PSR J1740−3052: a pulsar with a massive companion

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ABSTRACT

We report on the discovery of a binary pulsar, PSR J1740−3052, during the Parkes multibeam survey. Timing observations of the 570-ms pulsar at Jodrell Bank and Parkes show that it is young, with a characteristic age of 350 kyr, and is in a 231-d, highly eccentric orbit with a companion whose mass exceeds $11\,M_\odot$. An accurate position for the pulsar was obtained using the Australia Telescope Compact Array. Near-infrared 2.2-μm observations made with the telescopes at the Siding Spring observatory reveal a late-type star coincident with the pulsar position. However, we do not believe that this star is the companion of the pulsar, because a typical star of this spectral type and required mass would extend beyond the orbit of the pulsar. Furthermore, the measured advance of periastron of the pulsar suggests a more compact companion, for example, a main-sequence star with radius only a few times that of the Sun. Such a companion is also more consistent with the small dispersion measure variations seen near periastron. Although we cannot conclusively rule out a black hole companion, we believe that the companion is probably an early B star, making the system similar to the binary PSR J0045−7319.

Key words: binaries: general – stars: late-type – stars: mass-loss – pulsars: general – pulsars: individual: PSR J1740−3052 – X-rays: stars.

1 INTRODUCTION

Radio pulsars in binary systems provide a wealth of information about neutron stars, their companions, and binary evolution.

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Through radio and optical observations of double neutron star and neutron star–white dwarf binaries, an overall picture of binary pulsar evolution has emerged (see, e.g. Bhattacharya & van den Heuvel 1991; Phinney & Kulkarni 1994). Young pulsars lose energy in the form of particles or electromagnetic waves and are believed to spin down with an approximately constant magnetic field, eventually reaching the point at which the radio emission mechanism is no longer effective. An isolated neutron star will never again be observed as a radio pulsar. However, a neutron star with a non-degenerate companion may be 'recycled' by accreting

mass and orbital angular momentum from the evolving companion in an X-ray binary phase. The spin period of the pulsar is decreased, its magnetic field is reduced, and it begins to emit as a radio pulsar once more. There are several possible branches to this evolution. Low-mass companions permit stable mass transfer to the neutron star over the lifetime of the giant phase, resulting in pulsars with spin periods of a few milliseconds and low-mass He white dwarf companions. Unstable mass transfer from higher-mass red giants may yield pulsars with slightly longer spin periods and heavier, CO white dwarf companions. A companion massive enough to undergo a supernova explosion itself will result in either an unbound pair of neutron stars, one recycled, and the other young, or a double neutron star system such as PSR B1913+16 (Hulse & Taylor 1975).

The precursors to these evolved binary systems must be young neutron stars with non-degenerate companions, and some of these neutron stars should be visible as radio pulsars. Indeed, two such objects have been reported to date: PSR B1259-63, with a $\sim 10\,M_\odot$ Be-star companion (Johnston et al. 1992), and PSR J0045$-$7319, whose companion is a B star also of mass $\sim 10\,M_\odot$ (Kaspi et al. 1994). Both of these main-sequence binaries are believed to be progenitors of high-mass X-ray binaries (HMXBs).

In this paper, we report on the discovery of a third young radio pulsar with a massive companion. PSR J1740$-$3052 is a 570-ms pulsar which is in a 231-d binary orbit with a companion of minimum mass $11\,M_\odot$. This pulsar was discovered in the ongoing Parkes multibeam pulsar survey, a large-scale survey for pulsars currently being carried out using the 13-beam 1374-MHz receiver on the Parkes 64-m radio telescope of the Australia Telescope National Facility (Manchester et al. 2001). The discovery observations, radio-pulse timing and interferometric observations, and the results obtained from them, are described in Section 2. Near-infrared observations made to identify the pulsar companion are described in Section 3. Radio and X-ray observations made around periastron passages are described in Section 4. In Section 5 we discuss the implications of the observational results and the nature of the pulsar companion.

2　RADIO OBSERVATIONS AND TIMING SOLUTION

2.1　Observations and data reduction

PSR J1740$-$3052 was initially observed on 1997 August 25, and the survey reduction software identified it as a candidate with a 570-ms period and dispersion measure (DM) of $739\,cm^{-3}\,pc$. Survey parameters and procedures are described in detail by Manchester et al. (2001). The confirmation observation gave a period which was substantially different from the initial discovery period, indicating possible membership of a binary system. The pulsar has since been observed in a series of timing measurements at both the Parkes 64-m telescope and the Lovell 76-m telescope at Jodrell Bank Observatory.

At Parkes, most data are recorded using the central beam of the multibeam system, with a $2 \times 96 \times 3$-MHz filterbank centred on 1374 MHz and a 1-bit digital sampling rate of $250\,\mu s$. Details of the timing observations may be found in Manchester et al. (2001). The pulsar is also frequently observed at 660 MHz, using a filterbank consisting of $2 \times 256 \times 0.125$-MHz channels.

Observations at Jodrell Bank are made in a band centred near 1400 MHz. The filterbank consisted of $2 \times 32 \times 3$-MHz channels
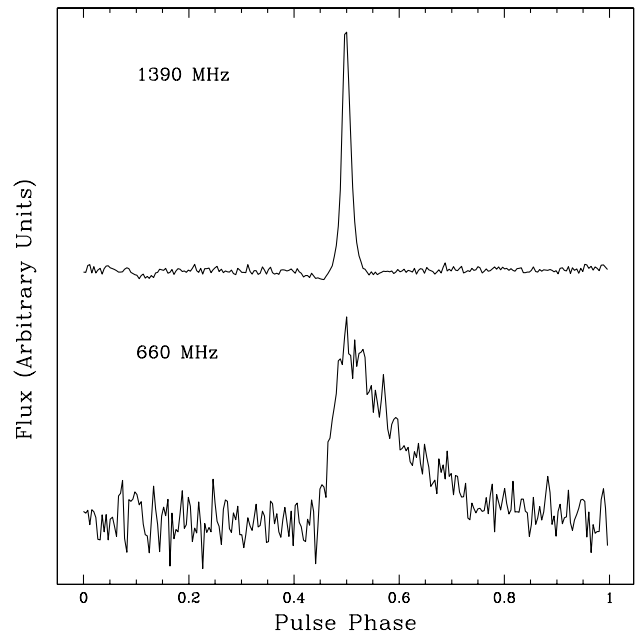

Figure 1. Mean pulse profiles at 1390 and 660 MHz. Integration times were 11.2 h at 1390 MHz, and 11.6 h at 660 MHz. The dispersion smearing is 1.11 ms at 1390 MHz, and 5.36 ms at 660 MHz. The small dip at the leading edge of the 1390-MHz profile is an instrumental artefact. The scattering time-scale derived from the 660-MHz profile is roughly 58 ms. This scales by $\nu^{-4.4}$ to about 9 ms at 1 GHz, only 25 per cent of the value predicted by the Taylor & Cordes (1993) model.

centred on 1376 MHz until 1999 August, and $2 \times 64 \times 1$-MHz channels centred on 1396 MHz thereafter.

Data from both Parkes and Jodrell Bank are de-dispersed and folded at the predicted topocentric pulsar period. This process is performed offline for the Parkes data and online for the Jodrell Bank data. Total integration times per observation are typically 10 min at Parkes and 30 min at Jodrell Bank. Each pulse profile obtained by summing over an observation is convolved with a high signal-to-noise ratio 'standard profile' producing a topocentric time-of-arrival (TOA). These are then processed using the TEMPO program.[1] Barycentric corrections are obtained using the Jet Propulsion Laboratory DE200 Solar system ephemeris (Standish 1982). The standard profiles at the two observing frequencies are shown in Fig. 1.

2.2　Interferometric position determination

As PSR J1740$-$3052 lies close to the ecliptic and is a member of a long-period binary system, its position cannot be well determined yet through standard pulsar timing analyses. We therefore undertook observations with the six-element Australia Telescope Compact Array (ATCA) on 1999 April 20. Pulsar gating mode was used for simultaneous observations at frequencies of 1384 and 2496 MHz, with a 128-MHz bandwidth in both polarizations at each frequency. The source 1934–638 was used to give the primary flux density calibration and the three sources 1714–252, 1751–253 and 1830–360 were used as phase calibrators. The MIRIAD software package[2] was used to produce on- and off-pulse images of the pulsar field, and to fit a point source to the differenced image.

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[1] See http://pulsar.princeton.edu/tempo.

[2] See http://www.atnf.csiro.au/computing/software/miriad.

Table 1. Parameters of PSR J1740−3052.

Measured Parameters

RA (J2000)[a]	$17^{\mathrm{h}}40^{\mathrm{m}}50\overset{\mathrm{s}}{.}031(5)$
Dec. (J2000)[a]	$-30°52'04\overset{''}{.}1(3)$
Dispersion Measure (cm^{-3} pc)	740.9(2)
Period (s)	0.570 309 580 513(16)
Period Derivative	$2.549\,69(4) \times 10^{-14}$
Epoch of Period (MJD)	51 452.0
Orbital Period (d)	231.029 65(3)
Projected Semimajor Axis (light-s)	756.9087(4)
Eccentricity	0.578 8720(4)
Epoch of Periastron (MJD)	51 353.512 33(3)
Longitude of Periastron (degrees)	178.646 13(6)
Advance of Periastron (degrees yr^{-1})	0.00021(7)
Derivative of Projected Semimajor Axis[b]	$<4 \times 10^{-11}$
Derivative of Orbital Period[b]	$<4 \times 10^{-8}$
Data Span (MJD)	51032−51872
rms Timing Residual (ms)	0.8
Flux Density at 1400 MHz (mJy)	0.7(2)

Derived Parameters

Galactic Longitude (degrees)	357.8
Galactic Latitude (degrees)	−0.13
Distance (kpc)	∼11
Characteristic Age (yr)	3.5×10^5
Surface Magnetic Field (G)	3.9×10^{12}
Rate of Energy Loss (erg s^{-1})	5.5×10^{33}
Mass Function (M$_\odot$)	8.723 248(12)

[a] Position determined from interferometric observation.
[b] Fit while holding all other parameters constant at the values shown.

These images were made separately using each of the phase calibrators at each of the two frequencies, yielding five semi-independent determinations of the position (the calibration source 1830–360 was resolved for long baselines at 2496 MHz and therefore was not usable at this frequency) from which the position and its uncertainty were derived. This position is listed in Table 1. In these and the other entries in this table, the uncertainty is given in parentheses and refers to the last quoted digit.

2.3 Timing results and implications

Continued timing observations at Jodrell Bank and Parkes confirmed that PSR J1740−3052 is a member of a binary system in a highly eccentric orbit. Fig. 2 shows the measured period variation of PSR J1740−3052 through the orbital period of 231 d. Subsequently, we performed a phase-coherent analysis of the arrival times over the period 1998 August 7–2000 November 23, using the main-sequence-star binary model of Wex (1998) in TEMPO. The results are summarized in Table 1. The errors are twice the formal 1σ values from the TEMPO solution; we consider these to be conservative estimates of the true 1σ errors. Timing residuals are shown in Fig. 3. The DM was obtained using the 1400-MHz observations and five 660-MHz observations at orbital phases far from periastron. Uncertainties in the pulse arrival times were determined by requiring that the reduced χ^2 be 1.0 for the individual data sets from the different receivers and telescopes. There are clearly some remaining systematic trends in the residuals. As the orbital period is roughly eight months and the sampling is irregular, we are not yet able to distinguish fully between orbital and annual effects in the data. For this reason, we have fixed the position at that determined by the ATCA observations, and find, in the best simultaneous fit of all parameters, a marginally significant result for the advance of
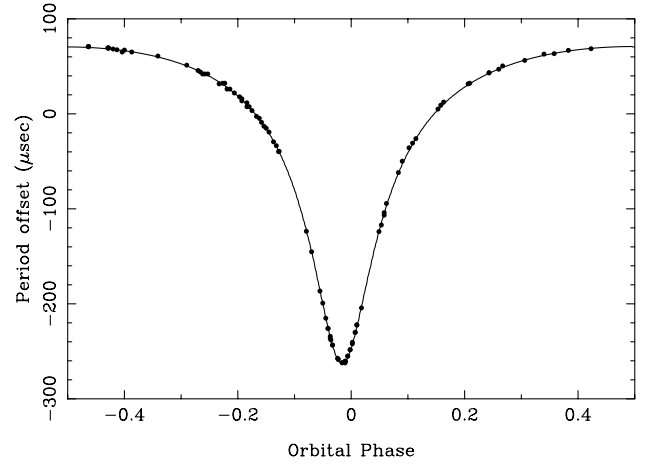
Figure 2. Observed variations of the Solar system barycentric period of PSR J1740−3052 over the 231-d orbital period measured using the 76-m Lovell telescope at Jodrell Bank Observatory and the 64-m telescope at Parkes. The curved line represents the fit of a binary model to the data. Orbital phase zero is periastron, which occurs nearly in the plane of the sky.

periastron, $\dot{\omega}$. If $\dot{\omega}$ is not included in the fit, the overall reduced χ^2 increases from 1.05 to 1.20; this increases our confidence in the significance of the parameter. With continued long-term timing, it should be possible to refine the position as well as $\dot{\omega}$ and other orbital parameters such as the change in projected semimajor axis, $\dot{x}$, and the orbital period derivative, $\dot{P}_{\mathrm{b}}$.

The spin parameters for PSR J1740−3052 yield a characteristic age of $\tau_{\mathrm{c}} = P/2\dot{P} = 3.5 \times 10^5$ yr, and a relatively high implied surface dipole magnetic field strength of $B_0 = 3.2 \times 10^{19}(P\dot{P})^{1/2} = 3.9 \times 10^{12}$ G. The pulsar is clearly young and the high magnetic field and long period suggest that it has not undergone accretion of mass and angular momentum from its companion.

Using the Taylor & Cordes (1993) model for the free electron density distribution in the Galaxy and the measured DM, we obtain an estimated distance of 11 kpc for PSR J1740−3052, with a nominal uncertainty of about 25 per cent.

A lower limit on the companion mass m_2 can be derived from the mass function, assuming that the pulsar mass is $m_1 = 1.35\,\mathrm{M_\odot}$, as observed for neutron stars in binary radio pulsar systems (Thorsett & Chakrabarty 1999),

$$f_1(m_1, m_2, i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{4\pi^2}{T_\odot}\frac{x^3}{P_{\mathrm{b}}^2} = \frac{4\pi^2}{T_\odot}\frac{(a_1 \sin i)^3}{c^3 P_{\mathrm{b}}^2}, \quad (1)$$

where $x = a_1 \sin i/c$ is the projected semimajor axis of the pulsar orbit, P_{b} is the orbital period, c is the speed of light and $T_\odot \equiv GM_\odot/c^3 = 4.925\,490\,947\,\mu$s. Taking $\sin i = 1$, the minimum companion mass is $11\,\mathrm{M_\odot}$, and the mass derived using the median inclination angle of $i = 60°$ is roughly $16\,\mathrm{M_\odot}$. This suggests that the companion of the pulsar is either a black hole or a non-degenerate star even more massive than the Be-star companion (SS2883) of PSR B1259−63. If the companion is non-degenerate, the high mass implies that it must be either an early main-sequence B star or else a late-type supergiant. We will consider these two cases and that of a black hole in discussing the implications of our observations, in the end coming to the conclusion that a B star is the most likely companion, although we have no direct evidence for such a star at the position of the pulsar.

An important point to consider is the size of the companion. An early B star of $11\,\mathrm{M_\odot}$ is expected to have a radius of 6 or $7\,\mathrm{R_\odot}$ (e.g. Cox 2000), much smaller than the pulsar orbit. Of course, a black
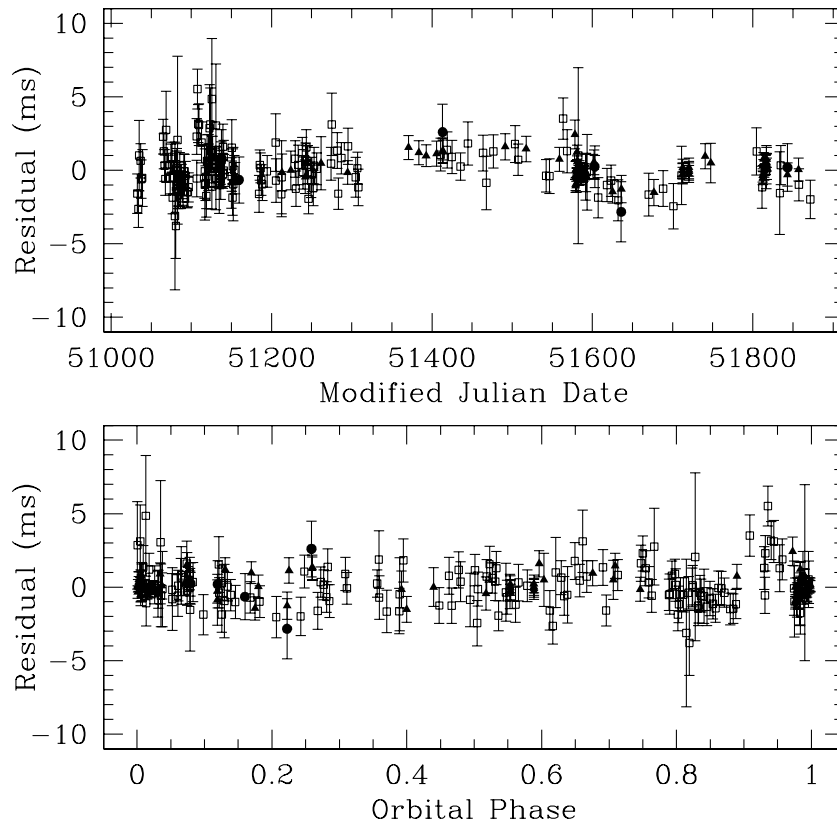
Figure 3. Timing residuals relative to the best-fitting solution for PSR J1740−3052 over the period 1998 August 7–2000 November 23. Open squares represent Jodrell Bank 1400-MHz data, filled triangles Parkes 1400-MHz data and filled circles 660-MHz data. Top panel: residuals as a function of time. Bottom panel: residuals as a function of orbital phase, where phase 0/1 is periastron.

hole will also fit this criterion. Late-type supergiants, on the other hand, have typical radii of several hundred $R_\odot$ (e.g. van Belle et al. 1999), comparable to or larger than the projected orbital semimajor axis of the pulsar of 757 light-seconds, which is about 325 $R_\odot$ or 1.5 au. The distance of closest approach of the two bodies may be as small as 0.72 au, depending on the orbital inclination angle. However, to date, there has been no evidence of eclipse of the pulsar at any phase of the orbit (Section 4.1). Furthermore, the youth of the pulsar and eccentricity of the orbit indicate that no significant mass has been transferred from the companion to the pulsar. Thus, if the companion is in fact a late-type supergiant, it must be confined within its Roche lobe. We use the formula of Eggleton (1983) to estimate the radius of the Roche lobe of the companion star near periastron, arriving at roughly 0.4 au for stellar masses in the range 11 to 16 $M_\odot$. A late-type companion must therefore have a radius smaller than this, unusually small for such a star. On the assumption that the star fills (or nearly fills) its Roche lobe, the lack of eclipses requires the inclination angle to be $\lesssim 70°$, resulting in a companion mass of $\gtrsim 12.5\,M_\odot$.

2.4 The advance of periastron

As mentioned in Section 2.3, the pulsar timing solution shows an advance of periastron, $\dot\omega = 0°\!.00021(7)\,\mathrm{yr}^{-1}$. This may be due to a combination of general-relativistic and classical effects. For a compact companion, general relativity predicts an advance of

$$\dot\omega = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}[T_\odot(m_1+m_2)]^{2/3}(1-e^2)^{-1} = 0°\!.00023\,\mathrm{yr}^{-1},$$

(2)

where e is the orbital eccentricity and we assume a pulsar mass of $m_1 = 1.35\,M_\odot$ and a companion mass of $m_2 = 16\,M_\odot$. The observed value of $\dot\omega$ is comparable to this, so that a black hole companion is certainly permitted by the observations. Classical contributions to $\dot\omega$ and to $\dot x$, the derivative of the projected orbital semimajor axis, may come from a quadrupole moment of a companion star, induced either by the stellar rotation or by tides raised by the neutron star (Lai, Bildsten & Kaspi 1995; Kaspi et al. 1996; Wex 1998). For a stellar quadrupole moment q, the expected classical contributions to $\dot\omega$ and $\dot x$ are (Wex 1998)

$$\dot\omega = \frac{3\pi q}{P_b a_1^2 (1-e^2)^2}\left(1-\tfrac{3}{2}\sin^2\theta + \cot i \sin\theta\cos\theta\cos\Phi_0\right)$$

$$= 830\left(\frac{q}{\mathrm{au}^2}\right)\sin^2 i\left(1-\tfrac{3}{2}\sin^2\theta + \cot i \sin\theta\cos\theta\cos\Phi_0\right)°\,\mathrm{yr}^{-1},$$

(3)

$$\dot x = \frac{3\pi q}{P_b c a_1^2 (1-e^2)^2}(a_1\sin i)\cot i \sin\theta\cos\theta\sin\Phi_0$$

$$= 3.5\times 10^{-4}\left(\frac{q}{\mathrm{au}^2}\right)\sin^2 i \cot i \sin\theta\cos\theta\sin\Phi_0,$$

(4)

where Φ_0 is the precession phase, and θ is the angle between the orbital angular momentum and the spin vector of the star or the line perpendicular to the plane of the tidal bulge.

To estimate the relative importance of the spin and tidal quadrupoles, q_S and q_T, for a B main-sequence star, we follow the reasoning of Lai, Bildsten & Kaspi (1995) and take the ratio

$$\frac{q_S}{q_T} \sim \left(\frac{P_b}{P_S}\right)^2 \frac{(m_1+m_2)}{m_1}(1-e)^3,$$

(5)

where P_S is the spin period of the star, which we estimate to be 2×10^5 s, similar to that for the B1V companion to PSR J0045−7319 (Bell et al. 1995). From this, we derive $q_S/q_T \sim 10^4$; consequently the tidal quadrupole is negligible in equations (3) and (4) above.

The measured non-general-relativistic contribution to $\dot{\omega}$ is $\lesssim 0°\!.00012\,\mathrm{yr}^{-1}$. Assuming $i = 60°$, $\theta = 20°$ (Bailes 1988) and $\Phi_0 = 45°$, we find $q_S \lesssim 2.0 \times 10^{-7}\,\mathrm{au}^2$. The rotationally induced quadrupole moment, q_S, is given by (Cowling 1938)

$$q_S = \frac{2}{3} \frac{k R_2^5 \Omega^2}{G m_2} \tag{6}$$

where G is Newton's constant, $\Omega = 2\pi/P_S$ is the stellar angular velocity, m_2 and R_2 are the companion mass and radius, and k is the apsidal constant representing the structure of the star, estimated for such a star to be ~ 0.01 (Schiff 1958; Claret & Gimenez 1992). With a radius estimate of $6.5\,\mathrm{R}_\odot$ as for the companion to PSR J0045−7319 (Bell et al. 1995), this leads to an estimate of the stellar rotational angular velocity of $\Omega \lesssim 2.7 \times 10^{-5}\,\mathrm{rad\,s}^{-1}$, $P_S \gtrsim 2.3 \times 10^5$ s, consistent with that used above in equation (5).

Based on this estimate of the spin quadrupole, the change in the projected semimajor axis is predicted to be $\dot{x} \lesssim 4.6 \times 10^{-11} \sin^2 i \cot i \sin\theta \cos\theta \sin\Phi_0$, comparable to our measured limit of 4×10^{-11} and providing no constraints on the inclination angle or precession phase.

In the case of a late-type companion, we estimate $R_2 \sim 0.35\,\mathrm{au}$ based on the Roche lobe argument in Section 2.3, $m_2 = 12.5\,\mathrm{M}_\odot$, $i = 70°$ and $k \sim 0.03$ (Claret, private communication). The spin of the star, Ω, is not well known. Based on an estimate of $v \sin i \simeq 1\,\mathrm{km\,s}^{-1}$ for late-type suppergiants (de Medeiros & Mayor 1999), we arrive at $\Omega \simeq 1.2 \times 10^{-7}\,\mathrm{rad\,s}^{-1}$, and hence $q_S \simeq 3.0 \times 10^{-6}\,\mathrm{au}^2$ for a 12.5-$\mathrm{M}_\odot$ star. However, as the radius of the star must be significantly smaller than that of most supergiants, $v \sin i$ could well be larger. An estimate of $\Omega \simeq 3.1 \times 10^{-7}\,\mathrm{rad\,s}^{-1}$ and hence $q_S \simeq 2.0 \times 10^{-5}\,\mathrm{au}^2$ comes from setting the stellar rotational rate equal to the orbital frequency.

The quadrupole moment due to a tide, q_T, can be written as

$$q_T = k \frac{m_1}{m_2} R_2^2 \left(\frac{R_2}{r}\right)^3 \tag{7}$$

where r is the centre-of-mass separation at any given time (Lai et al. 1995). Under the same assumptions given above for a late-type companion, we find $q_T \simeq 5.3 \times 10^{-6}\,\mathrm{au}^2$ averaged over the orbit. Thus the static tidal and the rotational quadrupole moments may well be of roughly the same order of magnitude, although probably not aligned.

The tidal quadrupole will not contribute to the value of $\dot{x}$ in equation (4) given above, as the tidal bulge will be aligned with the orbital plane. The measured limit of $\dot{x} < 4.0 \times 10^{-11}$, combined with the assumptions that $i = 70°$ and $\theta = 20°$, yields a value of $q_S \lesssim 1.6 \times 10^{-6}\,\mathrm{au}^2$ or $\Omega \lesssim 8.0 \times 10^{-8}\,\mathrm{rad\,s}^{-1}$ for $\Phi_0 = 45°$, slightly smaller than our above estimate.

However, both the static tidal and rotational quadrupole moments will contribute to the value of $\dot{\omega}$, although, given the difference in magnitudes and alignments, the contributions will differ in size and perhaps also in sign. Using the estimate of q_S derived in the preceding paragraph, we arrive at a maximum rotational quadrupole contribution of $0°\!.0013\,\mathrm{yr}^{-1}$ to $\dot{\omega}$. The estimate of the static tidal contribution is larger, $\sim 0°\!.0044\,\mathrm{yr}^{-1}$. The actual measured value of $\dot{\omega}$ is $0°\!.00021(7)\,\mathrm{yr}^{-1}$, about an order of magnitude smaller than either of these values.

With the simple assumptions we have made, it is difficult to reconcile the observed and predicted values of $\dot{\omega}$ for a late-type supergiant companion. It may be possible to do so through fine-tuning of the stellar spin, the precession phase and the spin inclination angle, but such a solution seems unlikely.

3 NEAR-IR SEARCH FOR THE COMPANION

In order to clarify the nature of the companion, we undertook observations in other wavebands. PSR J1740−3052 lies only $0°\!.13$ from the Galactic plane, very close to the Galactic Centre and at a distance of roughly 11 kpc; large amounts of extinction are therefore expected at optical wavelengths. Indeed, there is no object at the pulsar position in the Digitised Sky Survey (DSS), which covers the V-band to approximately magnitude 16. There is also no sign of an optical image on deeper Sky Survey photographs taken with the United Kingdom Schmidt Telescope (UKST), to limiting magnitudes of 21 in B, 20 in R and 18 in I. We therefore carried out observations at infrared wavelengths.

On 1999 May 2 (MJD 51300, binary phase 0.77), we obtained K-band (2.2 μm) spectroscopic observations using the Max Planck Institut für Extraterrestriche Physik (MPE) near-infrared imaging spectrograph 3D (Weitzel et al. 1996) on the 3.9-m Anglo-Australian Telescope (AAT), pointing at the position determined from the ATCA observation. This observation revealed a bright star with a K-band magnitude of 10.05 ± 0.05 within 1 arcsec of the nominal position. The observations were made using the tip–tilt correction system ROGUE (Thatte et al. 1995). 3D uses an integral field unit to split the light from a spatial grid of 16×16 0.4-arcsec pixels into 256 separate spectra. The effective resolution, $\lambda/\Delta\lambda$, of 1100 is obtained by combining the two spectra whose wavelength centre is shifted by half a pixel using a piezo-driven flat mirror. We observed HD 161840 (spectral type B8V) as an atmospheric standard. A Lorentzian was fitted to the hydrogen Brackett γ absorption during reduction. We also observed HD 169101
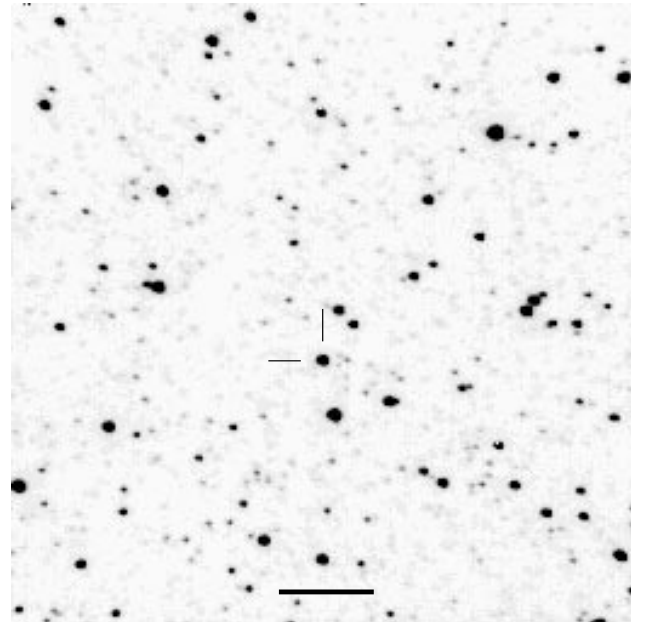

Figure 4. Image of the PSR J1740−3052 field taken with the Siding Spring Observatory 2.3-m telescope at 2.2 μm (K band). The coincident late-type star, near the centre of the figure, is marked, and the thick horizontal bar is of length 20 arcsec. North is at the top of the figure and east to the left.

(spectral type A0V) as a flux calibrator, assuming $V - K = 0$. Data were reduced using routines written for the GIPSY data reduction package (van der Hulst et al. 1992). The reduction sequence involved flat-fielding, bad pixel correction, merging of the separate images corresponding to the two subspectra, wavelength calibration, and formation of a data cube. The final spectrum of the source, which had an effective integration time per pixel of 1680 s, was then extracted from the merged cube, and divided by the atmospheric standard.

At the same time, we obtained a 2×2 arcmin^2 K-band image of the field using the near-infrared array camera CASPIR (McGregor et al. 1994) on the Australian National University 2.3-m telescope at the Siding Spring Observatory. The exposure time was 1 min, and the limiting K magnitude was ~ 17. This image is shown in Fig. 4.

The bright star from the 3D observation was identified on the CASPIR image as shown in Fig. 4, with a consistent K-band magnitude of 10.03 ± 0.01. Astrometric reduction of this image was performed at the Royal Observatory, Edinburgh. 12 secondary reference stars were identified on both the K-band image and an archival UKST R-band plate. Positions of these stars and hence the candidate star were related to the *Hipparcos* reference frame using the Tycho-AC catalogue (Urban, Corbin & Wycoff 1998) and SuperCOSMOS digitized images (Hambly et al. 1998). This yielded a position for the star of RA(2000) $17^h40^m50\overset{s}{.}01(1)$, Dec.(2000) $30°52'03\overset{''}{.}8(2)$. Within the combined errors, this position agrees with the position of the pulsar given in Table 1. A simple count yields a density of objects bright enough to be detected in the CASPIR image of roughly 0.015 per arcsec^2. Using an error region of 0.86 arcsec^2, which includes the 95 per cent confidence regions for both the radio and optical positions, the probability of a chance coincidence is 1.3 per cent.

We note that the candidate companion star is included in the Point Source Catalogue of the Two Micron All Sky Survey (2MASS) collaboration, with the designation 2MASSI 1740500−305204. In an observation on 1998 August 14 (binary phase 0.64), the survey determined J, H and K apparent magnitudes of 14.523 ± 0.046, 11.441 ± 0.024 and 10.009 ± 0.030, respectively. Within the uncertainties, therefore, the star appears to be stable in magnitude.

The K-band spectrum obtained with the AAT is shown in Fig. 5, with the most prominent lines indicated. There is a significant absorption of metals and both ^{12}CO and ^{13}CO. We have compared the spectrum with those of catalogue sources (Kleinmann & Hall 1986; Wallace & Hinkle 1997) by eye and by calculating equivalent widths. The results indicate that the star is likely to have a spectral type between K5 and M3.

Fig. 5 also indicates hydrogen Brackett γ in emission. The presence of this line in late-type stars is usually taken to indicate the presence of a compact companion with a hot accretion disc providing the ionizing flux, for example, as in the X-ray binary GX1+4 (Davidsen, Malina & Bowyer 1977; Chakrabarty & Roche 1997). In the case of PSR J1740 − 3052, we believe that there is no accretion disc (see Section 4.3 below), and so the heating photons must have another source. In principle, they could come from a shock at the interface between the pulsar and supergiant winds. However, at the nominal distance of 11 kpc, the observed strength of the Brackett γ is 20 per cent of the spin-down luminosity of the pulsar; as Brackett γ is only one of the many recombination lines of ionized hydrogen, we argue that the pulsar cannot provide sufficient energy to produce the observed line strength.

Because of this dilemma, further K-band spectroscopic observations of the late-type star were made using CASPIR on the 2.3-m telescope at Siding Spring Observatory on 2000 November 4 (binary phase 0.16). The A0 star BS6575 was used as a flux calibrator, with an interpolation over Brackett γ during reduction. This observation gave a spectrum similar in appearance to that in Fig. 5 but with no significant indication of Brackett γ. As a further check, a K5 star (BS6842) and an M1 star (BS6587) were used in calibration for the supergiant spectrum − in no case was significant Brackett γ seen. It therefore appears that the Brackett γ emission seen in Fig. 5 is highly variable. Variable Brackett γ emission is seen in late-type stars which vary in magnitude (Lançon & Wood 2000) but it is difficult to explain in an apparently stable star such as this one. Perhaps the star is indeed variable, and the three different observations happen to have been taken at the same pulsational phase. We note that the spacing in days between the two CASPIR observations is roughly twice that between the 2MASS observation and the initial CASPIR/3D observation.

The 2MASS observations can be used to determine the extinction towards the star and hence its bolometric magnitude. For spectral types ranging from K5 to M3, the intrinsic $J - K$ colour should be between 0.99 and 1.12, and the intrinsic $H - K$ colour between 0.19 and 0.25 (Houdashelt et al. 2000). Using the standard universal extinction law (Rieke & Lebofsky 1985) to derive $A_K/E(J - K) = 0.66$ and $A_K/E(H - K) = 1.78$, we find that the K-band extinction A_K must be in the range 2.1 to 2.3 mag. The K-band bolometric correction is approximately 2.6 for a K5 star and 2.7 for an M3 star (Houdashelt et al. 2000). Thus if the star were at the estimated pulsar distance of ~ 11 kpc, the observed K magnitude of about 10.03 would imply a bolometric magnitude in the range -4.6 to -4.9. This luminosity implies a stellar mass of only 6 to 7 M$_\odot$ for a supergiant (Maeder & Meynet 1989), not large enough to make this star the pulsar companion.

It is well recognized that distances estimated from the Taylor & Cordes (1993) DM model may be significantly in error. The models of Maeder & Meynet (1989) predict a bolometric magnitude of -6.5 for a 12-M$_\odot$ star, requiring the system to be at a distance of 23 kpc − more than twice as far as predicted by the DM model. We do not believe this to be likely, but it is not impossible.

A further problem which arises with identifying this star as the companion, at either distance, is the stellar radius. As noted in Section 2.3, red supergiants have radii of several hundred R$_\odot$ (van Belle et al. 1999), larger than what is permitted by the pulsar orbit.
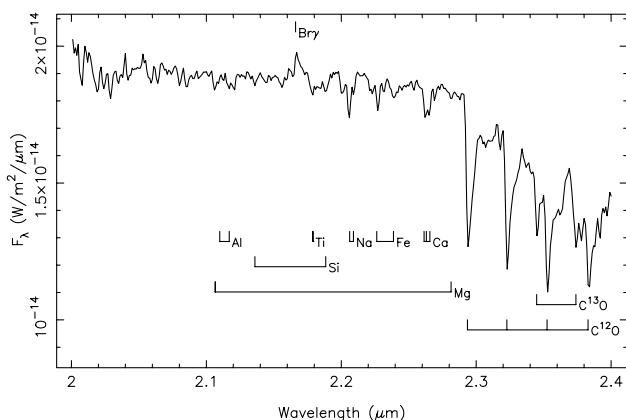

Figure 5. 2.2 μm (K-band) spectrum of the late-type star at the position of PSR J1740−3052 obtained with the 3D instrument on the AAT. Prominent spectral lines are labelled.
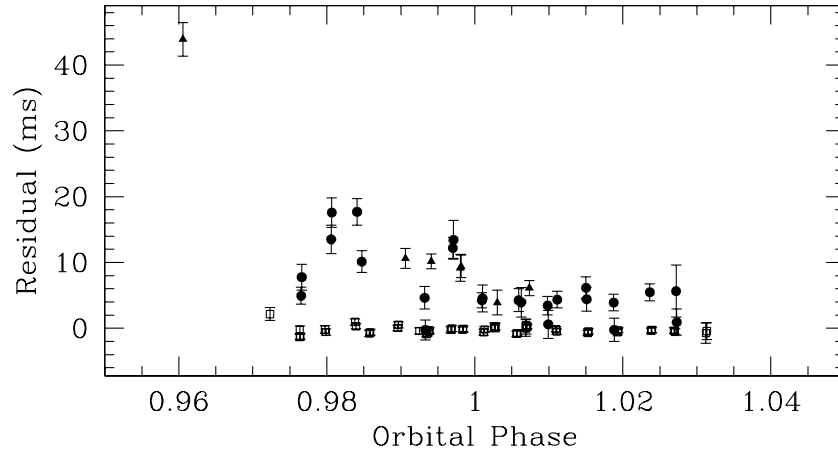
Figure 6. Residuals at 660 and 1390 MHz as a function of orbital phase near the periastrons of 2000 February 10 and 2000 September 28. Periastron is at orbital phase 1.0. 1390-MHz data are indicated by open squares, 2000 February 660-MHz data by filled circles, and 2000 September 660-MHz data by filled triangles. There is clear evidence for variation in the DM before periastron. We believe that the 660-MHz point at phase ~ 0.96 is likely to be reliable.

In fact, requiring the companion to be contained within the Roche lobe forces the stellar radius to be less than 0.4 au. In short, the luminosity and radius required for a late-type supergiant make it unlikely that this star is the pulsar companion. If the observed star lies near the Galactic Centre at a distance of 8.5 kpc, its bolometric luminosity would be approximately -4.3, consistent with that of the approximately solar-mass red giants which dominate the Galactic bulge stellar population. We believe that this is the most self-consistent explanation of the properties of this star.

It therefore appears that the positional agreement between the late-type star and the pulsar is indeed a coincidence. If there were to be a B star hidden by the light of the late-type star and at the estimated pulsar distance of 11 kpc, its K-band magnitude would be roughly 15 and it would not appreciably change the observed K-band spectrum.

4 OBSERVATIONS NEAR PERIASTRON

In a further attempt to distinguish between a black hole and a non-degenerate companion, we undertook dual-frequency radio monitoring campaigns of the pulsar around the periastrons of 2000 February 10 (MJD 51584.5) and 2000 September 28 (MJD 51815.5). Observations were made at Parkes on most days in the periods 2000 February 5–17 and 2000 September 19–30 at centre frequencies of 660 and 1390 MHz. The goals of these campaigns were to verify the absence of eclipses and to look for evidence of variations in the dispersion measure and rotation measure (RM) of the pulsar, as such changes might be expected from the interaction of the pulsar signal with the wind from a non-degenerate companion.

4.1 Timing observations

The Parkes dual-frequency timing observations were performed at 660 MHz using a $2 \times 256 \times 0.125$-MHz filterbank and, using the central beam of the multibeam receiver, at 1390 MHz with a $2 \times 512 \times 0.5$-MHz filterbank, both employing the 1-bit digitization system described in Section 2.1. The pulsar was detected on each observing day, demonstrating conclusively that there is no eclipse. Fig. 6 shows timing residuals of the 660- and 1390-MHz data as a function of orbital phase, with the DM held constant at the value given in Table 1. There is clear evidence for increased and variable dispersion before periastron. This pattern is consistent with the

observed longitude of periastron, as the companion is between us and the pulsar before periastron, and beyond the pulsar after periastron. Therefore, one would expect increased DMs before periastron and more stable values after.

These observations show that the increase in DM on any given day relative to the reference DM of $740.9(2)\,\mathrm{cm^{-3}\,pc}$ is typically of the order of 1 or $2\,\mathrm{cm^{-3}\,pc}$. For the observations before periastron, the extra distance travelled across the pulsar orbit is about 10^{13} cm, or 0.67 au, leading to an estimated electron density inside the orbit of a few $\times 10^5\,\mathrm{cm^{-3}}$.

We once again consider the possibility of a late-type, cool, bright star as the companion. The expected stellar wind from such a star is of the order of $10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$ (e.g. Dupree 1986) with an ionized fraction of 0.002–0.02 (Drake & Linsky 1983). The closest approach of the two stars for $i = 70°$, $m_2 = 12.5\,\mathrm{M_\odot}$ is only 0.75 au, just twice the maximum possible stellar radius based on Roche lobe considerations. Assuming a distance of about 0.75 au from the companion centre and a stellar wind velocity of $\sim 30\,\mathrm{km\,s^{-1}}$ (Dupree 1986), we arrive at an estimate for an ionized mass-loss rate of a few $\times 10^{-11}\,\mathrm{M_\odot yr^{-1}}$, and therefore an overall mass-loss rate of 10^{-9}–$10^{-8}\,\mathrm{M_\odot\,yr^{-1}}$. This is smaller by two orders of magnitude than the expected rate for these stars, which could possibly be explained if the mass loss is very clumpy as found, for example, in α Ori (e.g. Skinner & Whitmore 1987). However, we believe that this low mass-loss rate casts further doubt on the association of the late-type star with the pulsar.

In the case of an early B star, we follow the arguments of Kaspi et al. (1996) and references therein in adopting the following law for the wind velocity v_w:

$$v_w(r) = v_\infty(1 - R_2/r)^{1/2}, \qquad (8)$$

where r is the distance from the centre of mass of the star and v_∞ is 1–3 times the escape velocity $v_{esc} \approx 725\,\mathrm{km\,s^{-1}}$. The electron density $n_e(r)$ at any point r from the star can be found from mass conservation,

$$\dot{M} = 4\pi r^2 n_e(r) m_p v_w(r) \qquad (9)$$

where $\dot{M}$ is the mass-loss rate and m_p is the proton mass. For the observations just before periastron, we integrate numerically along
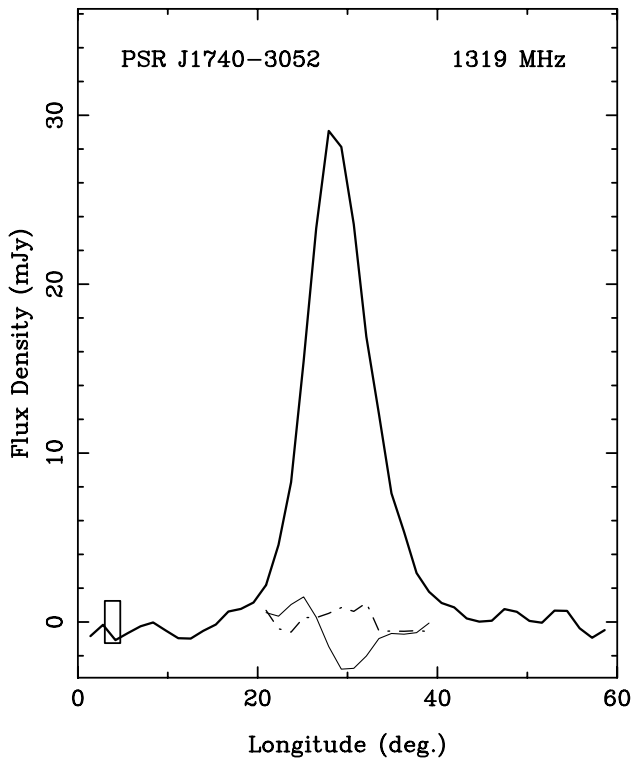
Figure 7. Mean pulse polarization profile for PSR J1740−3052 obtained by summing 5.85 h of data obtained at 1318.5 MHz in 2000 February. The upper solid line is the total intensity, Stokes I, the dot–dashed line is the linearly polarized component, $L = (Q^2 + U^2)^{1/2}$, and the lower solid line is Stokes $V = I_{LH} - I_{RH}$. The box at the left of the baseline has a height of four times the baseline rms noise and a width equal to the effective time resolution of the profile, including the effects of interstellar dispersion. Position angles were not significant, and hence are not plotted.

the line of sight through the pulsar orbit in the following manner:

$$I = \int \frac{1}{\sqrt{1 - R_2/r}} \frac{1}{r^2} \, dl \qquad (10)$$

in order to find the expected difference in DM. The end result is

$$\dot{M} = 1.1 \times 10^{-9} \left(\frac{v_\infty}{v_{esc}} \right) \frac{\Delta DM}{I} \, M_\odot \, yr^{-1} \qquad (11)$$

where ΔDM is the difference in DM before and after periastron in units of cm^{-3} pc and I is in units of au^{-1}. Both ΔDM and I are of the order of unity here, implying a mass-loss rate of a few $\times 10^{-9} \, M_\odot \, yr^{-1}$, roughly what is predicted for early-type stars of this mass in the Galaxy (e.g. de Jager et al. 1988). We note that this mass-loss rate is two orders of magnitude higher than the upper limit found for PSR J0045−7319 in the small Magellanic Cloud, lending support to the argument for a metallicity dependence of the mass-loss rate for such stars (Kaspi, Tauris & Manchester 1996). We conclude that the observed DM variations are better explained by an early B-star companion than by a late-type supergiant.

4.2 Polarimetric observations

The polarization of the mean pulse profile was measured on a total of 18 days before, during and after the 2000 February periastron, and on several other occasions throughout the orbit, using the centre beam of the multibeam receiver and the Caltech correlator (Navarro 1994). The centre frequency and bandwidth were 1318.5 and 128 MHz, respectively. Observations were made in pairs at orthogonal position angles, typically for 30 min at each angle; summing of these orthogonal pairs removes most of the effects of instrumental polarization. Data were calibrated following standard procedures (Navarro et al. 1997), except that the full frequency resolution of the correlator, 128×1 MHz, was retained during the processing.

In general, the mean pulse profile is weakly polarized. Fig. 7 shows the mean profile resulting from adding all the data obtained over the periastron period, between 2000 February 4 and February 17, a total of 5.85 hours of observation. The average linear polarization $\langle L \rangle / \langle I \rangle$, where $L = (Q^2 + U^2)^{1/2}$, is only 1 ± 4 per cent. However, there is some significant circular polarization, with a hint of a sense reversal near the pulse peak. This suggests that the very narrow pulse [full width at half-maximum (FWHM) of 8° of longitude] is from the core region of the polar cap (e.g. Rankin 1983).

It is possible that the very low linear polarization is due to Faraday depolarization in the wind of the companion. This effect is seen in the eclipsing Be-star system PSR B1259−63 (Johnston et al. 1996). To investigate this we summed the individual channel data for each orthogonal pair over a range of RM from −5000 to +5000 rad m^{-2} in steps of 50 rad m^{-2}. Where significant linear polarization was found, an improved value of the RM was computed from a weighted mean position angle difference between the two halves of the observed band. On three of the 20 or so observations made away from periastron, on 2000 February 28, March 26 and May 31, significant linear polarization (20–30 per cent) was observed with RM of +180, −85 and −220 rad m^{-2}, respectively. No significant polarization (<10 per cent) was observed at any RM within the search range during the periastron period or on other occasions.

These results suggest that Faraday rotation is occurring in the wind of the companion star and that it is highly variable. Combined with the DM variations of 1 or 2 cm^{-3} pc during periastron passage (Section 4.1), the RM changes indicate that the magnetic field strength in the wind region (weighted by the local electron density) is at least a few times 0.1 mG. The observed variations suggest that the field structure is complex, and so this value, which is integrated along the line of sight, is a lower limit to the actual field strength in the wind region.

The very existence of DM and RM variations appears to argue against a black hole as the pulsar companion, although it is perhaps plausible that the passage of the signal through the extended atmosphere of the late-type star could be responsible for the variations if the late-type star is foreground and the geometry is favourable.

4.3 Archival X-ray observations

For a non-degenerate companion, particularly an extended giant star, accretion of companion wind material on to the neutron star could in principle occur near periastron, where the distance of closest approach is 0.72 au/$\sin i$. Such accretion might result in observable X-ray emission.

To investigate this possibility, we examined archival X-ray observations of the field near PSR J1740−3052. Serendipitously, the *ASCA* X-ray telescope (Tanaka, Inoue & Holt 1994) observed a field containing PSR J1740−3052 on 1995 September 26 (Sequence ID 53016050) as part of its survey of Galactic ridge

emission. This is only 19 days after a periastron passage. In addition, the source was only 8 arcmin from the centre of the field of view in the observation.

We have reduced data from the two co-aligned Gas Imaging Spectrometers (GIS) onboard *ASCA*. The effective total GIS exposure was 2×12.5 ks. We used the standard *ASCA* data analysis tool XSELECT to produce a first image of the field, for both GIS2 and GIS3. For this image, we included counts having energies between 2 and 10 keV, as softer emission is likely to have been absorbed, given the large expected column density towards the source (see below). The resulting image was exposure corrected, and was further corrected for variations in the particle background over the fields-of-view using the FTOOL ASCAEXPO. For details, see Roberts, Romani & Kawai (2001). The corrected GIS2 and GIS3 images were combined and smoothed with a Gaussian function having FWHM 50 arcsec.

No significant emission was detected from the pulsar position. To set an upper limit on the flux, we first found the rms scatter of the image, 1.5×10^{-7} count s^{-1} cm^{-2} pixel^{-1}. This number was then multiplied by the number of pixels (117) in the half-power region of the *ASCA* point-spread function. Multiplying by two for the full power, and by three to yield a 3σ upper limit, we find that the observed flux from the source in the 2–10 keV band is $< 1 \times 10^{-4}$ count s^{-1} cm^{-2}.

In order to determine the upper limit on the energy flux and hence on the source luminosity, we assume a simple power-law model having photon index -2, and an equivalent neutral-hydrogen absorbing column of $N_H \simeq 3 \times 10^{22}$ cm^{-2}. We use HEASARC's tools[3] to convert the above upper limit on the photon flux into an upper limit on the unabsorbed energy flux, 1.4×10^{-12} erg s^{-1} cm^{-2}, in the 2–10 keV band. For a distance of 11 kpc as estimated from the DM of the pulsar (see Section 2.3), an upper limit on the 2–10 keV luminosity of the source $L_x < 2 \times 10^{34}$ erg s^{-1} is implied. Assuming the simplest possible accretion model, this implies $\dot{M} < L_x R_p / G m_1 = 1.8 \times 10^{-12}$ M$_\odot$ yr^{-1}, where $R_p = 10$ km and $m_1 = 1.35$ M$_\odot$ are the assumed neutron star radius and mass, respectively.

Given this upper limit, accretion is very unlikely to have occurred. Such a low $\dot{M}$ is unlikely to have sufficient pressure to overcome the pulsar wind pressure (see, e.g. Tavani, Arons & Kaspi 1994), so it is unlikely for the material to have come within the accretion radius. We note, however, that our upper limit does not preclude the existence of non-thermal shock-powered X-rays like those seen in the pulsar/Be star binary PSR B1259 − 63 near periastron (Kaspi et al. 1995; Hirayama et al. 1996). The shock emission is ultimately powered by the spin-down of the pulsar. PSR J1740−3052 has a much smaller spin-down luminosity than PSR B1259−63 and is much more distant. Even in the unlikely event that *all* of the spin-down luminosity of PSR J1740−3052 ($\dot{E} = 5.5 \times 10^{33}$ erg s^{-1}, see Table 1) were converted into shock emission in the X-ray band, it would be unobservable in the archival *ASCA* data.

5 DISCUSSION

On evolutionary grounds, there is no reason to prefer one type of candidate companion over another. As we have discussed above, PSR J1740−3052 is a young pulsar which has not undergone an episode of mass transfer from its companion. The characteristic

age of the pulsar is 3.5×10^5 yr, while a late-type supergiant star might be expected to evolve from an OB star in $\sim 10^7$ yr, making either type of non-degenerate companion consistent from the point of view of stellar ages. The fact that the system remained bound on formation of the neutron star suggests that the pre-supernova star was the less massive of the two at the time of the explosion. This is consistent with evolutionary scenarios involving mass transfer on to the initially lighter star (Portegies Zwart & Yungelson 1998). This mass transfer may have also somewhat accelerated the evolution of the companion. Alternatively, a suitably oriented kick on formation could have kept the system bound (Bailes 1988; Tauris & Takens 1998). In the case of a black hole companion, the neutron star would be the second-formed compact object, as the black hole progenitor would have been more massive initially.

Two pulsar systems are currently known to have non-degenerate companion stars, PSRs B1259−63 (Johnston et al. 1992) and J0045−7319 (Kaspi et al. 1994), and these contain Be and B stars, respectively. These systems are considered likely progenitors of HMXBs. If, as we believe is likely, the companion to PSR J1740−3052 is also an early B star, then this system will also likely become an HMXB in the future, as the neutron star begins to accrete matter from the wind of the evolving companion. As the companion evolves to overflow its Roche lobe, the system will enter a common-envelope phase and the neutron star will begin to spiral in. The current orbital period of this system, 231 d, makes the outcome after this point uncertain (van den Heuvel 1993). The neutron star may spiral in completely, resulting in a red giant star with a neutron star core: a Thorne–Żytkow object (Thorne & Żytkow 1977). Alternatively, there may be enough energy released during the orbital spiral-in to eject the common envelope, leaving behind the evolved core of the companion. Given the current mass of the companion, this core is likely to undergo a supernova explosion itself, leaving behind either a bound double neutron star system such as PSR B1913+16, or else two isolated neutron stars, one mildly recycled, one young.

We have argued throughout this paper that the companion is most likely to be an early-type B star rather than a black hole or the late-type star which is coincident with the position of the pulsar. Our arguments may be summarized as follows.

(i) The magnitude of the late-type star coincident with the pulsar position can be made consistent with the bolometric magnitude of an 11-M$_\odot$ star only if the DM estimate of the distance to the pulsar is low by a factor of 2. In contrast, the colours and magnitude of the star are perfectly consistent with an asymptotic giant branch star of about 1 M$_\odot$ at the Galactic Centre.

(ii) An early B main-sequence star at the nominal pulsar distance of about 11 kpc and hidden by the late-type star would not significantly alter the observed K-band magnitude or spectrum.

(iii) The radii of late-type supergiant stars are as large as or larger than the orbit of the pulsar. No significant mass has been transferred to the pulsar from the companion, requiring the companion to be confined inside its Roche lobe of radius roughly 0.4 au, improbably small for a late-type supergiant. Such a small radius would also require either a higher temperature or a smaller luminosity for the star, contrary to our understanding of the evolution of these objects (Maeder & Meynet 1989).

(iv) Even for a late-type supergiant of the small required radius, the calculated magnitudes of the tidal and spin quadrupoles predict an advance of periastron in the orbit of the pulsar an order of magnitude larger than that observed. In contrast, similar estimates for an early B star predict values not much larger

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[3] WEBSPEC (http://heasarc.gsfc.nasa.gov/cgi-bin/webspec) and W3PIMMS (http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html).

than the general-relativistic prediction, and a good match to the observations. A black hole companion is also consistent with these observations.

(v) The existence of orbital-phase-dependent DM and RM variations argues for a non-degenerate companion of some kind, and against a black hole companion unless there is a fortuitous alignment between the orbit of the pulsar and the extended wind of the foreground late-type star. Furthermore, the observed magnitude of the DM variations implies a stellar wind two orders of magnitude smaller than that predicted for late-type stars (e.g. Dupree 1986), but consistent with that expected for an early B star.

All points considered, we find that the bulk of the evidence points to a non-degenerate companion, but to an early B star rather than to the late-type star observed to be coincident with the pulsar position. It should be possible to establish whether or not the late-type star is the companion through a careful search for Doppler radial velocity variations in the stellar spectrum. The expected total range of radial velocity variation is $22\,\mathrm{km\,s^{-1}}$ for an $11\text{-}M_\odot$ companion, or $15\,\mathrm{km\,s^{-1}}$ for a $16\text{-}M_\odot$ companion; this should be measurable with a high-resolution spectrometer. Further multi-frequency radio monitoring of the orbital DM and RM variations will lead to a characterization of the wind of a non-degenerate companion. Finally, continued long-term timing of the pulsar will lead to precise values of $\dot{\omega}$ and $\dot{x}$, allowing a separation of general-relativistic effects from those caused by the quadrupole of a non-degenerate companion, thus providing final proof of the nature of the companion.

REFERENCES

Bailes M., 1988, A&A, 202, 109
Bell J. F., Bessell M. S., Stappers B. W., Bailes M., Kaspi V. M., 1995, ApJ, 447, L117
Bhattacharya D., van den Heuvel E. P. J., 1991, Phys. Rep., 203, 1
Chakrabarty D., Roche P., 1997, ApJ, 489, 254
Claret A., Gimenez A., 1992, A&AS, 96, 255
Cowling T. G., 1938, MNRAS, 98, 734
Cox A. N., ed., 2000, Allen's astrophysical quantities, 4th edn. AIP Press, Springer, New York
Davidsen A., Malina R., Bowyer S., 1977, ApJ, 211, 866
de Jager C., Nieuwenhuijzen H., van der Hucht K. A., 1988, A&AS, 72, 259
de Medeiros J. R., Mayor M., 1999, A&AS, 139, 433
Drake S. A., Linsky J. L., 1983, ApJ, 274, L77
Dupree A. K., 1986, ARA&A, 24, 377
Eggleton P. P., 1983, ApJ, 268, 368
Hambly N. C., Miller L., MacGillivray H. T., Herd J. T., Cormack W., 1998, MNRAS, 298, 897
Hirayama M., Nagase F., Tavani M., Kaspi V. M., Kawia N., Arons J., 1996, PASJ, 48, 833
Houdashelt M. L., Bell R. A., Sweigart A. V., Wing R. F., 2000, AJ, 119, 1424
Hulse R. A., Taylor J. H., 1975, ApJ, 195, L51
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., 1996, MNRAS, 279, 1026
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., Tavani M., Nagase F., Hirayama M., Hoshino M., Aoki T., Kawai N., Arons J., 1995, ApJ, 453, 424
Kaspi V. M., Bailes M., Manchester R. N., Stappers B. W., Bell J. F., 1996, Nat, 381, 584
Kaspi V. M., Tauris T., Manchester R. N., 1996, ApJ, 459, 717
Kleinmann S. G., Hall D. N. B., 1986, ApJS, 62, 501
Lai D., Bildsten L., Kaspi V. M., 1995, ApJ, 452, 819
Lançon A., Wood P. R., 2000, A&AS, 146, 217
Maeder A., Meynet G., 1989, A&A, 210, 155
Manchester R. N. et al., 2001, MNRAS, in press
McGregor P., Hart J., Downing M., Hoadley D., Bloxham G., 1994, Exp. Astron., 3, 139
Navarro J., 1994, PhD thesis, California Institute of Technology
Navarro J., Manchester R. N., Sandhu J. S., Kulkarni S. R., Bailes M., 1997, ApJ, 486, 1019
Phinney E. S., Kulkarni S. R., 1994, ARA&A, 32, 591
Portegies Zwart S. F., Yungelson L. R., 1998, A&A, 332, 173
Rankin J. M., 1983, ApJ, 274, 333
Rieke G. H., Lebofsky M. J., 1985, ApJ, 288, 618
Roberts M. S. E., Romani R. W., Kawai N., 2001, ApJS, 133, 451
Schiff L. I., 1958, Phys. Rev. Lett., 1, 254
Skinner C. J., Whitmore B., 1987, MNRAS, 224, 335
Standish E. M., 1982, A&A, 114, 297
Tanaka Y., Inoue H., Holt S. S., 1994, PASJ, 46, L37
Tauris T. M., Takens T. M., 1998, A&A, 330, 1047
Tavani M., Arons J., Kaspi V. M., 1994, ApJ, 433, L37
Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674
Thatte N. A., Kroker H., Weitzel L., Tacconi-Garman L. E., Tecza M., Krabbe A., Genzel R., 1995, in Fowler A., ed., Proc. SPIE Vol. 2475, Infrared Detectors and Instrumentation for Astronomy, SPIE, Bellingham, p. 228
Thorne K. S., Żytkow A. N., 1977, ApJ, 212, 832
Thorsett S. E., Chakrabarty D., 1999, ApJ, 512, 288
Urban S. E., Corbin T. E., Wycoff G., 1998, AJ, 115, 2161
van Belle G. T. et al., 1999, AJ, 117, 521
van den Heuvel E. P. J., 1993, in Phillips J. A., Thorsett S. E., Kulkarni S. R., eds, ASP Conf. Ser. Vol. 36, Planets Around Pulsars. Astron. Soc. Pac., San Francisco, p. 123
van der Hulst J. M., Terlouw J. P., Begeman K. G., Zwitser W., Roelfsema P. R., 1992, in Worrall D. M., Biemesderfer C., Barnes J., eds, ASP Conf. Ser. Vol. 25, Astronomical Data Analysis Software and Systems I. Astron. Soc. Pac., San Francisco, p. 131
Wallace L., Hinkle K., 1997, ApJS, 111, 445
Weitzel L., Krabbe A., Kroker H., Thatte N., Tacconi-Garman L. E., Cameron M., Genzel R., 1996, A&AS, 119, 531
Wex N., 1998, MNRAS, 298, 997

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