Mon. Not. R. Astron. Soc. **267**, 125–128 (1994)

Two radio pulsars in the globular cluster NGC 6624

J. D. Biggs,[1,2,3] M. Bailes,[1] A. G. Lyne,[1] W. M. Goss[4] and A. S. Fruchter[5]

[1] *University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield SK11 9DL*
[2] *Universities Space Research Association, NASA/Goddard Space Flight Center, Mail code 681, Greenbelt, MD 20771, USA*
[3] *Department of Applied Physics, Curtin University of Technology, PO Box U1987, Perth, Western Australia 6001*
[4] *National Radio Astronomy Observatory, Very Large Array, PO Box 0, Socorro, NM 87801, USA*
[5] *Astronomy Department, University of California, Berkeley, CA 94720, USA*

Accepted 1993 October 7. Received 1993 September 1

ABSTRACT

We report the discovery and accurate timing measurements of two single radio pulsars in the globular cluster NGC 6624. PSR 1820 − 30A is a 5-ms pulsar that is located close to the low-mass X-ray binary 4U 1820 − 30. It seems that the recently reported radio detection of 4U 1820 − 30 with the VLA is, in fact, that of the pulsar. The observed period and period-derivative of PSR 1820 − 30A make it disturbingly young, and also conflict with the accretion spin-up theory unless acceleration in the cluster potential is largely responsible for the observed period-derivative. This requires that the cluster core lies much closer to the pulsar than has been believed hitherto. Such an explanation may also explain the anomalous orbital period-derivative of 4U 1820 − 30. PSR 1820 − 30B has a pulse period of 378 ms, which is unusually long for a pulsar associated with a globular cluster, and also has an unusually large inferred magnetic field. If the neutron star is primordial, then this suggests that its magnetic field has decreased only slightly, if at all, since its formation.

Key words: stars: individual: 4U 1820 − 30 – stars: magnetic fields – pulsars: individual: 1820 − 30A – pulsars: individual: 1820 − 30B – globular clusters: individual: NGC 6624 – X-rays: stars.

1 INTRODUCTION

The discovery of the first millisecond pulsar in the globular cluster M28 (Lyne et al. 1987) arose from the realization that millisecond pulsars may be the product of a spin-up process, such as that thought to be occurring in low-mass X-ray binary systems (Alpar et al. 1982), which are particularly numerous in globular clusters (Katz 1975). Since then, globular clusters have been shown to contain many millisecond pulsars, and it is now generally accepted that globular cluster pulsars are either old neutron stars that were formed very early in the cluster's history, and which have been 'recycled' by spin-up resulting from mass transfer from a binary companion (Hut & Verbunt 1983; Verbunt & Hut 1987), or pulsars that formed in the accretion-induced collapse of a white dwarf (Grindlay & Bailyn 1988).

NGC 6624 is one of the most massive and dense globular clusters associated with the Galaxy, and optically exhibits the surface brightness profile of a collapsed core (Djorgovski & King 1986, and references therein). It was therefore a prime target for the millisecond pulsar survey of globular clusters at Jodrell Bank, and soon revealed the presence of two pulsars (Biggs et al. 1990), one of which is a 5.4-ms pulsar, the other a more normal pulsar of 378-ms period. This globular cluster also contains the high-luminosity X-ray source 4U 1820 − 30 near its core (Giacconi et al. 1974). Interest in this source was stimulated by the discovery of a 685-s modulation of its X-ray emission (Stella, Priedhorsky & White 1987), which is attributed to an orbital period. Such a short orbital period suggests that 4U 1820 − 30 must be a low-mass X-ray binary (LMXB), with a 0.05-$M_\odot$ helium degenerate dwarf companion (Stella et al. 1987). While theoretical considerations suggested that the orbital period-derivative of the system should be at least $+0.06$ ms yr^{-1} (Rappaport et al. 1987), the value was, in fact, found to be -0.074 ± 0.013 ms yr^{-1} (Tan et al. 1991), challenging the standard evolutionary model for this system.

More recently, Johnston & Kulkarni (1992) claimed to have detected the radio counterpart of 4U 1820 − 30, a detection that would be quite useful because the accurate position would facilitate its optical study in the crowded globular cluster field, and may provide an alternative method for studying this X-ray source. At their proposed position for 4U 1820 − 30, the maximum possible acceleration toward the cluster core could not explain the observed period-derivative of the LMXB (van der Klis et al. 1993). Our observations not only identify this radio source with the millisecond pulsar, PSR 1820 − 30A, rather than the LMXB, but also suggest that the location of the cluster core is very close to both the pulsar and the LMXB.

If the neutron stars in globular clusters are primordial, then a comparison of their magnetic flux densities with those of the disc population gives us some idea of their magnetic field evolution. The long-period pulsar PSR 1820 − 30B provides us with such an opportunity.

2 OBSERVATIONS

PSR 1820 − 30A and 1820 − 30B were discovered by Biggs et al. (1990) in a survey of globular clusters using the 76-m Lovell telescope at Jodrell Bank at 610 MHz (Biggs, Lyne & Brinklow 1989; Biggs, Lyne & Johnston 1989). Subsequent observations were undertaken between 1990 April and 1992 November at frequencies between 408 and 1660 MHz in order to obtain the timing parameters of both pulsars. Pulse arrival times were obtained by convolution of the pulse profiles with appropriate templates and reduced to the barycentre of the Solar system using the JPL ephemeris DE200 (Standish 1982). These data were then fitted using standard models for such parameters as the pulsar period, period-derivative and position. The results of this analysis are presented in Table 1. These simple slow-down models describe the data with high precision and there is no evidence for any companion body orbiting either pulsar.

Pulsed flux densities have been determined at several frequencies on a number of occasions for both pulsars. While the measured flux densities are somewhat variable, presumably due to diffractive or refractive effects in the interstellar medium, the mean values are given in Table 1 and shown in Fig. 1. These flux densities suggest that the spectral index α (flux density $\propto \nu^{\alpha}$) is ~ -3 for PSR 1820 − 30A and ~ -2 for PSR 1820 − 30B.

We have also used the VLA to obtain synthesis maps of the cluster centred on 1490 MHz in the A configuration and on 4860 MHz in the B configuration. A source of 0.43 ± 0.03 mJy was detected at 1490 MHz at a position close to the millisecond pulsar 1820 − 30A. This position is given in the table, and is coincident with the pulsar position within the errors of measurement. The flux density is also consistent with that of the pulsar. At 4860 MHz, a weak source was detected at the same position with a flux density of 0.08 ± 0.03 mJy, consistent with the steep spectrum of the pulsar.

At 1490 MHz, PSR 1820 − 30B is detected with a flux density of 0.19 ± 0.06 mJy, roughly consistent with the pulsed flux density at this frequency. The absence of a detection of this pulsar at 4860 MHz confirms the pulsar's steep spectrum.

The pulse profile of PSR 1820 − 30A is relatively wide with a duty cycle of ≈ 25 per cent, and that of PSR 1820 − 30B is narrow with a duty cycle of ≈ 3 per cent.

3 DISCUSSION

There can be no doubt that both PSR 1820 − 30A and PSR 1820 − 30B are associated with the globular cluster NGC 6624. Both pulsars are located within 14 arcsec of the optical centre of the cluster as defined by Shawl & White (1986), and their dispersion measures are the same to within 0.2 pc cm^{-3} (see Table 1). At the nominal distance of the cluster (~ 6.4 kpc) the dispersion measure implies a mean electron density of 0.015 cm^{-3}, consistent with models of the interstellar medium (Taylor, Manchester & Lyne 1993).

3.1 PSR 1820 − 30A

PSR 1820 − 30A is a solitary 5.44-ms pulsar near the core of NGC 6624 and also close to the X-ray source 4U 1820 − 30. In Fig. 2, we have plotted the position of the pulsar and the VLA source, the X-ray source and two published positions for the optical centre of NGC 6624. The coincidence of the position estimates of the pulsar and VLA source is apparent. At 1465 MHz, the flux density of PSR 1820 − 30A is about 0.38 mJy (Fig. 1), consistent with the 0.43 mJy of the VLA source. This is also clearly the same source as that measured by Johnston & Kulkarni (1992) at RA(B1950.0) = $18^h20^m27\overset{s}{.}74$, Dec.(B1950) = $-30°23'15\overset{''}{.}8$, which was observed to have a flux density of 0.56 ± 0.06 mJy. The positions are in good agreement, as are the flux

Table 1. Measured and derived parameters.

	PSR 1820–30A	PSR 1820–30B
Pulsar period, P	5.4400022788(4 ± 1) ms	378.5964740(0 ±1) ms
Pulsar period derivative, $\dot{P}$	$3.38(5 \pm 1) \times 10^{-18}$	$31.(5 \pm 3) \times 10^{-18}$
Epoch (MJD)	48600	48504
Dispersion measure, DM	86.8 ± 0.1 cm^{-3} pc	87.0 ± 0.1 cm^{-3} pc
Right ascension (1950.0)	$18^h20^m27\overset{s}{.}72 \pm 0.02^s$	$18^h20^m28\overset{s}{.}82 \pm 0.03^s$
Declination (1950.0)	$-30°23'16\overset{''}{.}5 \pm 0.4''$	$-30°23'18'' \pm 3''$
Flux density at 408 MHz	49 ± 7 mJy	2.6 ± 0.8 mJy
Flux density at 610 MHz	9 ± 2 mJy	1.2 ± 0.4 mJy
Flux density at 1400 MHz	0.40 ± 0.03 mJy	0.07 ± 0.03 mJy
Flux density at 1660 MHz	0.31 ± 0.03 mJy	0.07 ± 0.03 mJy
Pulsar Characteristic age, $\tau_c = P/2\dot{P}$	2.5×10^7 yr	2.0×10^8 yr
Pulsar surface magnetic field, B	4.5×10^9 G	1.1×10^{11} G
VLA Right ascension (1950.0)	$18^h20^m27\overset{s}{.}72 \pm 0.01^s$	$18^h20^m28\overset{s}{.}78 \pm 0.02^s$
VLA Declination (1950.0)	$-30°23'16\overset{''}{.}0 \pm 0.2''$	$-30°23'17\overset{''}{.}7 \pm 0.4''$

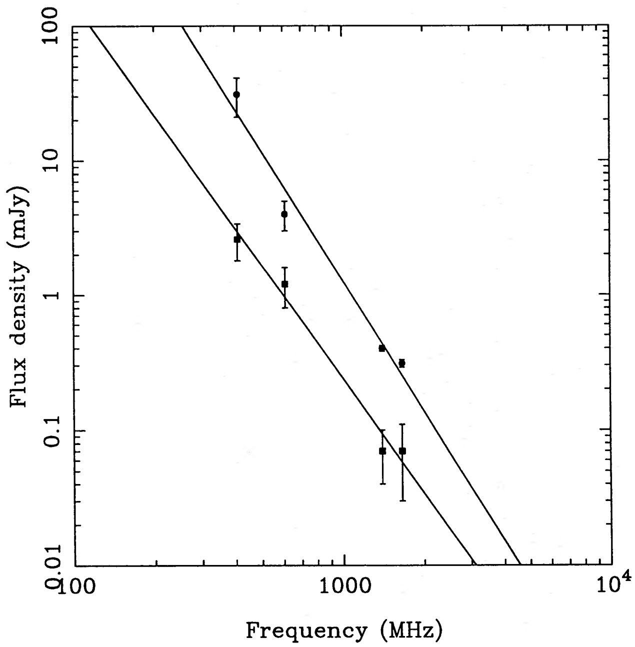

Figure 1. Mean pulsed flux densities for PSR 1820 − 30A (upper) and PSR 1820 − 30B (lower).

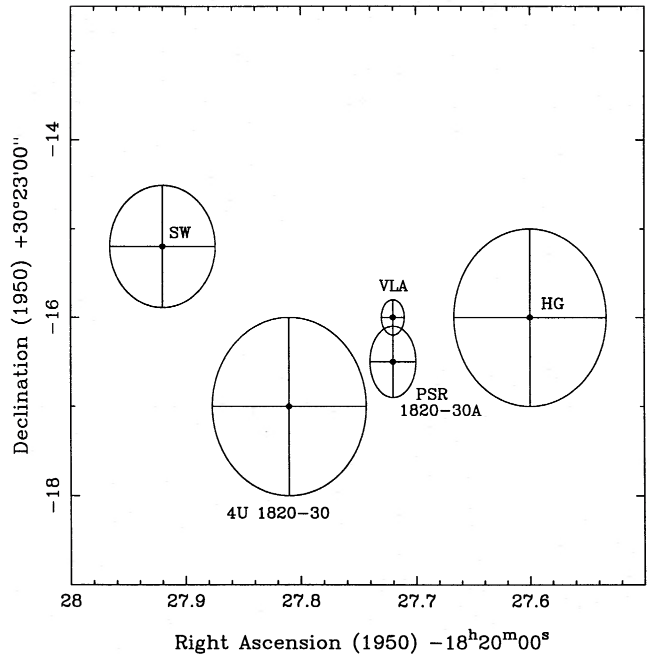

Figure 2. The positions of PSR 1820 − 30A, the VLA source (Table 1) and 4U 1820 − 30 (Hertz & Grindlay 1985). The estimated positions of the cluster centre are indicated by SW (Shawl & White 1986) and HG (Hertz & Grindlay 1985), respectively. The ellipses round each source indicate the 1σ uncertainty in its position. The period-derivative of the pulsar suggests that the cluster centre is, in fact, located very close to the pulsar (see text).

densities, in view of the observed variability of the pulsar. Given this similarity of the pulsed and VLA flux densities, there is little room for any of the radio flux detected near the cluster centre in the VLA observations to be associated with the X-ray source. The flux density of the source at 4885 MHz measured by the VLA, 0.08 ± 0.03 mJy, is somewhat greater than the extrapolated pulsar spectrum of Fig. 1. However, since the pulsar is likely to suffer strong interstellar scintillation at this frequency, the source is probably also the pulsar.

It is unlikely that 4U 1820 − 30 is associated with PSR 1820 − 30A, even though they are positioned close on the sky. The Jodrell Bank timing observations were examined for variation at the 685-s period detected by Stella et al. (1987), but none was found. Furthermore, it is very unlikely that PSR 1820 − 30A would have been detected in the Jodrell Bank survey if it were in such a rapid binary system, because of pulse smearing by Doppler period variations (Biggs & Lyne, in preparation).

The measured rotational period-derivative of the pulsar implies a surface magnetic field B of about 4.5×10^9 G, a large value for a millisecond pulsar. The pulse period of 5.4 ms is less than the minimum spin-period of 7.5 ms predicted by the canonical spin-up relation, $P \approx 1.9 \times 10^{-9}\ B^{6/7}$ ms (Bhattacharya & van den Heuvel 1991, and references therein). Within the spin-up theory there is no doubt room for such a short period immediately after accretion has ceased, but the most disturbing aspect of this pulsar's spin parameters is the implied youth of the object, arising again from the large period-derivative. Since the pulsar already has a shorter period than the spin-up theory allows, its true age since spin-up must therefore be much less than its characteristic age of 25 Myr.

These uncomfortable conclusions arise from the large observed period-derivative, and we now consider whether the value can be significantly affected by radial acceleration in the cluster gravitational potential field, an effect that has been observed in other cluster pulsars (Wolszczan et al. 1989). The period-derivative $\dot{P}$ is affected by an amount given by

$$\frac{\dot{P}}{P} = \frac{a}{c}, \tag{1}$$

where P is the period of the pulsar, a is the component of acceleration along the line of sight, and c is the speed of light. In order to estimate the size of the effect, we need to know the position of the pulsar relative to the cluster centre. Two positions of the cluster centre have been published in recent years (Hertz & Grindlay 1985; Shawl & White 1986), although these differ from one another by about 4 arcsec and from that of PSR 1820 − 30A by 2 arcsec. At the nominal distance of about 2 arcsec from either estimate of the cluster core position, and using the detailed model of the cluster potential developed by van der Klis et al. (1993), we find that at most the period-derivative could be affected by 3×10^{-19}, an order of magnitude lower than the observed value of 3×10^{-18}.

It has been noted earlier that the X-ray source 4U 1820 − 30, lying very close to the pulsar, has an anomalous orbital period-derivative which also cannot be explained by cluster acceleration (van der Klis et al. 1993). These two circumstances lead us to consider whether the core of NGC 6624 is much nearer the pulsar and the X-ray source than the most recent estimates of the position suggest, so that both their period-derivatives are severely contaminated by gravitational acceleration. Since at least one of these determinations must be in error, we suggest that both estimates of the optical position of the cluster core are in error by 2 arcsec and that the centre of the cluster is, in fact, very close to the pulsar and the X-ray source, so explaining their anomalous period-derivatives. Recent optical observations with *HST* are consistent with this hypothesis (I. King, personal communication).

3.2 PSR 1820 − 30B

PSR 1820 − 30B has a period-derivative of 31.5×10^{-18}. It does not seem that this value can be significantly contaminated by the cluster potential, as we have suggested is the case for PSR 1820 − 30A. At the nominal distance of the pulsar to the cluster centre (14 arcsec), the mass model by van der Klis et al. (1993) suggests that the maximum acceleration is an order of magnitude too small to affect the period-derivative significantly, even when the uncertainty of the cluster core position is taken into account. This implies that the inferred magnetic flux density is 1.1×10^{11} G, rather high for a pulsar that is associated with a globular cluster. The characteristic age is 2×10^8 yr. If the neutron star is primordial, then its magnetic field has not decayed by more than two orders of magnitude over the lifetime of the cluster. This supports models in which the magnetic flux densities of pulsars do not decay forever, but either cease decaying (Kulkarni 1986; Srinivasan & Bhattacharya 1987; Sang & Chanmugam 1990), or only decay as the result of mass accretion (Taam & van den Heuvel 1986; Bailes 1989; Romanin 1990; Srinivasan et al. 1990).

The characteristic age of PSR 1820 − 30B suggests that it was spun up $\lesssim 2 \times 10^8$ yr ago by the accretion of matter from a companion star. The major difficulty is explaining the absence of PSR 1820 − 30B's companion. There are three possibilities. The companion may have been involved in some sort of ionizing encounter with another star in the dense core of NGC 6624. Alternatively, if it was a collision with a main-sequence star that led to the spin-up of the pulsar, then the companion may have been completely tidally disrupted, forming a disc around the pulsar which was subsequently spun-up by the material. In another scenario, radiation from the spun-up pulsar may have annihilated the companion (van den Heuvel & van Paradijs 1988).

The binary pulsar PSR 1718 − 19 which is associated with the globular cluster NGC 6342 appears to be causing its companion to overflow its Roche lobe, even though it has a very small rotation rate (Lyne et al. 1993). Such a system may make a suitable progenitor for PSR 1820 − 30B. PSR 1718 − 19 currently has an orbital period of 6 h and a rotation period of about 1 s. If, in the future, the companion continues to lose mass, it is possible that some fraction of this may be accreted on to the pulsar, reducing its magnetic flux density and shortening its period before the companion becomes totally destroyed. A pulsar similar to PSR 1820 − 30B may then result.

ACKNOWLEDGMENTS

The component of this work undertaken by JDB at NASA/GSFC was supported through contract NAS530442. We thank Dr R. N. Manchester for assistance in confirming these pulsars with the Parkes antenna. The Very Large Array of the National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.

REFERENCES

Alpar M. A., Cheng A. F., Ruderman M. A., Shaham J., 1982, Nat, 300, 728
Bailes M., 1989, ApJ, 342, 917
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1
Biggs J. D., Lyne A. G., Brinklow A., 1989, in Ögelman H., van den Heuvel E. P. J., eds, Timing Neutron Stars. Kluwer, Dordrecht, p. 157
Biggs J. D., Lyne A. G., Johnston S., 1989, in Hunt J., Battrick B., eds, Proc. 23rd ESLAB Symp. on Two Topics in X-ray Astronomy. ESA, Noordwijk, p. 293
Biggs J. D., Lyne A. G., Manchester R. N., Ashworth M., 1990, IAU Circ. No. 4988
Djorgovski S., King I. R., 1986, ApJ, 305, L61
Giacconi R., Murray S., Gursky H., Kellogg E., Scheier E., Matilsky T., Kock D., Tananbaum H., 1974, ApJS, 27, 37
Grindlay J. E., Bailyn C. D., 1988, Nat, 336, 48
Hertz P., Grindlay J. E., 1985, ApJ, 298, 95
Hut P., Verbunt F., 1983, Nat, 301, 587
Johnston H. M., Kulkarni S. R., 1992, ApJ, 393, L17
Katz J. I., 1975, Nat, 253, 698
Kulkarni S. R., 1986, ApJ, 306, L85
Lyne A. G., Brinklow A., Middleditch J., Kulkarni S. R., Backer D. C., Clifton T. R., 1987, Nat, 328, 399
Lyne A. G., Biggs J. D., Harrison P. A., Bailes M., 1993, Nat, 361, 47
Rappaport S., Jones L. A., Ma C. P., Joss P. C., 1987, ApJ, 322, 842
Romani R. W., 1990, Nat, 347, 741
Sang Y., Chanmugam G., 1990, ApJ, 363, 597
Shawl S. J., White R. E., 1986, AJ, 91, 312
Srinivasan G., Bhattacharya D., 1987, in Helfand D. J., Huang J., eds, Proc. IAU Symp. No. 125, The Origin and Evolution of Neutron Stars. Reidel, Dordrecht, p. 109
Srinivasan G., Bhattacharya D., Muslimov A. G., Tsygan A. I., 1990, Curr. Sci., 59, 31
Standish E. M., 1982, A&A, 114, 297
Stella L., Priedhorsky W., White N. E., 1987, ApJ, 312, L17
Taam R. E., van den Heuvel E. P. J., 1986, ApJ, 305, 235
Tan J. et al., 1991, ApJ, 374, 291
Taylor J. H., Manchester R. N., Lyne A. G., 1993, ApJS, 88, 529
van den Heuvel E. P. J., van Paradijs J., 1988, Nat, 334, 227
van der Klis M. et al., 1993, MNRAS, 260, 686
Verbunt F., Hut P., 1987, in Helfand D. J., Huang J., eds, Proc. IAU Symp. No. 125, The Origin and Evolution of Neutron Stars. Reidel, Dordrecht, p. 187
Wolszczan A., Kulkarni S. R., Middleditch J., Backer D. C., Fruchter A. S., Dewey R. J., 1989, Nat, 337, 531