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A search for nonthermal radio emission from OB and WR stars with RATAN-600

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Abstract. We have searched for nonthermal radio emission from 40 OB and WR stars. Enhanced nonthermal radio emission from an early-type star could be evidence for the presence of a collapsed companion, and thus for its origin as the result of a supernova explosion in a massive binary. As shown in the evolutionary calculations of joint evolution of a neutron star and a normal star in binaries (Lipunov & Prokhorov 1987), a considerable fraction of neutron stars in binary systems having an optical companion must be in the ejector state. A neutron star in this state generates a relativistic wind like an isolated radio pulsar. Most ejectors in binary systems can not be identified as radio pulsars because of absorption of radiowaves in the stellar wind of the normal companion, but instead, they may appear as sources of high-energy quanta due to the synchrotron radiation of relativistic particles (ejected by the radio pulsar) in the magnetic field of a normal star (Lipunov & Prokhorov 1984; Lipunov & Nazin 1994). In this case a source of nonthermal radiation in a wide range from radio to hard gamma-ray may appear as a result of a specific reflection effect in the magnetic field of the optical companion. Cyg X-3 and the periodic radioburster LS I $+61^0303$ may be examples of just this kind. To test this idea, measurements of radio flux densities in the range from 0.96 to 21.7 GHz from selected OB and WR stars were made with the RATAN-600. No nonthermal radio emission from the selected stars were detected.

Key words: stars: early-type – stars: Wolf-Rayet – stars: binaries: close – radio continuum: stars – radiation mechanisms: non-thermal

1. Introduction

Early-type stars were expected to be detectable as sources of free-free radio emission, because their stellar winds form a large volume of dense, ionized gas (Panagia & Felli 1975; Wright & Barlow 1975). Quite unexpectedly, some early-type stars are now known to be strong sources of nonthermal emission. The nonthermal sources detected to date have been either the very luminous OB or Wolf-Rayet stars (Abbott et al. 1984), or the highly magnetic, helium peculiar, Bp-type stars (Drake et al. 1987). Radio emission from a Wolf-Rayet (WR) star was first detect toward γ^2 Vel by Seaquist (1976). Subsequently, more than 40 WR stars have been detected at radio wavelengths. It was initially thought that stellar radio radiation was produced only by free-free emission in an ionized wind and that this emission could be used to determine accurate stellar mass loss rates. Abbott et al. (1984) first suggested that not all the radio emission from massive stars is necessarily produced by a thermal wind. They showed that the time-variable nonthermal emission from several OB and WR stars may be produced by accretion onto an undetected compact companion.

One current explanation for the large peculiar velocities of runaway stars is that they result from supernova explosion in massive binaries. A search for relativistic objects among runaway OB stars has been carried out by several groups. Gies & Bolton (1986) conducted a search for time variations, indicative of orbital motion about a compact companion, in the radial velocities of 36 bright OB runaways. They also used existing X-ray observations of their candidates to search for evidence of accretion onto a neutron star (NS) or black hole. They found no evidence for compact companions. Philp et al. (1996) have conducted a VLA search for radio pulsars at the positions of 44 nearby OB runaway stars. No new pulsars were found in their survey. Sayer et al. (1996) have undertaken a search for pulsars towards 40 OB runaway stars with the NRAO 140ft telescope. Their survey was sensitive to long-period pulsars with flux densities of 1mJy or more. No pulsar companions to OB runaways were discovered. Up to now a high number of spectroscopic and photometric investigations of runaway stars have been performed. Periodic or quasiperiodic variability of radial velocities with amplitudes of $10-30$ km s^{-1} and periods of $1-100$ days has been suspected for several runaway OB stars. Strict periodicity is not proved yet. To search for relativistic objects among runaway stars is a very difficult observational problem, but it is a very important problem from the point of view of investigations of evolutions of high mass close binary systems. The recent discovery of the radio pulsar PSR B1259-63 in close binary system with a massive Be star is of a great significance in that respect. The orbital period of this Be binary pulsar system is about 3.4 years and the eccentricity of the orbit is very high,

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$e = 0.87$, which suggests a supernova explosion in high mass close binary system.

As shown in the calculations of joint evolution of neutron and normal stars in binaries (Kornilov and Lipunov 1983) a considerable fraction of neutron stars in binary systems having an optical companion must be at the ejector state. A neutron star in this state generate a relativistic wind like an isolated radio pulsar. It was also shown that for a remote observer some neutron stars in these binaries can appear as radio pulsars (Kornilov and Lipunov 1984). But the number of the binary radio pulsars with optical companions actually observed can be significantly suppressed for the absorption of radiowaves in the stellar wind of the normal companion. Illarionov and Sunyaev (1975) noted the fact that radiowaves with a wavelength longer than 75 cm, which make it possible to observe most of the radio pulsars, are absorbed effectively in the stellar wind of a normal star. The eclipse of pulsed radio emission from PSR B1259-63 for six weeks or more around periastron is evidence in favour of this assumption.

There is the important factor which helps (from the point of view of observation) in distinguishing neutron star in a binary system from a single NS. It should be recalled that most (99.99%) of the energy is dissipated by single radio pulsars in the form of relativistic particles and low-frequency electromagnetic waves which are not observable. In the case of a binary system, however, the normal star may trap a considerable part of the relativistic wind and convert it into a form in which it can be detected. This gives rise to an interesting analog of the classical reflection or heating effect (Lipunov & Nazin 1994). Thus, an ejecting NS in a pair with a normal star can appear as a new phenomenon — an “induced radiopulsator”. Synchrotron radioemission of relativistic particles captured by the magnetic field of the optical star must be strictly periodic due to the rotation of a normal star (Lipunov & Nazin 1994). The period of an “induced radiopulsator” may be confined to the interval of some hours to some days. This model was proposed by Lipunov & Nazin (1994) for the known source of variable nonthermal radiowaves at centimeter wavelengths, LS I $+61^0303$. In their model, the relativistic electrons injected by the radio pulsar are captured by the magnetosphere of the optical star when the pulsar passed near periastron. Then the captured electrons are cooled slowly due to synchrotron losses.

In this paper we report on the results of radio observations of selected OB and WR stars using the RATAN-600. We have mainly searched nonthermal radio emission from ejecting neutron stars appearing as an “induced radiopulsator” in binary system. In the first part we discuss evolutionary status of systems involved and describe the candidate selection, observations and reduction, and in the second part we discuss the results and present our conclusions.

2. Evolutionary status of (OB+CO) and (WR+CO) binary systems

The existence of binary OB and WR stars with relativistic companions is consistent with the modern evolutionary scenario for high mass close binary systems (Paczynski 1971; Tutukov & Yungelson 1973; van den Heuvel 1976; Kornilov & Lipunov 1983). The X-ray quiet OB star paired with compact object stage (OB+CO) follows the WR star + OB star stage (OB+WR), when the WR star explodes as a supernova. The binary system remains bounded because the less massive star in the system explodes. The newly formed (OB+CO) system remains X-ray quiet for a long time because the OB does not fill its Roche lobe (this is not true when an OB star is the Be star with strong rotationally induced equatorial wind). Also, the physical activity of a young neutron star (rapid rotation with strong magnetic field, ejection of relativistic particles) may prevent accretion of matter (Kornilov & Lipunov 1983). The remarkable peculiarities of these systems such as large peculiar velocities and high values of the distance from the Galactic plane, z, are due to a supernova explosion. According to the modern interpretation, at least several of the runaway stars are close binary (OB+CO) systems.

Just after the X-ray binary stage, when the OB star has transferred the main part of its hydrogen envelope to the relativistic object and away from the system, a Wolf-Rayet star paired with a compact object (WR+CO) may be formed. Wolf-Rayet stars formed as the result of the secondary mass exchange will have high space velocities and significant height out of the Galactic plane because they have kick velocities obtained due to supernova explosions in binary systems.

Tutukov & Yungelson (1973) and van den Heuvel (1976) put forward the idea that the WR stars located at the centres of ring nebulae may be considered as a (WR+CO) binary systems, i.e. the “second generation” WR stars containing relativistic objects as companions. Many candidates for (WR+CO) binary systems have been suggested recently (Cherepashchuk 1982). About a dozen “single” WR stars with high values of z and quasiperiodical spectral and photometric microvariability are suspected to be (WR+CO) binaries. Most of them are surrounded by ring nebulae. For many of these “single” WR stars strict periodicity is not proved, moreover, some short-term physical variability of these stars is suspected in many cases (Gosset & Vreux 1987; Vreux 1985; Vreux et al. 1985) with the periods about $0.3 - 0.5$ days which could be initiated by tidal effects in close binary systems. In the case of at least two WR stars (HD 50896/EZ CMa and HD 197406/V 1696 Cyg) their binary nature seems to be very probable. An important characteristic feature of (OB+CO) and (WR+CO) binaries is the presence of variable nonthermal radio emission, which may be due to the young neutron star activity.

3. Candidate selection and the expected radio flux densities

The source list includes 40 OB and WR stars selected as possible candidates of the close binary systems with unknown compact objects. All sources were selected based on their characteristic features (Cherepashchuk et al. 1996).

Characteristic features of (OB+CO) binary systems are the following:

1. Periodic microvariability of radial velocities of the OB star which is due to the presence of a relativistic object as a companion (the companion may also be an ordinary star).
2. A high value (up to 100 km s^{-1}) of the space peculiar velocity (the OB star in many cases is a runaway star), due to the kick that the binary system acquires after the supernova explosion. The idea of searching for relativistic objects among runaway OB stars was proposed by Shklovsky (1976).
3. A high value of $|z|$, the height above galactic plane, which is also due to the supernova explosion that occured in a (WR+OB) binary system.
4. The OB star may have anomalous chemical composition, in particular, it may be overabundant in the elements of the CNO group. This may be due to the enrichment of the atmosphere of the OB by CNO elements during the supernova explosion.
5. The presence in an (OB+CO) binary system of a radio pulsar or at least of variable nonthermal radio emission, which may be due to young neutron star activity.

Some pecularities for (WR+CO) stars may also be pointed out:

1. A high peculiar space velocity due to the supernova explosion in the binary system (OB+WR).
2. A large height $|z|$ above the Galaxy plane.
3. The presence of a ring nebula surrounding the WR star, which is formed in the stage of common envelope evolution.
4. Peculiar emission line spectra: variability of lines, the presence of emission lines with high ionization potential etc.
5. Strong and variable X-ray radiation due to accretion of matter from the stellar wind of the WR star onto the relativistic object. However, accretion of matter may be prevented by a rapidly rotating magnetized neutron star (the "ejector" or "propeller" regime) which is accumulated high angular momentum during secondary mass exchange in binary system. In this case the nonthermal radio emission may be present due to the young neutron star activity and a relativistic object can appear, e.g., as a radio pulsar or as an "induced radiopulsator" (Lipunov & Nazin 1994).

All selected OB and WR stars have at least one of the enumerated pecularities and have distances less than 4 kpc.

As a mechanism of nonthermal emission, the model of an "Induced Pulsator" proposed by Lipunov & Nazin (1994) was chosen. In their model the relativistic electrons injected by the radio pulsar (ejecting neutron star) are captured by the magnetosphere of the optical star when the pulsar passed near periastron. Then the captured electrons are cooled slowly due to the synchrotron losses. This model was successfully applied by Lipunov & Nazin (1994) to the radio source LS I $+61^0303$ data. Based on this model, expected radio flux densities at each frequency from a star at the distance d can be obtained. These flux densities at maximum of outburst are given in Table 1. A numerical integration code was used to calculate their values. It is known that the radio emission from LS I $+61^0303$ is characterized by nonthermal periodic outbursts of variable amplitude, with a period ~ 26.5 days (Taylor & Gregory 1982, 1984; Coe et al. 1983), assumed to be coincident with the orbital period of the system. Radio flares lasting several days occur every orbit. Between radio outbursts the flux density changes significantly, varying from tens to hundreds of mJy at the centimeter wavelengths. It should be noted that radio flares in similar binary systems with very long orbital period are difficult to detect as most of their radio variation can occur in a relatively small portion of the orbit and can be missed if the systems are observed at widely separated epochs.

Table 1. The expected radio flux densities at a maximum of outburst from a binary system at $d = 2$ kpc corresponding to Lipunov & Nazin (1994)

ν, GHz	0.96	2.3	3.9	7.7	11.2	21.7
Flux density, mJy	450	360	320	265	240	205

4. Observations

All sources from the list were observed from March 27 to April 4 1997 in the continuum with the RATAN-600 (Radio Astronomical Telescope Academy Nauk (science) of Russia). The main advantage of the RATAN-600 is the multi-frequency $(1 - 31$ cm wavelength) and the high brightness temperature sensitivity. Observations were made at the meridian transit with the North sector in the transit regime (Haikin et al. 1972) at frequencies of 21.7, 11.2, 7.7, 3.9, 2.3, and 0.96 GHz. The large focal spot without abberations formed by the RATAN-600 antenna system and the arrangement of feed-cabines with secondary mirrors allow us to measure the antenna temperatures of radio sources simultaneously at several frequencies. As detectors we have used broad band radiometers with low noise amplifiers (LNA) with high-electron-mobility transistors (HEMT), cooled to a temperature of 15 K (except for 13 cm and 31 cm) by closed cycle microcryogenic system (Berlin & Nizhelskii 1991). The receiver bandwidth was $5 - 10$% of the center frequency. The two-horn receivers at 1.4 cm, 2.7 cm and 3.9 cm were used in a two-beam modulation regime in order to account for the influence of the atmosphere. The single-feedhorn receivers at 7.6, 13 and 31 cm have a noise-added gain-balanced mode of operation. They have been used in a one beam modulation regime. The integration time for all receivers was 0.1 sec, but there is the possibility to reduce a data set to the optimal interval of sampling for different wavelengths without loss of sensitivity. The parameters of receivers and antenna for mean elevation (H = 46^o) are given in Tables 2 and 3.

The antenna temperature calibration was made with a signal from a calibration noise generator. This signal was fed to the radiometer 3 minutes before the source transit. Based on observations of secondary calibrators we derived the calibration of antenna temperatures. As secondary calibrators we used the radio sources 3C48, 3C147, 3C161, 3C286, DR21, NGC7027, 0237-23 and P2128+04. Their flux densities are taken from papers by Ott et al. (1994), Kuhr et al. (1981), Moellenbrock et

Table 2. The parameters of receivers for zero declination

Wave length cm	Central freq-cy GHz	Band width GHz	Sensi-tivity mK	Sensi-tivity mJy	T_{LNA} K	T_{sys} K
1.4	21.70	2.5	3.5	35	23	77
2.7	11.20	1.4	3	10	18	70
3.9	7.70	1.0	3	11	14	62
7.6	3.9	0.6	2.5	7	8	37
13.0	2.30	0.4	8	25	35	95
31.2	0.96	0.12	15	35	21	105

Note: the sensitivity of receivers is given for 1 second integration time; T_{LNA} — noise temperature of LNA; T_{sys} — noise temperature of antenna + radiometer system

Table 3. The parameters of radiotelescope for zero declination

Wave length cm	Central freq-cy GHz	Stokes para-meter	Positional angle of antenna	HPBW α arcsec	 δ arcmin
1.4	21.7	I	90	11	1.8
2.7	11.2	I	90	21	3.4
3.9	7.7	I	90	30	4.8
7.6	3.9	I	0	58	9.4
13.0	2.3	I	90	100	15.6
31.0	0.96	I	90	240	38.7

Table 4. The RMS errors on right ascension

f, GHz	0.96	2.3	3.9	7.7	11.2	21.7
δRA,sec	0.8	0.5	0.3	0.15	0.1	0.05

al. (1996), and Perley (1982) and linked to the absolute scale of Baars et al. (1977). Also the polarization parameters have been taken into account (Tabara & Inoue 1980). The flux densities of secondary calibrators calculated for the RATAN-600 frequencies are given in Table 5.

The reduction of observational data (written as FITS-files using the RATAN-600 data collection system (Chernenkov 1996)) consists of separating the useful signal from the system noise and the calculation of useful signal parameters. In processing we have used the priori information about the shape of source response for transit through the antenna beam. Separation of sources and an estimate of their parameters was made by Gaussian analysis of noise records (Verkhodanov, 1995) and by the optimum filtering procedure (Larionov, 1987). Firstly, the records were cleaned of interferences. The detection threshold was determined from the signal to noise ratio (S/N) and is equal to $2 - 3\sigma$ for weak sources. In Table 4 we give the RMS errors of right ascension for single measurement for mean elevations.

Since the accuracy of right ascension is efficiently high, in many cases weak sources can also be identified with confidence with the observed star even though the beam width in declination is very large (especially at low elevations).

5. Discussion of results and conclusion

No radio emission from the selected OB and WR stars was detected. In Table 6 the upper limits are given. Recall that we have mainly searched for ejecting neutron stars appearing as “induced radiopulsators” rather then ordinary radio pulsars. In order for the neutron star to be detectable as radio pulsar, the pulsar-optical star separation would have to be sufficiently large that the radio emission is not eclipsed by the stellar wind. The expected flux densities from OB+ and WR+ejecting NS systems fall in the range from tens to hundreds of milliJynsky at the centimeter wavelengths corresponding to the model of an *Induced Pulsator* (see Table 1).

The numerical simulation of the evolution of NS (Lipunov & Prokhorov 1987) shows that the fraction of ejecting neutron stars in massive systems with OB and WR components may be as high as several tens of percent of the total number of such binary systems containing neutron stars and black holes (see Lipunov & Prokhorov 1987). But the number of binary radio pulsars with optical companions actually observed can be significantly suppressed due to the presence of a massive stellar wind of a normal star. A more detailed computation carried out by Lipunov and Prokhorov (1984, 1987), as well as an independent study by Dewey and Cordes (1987), confirmed the original estimate that only about 0.5 percent of the total number of radio pulsars can reside in massive binary systems with optical companions. These calculations took into account such effects as radiowave absorption, radiation delay due to dispersion measure, and Faraday rotation in the magnetic field of the stellar wind from the optical companion. Thus, most ejecting neutron stars in massive binary systems can be detected only due to their indirect appearances, for example, as “induced radiopulsators” corresponding to the model by Lipunov & Nazin (1994).

The expected calculated radio flux densities is high enough but they are at a maximum of outburst. Between radio outbursts the radiation fluxes can change significantly. Binary systems with long orbital period and/or high value of eccentricity are difficult to detect as most of their radio variation can occur in a relatively small portion of the orbit and can be missed if the systems are observed at widely separated epochs. However, in this case, one might be able to detect the neutron star as a radio pulsar due to the sufficiently large pulsar-normal star separation.

Our negative results of the radio observations may indicate that 1) massive binaries tend to be disrupted when one member undergoes supernova; 2) involved systems have high values of orbital periods and/or eccentricities and we could miss radio outburst occuring in a relatively small portion of the orbit; 3) in such systems ((OB+CO) and (WR+CO) binaries) different a mechanism operates other than the “induced radiopulsator” one.

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Table 5. Flux densities of secondary calibrators

Object	Coordinates(1950)		Flux density (Jy) for different frequencies (GHz)					
	α	δ	0.96	2.3	3.9	7.7	11.2	21.7
3C 48	01 34 49.83	+32 54 20.5	21.90	10.91	6.88	3.63	2.50	1.24
$0237-23^{k,m}$	02 37 52.80	−23 22 06.2	6.61	5.59	3.99	2.20	1.48	0.70
3C 138	05 18 16.53	+16 35 26.8	11.25	6.66	4.71	2.87	2.09	1.13
3C 147	05 38 43.51	+49 49 42.8	29.62	14.80	9.41	5.07	3.54	1.82
3C 161	06 24 43.19	−05 51 11.8	24.10	12.80	8.11	4.16	2.76	1.40
$0923+39^{k,m}$	09 23 55.42	+39 15 23.5	2.21	4.63	9.08	13.43	12.97	10.3
$1245-19^{k,p}$	12 45 45.22	−19 42 57.5	6.78	4.29	2.99	1.76	1.28	0.70
3C 286	13 28 49.66	+30 45 58.6	17.20	11.52	8.57	5.53	4.22	2.49
DR 21	20 37 14.2	+42 09 07.0	5.0	12.10	17.40	21.67	20.72	19.1
NGC7027	21 05 09.4	+42 02 03.1	0.91	2.64	5.05	6.33	6.02	5.51
P2127+04	21 28 02.64	+04 49 04.2	4.60	3.20	2.37	1.60	1.30	0.89

Note: k - data from Kuhr et al.(1981), m - from Moellenbrock et al. (1996), p - from Perley (1982)

Table 6. Summary of the OB and WR stars observations with the RATAN-600

Star	Spectral type	d (kpc)	Flux density (mJy)					
			0.96 GHz	2.3 GHz	3.9 GHz	7.7 GHz	11.2 GHz	21.7 GHz
HD 17543	B6 V	0.19	< 190	< 40	< 17	< 30	< 40	< 140
HD 23466	B3 V	0.24	< 180	< 80	< 18	< 40	< 40	< 140
HD 24190	B2 V	0.72	< 400	< 150	< 19	< 30	< 40	< 180
HD 24912	O7e	0.53	< 370	< 100	< 24	< 30	< 50	< 140
HD 25799	B3 V	0.41	< 240	< 50	< 24	< 30	< 30	< 140
HD 30211	B5 IV	0.13	< 270	< 40	< 26	< 30	< 80	< 120
HD 37202	B2 IVe	0.15	< 490	< 70	< 13	< 50	< 40	< 180
HD 37737	O9.5 III	2.16	< 460	< 100	< 30	< 50	< 56	< 180
WR 6	WN4	1.56	< 200	–	< 25	< 50	< 80	< 210
WR 7	WN4	3.49	< 160	< 100	< 23	< 30	< 40	< 130
WR 8	WN7	3.47	< 120	< 70	< 87	< 60	< 50	< 250
WR 19	WC4	2.34	< 80	< 70	< 39	< 50	< 40	< 160
HD 138485	B3 V	0.40	< 90	< 50	< 22	< 90	< 40	< 130
HD 142096	B3 V	0.18	< 70	< 90	< 21	< 30	< 30	< 140
HD 143275	B0.2 IV	0.17	< 50	< 40	< 23	< 40	< 30	< 130
HD 149881	B0.5 III	2.50	< 100	< 40	< 19	< 30	< 40	< 160
WR 85	WN6	3.10	–	< 270	< 90	< 80	< 70	< 330
WR 86	WC7	1.95	< 210	< 170	< 63	< 110	< 80	< 230
WR 87	WN7	2.88	–	< 180	< 160	< 170	< 90	< 320
HD 161573	B4 V	0.26	< 120	< 50	< 19	< 20	< 20	< 110
WR 113	WC8+O8 V	2.00	–	< 80	–	< 50	< 40	< 190
WR 118	WC10	3.70	–	< 340	< 99	< 50	< 80	< 130
WR 121	WC9	2.06	< 440	< 150	–	< 160	< 68	< 190
HD 178329	B3 V	0.43	< 290	< 40	< 9	< 20	< 20	< 70
WR 125	WC7	2.13	< 190	< 50	< 12	< 20	< 20	< 80
WR 126	WC5	4.00	< 650	< 40	< 14	< 30	< 30	< 140
HD 188001	O8e	2.46	< 240	< 70	< 14	< 40	< 40	< 160
HD 188209	O9.5 I	2.32	< 450	< 40	< 15	< 30	< 20	< 80
WR 133	WN5+O9 I	2.09	< 410	< 60	< 19	< 40	< 30	< 100
WR 134	WN6	2.09	< 400	< 120	< 16	< 50	< 50	< 140
WR 135	WC8	2.09	< 390	< 110	< 15	< 30	< 40	< 190
WR 136	WN6	1.82	< 470	< 160	< 21	< 30	< 30	< 110
HD 198784	B2 V	0.36	< 250	< 50	< 12	< 20	< 20	< 80
HD 203064	O8 Ve	0.53	< 410	< 50	< 11	< 20	< 20	< 80
HD 207330	B3 III	0.25	< 290	< 80	< 16	< 20	< 30	< 90
HD 209961	B2 V	0.49	< 300	< 60	< 13	< 20	< 20	< 70
HD 214930	B2 IV	0.75	< 180	< 50	< 7	< 20	< 30	< 80

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