocity values are small). Since the number of spectroscopic and eclipsing binaries among OB-type stars constitute ~0.4-0.5 of the total number of OB-type stars, we can roughly expect to find runaway B-type stars in about a little less than half of the SNRs and,according to Iben & Tutukov [2], in each SNR which contain PSR.

Our analysis of the data of the stars which have projections on the central parts ($\theta/6$) of the SNRs show that none of the SNRs examined in this work include an O-type star as expected. Within 32 of the SNRs in our sample, there are B-star candidates and these stars should be observed to identify their spectral types. In the remaining 16 of the SNRs, there is no candidate B-type star. On the other hand, we expect to find B-type stars earlier than B8 ($M > 2.9\,M_\odot$) in only 23 of the SNRs in our sample based on the data of the progenitor mass ($>7\text{-}8\,M_\odot$) and the mass ratio of the components (>0.25). But it is difficult to estimate the number of runaways

Among the 7 SNRs which contain PSRs, 4 of them do not have B-type stars, therefore, the result given by Iben & Tutukov [2] should be re-analysed. Among the 8 SNRs which contain other types of NSs, 3 of them do not contain B-type stars (see Table 1). On the other hand, out of the 7 SNRs, 2 of them are F-type and 2 of them are C-type, in other words, they contain pulsars with large values of $\dot{E}$. But among the 8 SNRs which contain other types of NSs only 1 of them is not S-type and this is not related to a less precise search, because on average they are not more distant sources compared to the SNRs which contain radio pulsars. Therefore, these SNRs contain neutron stars with small values of $\dot{E}$ (Guseinov et al. [37]).

While examining the distances of NSs from geometrical centers of the SNRs which they are connected to, F-type SNRs should be excluded as such plerionic SNRs are formed by interaction between the strong (active) pulsar with the surrounding plasma. If we take this into consideration,the average distance of radio pulsars from the geometrical centers of SNRs is larger compared to the cases of other types of NS (see Table 1). This shows that radio pulsars have on average larger space velocities compared to other types of NS.We do not consider SNR G111.7-2.1 (Cas A) in this comparison,because this SNR is very young (age ~300 yr) that its point source is located at the geometrical (explosion) center of Cas A.

Radio pulsars in SNRs, which we consider in this work (see Table 1), also have high rotational velocity compared to 5 X-ray pulsars among the 8 NSs which belong to other types of NS. There is no PWN around these NSs (of other types) except CXOU J 061705.3+222127.

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ПОИСК УБЕГАЮЩИХ ОВ-ЗВЕЗД В ОСТАТКАХ СВЕРХНОВЫХ

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Поиск убегающих звезд в остатках сверхновых позволяет оценить отношение масс в двойных системах, в которых происходит вспышка сверхновой. Такой метод дает информацию также об относительном содержании спектроскопических и тесных двойных среди звезд главной последовательности с массами $>7-8\,M_{\odot}$. Более важно, что этим путем больше будем знать о пространственных скоростях и периодах вращения пульсаров. Мы искали убегающие ОВ-звезды в центральных частях 48 остатков сверхновых, находящихся на расстояниях, меньше 3 кпк. В 16-и остатках нашей выборки нет ни одного кандидата в звезды типов О или В, тем самым мы показываем, что пульсары (точечные источники) могут рождаться не только в спектроскопических и тесных двойных. Представлен список звезд, являющихся кандидатами убегающих звезд типа В, расположенных в остатках сверхновых. Спектроскопические исследования этих кандидатов могут дать возможность для решения вышеотмеченных проблем.

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