OPTICAL DETECTION OF TWO INTERMEDIATE-MASS BINARY PULSAR COMPANIONS

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ABSTRACT

We report the detection of probable optical counterparts for two intermediate-mass binary pulsar (IMBP) systems, PSR J1528–3146 and PSR J1757–5322. Recent radio pulsar surveys have uncovered a handful of these systems with putative massive white dwarf companions, thought to have an evolutionary history different from that of the more numerous class of low-mass binary pulsars with He white dwarf companions. The study of IMBP companions via optical observations offers us several new diagnostics: the evolution of main-sequence stars near the white dwarf–neutron star boundary, the physics of white dwarfs close to the Chandrasekhar limit, and insights into the recycling process by which old pulsars are spun up to high rotation frequencies. We were unsuccessful in our attempt to detect optical counterparts of PSR J1141–6545, PSR J1157–5112, PSR J1435–6100, and PSR J1454–5846.

Subject headings: binaries: close — pulsars: general — stars: neutron — white dwarfs

1. INTRODUCTION

The majority of recycled pulsars are in low-mass binary pulsar (LMBP) systems, consisting of a neutron star and a low-mass white dwarf. The LMBPs are widely considered to be descendants of the low-mass X-ray binaries. The progenitors are thus a massive star primary (which gives rise to the neutron star) and a low-mass (≤1 M⊙) secondary. In contrast, double neutron star binaries, exemplified by PSR B1913+16, descend from binaries in which both the primary and secondary are massive stars, each forming a neutron star.

Over the past few years, astronomers have come to appreciate the existence of another class of binary pulsars, the so-called intermediate-mass binary pulsars (IMBPs) with massive C-O or O-Ne-Mg white dwarf companions. As suggested by their name, IMBPs are thought to descend from binary star systems with a massive primary and a secondary that is intermediate in mass. First, the primary becomes a neutron star through a supernova explosion. Later, the secondary evolves into a massive white dwarf, transferring matter to the pulsar and recycling it in the process (van den Heuvel 1994; Tauris et al. 2000; Taam et al. 2000). As in LMBP systems, tidal damping circularizes the orbit because the supernova occurs before the companion becomes a compact object. Sixteen candidate IMBP systems are currently known.

Not all pulsars with massive white dwarf companions share this evolutionary path. PSR B2303+46 (Stokes et al. 1985) and PSR J1141–6545 (Kaspi et al. 2000) have companions with masses similar to the IMBP systems; however, these slowly rotating pulsars appear to be unrecycled, and their orbits are eccentric. In systems such as these, it is thought that neither the primary nor the secondary was initially massive enough to form a neutron star. As the primary evolved into a massive white dwarf, it transferred matter to the secondary, thereby making the secondary massive enough to eventually become a neutron star. Here again the final outcome is a massive white dwarf and a neutron star, but because the supernova occurs after the primary has become a white dwarf, the orbit remains eccentric, and the neutron star is not recycled (Tauris & Sennels 2000). Although only two such systems are known, they may exist in numbers greater than neutron star binary systems (Portegies Zwart & Yungelson 1999). The detection of the white dwarf companion via optical observations can help us clarify this interesting evolutionary path (van Kerkwijk & Kulkarni 1999).

Apart from these tests of binary evolution, these systems may offer us new insights into the physics of how neutron stars are spun up by accretion. It is clear that the mass transfer of the recycling process results in a decreased magnetic field as well as an increased rotation rate for the neutron star. The spin period at the end of the spin-up phase, , is a critical input to pulsar recycling models. A comparison of the white dwarf age from cooling models with the pulsar spin-down age (which assumes that P0 is much smaller than the current spin period) can, in principle, allow us to determine P0 (Camilo et al. 1994).

2. OBSERVATIONS

We have obtained optical observations of fields containing six IMBP systems discovered in recent radio pulsar surveys with the Parkes radio telescope (Fig. 1 and Table 1; Camilo et al. 2001; Edwards & Bailes 2001a; Kaspi et al. 2000). We observed PSR J1141–6545, PSR J1157–5112, PSR J1435–6100, PSR J1528–3146, PSR J1454–5846, and PSR J1757–5322 in the R band on the nights of 2002 August 6–8 with the Magellan Instant Camera (MagIC) on the 6.5 m Baade telescope at the Magellan Observatory. Seeing was generally good, but some targets were observed at high air mass, giving a broader point-spread function. Conditions were photometric on August 6 and 8, but there were clouds present on August 7. Each of our six targets was observed for two 10 minute exposures on one of the photometric nights, except for PSR J1528–3146. These data were reduced following standard practices (bias subtraction, flat-fielding with dome flats), photometrically calibrated with observations of the Stetson standard star L112-805, and astrometrically calibrated using the USNO B-1.0 catalog. The astrometric uncertainty in all observations presented here is dominated by the tie between the USNO-B1.0 system and the International Celestial Reference Frame (~0.2 in each coordinate).

On the night of 2003 June 4, we observed PSR J1528–3146 once again with MagIC. Conditions were not photometric but better than on our previous attempt. We obtained two exposures
Fig. 1.—Images of fields of PSR J1141–6545, PSR J1157–5112, PSR J1435–6100, PSR J1528–3146, PSR J1454–5846, and PSR J1757–5322. Circles indicate the 3σ uncertainty in the pulsar position; tick marks show the pulsar position where a plausible counterpart was detected. Large images are in the $R$ band. For PSR J1528–3146, the inset shows the $B$-band image. For PSR J1757–5322, the inset in the upper left-hand corner shows the $R$-band image after the subtraction of the bright star near the pulsar position, and the inset in the lower left-hand corner shows the image. For PSR J1141–6545, the timing position from Bailes et al. (2003) was used; in all other cases, positions were taken from the references in Table 1.

Table 1

| Pulsar      | $P$ (ms) | $B$ (10$^7$ G) | $t_c$ (Gyr) | $P_0$ (days) | $e$ | $m_{\text{max}}$ ($M_\odot$) | $d^*$ (kpc) | Ref. |
|-------------|----------|----------------|-------------|--------------|----|-----------------------------|------------|------|
| J1141–6545  | 393.9    | 1300           | 0.0014      | 0.20         | 1.8 $\times$ 10$^{-1}$ | 0.97          | 2.5   | 1               |
| J1157–5112  | 43.6     | 2.5            | 4.8         | 3.51         | 4.0 $\times$ 10$^{-5}$ | 1.18          | 1.3   | 2               |
| J1435–6100  | 9.3      | 0.5            | 6           | 1.35         | 1.9 $\times$ 10$^{-4}$ | 0.90          | 2.2   | 3               |
| J1454–5846  | 45.2     | 6              | 0.9         | 12.42        | 1.8 $\times$ 10$^{-4}$ | 2.1           | 0.80  | 4               |
| J1528–3146  | 60.8     | 3.9            | 3.9         | 3.18         | 2.0 $\times$ 10$^{-4}$ | 0.94          | 0.96  | 2               |
| J1757–5322  | 8.9      | 0.49           | 5.3         | 0.45 (4 ± 4) | 10$^{-4}$             | 0.55          | 0.96  | 2               |

* Distance estimated from dispersion measure using model of Cordes & Lazio (2002).

References.—(1) Kaspi et al. 2000; (2) Edwards & Bailes 2001b; (3) Camilo et al. 2001; (4) B. A. J. Jacoby et al. 2006, in preparation.
stars that were used to improve the sky frames in a second round of sky subtraction. Astrometry was again provided by the USNO B-1.0 catalog, and photometric calibration by comparison with several 2MASS stars in the field. There is no object present at the pulsar’s position to the detection limit of the image, \( K_s = 20.8 \). The implied limit on the color corresponds to a main-sequence spectral type of \( \sim M4 \) or earlier and is thus consistent with a white dwarf.

Several of these fields are rather crowded; this was especially problematic in the case of PSR J1435–6100, whose position overlaps with three blended objects in our image. On the night of 2003 June 6, we obtained a spectrum of the bright object near the pulsar position with the Low Dispersion Survey Spectrograph 2 (LDSS2) on the Clay telescope, and determined that it is a reddened F-type main-sequence star and thus not associated with the pulsar. We used the DAOPHOT ALLSTAR task to subtract stars near the positions of PSR J1157–5112 and PSR J1435–6100, eliminating the possibility of fainter counterparts hidden by the nearby brighter objects in these cases.

3. DISCUSSION AND CONCLUSIONS

We detected optical counterparts for two out of the six IMBP systems we studied, PSR J1528–3146 and PSR J1757–5322. From Table 1, one sees that these are the two nearest targets. Thus, it is quite possible that deeper observations would reveal the counterparts in the remaining binaries as well.

In Figure 2, we show cooling curves for hydrogen atmosphere white dwarfs with masses from 0.5 to 1.2 \( M_\odot \), along with the observationally inferred absolute \( R \) magnitudes of massive white dwarf pulsar companions versus the spin-down ages of their pulsars. The absolute magnitudes have large uncertainties that are difficult to quantify because the only constraint on the pulsar distances is based on dispersion measure–distance model of Cordes & Lazio (2002); however, this exercise is still instructive. We note that in all cases where optical observations failed to detect an IMBP counterpart, the predicted magnitude is fainter than the observation’s detection threshold.

As previously mentioned, it is thought that the companion stars in the PSR J1141–6545 and PSR B2303+46 systems must have been fully evolved by the time the pulsars formed. Therefore, in these systems, the pulsar age does not constrain the white dwarf age, and the failure to detect the PSR J1141–6545 companion is not troubling. The detected optical counterpart of PSR B2303+46 (van Kerkwijk & Kulkarni 1999) is significantly fainter than predicted by the cooling model based on the pulsar’s spin-down age. In addition to the expectation that the white dwarf is older than the pulsar, this object has the largest \( z \)-distance from the Galactic plane in this sample; it is above much of the ionized gas in the Galactic disk, so the dispersion measure–based distance estimate could be significantly smaller than the true distance.

In all of the other systems, the neutron star formed first, and the pulsar’s spin-down age should, in principle, correspond to the time since the end of the companion’s evolution. The other five detected objects are all brighter than predicted by the cooling curves if they are as old as their pulsars’ characteristic ages. Although there is a large uncertainty associated with the absolute magnitude of each object, as a group, they suggest that the standard spin-down model for pulsars may in fact significantly overestimate the pulsar age in these cases, possibly because \( P_0 \) was not much smaller than the current spin period.

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REFERENCES

Bailes, M., Ord, S. M., Knight, H. S., & Hotan, A. W. 2003, ApJ, 595, L49
Benvenuto, O. G., & Althaus, L. G. 1999, MNRAS, 303, 30
Bergeron, P., Wesemael, F., & Beauchamp, A. 1995, PASP, 107, 1047
Camilo, F., Thorsett, S. E., & Kulkarni, S. R. 1994, ApJ, 421, L15
Camilo, F., et al. 2001, ApJ, 548, L187
Cordes, J. M., & Lazio, T. J. W. 2002, preprint (astro-ph/0207156)
Edwards, R. T., & Bailes, M. 2001a, ApJ, 547, L37
———. 2001b, ApJ, 553, 801
Kaspi, V. M., et al. 2000, ApJ, 543, 321
Kulkarni, S. R. 1986, ApJ, 306, L85
Lundgren, S. C., Foster, R. S., & Camilo, F. 1996, in ASP Conf. Ser. 105, Pulsars: Problems and Progress, ed. S. Johnston, M. A. Walker, & M. Bailes (IAU Colloq. 160; San Francisco: ASP), 497
Neckel, T., & Klare, G. 1980, A&AS, 42, 251
Portegies Zwart, S. F., & Yungelson, L. R. 1999, MNRAS, 309, 26
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Stokes, G. H., Taylor, J., & Dewey, R. J. 1985, ApJ, 294, L21
Taam, R. E., King, A. R., & Ritter, H. 2000, ApJ, 541, 329
Tauris, T. M., & Sennels, T. 2000, A&A, 355, 236
Tauris, T. M., van den Heuvel, E. P. J., & Savonije, G. J. 2000, ApJ, 530, L93
van den Heuvel, E. P. J. 1994, A&A, 291, L39
van Kerkwijk, M. H., Bassa, C. G., Jacoby, B. A., & Jonker, P. G. 2005, in ASP Conf. Ser. 328, Binary Radio Pulsars, ed. F. A. Rasio & I. H. Stairs (San Francisco: ASP), 357
van Kerkwijk, M. H., & Kulkarni, S. R. 1999, ApJ, 516, L25