A 1.05 $M_\odot$ COMPANION TO PSR J2222–0137: THE COOLEST KNOWN WHITE DWARF?

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ABSTRACT

The recycled pulsar PSR J2222–0137 is one of the closest known neutron stars (NSs) with a parallax distance of 267 $\pm$ 1.2 pc and an edge-on orbit. We measure the Shapiro delay in the system through pulsar timing with the Green Bank Telescope, deriving a low pulsar mass ($1.20 \pm 0.14 M_\odot$) and a high companion mass ($1.05 \pm 0.06 M_\odot$) consistent with either a low-mass NS or a high-mass white dwarf. We can largely reject the NS hypothesis on the basis of the system’s extremely low eccentricity ($3 \times 10^{-4}$)—too low to have been the product of two supernovae under normal circumstances. However, despite deep optical and near-infrared searches with Southern Astrophysical Research and the Keck telescopes we have not discovered the optical counterpart of the system. This is consistent with the white dwarf hypothesis only if the effective temperature is $<3000$ K, a limit that is robust to distance, mass, and atmosphere uncertainties. This would make the companion to PSR J2222–0137 one of the coolest white dwarfs ever observed. For the implied age to be consistent with the age of the Milky Way requires the white dwarf to have already crystallized and entered the faster Debye-cooling regime.

Key words: binaries: general – pulsars: individual (PSR J2222-0137) – stars: distances – stars: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

PSR J2222–0137 (hereafter PSR J2222) is a 33 ms radio pulsar discovered in the Green Bank Telescope (GBT) 350 MHz drift-scan pulsar survey (Boyles et al. 2013). With a dispersion measure of 3.27 pc cm$^{-3}$, it appeared to be one of the closest pulsars to the Earth. Further observations showed PSR J2222 was in a binary system with an orbital period of 2.45 days and a minimum companion mass of about 1 $M_\odot$. This sort of system straddles the line between potential companion types. It could be a double-neutron star (DNS), of which there are only roughly 12 and whose study is crucial to understanding the formation of sources of kilohertz gravitational waves (e.g., Kim et al. 2003) and testing general relativity (e.g., Stairs 2010). Or, it could be a pulsar with a massive white dwarf companion—a so-called “intermediate-mass binary pulsar” (IMBP)—that descended from a binary with a more massive companion than in traditional systems with pulsars and low-mass white dwarfs (van den Heuvel 2004; Tauris et al. 2000, 2011, 2012). IMBP systems are rare, with fewer than 20 known, and massive white dwarfs are themselves rare, with fewer than 8% of the white dwarfs (WDs) from optical surveys having masses above 0.9 $M_\odot$ (Gianninas et al. 2011). Understanding the formation and evolution of IMBP systems provides a crucial piece in our understanding of binary evolution and pulsar recycling, and helps delineate evolutionary paths between low-mass NSs and high-mass white dwarfs (Tauris 2011).

Deller et al. (2013) used very long baseline interferometry astrometry to measure the parallax of PSR J2222 with exquisite precision. They find a distance of 267 $^{+1.2}_{-0.9}$ pc (it is the second closest binary pulsar system and one of the closest NSs of any type). The astrometric data also suggested an edge-on orbit, opening up the possibility of a measurement of the Shapiro delay (Shapiro 1964), which gives two post-Keplerian parameters of the system and hence determines the component masses (e.g., Demorest et al. 2010). Here we present the detailed timing analysis of the PSR J2222 system, including the measurement of the Shapiro delay and the determination of the masses (Section 2.1). We then present deep optical and near-infrared searches for the companion to PSR J2222 (Section 2.2), which we use to constrain models of its formation and evolution (Section 3). We find that the system almost certainly must be an IMBP system, but that we do not detect the companion, constraining it to be one of the coolest white dwarfs ever observed. Unlike some sources where temperature inferences are highly dependent on white dwarf model atmospheres (e.g., Gates et al. 2004), this measurement is robust, given the small uncertainties on the mass and (especially) distance. We conclude in Section 4.

2. OBSERVATIONS AND ANALYSIS

2.1. Radio Observations

Radio observations of PSR J2222 to measure the Shapiro delay occurred in the last week of 2011 May with the 100 m Robert C. Byrd GBT.10 We had a 6 hr observation taken around

10 The Robert C. Byrd Green Bank Telescope (GBT) is operated by the National Radio Astronomy Observatory which is a facility of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
superior conjunction of the binary system augmented by five 2 hr observations at each of the other five Shapiro extrema, all using the Green Bank Ultimate Pulsar Processing Instrument (GUPPI; DuPlain et al. 2008). The 800 MHz of bandwidth centered at 1500 MHz in two orthogonal polarizations was separated into 512 Nyquist-sampled frequency channels of width 1.5625 MHz via a polyphase filter bank. These channels, sampled at 8 bits, provided full polarization information and an effective time resolution of 0.64 μs. Each channel was coherently dedispersed at the nominal dispersion measure of the pulsar (3.27761 pc cm$^{-3}$ at the time, although we later refined this measurement). Each observing session was broken into 30 minute observations of PSR J2222 separated by 60 s calibration scans of the extragalactic radio source 3C 190. The calibration scans were taken in the same mode as the pulsar observations, but also included a 25 Hz noise diode inserted into the receiver.

Data reduction was performed using the PSRCHIVE package (Hotan et al. 2004). Flux calibration used the on- and off-source scans of 3C 190. This was followed by removal of radio frequency interference by the psrzap utility. The calibrated pulse profile determined from the long observation covering conjunction is given in Figure 1. The data were aligned in time using the best ephemeris (below), divided into 16 frequency channels, and refit for dispersion measure and rotation measure using a bootstrap error analysis. We found that the period-averaged flux density varied by a factor of a few over the course of long observations due to scintillation, with an average of 1–2 mJy at 1500 MHz. Individual times of arrival (TOAs) were measured from the folded total-intensity profiles using the frequency domain algorithm in PSRCHIVE (Taylor 1992). A template was created by fitting three Gaussians to the summed pulse profile. From these Gaussian components, we created a noise-free template with the phase of the fundamental component in the frequency domain rotated to zero. The observations were divided into two minute segments, with one TOA measured for each segment. Note that since interstellar scintillation caused the flux to vary considerably, there was a proportional change in the TOA precision that varied over the data set.

These data were combined with previous data taken for the discovery observations of PSR J2222 (Boyles et al. 2013) to produce a timing model. We used the “DD” model (Damour & Deruelle 1985, 1986) in TEMPO, which incorporates the Shapiro delay. The astrometric data for this model were taken from Deller et al. (2013), and we used the DE421 JPL ephemeris (Folkner et al. 2009). Timing fits with no Shapiro delay were statistically unacceptable, with an rms residual of 9.3 μs ($\chi^2 = 4539.4$ for 931 degrees of freedom), and a clear Shapiro delay signature was obvious in the residuals (Figure 2). With the Shapiro delay included in the fit the rms residual was 4.2 μs ($\chi^2 = 930$ for 929 degrees of freedom), with no obvious remaining structure in the residuals (varying the astrometric parameters within the uncertainties from Deller et al. 2013 changed the timing results by $\ll 1\sigma$). The Shapiro delay determines the inclination of the orbit and the companion mass; this is then combined with the binary mass function to determine the pulsar’s mass. Due to the combination of several different and much less precise observing modes from earlier monitoring with the high-precision Shapiro delay campaign, we estimated the timing parameters with a bootstrap error analysis. We give the full timing results, with 1σ error estimates from the bootstrap analysis, in Table 1.

Our data consist of high-quality coherently dedispersed data from an intensive one week campaign and a few other epochs. The remainder of the data were both less precise and less uniform, with a wider range of observation frequency and
instrumental setup. This makes it difficult (if not impossible) to robustly constrain long-term secular changes like periastron precession ($\dot{\omega}$; Lorimer & Kramer 2012). Nonetheless, we tried a fit with $\dot{\omega}$ fixed to the value predicted by general relativity ($\approx 0.08$ yr$^{-1}$). The resulting fit was good, with the rms decreasing to about 3.8 $\mu$s. The pulsar and companion masses each increased by about 1% compared to the values in Table 1. Given the small eccentricity and inhomogeneous data set with large gaps we do not believe that fitting for $\dot{\omega}$ is viable at this time, but encourage further long-term monitoring of this system to establish its secular behavior.

### 2.2. Optical/IR Observations

We observed the position of PSR J2222 at optical and near-infrared wavelengths, as listed in Table 2. The deepest Keck observations used the red side of the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the 10 m Keck I telescope. The data were reduced using standard procedures in IRAF, subtracting the bias, dividing by flatfields, and combining the individual exposures. The seeing was about 0.8 in the combined $R$ image, and 0.7 in the combined $I$ image. We computed an astrometric solution fitting for a shift and separate scales and rotations along each axis (i.e., a six parameter fit) using 100 non-saturated stars identified from the Sloan Digital Sky Survey (SDSS) Data Release 10 (DR10; Ahn et al. 2014), giving rms residuals of 0.2 in each coordinate. We did photometric calibration relative to SDSS photometry, identifying 23 well-detected, well-separated, non-saturated stars, and transforming from the SDSS filter set to Johnson–Cousins using the appropriate transformation equations.$^{12}$ The zero-point uncertainty was <0.01 mag, although there are systematic uncertainties coming from our filter transformations. We see no object at the position of the pulsar (Figure 3); the closest object is about 2$''$ from the position of the pulsar (about 10x away) and appears extended ($R = 23.1 \pm 0.1$ and statistical position uncertainties of $\pm 0.3'$ in each coordinate). We determined the 3$\sigma$ upper limits using sExtractor (Bertin & Arnouts 1996) to determine the magnitude that gave a 0.3 mag uncertainty (verified with fake-star tests), which we give in Table 2.

We observed PSR J2222 in $r$-band with the Goodman Spectrograph (Clemens et al. 2004) on the 4.1 m Southern Astrophysical Research (SOAR) telescope over two nights in 2013 July. All exposures were dithered and binned by a factor of two in both dimensions. The frames were bias-subtracted and flattened with a dome flat. We then used a median of the data (having masked the scattered-light halos of three saturated stars) from the second night constructed without registration to create a sky flat, which we smoothed with a $20 \times 20$ pixel boxcar filter. This corrects for larger-scale brightness variations. Cosmic rays were interpolated on individual exposures using the lacosmic routine (van Dokkum 2001). The seeing varied considerably over the course of the observations, going from 1.1'-1.2'$. We then shifted each exposure by an integer number of pixels for registration and summed them. The final summed image has an effective seeing of 1.3' and a total exposure time of 2.6 hr. The photometric zero-point was again computed relative

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12 See http://www.sdss.org/dr5/algorithms/sdssUBVRITransform.html#Lupton2005.
Figure 3. Optical images of the field of PSR J2222: LRIS R band (left), LRIS I band (middle), and SOAR r band (right). The position of PSR J2222 is indicated with the ticks at the center, which begin 0′′5 from the pulsar (larger than the position uncertainty of the pulsar combined with the astrometric uncertainty of the image). North is up, east to the left, and the image is 1′′ in size. On the R-band image we also indicate the field-of-view covered by our NIRC2 image, with the region masked apparent in the lower-right.

(A color version of this figure is available in the online journal.)

Table 1

| Parameters            | Value               |
|-----------------------|---------------------|
| Spin period (s)       | 0.032817859053065(3) |
| Period derivative (s s⁻¹) | 5.865(7) × 10⁻²⁰   |
| Dispersion measure (pc cm⁻³) | 3.2842(6)          |
| Rotation measure (rad m⁻²) | +2.6(1)             |
| Reference epoch (MJD) | 55743               |
| Right ascension (J2000) | 22:22:05.969101(1) |
| Declination (J2000)   | 22:05:15.961(1)     |
| R.A. proper motion (mas yr⁻¹) | 44.73(4)           |
| Decl. proper motion (mas yr⁻¹) | −5.68(6)          |
| Parallax (mas)        | 3.7474(013)         |
| Position epoch (MJD)  | 55743               |
| Span of timing data (MJD) | 55005–55922        |
| Number of TOAs        | 943                 |
| rms residual (µs)     | 4.2                 |

| Binary parameters      |                   |
|------------------------|-------------------|
| Orbital period (days)  | 2.4457599929(3)   |
| Projected semi-major axis (lt-s) | 10.9480276(12)  |
| Epoch of periastron (MJD) | 55742.13242(0)   |
| Orbital eccentricity   | 3.8086(15) × 10⁻⁴ |
| Longitud of periastron (deg) | 119.778(12)   |
| Mass function (M₀)     | 0.22907971(8)     |
| sin i                  | 0.9985(3)          |
| Companion mass (M₀)    | 1.05(6)            |

| Derived parameters     |                   |
|------------------------|-------------------|
| Distance (pc)          | 267.3±1.2         |
| Transverse velocity (km s⁻¹) | 57.1±0.9          |
| Orbital inclination (deg) | 86.8(4)          |
| Intrinsic period derivative (s s⁻¹) | 4.33(5) × 10⁻¹⁰ |
| Surface magnetic field (10² G) | 0.719            |
| Spin-down luminosity (10¹⁰ erg s⁻¹) | 1.72              |
| Characteristic age (Gyr) | 33.8             |
| Pulsar mass (M₀)       | 1.20(14)          |
| Flux density at 1500 MHz (mJy) | 1–2              |

Notes. Values in parentheses are uncertainties on the last digit. For the timing data derived here, the uncertainties were derived from a bootstrap analysis and are quoted at the 1σ level.

a During the initial timing observations we calculated a TOA every 10 minutes. During the new observations described here we calculated a TOA every two minutes.

b Values are from Deller et al. (2013) and were held fixed for the timing fit.

c Values are corrected for Shklovskii effect.

d We used the “DD” model (Damour & Deruelle 1985, 1986).

e The NIRC2 camera can be utilized in three different magnification modes. We used the “wide” camera with a 40′ square field of view.

Table 2

| Instrument | Date          | Filter | Exposure | Limiting Magnitude |
|------------|---------------|--------|----------|---------------------|
|            |               |        |          |                     |
| SOAR/Goodman | 2013 Jul 2 | r      | 300 + 3 × 600 | 26.4 ± 0.8          |
| SOAR/Goodman | 2013 Jul 3 | r      | 18 × 400   | 26.3 ± 0.3          |
| Keck I/LRIS(red) | 2013 Aug 4 | R      | 2 × 300   | 26.3 ± 0.3          |
| Keck I/LRIS(red) | 2013 Aug 4 | I      | 2 × 300   | 26.0 ± 0.3          |
| Keck II/NIRC2   | 2013 Oct 12 | K′     | 60 + 5 × 120 | 21.0 ± 0.3         |

Notes.

3 σ limiting magnitudes at the position of the pulsar.

b Absolute magnitude limits computed for a distance of 267 pc and an extinction of A_V = 0.12 mag.

c The two SOAR observations were combined.

d The NIRC2 camera can be utilized in three different magnification modes. We used the “wide” camera with a 40′ square field of view.

to the SDSS DR10 data, using 31 stars. The astrometric solution was done using six 30 s exposures through http://astrometry.net (Lang et al. 2010). As with the Keck data, we see no object at the position of the pulsar (Figure 3) and give a 3σ upper limit in Table 2.

While they were taken through different filters and with very different instruments/resolutions, we tried combining the Keck R-band and SOAR r-band images using swarp (Bertin et al. 2002). We still see no source at the position of the pulsar. The data are sufficiently different that a limiting flux is difficult to compute, but it could be as much as 0.3 mag fainter than the limits in Table 2.

The near-infrared observations come from the NIRC2 camera on the 10 m Keck II telescope, and used the Laser Guide Star Adaptive Optics (AO) system (van Dam et al. 2006). The data were taken through thin clouds and the AO corrections were not optimal, resulting in a delivered image quality of 0′′2 FHWM. The images were reduced using a custom pipeline implemented with python and pyraf using dark frames and dome flats. A sky fringe frame was created by combining dithered images of multiple targets with the bright stars masked. We used SExtractor (Bertin & Arnouts 1996) for the preliminary detection and masking of stars. The fringe frame was subtracted from the flat-fielded data after being scaled to the appropriate sky background level. Before coadding the frames, each frame was corrected for optical distortion using a distortion solution
measured for NIRC2. A faint glare has been visible in the lower right (southwest) corner of the NIRC2 wide camera images starting in 2009 August. The shape and amplitude of the glare vary with telescope orientation, resisting correction through surface fitting or modeling. Instead we masked the glare using a triangular region. There was no independent photometric calibration that night, and only a single star is visible on the co-added image. To determine a photometric zero-point, we used photometry for that star from the SDSS DR10. We then employed the empirical main-sequence color relations from Covey et al. (2007), inferring the $g-i$ color from the observed $g-K_s$ color (we ignore differences between $K_s$ and $K$-filters). For this star (SDSS J222204.76+013658.9) we infer a spectral type of K2.5 and predict $K_s = 16.9$. We expect zero-point uncertainties of ±0.2 mag or so based on comparison of the other SDSS colors to those predicted using Covey et al. (2007). Again, we see no object at the position of the pulsar, and give 3σ upper limits in Table 2.

3. DISCUSSION

3.1. A Low-mass Neutron Star?

Since we do not detect the optical counterpart of the companion, the first inference is that the companion could be a low-mass NS. It would be the lowest mass NS known (Lattimer et al. 2012; Özel et al. 2013), although it is only the low-mass NS. It would be the lowest mass NS known (Lattimer et al. 2012; Özel et al. 2013), although it is only the low-mass NS. It would be the lowest mass NS known (Lattimer et al. 2012; Özel et al. 2013), although it is only the low-mass NS. It would be the lowest mass NS known (Lattimer et al. 2012; Özel et al. 2013), although it is only

The normal formation scenario for a DNS involves two core-collapse supernova explosions, with the eccentricity the result of the second explosion and its kick, and no final mass-transfer phase to circularize the orbit (e.g., Tauris & van den Heuvel 2006). In contrast, formation via an electron-capture supernova (ECS; Miyaji et al. 1980) could result in a significantly lower NS mass (Schwab et al. 2010; Ferdman et al. 2013) along with a lower supernova kick (Podsiadlowski et al. 2004; van den Heuvel 2004). PSR J2222 has a low transverse velocity (58 km s$^{-1}$), although higher than some systems thought to be the products of ECSs (given the age of the system, this velocity may be more related to motion in the Galactic potential than birth conditions). This may reflect the velocity dispersion of the progenitor systems. However, the contrast between PSR J2222 and other systems thought to be the results of ECSs (e.g., PSR J1906+0746 or PSR J0737−3039; Ferdman et al. 2013) is extreme, with the ratio of eccentricities above 200 as mentioned previously. In a scenario without a kick we can place an upper limit on the amount of material that could have been ejected

by the explosion to $(M_{	ext{PSR}} + M_e) = 8 \times 10^{-4} M_\odot$ (with $M_{\text{PSR}}$ the pulsar mass and $M_e$ the current companion mass; e.g., Bhattacharya & van den Heuvel 1991). This is a much tighter bound than in any of the other systems proposed for this mechanism, and difficult to reconcile with the change in binding energy needed to form an NS (Freire & Tauris 2014): all confirmed DNS systems are found above this line.

(A color version of this figure is available in the online journal.)

3.2. An Intermediate-mass Binary Pulsar?

The other possible scenario is that the companion could be a massive WD, making the system an IMBP. Its orbital eccentricity is somewhat high compared to most low-mass binary pulsars of similar periods (based on Phinney 1992), but not nearly as high as a DNS, consistent with an IMBP classification (Camilo et al. 2001). It falls in the locus of other CO WDs in the “Corbet” (binary period versus spin period)
Figure 5. Absolute $R$ magnitude plotted against WD mass for massive and/or cool WDs. We show the IMBPs and massive WDs from van Kerkwijk et al. (2005) and Jacoby et al. (2006), with PSR J1141−6545 updated from Antoniadis et al. (2011) and PSR J1439−5501 from Pallanca et al. (2013). Data from bands other than $R$ were converted to $R$ using the photometry of Tremblay et al. (2011) and with extensions from Drimmel et al. (2003) computed for the distances of the pulsars, except for updated extinctions for PSR J1439−5501 (Pallanca et al. 2013) and PSR B2303+46 (van Kerkwijk & Kulkarni 1999). All other pulsar data come from Manchester et al. (2005; ver. 1.48), Distances are from Cordes & Lazio (2002), except PSRs J1022+1001 and J2145−0750 (A. T. Deller et al. 2014, private communication), PSR J1141−6545 (Ord et al. 2002), and PSR J1439−5501 (Pallanca et al. 2013). When the inclination is not constrained, the point is at the median value (inclination of 60°) but a range is indicated by the error bars, and we allow a maximum companion mass of 1.4 $M_\odot$. We also show the approximate truncation of the WD cooling sequence from the halo globular cluster NGC 6397 (square; Richer et al. 2006; Hansen et al. 2007; Richer et al. 2011) and other than $R$ except for updated extinctions for PSR J1439−5501 (Pallanca et al. 2013). In Figure 5, we plot the absolute magnitude against WD mass for pulsar+WD systems as well as select cool WDs with parallax distances: even compared to the observed truncation of the cooling sequence in old halo globular clusters like NGC 6397 (Richer et al. 2013) or M4 (Bedin et al. 2009), the putative companion is far fainter: at the distance of NGC 6397, our limit of $M_R > 19.1$ translates to an apparent magnitude of $R > 31.6$, compared to $R \approx 29$, or $M_R \approx 16$ for the coolest WDs seen in NGC 6397. Some of the difference comes from the change in radius: a 1.0 $M_\odot$ WD has a radius about 65% of that of a typical 0.6 $M_\odot$ WD, leading to a 1 mag change in brightness at the same effective temperature. However, the difference in Figure 5 is more like 2.5 mag, so the companion to PSR J2222 must also be cooler than the known thick disk/halo WDs.

Beyond the absolute magnitude, which is directly computable from observable quantities, we can limit the radius/temperature of a putative WD by using our $R$-band absolute magnitude limit to constrain the bolometric luminosity. This is more complicated, as it involves atmosphere calculations in an uncertain and poorly tested regime, but it should be reasonably reliable. We use the synthetic photometry and evolutionary models from Tremblay et al. (2011) and Bergeron et al. (2011) for H and He atmospheres, respectively. For isolated WDs pure He atmospheres can be largely excluded because of Bondi-Hoyle accretion from the ISM (Bergeron 2001), and even small amounts of hydrogen mixed into the helium can cause near-infrared flux deficiencies like pure hydrogen (see below; Bergeron & Leggett 2002). However, the binary orbit and MSP wind in this system could have inhibited such accretion and therefore a He atmosphere is possible. In any case, a pure He atmosphere will serve as a limiting case compared to the H models. These models are used to convert the absolute magnitude limits into temperature limits, so for simplicity we use the 1.0 $M_\odot$ models (differences in bolometric corrections as a function of mass are small, <0.05 mag).

The most constraining limit is again from the $R$-band data, where $M_R > 19.1$ implies $T_{\text{eff}} < 1700$ K (see Figure 6) for an H atmosphere. The He-atmosphere models do not...

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extend to sufficiently cool temperatures but stop at \(T_{\text{eff}} = 3500\, \text{K} \) with \(M_R = 17.7\). At lower temperatures the details of the atmospheric physics are rather uncertain, but a blackbody is likely an acceptable approximation (P. Bergeron 2014, private communication). With an He atmosphere an effective temperature an acceptable approximation (P. Bergeron 2014, private communication). With an He atmosphere an effective temperature an acceptable approximation.

The models span the \(\pm 2\sigma\) mass range of PSR J2222’s companion, from 0.95 \(M_\odot\) to 1.15 \(M_\odot\), and include thin (hydrogen \(10^{-10}\) by mass; dashed lines) and thick (hydrogen \(10^{-4}\) by mass; solid lines) hydrogen atmospheres. The spin-down age of the pulsar \(\tau_c\) is 34 Gyr and is far to the right. Instead, we show with a vertical dotted line the age of the Milky Way’s inner halo (Kalirai 2012) as an upper bound to the age of any star not found in a globular cluster. The \(R\)-band upper limits are the horizontal dotted lines in the lower panel: in the top panel, the cooling curves stop when the implied \(R\)-band photometry reaches our upper limit (filled circles), which happens at an effective temperature of 2000–3000 K (3000 K is indicated by the dotted line in the top panel). To compute the synthetic photometry we have used the synthetic model for the 1.0 \(M_\odot\) DA WD to compute bolometric corrections as a function of effective temperature, which we then applied to the cooling models.

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Figure 7. Cooling of massive H-atmosphere CO WDs, based on the models of Bergeron et al. (2011); also see Kowalski & Saumon (2006); Holberg & Bergeron (2006); Tremblay et al. (2011). We show the effective temperature (top), and \(R\)-band (bottom) absolute magnitudes for ages of >1 Gyr. The models span the \(\pm 2\sigma\) mass range of PSR J2222’s companion, from 0.95 \(M_\odot\) to 1.15 \(M_\odot\), and include thin (hydrogen \(10^{-10}\) by mass; dashed lines) and thick (hydrogen \(10^{-4}\) by mass; solid lines) hydrogen atmospheres. The spin-down age of the pulsar \(\tau_c\) is 34 Gyr and is far to the right. Instead, we show with a vertical dotted line the age of the Milky Way’s inner halo (Kalirai 2012) as an upper bound to the age of any star not found in a globular cluster. The \(R\)-band upper limits are the horizontal dotted lines in the lower panel: in the top panel, the cooling curves stop when the implied \(R\)-band photometry reaches our upper limit (filled circles), which happens at an effective temperature of 2000–3000 K (3000 K is indicated by the dotted line in the top panel). To compute the synthetic photometry we have used the synthetic model for the 1.0 \(M_\odot\) DA WD to compute bolometric corrections as a function of effective temperature, which we then applied to the cooling models.

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useful observations. The occurrence of a nearby massive WD like the companion to PSR J2222 is reasonably consistent with expectations based on the observed binary population: there are five pulsar binaries from the ATNF Pulsar Catalog\(^\text{17}\) (Manchester et al. 2005) within 300 pc, and the other four have low-mass He WD companions. This 1/5 ratio is similar to that for CO WD compared to He WD companions in the whole ATNF catalog (also see Tauris et al. 2012), and the pulsars’ spin-down ages appear to have similar distributions for both companion types.

Finally, we can ask whether an NS is the most likely companion to an ultra-cool WD. Most binaries are assumed to have mass ratios near one (Pinsonneault & Stanek 2006, but see Sana et al. 2012), but a binary composed of two ultra-cool WDs would be just as hard to detect optically as a single object. If the companion were a lower-mass WD or a main-sequence star the binary could be visible, although it would require spectroscopic follow-up to identify the companion and in the absence of GAIA this has not been done for the majority of stars within a few hundred pc. So the situation of PSR J2222, with an NS companion, is reasonably plausible as the initial mass ratio would have been close to one and the chances of companion follow-up and identification after discovery of the pulsar are high.

4. CONCLUSIONS

We have determined an accurate mass for the partially recycled pulsar PSR J2222 and its companion; the latter is a value consistent with both an NS and a WD. Despite not finding the companion in a deep optical/near-infrared search, we reject a DNS explanation as the binary system shows evidence of circularizing requiring mass transfer after the last supernova. Instead, the companion is likely a high-mass WD. Using the extremely precise distance determination from Deller et al. (2013), we can set a robust limit of $M_g > 19.1$. This implies an very old and cool WD: fainter than all other pulsar companions by a factor of about 100, and fainter than the lower-mass “ultra-cool” WD in the solar neighborhood by a factor of about four. Converting this limit to a temperature depends somewhat on the assumed mass and composition, but we believe an effective temperature limit of $T_{\text{eff}} < 3000$ K is a robust upper limit. For such an object to not be older than the Milky Way requires that it have already entered the faster Debye cooling regime, i.e., that it already crystallized (also see Metcalf et al. 2004; Brassard & Fontaine 2005). Future searches, if they can detect the companion to PSR J2222, will be a unique probe of the very late stages of WD evolution, with a well-determined mass and radius that are not usually available for studies of such objects.

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