A Search for Pulsar Companions to OB Runaway Stars

R. W. Sayer[1]
Joseph Henry laboratories and Physics Department,
Princeton University, Princeton, NJ 08544

D. J. Nice[2]
National Radio Astronomy Observatory[3],
Edgemont Road, Charlottesville, VA 22903

V. M. Kaspi[4]
IPAC/Caltech/Jet Propulsion Laboratory,
770 S. Wilson Ave., Pasadena, CA 91125

ABSTRACT

We have searched for radio pulsar companions to 40 nearby OB runaway stars. observations were made at, 575 and 770 MHz with the NRAO 140 ft telescope. The survey was sensitive to long-period pulsars with flux densities of 1 mJy or more. One previously unknown pulsar was discovered, PSR J2044+4614, while observing towards target O star BD+45,3260. Follow-up timing observations of the pulsar measured its position to high precision, revealing a 9′ separation between the pulsar and the target star, unequivocally indicating they are not associated. The pulsar is ordinary, except that its dispersion measure, 315 pc cm^{-3}, is unusually high given its Galactic longitude $l = 85°$, Based on the non-detection of pulsars bound to target stars, we place a 95% confidence limit of 8% for the fraction of OB runaways having presently detectable pulsar companions. Assuming 30% of pulsars beam toward us and assuming most, young pulsars have luminosities above our detection threshold, we place an upper limit of 27% on the fraction of OB runaways with pulsar companions.

Subject headings: Pulsars: General - Stars: Early- Type Stars: Binaries: General - Pulsars: individual: J2044+4614

---

[1] E-mail: ron@pulsar.princeton.edu

[2] E-mail: dnice@nrao.edu

[3] Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

[4] Hubble Fellow; E-mail: vicky@ipac.caltech.edu

1. Introduction

Recently, two radio pulsar--main sequence binary systems were discovered. The first of these, PSR B1259–63, is a 48 ms radio pulsar in a highly eccentric, 3.3 yr orbit with a main-sequence Be star (Johnston *et al.* 1992). The second system, PSR J0045–7319, contains a 926 ms pulsar in an eccentric 51-day orbit with an otherwise normal B star (Kaspi *et al.* 1994). Both of these pulsars were discovered in general surveys that were not specifically directed towards binary systems or main sequence stars.

The systems fit neatly into a simple model of massive binary evolution. In a bound system of two stars, the more massive star evolves more quickly. During its giant phase, it transfers matter to its companion, leaving a relatively light helium core. This stellar core eventually explodes as a supernova, producing a neutron star. Because the majority of the system mass at the time of the explosion is in the companion, the system (consisting of the companion star and a neutron star remnant) would remain bound if mass loss during the supernova event, were symmetric (see, for example, Paczyński 1971 or Verbunt 1993).

In practice, it is known that supernovae cannot be completely symmetric. The strongest evidence for this is that the vast majority of pulsars are single stars, even though most of their progenitors are thought to have evolved in binary systems. By the simple evolutionary argument above, an asymmetric supernova explosion is required in most cases to eject the neutron star from the system. (The only way around this conclusion is to posit a large population of "hidden" neutron stars enshrouded in unevolved massive companions.) Detailed modeling of the pulsar population by Dewey & Cordes (1987) confirmed that asymmetric supernovae are required to produce the observed radio pulsar velocity distribution and binary fraction. A recent analysis suggests that true radio pulsar velocities are even higher than those used by Dewey & Cordes, exacerbating the need for strong kicks (Lyne & Lorimer 1994).

Under this scenario, the binary system may or may not be disrupted, depending on the orientation and magnitude of the supernova kick (Brandt & Podsiadlowski 1995 and Leonard & Dewey 1993). in either case, the remaining main-sequence star will be given a large velocity boost, likely becoming an OB runaway star. The precise definition of the OB runaway population varies somewhat, but typical defining parameters are a lower velocity limit of 25–40 $\mathrm{km\,s^{-1}}$ and/or an unusually large distance from the Galactic plane. A majority of stars in OB associations are in binary or multiple systems, but a much smaller fraction of the OB runaway population has clearly identified binary companions (Gies 1987). Blaauw (1961) extensively studied the OB runaway population, and concluded that they attained their high velocities as the result of rapid mass loss by binary companions, possibly via type II supernovae, a suggestion first made by Zwicky (1957). Gies & Bolton (1986) have formulated an alternate theory, in which OB stars are dynamically ejected from dense OB associations. However, their scenario does not exclude the likelihood that at least some OB runaways are ejected by the binary/supernova scheme.

If a neutron star remains bound to the main sequence companion of its progenitor, its presence might be detected in several ways. Sufficiently tight systems could be distinguished by spectroscopic variations due to orbital motion of the OB star. Several authors have surveyed runaways for evidence of orbital Doppler shifts from unseen companions (Gies & Bolton 1986; Stone 1982). However, this method has practical difficulties, as OB star atmospheres exhibit variability, limiting spectral velocity measurements to resolution of order 10 km s^{-1}. Further, highly eccentric systems (such as those of PSRs B1259–63 and J0045–7319) are particularly difficult to detect as most of their spectroscopic variation occurs on a timescale relatively short compared to the interval between observations. No compact companions to OB runaways have been detected by this method.

Alternatively, such a system might be observable as a high-mass X-ray binary (HMXB). HMXBs are systems in which a neutron star accretes matter from a massive star, either an evolved star, which overflows its Roche lobe, or a Be star, which loses mass via a stellar wind. Similarities between the kinematics of HMXBs and OB runaways suggest that HMXBs are in fact runaway stars with neutron star companions (van Oijen 1989). However, attempts to detect excess X-ray emission from runaway OB stars have not been successful (Kumar, Kallman, & Thomas 1983).

Finally, one might be able to detect the neutron star directly if it is a radio pulsar. In order for the neutron star to be detectable in this way, the pulsar- OB star separation would have to be sufficiently large that the radio emission is not eclipsed by the stellar wind, either due to quenching from infalling matter, or because of reflection, absorption, or dispersion in the wind. Indeed, the pulsed radio emission from PSR B1259–63 is eclipsed for 6 weeks around periastron (Johnston *et al. 1995).* However, radio observations of PSR J0045– 7319, which is seen throughout its orbit, suggest eclipse by any of the above mechanisms is unlikely for all but the tightest, or most eccentric, orbits around non-emission-line objects (Kaspi, Tauris, & Manchester 1995). Thus a search for pulsar companions to OB runaways is complementary to spectroscopic and X-ray searches, being most sensitive to systems with wide orbital separations and high eccentricities, precisely where the other methods fail.

We have undertaken a search for pulsars towards 40 OB runaway stars. The search is described in § 2 and § 3. No companions to the target stars were found, but one pulsar not associated with an OB star was discovered. Pulse timing observations of this source are described in § 4, and implications of our results are discussed in § 5. We are aware of two similar searches which have been made with somewhat different target lists (Kaspi, Manchester & D'Amico, in preparation; Philp 1995).

2. Search Observations and Analysis

Our source list of 40 O and B stars was garnered from lists compiled by Benkenstein & Bowers (1974), Stone (1979), Garmany, Conti, & Massey (1980), Stone (1982), Gies & Bolton (1986), and Gies (1987). These targets are all runaway stars, indicated either by anomalously high space velocities (typically 25 km s^{-1} or higher) or large distances from the Galactic plane. None of the target stars is known to be in a binary system.

Observations were made using the 140 ft (43 m) telescope at Green Bank, West Virginia, at 575 and 770 MHz. The observing frequencies used for individual sources were determined by telescope scheduling constraints. The telescope beam width (FWHM) was 52' at 575 MHz and 39' at 770 MHz. A digital Fourier transform spectrometer synthesized 512 spectral channels across a 40 MHz bandwidth in each of two polarizations, boxcar averaging for intervals of 1.024 ms. Spectra from opposite polarizations were summed, and power levels reduced to 1 bit (by comparison to a running average with 4s time constant) and written to magnetic tape. Each source was observed for 2^{22} sample intervals, or about 71.6 minutes.

To reduce the computational requirements of the project, power n Immurements from sets of eight adjacent spectral channels were summed for observations at 575 MHz, and sixteen channels were summed at 770 MHz. Despite the reduced frequency resolution, smearing of signals due to differential delays in the resulting pseudo-channels was no more than 1 ms for pulsars with dispersion measures up to 40 pc cm^{-3}, the range expected for the distances and Galactic latitudes of these stars.

The data set for each source thus consisted of a matrix of 2^{22} power level measurements in each of 64 frequency channels (32 channels for observations at 770 MHz). From these matrices we generated one-dimensional time sequences corresponding to 448 distinct dispersion measures from 0 to 2400 pc cm^{-3} (224 dispersion measures from 0 to 2900 pc cm^{-3} for observations at 770 MHz). Each time series was searched for pulsar-like signals: a Fourier power spectrum was calculated and searched for strong peaks both in single bins and in harmonically related sets of 2, 3, 4, 8, and 16 bins. Periods corresponding to bins with high signal-to-noise ratios were examined in the time domain (by inverting the Fourier complex coefficients at the candidate frequency and its harmonics), and signals which did not resemble pulsars (in particular, signals without relatively narrow peaks) were rejected. Details on the most promising pulsar candidates were recorded for visual inspection and possible re-observation. The algorithm used was essentially that of Nice, Fruchter, & Taylor (1995), and a more detailed analysis of the search procedure can be found in that paper.

The system noise temperature varied from source to source due to variations in sky background noise; typical values were 80 K at 575 MHz and 60 K at 770 MHz. The telescope gain was 0.29 K Jy^{-1}. Based on this gain, the 60 K system temperature, the *71.6* minute integration time, the 40 MHz bandwidth, and the use of two polarizations, the minimum detectable flux density was 1 mJy for long period, small duty cycle pulsars. The sensitivity was somewhat worse for pulsars with high dispersion measures (due to differential dispersion delays within spectral channels) and for pulsars with short periods (due to the finite sample interval). The calculated sensitivity as a function of dispersion measure and period is given in Figure 1.

Radio frequency interference of terrestrial origin is often a problem at low radio frequencies, and these observations were no exception. Data from six of our 40 runaway stars were contaminated by interference, usually manifested as numerous false "detections" by the pulsar search code. Because there is some possibility of detecting a pulsar even in the presence of interference, we have included all the target sources in Table 1. However, the sensitivity to weak pulsars in the direction of these sources was significantly reduced.

3. Search Results

We discovered one pulsar, PSR J2044+4614, while pointing towards target star BD+45,3260. The pulsar and target star are not associated (see § 4).

4. Observations of PSR J2044+4614

Timing observations of PSR J2044+4614 were made at regular intervals between July, 1994 and July, 1995, using the 140 ft telescope at 575 and 800 MHz. The timing measurements used the same spectrometer as the search observations, but since the pulsar period was known, the incoming data could be folded on-line, which allowed us to retain and process data with full amplitude precision and frequency resolution. Data collection and analysis procedures were identical to those of Arzoumanian *et al.* (1994). The pulse profiles at 575 and 800 MHz are shown in Figure 2.

The pulse arrival times were analyzed with the TEMPO code (Taylor & Weisberg 1989), incorporating astrometry based on the Jet Propulsion Laboratory DE200 ephemeris. Parameters derived from the timing model are given in Table 2. An isolated pulsar model fits the data well-there is no evidence for binary motion. The position of the pulsar differs from that of the target star BD+45,3260 by $9'$. Thus there is no doubt that the pulsar and star are not associated, but represent a chance superposition within the telescope beam.

The dispersion measure of this pulsar, 315 pc cm^{-3}, is a factor of 2 higher than those of other pulsars near Galactic longitude $l = 85°$ and near the Galactic plane, and is not readily accommodated by the smoothed-out electron density distribution model of Taylor & Cordes (1993). Several large HII regions in the Perseus arm of the Galaxy lie close to the pulsar's direction (Georgelin & Georgelin 1976). We consider it likely that the pulsar lies behind an unusually dense concentration of ionized material.

5. Discussion

We found no pulsars orbiting around 34 target OB runaway stars for which high quality data were collected. This result can be used to place a formal limit on the fraction of OB runaways with detectable pulsar companions. Let f be the probability that an OB runaway has a pulsar companion visible to us (i.e., above our threshold luminosity and beaming towards us). Then $(1 - f)$ is the probability of not detecting a pulsar around a given OB star, and $P(f) \equiv (1 - f)^n$ is the probability of not detecting any pulsars around $n = 34$ stars. A straightforward Bayesian analysis shows that f_{95}, a 95% confidence upper limit to f, can be calculated from

$$\frac{\int_0^{f_{95}} P(f)\,df}{\int_0^1 P(f)\,df} = 1 - (1 - f_{95})^{n+1} = 0.95, \tag{1}$$

which yields $f_{95} = 0.08$.

Placing a formal limit on the number of OB runaway stars with pulsar companions, detectable or not, is less straightforward. Due to pulsar beaming effects, not all pulsar companions to OB stars would be visible to us. The beaming fraction of pulsars is poorly known. Often the fraction that beam toward the Earth is assumed to be 20%, but for relatively young pulsars, as would be expected in orbit around a massive main sequence star, the beaming fraction is probably somewhat larger (e.g. Narayan & Vivekanand 1983). The pulsar luminosity function, usually analyzed independently of the beaming fraction, is also poorly understood. Narayan and Ostriker (1990) found a model with radio luminosity a function of the spin-down luminosity that describes their sample of pulsars well (their model "b"); this model suggests nearly all pulsars of age 8 x 10^6 or less (typical OB runaway ages) at the distances of our target stars would be above our luminosity threshold. Using this model and a beaming fraction of 30% we calculate that at most 27% of OB runaways have pulsar Companions. Omitting the six emission line stars from the sample (since the effects of the stellar wind may render their pulsar companions more difficult to detect), under the same assumptions, we conclude that at most 33% of OB runaway have pulsar companions. However we caution that it has been shown that models of the luminosity function below 10 mJy kpc^2 are heavily influenced by small number statistics because of pulsar survey selection effects (Lorimer et al. 1993), so our limits may be underestimates if there exists a large low **luminosity** pulsar population.

To summarize, our observations show that at most 8% of OB runaways have detectable pulsar companions, and that with tentative assumptions about the beaming fraction and luminosity function of pulsars, most OB runaways do not have any pulsar companions. This finding is complementary to spectroscopic searches for OB binaries (Gies & Bolton 1986, Stone 1982) and searches for X-ray emission from OB runaways (Kumar, Kallman, & Thomas 1983). Our observations were particularly sensitive to wide and/or eccentric binary systems, which would have been missed by the other search methods. No evidence has been found for neutron star companions to OB runaways. Since most O and B stars are formed in binaries, this supports the conclusion that massive binaries tend to be disrupted when one member undergoes supernova.

We thank S. Johnston for helpful discussions. The 140ft telescope is a facility of the National Radio Astronomy Observatory, operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation. VMK received support, from a Hubble Fellowship through grant number HF-1061.01-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract

NAS5-26555. Part of this research was carried out at the Jet Propulsion laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

‘1’able 1. Target OB Runaway Sims

Target Star	α (1950)	δ (1950)	Spectra] Type	Distance (kpc)	Frequency (MHz)	Reference[a]
HD4142	00’’41’’’39’	+47°35′26″	B5V	0.17	575	1
13s1)1117	01 04 36	+60 29	B5V	1.5-2.4	770	1
BD+60,169	01 05 51	+61 1230	B1V	2.0	770	1
BD+62,338	01 58 33	+62 36 04	B0.5V	2.64	770	1
111113268	02 08 03	+55 5526	O8Vnn	2.5	770	1
111)14220	02 16 15	-t-52 19 54	B2V		770	3
111)14633	0 2 19 46	+41 1512	O8.5V	2.48	770	2,4,6
111)19374	0 3 0 4 36	+17 4118	B2V	0.36	770	1
111)20218	03 13 22	+47 56 47	B2V	1.0–1.4	575	1
111)30650	04 47 58	+43 29 39	B6V		770	3
1I 1)34078	05 13 00	+34 1525	O9.5Ve	0.44	575	1
111)36576	05 30 36	+18 3023	B2IV-Ve		575	3
111)38666	05 44 08	--32 19 27	O9.5V	0.57	770	1
111)39478[b]	0 5 50 53	+26 2448	B2V	0.85-1.20	575	1
111)39680	05 51 55	+13 5048	O6V		770	3
111)41161	06 02 04	-t-48 1515	O8V		575	4,5
111)41534	06 02 29	–32 1012	B2.5V	0.26	770	1
111)43112	06 12 18	+13 5204	B1V		770	3
111)51480	06 54 48	- 1 0 4 5 2 4	B5p	0.35–0.40	770	1
HD78584	09 10 42	+79 29 22	B3	().78–0.89	770	1
111)93521	10 45 34	+37 5005	O9.5V	1.08	575	6
111)97991”	11 13 39	--03 11 57	B1V	0.76	575	1
111)149363”	16 31 48	- 0 6 0 1 5 9	B0.5V		770	3
111)149757	16 34 24	–10 2803	O9V	0.17	770	1
111)152623	16 52 46	–40 3454	0 7 V		770	5
111)151397	16 45 23	- - 3 9 4 1 0 2	B0.5V	2.3	770	1
111)157857	17 23 31	–lo 5701	0 7 e	2.4	575	1
111)172488[b]	18 38 04	–08 4558	B0.5V		770	3
111)175876[b]	18 55 13	–20 29 31	0 7		770	5
111)187567	19 47 52	+ 0 7 4 6 3 0	B2.5IVe		770	3
111)195907	20 31 04	+31 29 09	B1 .5V	0.53–0.65	770	1>3
111)197419	20 40 25	-t-35 16 34	B2Ve	0.54	575	1,3
BD+45,3260[c]	20 43 54	+46 1003	O9V	1.74	770	1
HD201345	21 05 52	+33 1140	O9p		770	3
111)201910”	21 09 28	+-40 5847	B5V	0.48	770	1,3
1 I 1)203064	21 16 35	-t-43 4405	O8Ve	0.88	770	5>6

Table 1— Continued

Target Star	α (1950)	δ (1950)	Spectral Type	Distance (kpc)	Frequency (MHz)	Reference[a]
HD206327	21 37 38	+61 19 46	B2V		770	4
HD235807	22 19 17	+55 17 56	B0.5IV	2.8	770	1
HD214930	22 39 02	+23 35 06	B2IV	0.44	770	1,3
HD216534	22 50 48	+49 35 56	B3V	0.83	770	1

[a] References: (1) Bekenstein & Bowers 1974; (2) Stone 1982; (3) Gies & Bolton 1986; (4) Stone 1979; (5) Garmany, Conti, & Massey 1980; (6) Gies 1987.

[b] Contaminated by terrestrial interference — reduced sensitivity to pulsars.

[c] Pulsar found nearby.

Table 2: Parameters of PSR J2044+4614.[a]

Right ascension (J2000)	$20^h44^m58\overset{s}{.}7(2)$
Declination (J2000)	$+46°14'54''(2)$
Period (s)	1.3927154634(2)
Period derivative	$6.8(8) \times 10^{-16}$
Epoch of period (MJD)	49700.0
Dispersion measure ($pc\,cm^{-3}$)	315.2(2)
Flux density at 575 MHz (mJy) . . .	1.5
Galactic Longitude (deg.)	85.4
Galactic Latitude (deg.)	2.15

---

[a] Figures in parentheses represent 2σ uncertainties in the least significant digit.

REFERENCES

Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, Aid, 422, 671

Bekenstein, J. D. & Bowers, R. L. 1974, ApJ, 190, 653

Blaauw, A. 1961, Bull. Astr. Inst. Netherlands, 15, 265

Brandt, N. & Podsiadlowski, P. 1995, MNRAS, 274, 461

Dewey, R. J. & Cordes, J. M. 1987, ApJ, 321, 780

Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 1063

Georgelin, Y. M. & Georgelin, Y. P. 1976, A&A, 49, 57

Gies, D. R. 1987, ApJS, 64, 545

Gies, D. R. & Bolton, C. T. 1986, ApJS, 61, 419

Johnston, S., Manchester, R. N., Lyne, A. G., Bailes, M., Kaspi, V. M., Qiao, G., & D'Amico, N. 1992, ApJ, 387, L37

Johnston, S., Manchester, R. N., Lyne, A. G., D'Amico, N., Bailes, M., Gaensler, B. M., & Nicastro, L. 1995, MNRAS. submitted

Kaspi, V. M., Johnston, S., Bell, J. F., Manchester, R. N., Bailes, M., Bessell, M., Lyne, A. G., & D'Amico, N. 1994, ApJ, 423, L43

Kaspi, V. M., Tauris, T. M., & Manchester, R. N. 1995, ApJ. Submitted

Kumar, C. K., Kallman, T. R., & Thomas, R. J. 1983, ApJ, 272, 219

Leonard, P. J. T. & Dewey, R. J. 1993, in Luminous High-Latitude Stars, ed. D. D. Sasselov, Astron. Sot. Pac. Conf. Ser. Vol. 45, 239

Lorimer, D. R., Bailes, M., Dewey, R. J., & Harrison, P. A. 1993, MNRAS, 263, 403

Lyne, A. G. & Lorimer, D. R. 1994, Nature, 369, 127

Narayan, R. & Ostriker, J. P. 1990, ApJ, 352, 222

Narayan, R. & Vivekanand, M. 1983, A&A, 122, 45

Nice, D. J., Fruchter, A. S., & Taylor, J. H. 1995, ApJ. In Press

Paczyński, B. 1971, ARAA, 9, 183

Philp, C. J. 1995, BAAS, 27, 880

Stone, R. C. 1979, ApJ, 232, 520

Stone, R. C. 1982, ApJ, 261, 208

Taylor, J. H. & Cordes, J. M. 1993, ApJ, 411, 674

Taylor, J. H. & Weisberg, J. M. 1989, ApJ, 345, 434

van Oijen, J. G. J. 1989, A&A, 217, 115

Verbunt, F. 1993, ARAA, 31, 93

Zwicky, F. 1957, Morphological Astronomy, (Berlin: Springer Verlag)

This preprint was prepared with the AAS LaTeX macros v4.0.

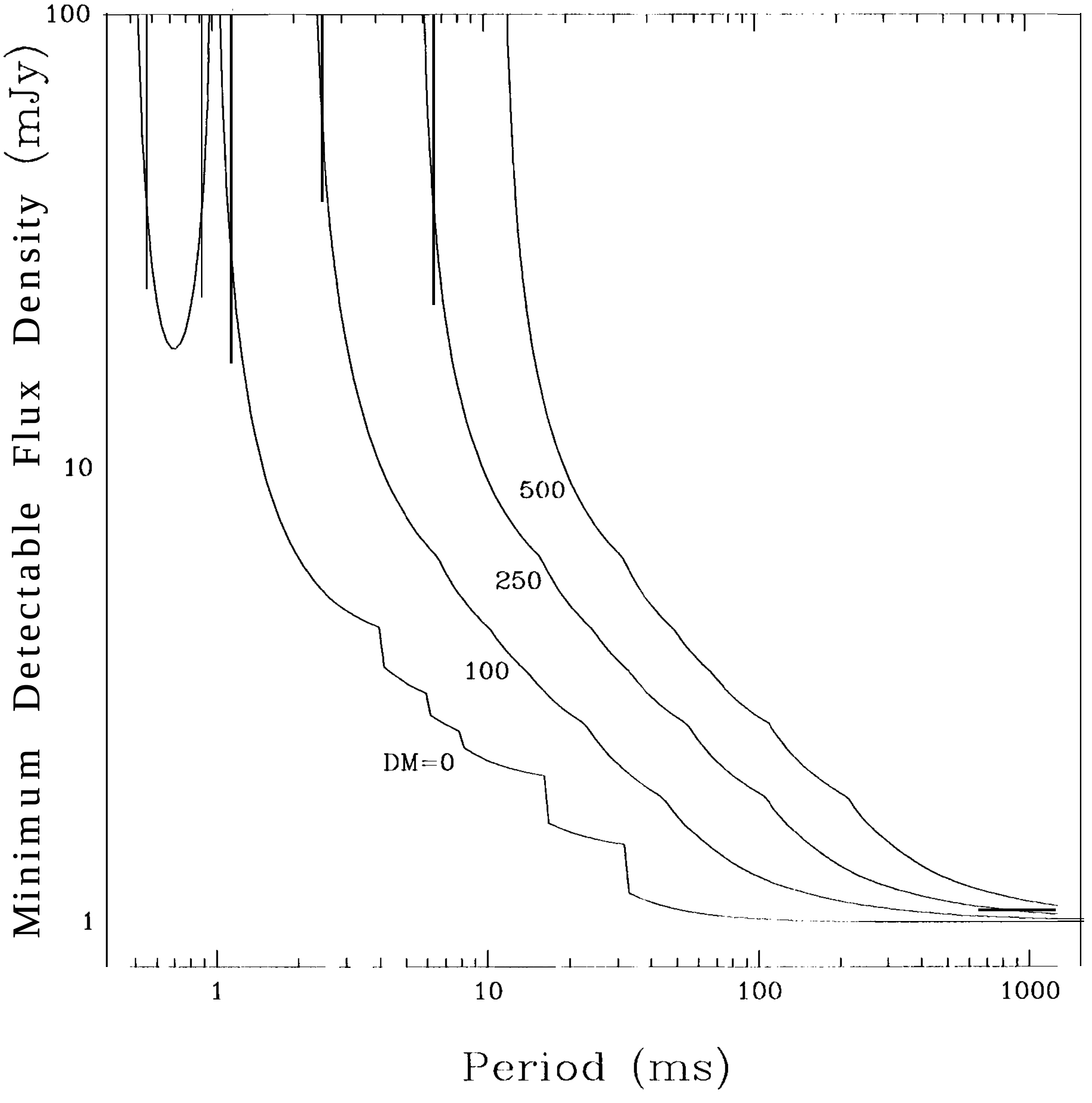

Fig. 1.- Calculated minimum detectable flux density limits for pulsars with dispersion measures of 0, 100, 250, and 500 pc cm^{-3} at an observing frequency of 770 MHz. Sensitivity was similar at 575 MHz. Discrete steps in the curves are a consequence of our search algorithm.

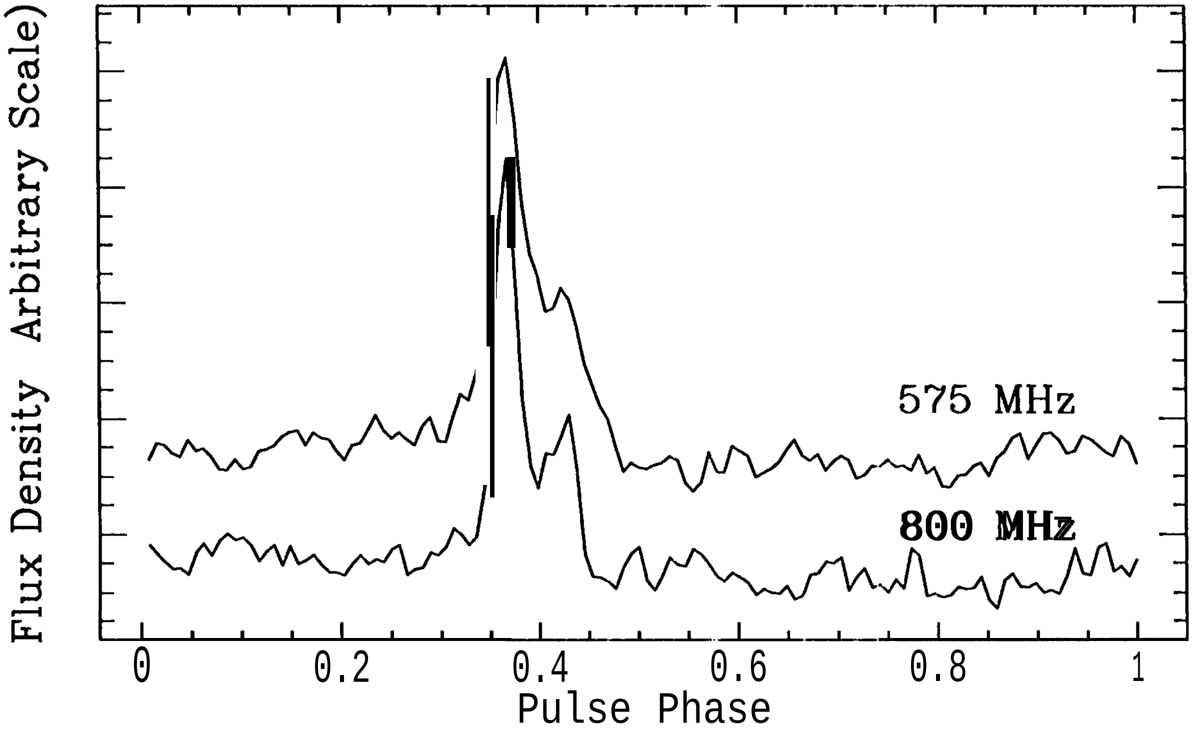

Fig. 2.- Radio emission patterns of PSRJ2044+4614 at 575 and 800 MHz over one pulse period.