A Multiwavelength Study of Nearby Millisecond Pulsar PSR J1400−1431: Improved Astrometry and an Optical Detection of Its Cool White Dwarf Companion

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Abstract

In 2012, five high-school students involved in the Pulsar Search Collaboratory discovered the millisecond pulsar (MSP) PSR J1400−1431, and initial timing parameters were published in Rosen et al. a year later. Since then, we have obtained a phase-connected timing solution spanning five years, resolving a significant position discrepancy and measuring $P$, proper motion, parallax, and a monotonic slope in dispersion measure over time. Due to PSR J1400−1431’s proximity and significant proper motion, we use the Shklovskii effect and other priors to determine a 95% confidence interval for PSR J1400−1431’s distance, $d = 270^{+130}_{-100}$ pc. With an improved timing position, we present the first detection of the pulsar’s low-mass white dwarf (WD) companion using the Goodman Spectrograph on the 4.1 m SOAR telescope. Deeper imaging suggests that it is a cool DA-type WD with $T_{\text{eff}} = 3000 \pm 100$ K and $R/R_\odot = (2.19 \pm 0.03) \times 10^{-2}$ ($d/270$ pc). We show a convincing association between PSR J1400−1431 and a $\gamma$-ray point source, 3FGL J1400.5−1437, but only weak ($3.3\sigma$) evidence of pulsations after folding $\gamma$-ray photons using our radio timing model. We detect an X-ray counterpart with XMM-Newton, but the measured X-ray luminosity ($1 \times 10^{29}$ erg s$^{-1}$) makes PSR J1400−1431 the least X-ray luminous rotation-powered MSP detected to date. Together, our findings present a consistent picture of a nearby ($d \approx 230$ pc) MSP in a 9.5-day orbit around a cool $\sim 0.3 M_\odot$ WD companion, with orbital inclination $i \gtrsim 60^\circ$.

Key words: binaries: general – pulsars: individual (J1400−1431) – stars: distances – white dwarfs

1. Introduction

PSR J1400−1431 is a 3.08 ms radio pulsar discovered by Pulsar Search Collaboratory (PSC) students (Rosen et al. 2013) in a portion of the Green Bank 350 MHz Drift Scan Survey (Boyles et al. 2013; Lynch et al. 2013). With a dispersion measure (DM) of 4.9 pc cm$^{-3}$, it is one of only five millisecond pulsars (MSPs) with a DM $< 5$ pc cm$^{-3}$. Since the DM provides a measure of the electron content along the line of sight, it can be used as a proxy for distance, given Galactic electron density models (e.g., Taylor & Cordes 1993; Cordes & Lazio 2002; Yao et al. 2017). Yao et al. (2017) describe the most recent electron density model, which predicts that J1400−1431 has a distance of only 350 pc.

Nearby MSPs allow high-precision measurements of astrometric parameters like proper motion and, in some cases, parallax through pulsar timing. The latter involves detecting the curvature of incoming wavefronts—a signature only found in timing residuals for a handful of nearby MSPs close to the ecliptic plane (Camilo et al. 1994a; Kaspi et al. 1994; Sandhu et al. 1997; Wolszczan et al. 2000; Jacoby et al. 2003; Hotan et al. 2004a; Löhmer et al. 2004; Splaver et al. 2005; Desvignes et al. 2016; Matthews et al. 2016; Reardon et al. 2016). However, parallax has also been detected using very long baseline interferometry (VLBI) follow-up in many other cases (Brink et al. 2002; Chatterjee et al. 2009). Together, distance and DM provide an average measure of free electrons along the line of sight to the pulsar (Toscano et al. 1999a; Lommen et al. 2006); combined with proper motion, transverse velocities can be derived to study an underlying distribution for MSPs (Toscano et al. 1999b) and compare it to velocity distributions for other subpopulations. Underlying velocity distributions provide estimates for pulsar natal kicks from the supernova explosions that created them (Hobbs et al. 2005).

Because of its proximity and brightness, J1400−1431 was considered for inclusion in pulsar timing arrays (PTAs; e.g., Demorest et al. 2013; Arzoumanian et al. 2015), but was dropped due to inconsistent detectability at 820 MHz and higher observing frequencies. Rosen et al. (2013) hypothesized that unreliable detections at higher frequencies were likely due to J1400−1431’s particularly steep spectrum.

We used a novel drift-scan technique to improve localization for this pulsar (see further discussion in P. A. Gentile & J. K. Swiggum 2017, in preparation), finding a position that differed...
by 6.7 from that published in Rosen et al. (2013). This difference is larger than the formal uncertainty, but since the previous timing solution was based on less than one year of timing data, it is subject to significant covariance between position and spin-down parameters. The offset also undoubtedly played a significant role in early detectability issues at higher frequencies. In this paper, we present an improved phase-connected timing solution for J1400−1431 with pulse times of arrival (TOAs) spanning five years, including those published in Rosen et al. (2013). The significantly longer timing baseline compared to that of the previous study rules out any covariance between fits for position and spin-down.

In Section 2 we provide a detailed description of our full radio timing analysis, including measurements of proper motion, a linear slope in DM over time, and first and second Laplace parameters (effectively the orbital eccentricity). We have also developed a posterior probability distribution for J1400−1431’s distance based on a timing parallax fit, combined with several other priors.

Nearby MSPs are also good candidates for multiwavelength follow-up. In Section 3 we describe our observing campaign and photometry analysis using the Keck Low-resolution Imaging Spectrometer (LRIS) and the Southern Astrophysical Research (SOAR) optical telescopes to image J1400−1431’s white dwarf (WD) companion. PSR J1400−1431 has spin and orbital parameters similar to other low-mass binary pulsars (LMBPs)—namely, its short spin period (P < 10 ms), low eccentricity (e < 10^{-3}), and a minimum companion mass, m_c,min = 0.26 M_⊙, which falls in a typical range for LMBPs, 0.15 M_⊙ < m_c < 0.4 M_⊙. These systems are thought to evolve from a neutron star accreting material from a low-mass star in its giant phase. Stable mass transfer causes the neutron star to spin faster, while its companion. Stable mass transfer causes the neutron star to spin faster, while its companion.

### Table 1

| Center Frequency (MHz) | Bandwidth (MHz) | N_{channels} | t_{sample} (µs) | Observing Mode | GUPPI Offset\(a\) (µs) | N_{TOA} |
|------------------------|-----------------|--------------|-----------------|----------------|-------------------------|---------|
| 350                    | 100             | 2048         | 81.92           | Incoherent     | 40.96                   | 52      |
| 350                    | 100             | 4096         | 81.92           | Incoherent     | 81.92                   | 101     |
| 350                    | 100             | 128          | 1.28            | Coherent Fold  | 7.68                    | 17      |
| 820                    | 200             | 2048         | 81.92           | Incoherent     | 20.48                   | 16      |
| 820                    | 200             | 128          | 0.64            | Coherent Fold  | 3.84                    | 17      |

**Note.** Mode-dependent instrumental timing offsets used for PSR J1400−1431.

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In order to improve upon the preliminary timing solution published in Rosen et al. (2013), we include those data here, but have reprocessed them according to the procedure described below. All timing observations were conducted with the Robert C. Byrd Green Bank Telescope (GBT) at either 350 or 820 MHz using the Green Bank Ultimate Pulsar Processing Instrument (GUPPI; DuPlain et al. 2008) with 100 or 200 MHz bandwidth, respectively, and sampled every 81.92 µs. Since J1400−1431 has not been observed as part of a dedicated timing proposal since 2013, many of the more recent TOAs come from using the pulsar to conduct test scans before Green Bank North Celestial Cap (GBNCC; Stovall et al. 2014) survey observations. Because of this, the setup/observing parameters changed slightly for different groups of TOAs, so we noted these changes and carefully accounted for any resulting systematics (e.g., GUPPI offsets; see Table 1). In addition, because of its frequent use as a test source, many scans were taken using incoherent search-mode (rather than coherent fold-mode), resulting in relatively coarse time sampling for MSP monitoring.

We identified the detections with the highest signal-to-noise ratio at each observing frequency after folding data with the correct spin period and DM at each epoch, then fit three Gaussians to the corresponding pulse profiles to generate noiseless standard profiles. Standard profiles were aligned using pas from PSRCHIVE\(^15\) (Hotan et al. 2004b).

We zapped RFI interactively with pazi and used standard profiles to generate four TOAs per epoch with pat—summing across time and averaging down to four frequency subbands. Most of our observations were taken at 350 MHz, so retaining some frequency-dependence in our TOAs allowed us to fit for a linear slope in DM over our entire data span (d DM/dt). In order to phase-connect the entire data set, we fit for spin, position, proper motion, DM, and binary parameters (see Table 2). Parameter fits were carried out with TEMPO\(^16\) timing software and the DE421 solar system ephemeris; the timing solution is referenced to UTC (NIST). Due to J1400−1431’s low eccentricity, we used the ELL1 binary model, described originally in Appendix A of Lange et al. (2001). The parameter uncertainties shown in Table 2 reflect 1-σ (68%) uncertainties on measured parameters. However, a global multiplicative error factor (EFAC) has been applied to individual TOA errors such that the resulting reduced χ^2 value is one. Fitting for all parameters in our current timing solution results in 4 µs root mean square (rms) residuals with no obvious systematic trends (see Figure 1).

The position reported in Table 2 differs from that published in Rosen et al. (2013) by 6.7; that timing solution was based on data spanning less than a year and was therefore likely affected by position/spin-down covariance. We found an initial phase-

\(^15\) http://psrchive.sourceforge.net/

\(^16\) http://tempo.sourceforge.net/
Table 2  
Measured and Derived Timing Parameters for PSR J1400–1431

| Parameter                      | Value          |
|-------------------------------|----------------|
| Spin and Astrometric Parameters |                |
| Ecliptic Longitude (J2000)    | 213.11366082(8) |
| Ecliptic Latitude (J2000)     | –2.1064331(18)  |
| Proper Motion in Ecliptic Lon. (mas yr⁻¹) | 34.75(19) |
| Proper Motion in Ecliptic Lat. (mas yr⁻¹) | –46(6)  |
| Parallax (mas)                | 3.6(11)        |
| Spin Period (s)               | 0.0030842326039194(8) |
| Period Derivative (s⁻¹)       | 7.23335(15) × 10⁻²¹ |
| Intrinsic Period Derivative (s⁻¹) | <2.2 × 10⁻²¹ |
| Dispersion Measure (pc cm⁻³)  | 4.93258(3)     |
| d DM/dt (pc cm⁻³ yr⁻¹)        | 1.8(3) × 10⁻⁷  |
| Reference Epoch (MJD)         | 56960.0        |
| Span of Timing Data (MJD)     | 56006–57751    |
| Number of TOAs               | 203            |
| Rms Residual (µs)             | 4.06           |
| EFAC                          | 1.8            |
|                                |                |
| Binary Parameters             |                |
| Orbital Period (days)         | 9.5474676743(19) |
| Projected Semimajor Axis (l-s) | 8.4212530(6)  |
| Epoch of Ascending Node (MJD) | 56958.38397673(9) |
| First Laplace Parameter       | 2.8(12) × 10⁻⁷ |
| Second Laplace Parameter      | 4.8(14) × 10⁻⁷ |
| Derived Parameters            |                |
| Right Ascension (J2000)       | 14:00:37.00370(15) |
| Declination (J2000)           | –14:31:47.0422(6) |
| Orbital Eccentricity          | 5.5(14) × 10⁻⁷ |
| Surface Magnetic Field (10⁷ Gauss) | <8.3 |
| Spin-down Luminosity (10⁴³ erg s⁻¹) | <3.0 |
| Characteristic Age (Gyr)      | >22            |
| Total Proper Motion (mas yr⁻¹) | 57(5)        |
| Transverse Velocity (km s⁻¹)  | 76(20)         |
| Shklovskii Period Derivative (s⁻¹) | 7(2) × 10⁻²¹ |
| Mass Function (Mₖ)            | 0.0070345527(14) |
| Minimum Companion Mass (Mₑ)   | 0.26           |

Notes. Quantities are listed with 68% (1σ) uncertainties on the last digit in parentheses. The intrinsic spin-down (Pₙa) is constrained by Pₑₗₖₒₖₛ = 5 × 10⁻²¹, upper/lower limits on other derived parameters come from Pₙa, assuming the pulsar’s moment of inertia I = 10⁴⁵ g cm² and a 90° offset between its rotational and magnetic axes.  
A Using the ELL1 binary timing model.  
B Computed using the distance derived from the timing parallax measurement with no correction.  
C Calculated assuming a pulsar mass, m_p = 1.35 M☉.

coherent timing solution for J1400–1431 spanning several years in late June of 2015 and started observing it using the corrected position shortly afterwards (MJD 57199). For 350/820 MHz GBT observations, a 6/7 position offset results in a 9/43% degradation in gain, respectively. Since the majority of our timing observations were conducted at 350 MHz, the offset did not result in a significant loss of sensitivity.

2.1. Flux Density Estimates and Scintillation

We refolded existing data and aligned profiles using our new timing solution, then summed profiles from separate frequency bands in-phase using paradd (see Figure 2). Figure 2 also includes relatively short test scans taken with the GBT at 820 and 1500 MHz at the best-fit timing position. With GBT data, we estimated flux densities between 350 and 1500 MHz by measuring signal-to-noise ratios in each case and applying the radiometer equation (see e.g., Lorimer & Kramer 2004). PSR J1400–1431 was first detected at low frequency in a LOW-frequency ARay (LOFAR; van Haarlem et al. 2013) census of MSPs (Kondratiev et al. 2016), but we obtained additional data for further study to generate the profile shown in Figure 2. With LOFAR data, we measured calibrated flux densities from 15 observations conducted over a period of about six months and quote the median value with 50% uncertainties (S51 = 33 ± 16 mJy) since we did not carefully account for flux density variations due to J1400–1431 getting close to the Sun during this observing campaign and difficulties in calibrating LOFAR pulsar flux density measurements (Murphy et al. 2017). We assume similar uncertainties for GBT flux density estimates, although they are likely even higher for nominal S220 and S1500 values since we do not yet have enough detections in these bands to average over flux density variability due to scintillation and other effects. Although scintillation may still be problematic for consistent detectability given its low DM, test observations at 820 and 1500 MHz suggest that J1400–1431 should be reevaluated for PTA inclusion.

Finally, Figure 2 shows summed profiles for J1400–1431 in three frequency bands (49.8, 64.5, and 79.2 MHz—each with 19.6 MHz bandwidth) obtained with the Long Wavelength Array (LWA; e.g., Taylor et al. 2012). As of 2015, only three other MSPs were detected in an initial census (Stovall et al. 2015), so J1400–1431 is one of very few MSPs detected at these low frequencies. Since we have not yet carefully accounted for flux density variations due to a variety of known factors (e.g., frequency, zenith angle, and local sidereal time), we omit flux density estimates for the LWA detections shown in Figure 2.

Owing to J1400–1431’s low DM, we expect it so scintillate heavily, and we see evidence of this in the significantly tailed distribution of 350 MHz TOA weights. However, looking at dynamic spectra from individual observations, there are no visible scintles, indicating that the scintillation timescale and bandwidth are too large to be resolvable by these observations. Because the scintillation timescales and bandwidths are not measurable in our data, we rely on estimates from the NE2001 (Cordes & Lazio 2002) electron density model to better understand J1400–1431’s scintillation behavior. For the GBT profiles shown in Figure 2, only the one at 350 MHz incorporates enough data to average out the effect of scintillation. That is, the total integration time (5.9 hr) far exceeds the scintillation timescale at 350 MHz (Δt_FISS,350 ≈ 25 minutes). In all cases, scintillation bandwidths are comparable to our observing bandwidths, but at higher frequencies, the scintillation timescales (Δt_FISS,820 ≈ 35 minutes and Δt_FISS,1500 ≈ 45 minutes) exceed the total integration time for each profile. This suggests that corresponding estimated flux densities in these cases do not properly account for the effects of scintillation and are therefore somewhat biased.

2.2. Constraining Distance

Given J1400–1431’s position and dispersion measure (DM = 4.9 pc cm⁻³), Galactic electron density models provide distance estimates along the pulsar’s line of sight:
270 pc (Taylor & Cordes 1993), 500 pc (Cordes & Lazio 2002), and most recently, 350 pc (Yao et al. 2017). Normally, DM distances can be highly uncertain, particularly for pulsars with high Galactic latitudes like J1400−1431 ($b = 45^\circ$). In comparison with earlier Galactic electron density models, Yao et al. (2017) improve on distance estimates for pulsars with $|b| > 40^\circ$ whose distances have been measured independently. For 80% of these pulsars, Yao et al. (2017) predict DM distances with uncertainties <40%, but for some nearby MSPs we can measure distances to higher precision with pulsar timing. In some cases, the curvature of incoming wavefronts (Backer & Hellings 1986) can be measured as a 6-month periodic signature in timing residuals with amplitude,

$$A_\varpi = \frac{P^2 \cos^2 \beta}{2 \, c \, d},$$

where $A_\varpi$ is the amplitude of the timing parallax signature, $\beta$ and $d$ are the pulsar’s ecliptic latitude and distance, respectively, $l$ is the Earth–Sun distance (1 au), and $c$ is the speed of light. Because of nearby distance estimates and its low ecliptic latitude ($\beta = 2^\circ$), we decided to include parallax in J1400−1431’s pulsar timing model (see Table 2) and detected it ($\varpi = 3.6 \pm 1.1$ mas) with $\sim 3\sigma$ significance. This measurement constrains the system’s distance inside the range $170 < d/pc < 710$ with 95% confidence, but the distribution is weighted toward larger distances since $d \propto 1/\varpi$ (see the cyan curve in Figure 3). We further refined these distance constraints using additional astrometric information.

Originally shown by Shklovskii (1970), the induced period derivative due to secular acceleration ($\dot{P}_{\text{Shklov}}$) can account for a significant fraction of the measured spin-down ($\dot{P}_{\text{meas}}$), which is composed of both intrinsic and kinematic components, $\dot{P}_{\text{meas}} = \dot{P}_{\text{int}} + \dot{P}_{\text{Shklov}}$. Following Nice & Taylor (1995), we also investigated the contributions on $\dot{P}_{\text{meas}}$ due to the pulsar’s acceleration perpendicular to the Galactic plane ($2.4 \times 10^{-22}$ s $^{-1}$, or 3% of $\dot{P}_{\text{meas}}$) and due to differential Galactic rotation ($1.4 \times 10^{-23}$ s $^{-1}$, or 0.2% of $\dot{P}_{\text{meas}}$). These effects are more than an order of magnitude smaller than $\dot{P}_{\text{Shklov}}$, so we consider them negligible for the discussion that follows. Assuming J1400−1431 is spinning down ($\dot{P}_{\text{int}} > 0$) and by imposing the constraint $\dot{P}_{\text{meas}} > \dot{P}_{\text{Shklov}}$, we place an upper limit on the pulsar’s distance and therefore a lower limit on its parallax.

We constrain the distance jointly through the parallax measurement and the Shklovskii effect, also applying corrections for the Lutz–Kelker bias (Lutz & Kelker 1973). Adopting the notation of Verbiest et al. (2010), we attempt to determine the true parallax $\varpi$ given the measurement $\varpi_0$ via

$$p(\varpi|\varpi_0) = \frac{p(\varpi_0|\varpi)p(\varpi)}{p(\varpi_0)},$$

where we use a normal distribution for $p(\varpi_0|\varpi) = \mathcal{N}(\varpi_0, \sigma_{\varpi_0}) = \exp\left(-\frac{(\varpi_0 - \varpi)^2}{2\sigma_{\varpi_0}^2}\right)/\sqrt{2\pi \sigma_{\varpi_0}^2}$ and take $p(\varpi_0)$ to be flat. We use a volumetric prior for $\varpi$ to account for the Lutz–Kelker bias,

$$p_P(\varpi) \propto \varpi^{-4},$$

and add an additional term to the prior to account for the Shklovskii effect. We infer a distribution on the distance based on the proper motion $\mu$ and spin-down,

$$\varpi_{\text{Shklov}} = \left(\frac{-f}{c(\dot{f}_{\text{meas}} - \dot{f}_{\text{int}})}\right)\mu^2 = A \mu^2,$$

with $A = -f/c(\dot{f}_{\text{meas}} - \dot{f}_{\text{int}})$. We take the proper motion to be given by $p(\mu_\parallel|\mu) = \mathcal{N}(\mu_\parallel, \sigma_\mu)$. Note that we have implicitly assumed that the parallax and proper motion distributions are independent (i.e., not correlated), but have verified this through exploration of the parameter space and believe it to be a robust assumption. Then, with the constraint that $\dot{f}_{\text{int}} < 0$, we obtain a lower limit on $\varpi$ given by the cumulative integral of the
distribution of $p(\mu_0 | \mu)$ transformed to $\varpi$,

$$p_\mu(\varpi) = \int_0^\varpi d\varpi' \frac{1}{\sqrt{8\pi A}} \frac{1}{\varpi' \sigma_\mu^2} e^{-\sqrt{\frac{\varpi'}{A} - \mu_0^2}}/2\sigma_\mu^2,$$

suitably normalized. Our final prior distribution $p(\varpi)$ is the product of $p_\mu(\varpi)$ and $p_\mu(\varpi)$, resulting in 95% confidence intervals on parallax and distance of $\varpi = 3.7^{+1.2}_{-1.4}$ mas and $d = 270^{+130}_{-80}$ pc. We use the confidence interval on distance to show corresponding parallax signatures in Figure 4, computed using Equation (1). In this figure, we also show binned timing residuals to illustrate the parallax signature measured with the pulsar timing techniques described earlier.

We checked the parallax fit with a bootstrap method (Efron 1979), generating 50,000 sets of TOAs by randomly sampling the original TOAs with replacement until each trial set had the same number of TOAs as the original. Starting with our best-fit timing solution, we re-fit for all parameters using each trial TOA file and recorded trial fit parameters.

Overall, the bootstrap reproduced the conclusions from our best-fit timing solution once we excluded non-physical results (such as negative parallaxes). The widths of the bootstrap posterior distributions for individual parameters were somewhat larger than the uncertainties reported by TEMPO, by a factor of 1–2 depending on the parameter. However, our conclusions remain largely unchanged: even if we assume a factor of 2 increase in the parallax uncertainties, the effect on the 95% confidence interval for the distance is negligible, going from 190–400 pc to 160–420 pc. We are obtaining more data as well as investigating further timing techniques to fully reconcile this issue.

### 3. Optical Follow-up

We used the Goodman Spectrograph on the 4.1 m SOAR Telescope (Clemens et al. 2004) in its imaging mode to obtain optical photometry of a $6' \times 6'$ field surrounding PSR J1400–1431. The object frames were bias-subtracted and flat-fielded using CCDPROC and other standard routines in IRAF17 (Tody 1986) and averaged together using the IMCOMBINE routine to create a final master frame. We then ran the master frame through astrometry.net (Lang et al. 2010) to obtain an astrometric calibration to a precision of better than $0''$.

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17 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

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### Table 3

| Telescope/Instrument | Date       | Filter | Airmass | Exposure (s) | Magnitude |
|----------------------|------------|--------|---------|--------------|-----------|
| SOAR/Goodman         | 2016 Jun 09| $R_c$  | 1.81    | 46 $\times$ 5| 22.5 $\pm$ 0.3|
| Keck I/LRIS(blue)    | 2016 Aug 02| $V$    | 2.03    | 180          | 23.41 $\pm$ 0.08|
| Keck I/LRIS(red)     | 2016 Aug 02| $R$    | 1.71    | 300          | 22.52 $\pm$ 0.04|
| Keck I/LRIS(red)     | 2016 Aug 02| $I$    | 1.92    | 300          | 21.99 $\pm$ 0.04|

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**Figure 2.** Integrated profiles for J1400–1431 show the radio intensity as a function of pulse phase at a variety of observing frequencies spanning 50–1500 MHz. Profiles obtained with LWA and LOFAR/GBT observations are plotted here with 128 and 256 bins, respectively. Frequency-dependent flux values (e.g., $S_{150}$) are shown next to the corresponding profiles, each with $\sim$50% uncertainty.

**Figure 3.** Posterior probability distribution function (black line) for the distance of PSR J1400–1431, based on Equation (5) for an intrinsic spin-down $f = 0$. We also show the distribution from the measured parallax (red line), the prior derived from the limit on the distance due to the Shklovskii effect (blue dashed line), the volumetric prior for the Lutz–Kelker correction (Equation (3); orange dotted line), and the combined prior distribution (green dashed–dotted line).
A visual inspection of the master object frame, a subset of which is shown in Figure 5, reveals a faint optical source at the precise location of J1400−1431 determined from the radio observations. We used the PHOT task in the IRAF/DAOPHOT package to extract aperture photometry of nearly two dozen stars in the field of view of the master frame, covering a range of magnitudes $R_c \simeq 15−20$. Our measured magnitude for each star was compared to the values reported by Qi et al. (2015) in order to determine the zero-point magnitude of our data set, after converting their $R_c$ photographic red band magnitudes into $R_c$ via the transformations of Bessell (1986). We then used PHOT to perform aperture photometry on the optical component of J1400−1431 and derived a final $R_c$-band magnitude of $R_c = 22.5 \pm 0.3$.

We obtained additional deeper imaging of J1400−1431 using the blue and red sides of the 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. At this time, J1400−1431 was only visible during the very beginning of the night, so the observations were obtained at somewhat high airmass (up to 2.0).

Guided by the SOAR detection, we were able to detect the counterpart to J1400−1431 in all three bands of the LRIS imaging as seen in Figure 5. We reduced the LRIS data using standard procedures provided by the LPIPE reduction framework. Astrometric calibration was performed against USNO-B (Monet et al. 2003), and the rms scatter against the catalog was $\sim 0\,' 4$ for 16−19 matched sources. Aperture photometry was measured using SExtractor (Bertin & Arnouts 1996). We photometrically calibrated the LRIS images using the Pan-STARRS 3π Steradian Survey (Chambers et al. 2016; Flewelling et al. 2016) catalog. In each image we identified ~20 stars that matched those from the catalog and were additionally not extended, saturated, or otherwise affected by bad pixels. We transformed the Pan-STARRS photometry into the Johnson–Cousins system using the results from Tonry et al. (2012) and determined zero-points for each LRIS image. Comparing observations of 15 other stars detected by both SOAR (in $R_c$) and Keck (in $R$), we found consistent results. All photometry results described here are summarized in Table 3.

In Figure 6 we plot these results on color−color and color−magnitude diagrams along with the predictions of model atmospheres for hydrogen (DA) and helium (DB) WD atmospheres from Tremblay et al. (2011) and Bergeron et al. (2011), respectively. From the color−color diagram it appears that the $R−I$ color is consistent either with an effective temperature $T_{\text{eff}} \approx 4800$ K or $T_{\text{eff}} \approx 3000$ K. This degeneracy is a result of collisionally induced absorption by molecular H$_2$ (Bergeron et al. 1995; Hansen 1998), which shifts flux from the near-infrared into the optical. However, from the $V−R$ color, only the cooler solution seems plausible. Fitting the extinction-corrected photometry as a function of $T_{\text{eff}}$ and angular size, we obtain a good solution for $T_{\text{eff}} \approx 3000 \pm 100$ K and $R/R_e = (2.19 \pm 0.03) \times 10^{-2} (d/270$ pc), where we have increased the uncertainty on $T_{\text{eff}}$ to account for the coarseness of our atmosphere grid.

### 4. Gamma-Ray Spectra and Timing

The radio timing position of PSR J1400−1431 reported in Table 2 is within 5/3 of the Fermi Large Area Telescope (LAT) source 3FGL J1400.5−1437 (which has a 95% confidence error ellipse of size $7\,\arcmin \times 4\,\arcmin$). A positional association was noted by Acero et al. (2015), and in the following discussion, we analyze the $\gamma$-ray source to evaluate the likelihood of an association and to search for evidence of $\gamma$-ray pulsations.

For this analysis, we extracted Pass 8 data starting from 2008 August 4 (the beginning of the LAT survey mode operation) and extending through 2017 March 1 (Mission Elapsed Time 239557517−510019205). We selected SOURCE class, front- and back-converting events (evclass=128 and etype=3) combined during the intervals of good science data (DATA_QUAL = 1 and LAT_CONFIG = 1) and restricted our events to those with a zenith angle smaller than 90°. We selected events between 100 MeV and 100 GeV from a 15° radius around the pulsar and performed a binned likelihood analysis over a $20^\circ \times 20^\circ$ region with $0\,' 1$ pixels. Starting with a model based on the 3FGL catalog (Acero et al. 2015), we modified the target source’s spectral model to be an exponentially cutoff power law of the form

$$ \frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \exp \left( -\frac{E}{E_{\text{cut}}} \right), $$

with normalization $N_0$ in photons cm$^{-2}$ s$^{-1}$ MeV$^{-1}$, reference energy $E_0$, cutoff energy $E_{\text{cut}}$, and photon index $\Gamma$. To perform the maximum likelihood fit, we used the P8R2_SOURCE_V6 instrument response functions with the Fermi Science Tools Framework.

19 The counterpart is visible directly in Pan-STARRS (PS1) stacked r- and i-band images, but is not listed in the corresponding catalog, suggesting a low-significance detection. In any case, we did not use PS1 to motivate follow-up because the data were released after discovery of the counterpart with SOAR.

20 http://www.astro.umontreal.ca/~bergeron/CoolingModels/
version v11r05p02 and the NewMinuit fitting function.\textsuperscript{21} The isotropic diffuse model was iso\_P8R2\_SOURCE\_V6\_v06\_SOURCE\_V6\_v06\_v06\_fits, with normalization left free, and the Galactic diffuse model (Acero et al. 2016) was gll\_iem\_v06\_fits, with index and normalization left free. In the initial fit, we held all values at the 3FGL catalog values except for the spectral parameters for the target source, and the normalization for sources within 6° of the target or flagged in the 3FGL catalog as being variable. We inspected the residuals map and found that one additional source at α = 218°281, δ = −17°992 was required to model the region, so this was added to the model. This source is positionally associated with the quasi-stellar object PKS 1430−178. The best-fit spectral parameters for the pulsar are presented in Table 4, where the “Test Statistic” (TS) is the source detection significance (Mattox et al. 1996). The exponentially cutoff power-law model is preferred to a pure power law with a confidence of 4σ (TS\_cut = 2Δlog(likelihood) between the model with and without the cutoff). We then used \texttt{gtfindsrc} to obtain an improved localization for the LAT source, which gave a position of α = 210°166, δ = −14°535 (only 0′7 from the radio timing position) with a 95% confidence radius of 3′3.

For the timing analysis, we selected photons from a region of radius 2° around the pulsar and assigned photon weights based on the best-fit spectral model. We computed a pulse phase for each selected LAT photon using the \texttt{fermi} plugin for TEMPO2 (Ray et al. 2011) and the best-fit radio timing model. The pulsation significance was determined using the weighted H-test (Kerr 2011) and the resulting H-test value was 17.4, corresponding to a significance of 3.3σ (see Figure 7). This is not sufficient to claim a secure detection, but suggests that weak LAT pulsations may be present from this source.

Although there is only weak evidence for the presence of pulsations, we find strong support for an association between

\textsuperscript{21} https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
\textsuperscript{22} http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
3FGL J1400.5−1437 and PSR J1400−1431, primarily due to their positional coincidence. The GeV spectrum of the 3FGL source shows significant curvature, providing additional support for an association. The $\Gamma$ and $E_{\text{cut}}$ values are also comparable to those of other MSPs in the Fermi Second Pulsar Catalog (2PC; Abdo et al. 2013). Finally, the marginal detection of pulsations provides additional evidence in favor of the identification of the $\gamma$-ray source with the pulsar, although not with certainty. Assuming this association is real, we can compare it to the rest of the MSP population, which are often $\gamma$-ray emitters.

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Table 4
LAT Spectral Analysis Results

| Parameter       | Value     |
|-----------------|-----------|
| 3FGL Source     | J1400.5−1437 |
| $\Gamma$        | 2.1(1)   |
| $E_{\text{cut}}$ (GeV) | 4.7(17) |
| Photon Flux ($\times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$) | 20(2) |
| Energy Flux ($\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$) | 10.2(6) |
| TS              | 391       |
| TS$_{\text{cut}}$ | 17.7      |

Note. Quantities in parentheses are 68% confidence uncertainties (statistical only) in the last digit.

Over the 0.1–100 GeV energy range.

Figure 6. Color–color (left) and color–magnitude (right) diagrams for PSR J1400−1431, based on the photometry in Table 3. The color–color diagram shows the $R − I$ color vs. the $V − R$ color along with synthetic photometry from Tremblay et al. (2011) and Bergeron et al. (2011) for hydrogen (DA; solid line) and helium (DB; dashed line). The synthetic photometry is labeled with the effective temperature, and the arrow shows a reddening vector for $A_V = 0.2$. The color–magnitude diagram shows the $R$ magnitude vs. the $R − I$ color with the same synthetic photometry models, which have been adjusted to have a radius of 0.0219 $R_e$ at a distance of 270 pc.

Figure 7. Weighted H-test vs. time computed both forwards (blue) and backwards (red) in time. While the H-test does not reach the 5$\sigma$ level, the rising H-test is indicative of a marginally detected pulsation. The mostly monotonic rise is an indication that the pulse timing model used to fold the data is phase-coherent over the full LAT mission.

Figure 8. Weighted H-test statistic vs. Test Statistic for the DC $\gamma$-ray source for the sample of MSPs in 2PC (Abdo et al. 2013). The red star shows PSR J1400−1431.
5. X-Ray Observations

PSR J1400–1431 was targeted with the X-ray Multi-mirror Mission, *XMM-Newton* on 2016 July 17 for a duration of 39.8 ks (ObsID 0780670101; PI S. Bogdanov). The European Photon Imaging Camera (EPIC) pn (Strüder et al. 2001) and MOS1/2 (Turner et al. 2001) instruments were configured in *full window mode* and used the thin optical blocking filters. We reprocessed the observation data files using the *XMM-Newton* Science Analysis Software (SAS25) version xmmssas_20160201_1833–15.0.0. The data were subjected to the standard flag, pattern, and pulse-invariant filtering. Periods of strong background flares were excised, which resulted in effective exposures of 35.4, 36.3, and 28.2 ks for the MOS1, MOS2, and pn, respectively. The cleaned data sets were used for the X-ray spectroscopic analysis presented below. Because of the 0.73 s read-out time of the pn and 2.6 s for MOS1/2, it was not possible to fold the data at the MSP period to study any X-ray pulsations.

Figure 9 shows the coadded representative color image from all three *XMM-Newton* detectors. It is evident that PSR J1400–1431 is a faint X-ray source and it is quite soft, with nearly all photons detected below ~1.5 keV. To produce spectra suitable for fitting, the pn, MOS1, and MOS2 data were grouped such that each energy bin contained at least 25 counts. The binned spectra from all three detectors were modeled jointly in XSPEC. Three single-component models were considered: a power law, a blackbody, and a non-magnetic neutron star hydrogen atmosphere model (NSATMOS; Heinke et al. 2006). Because of the limited photon statistics, in the spectroscopic analysis we fixed the value of the equivalent atomic hydrogen column density, $N_{\text{H}} = 1.5 \times 10^{20}$ cm$^{-2}$, determined from the empirical relation between DM and $N_{\text{H}}$ from He et al. (2013). In all cases, the tbabs model (Wilms et al. 2000) was used to account for the interstellar absorption along the line of sight.

A fit with a power law produces statistically acceptable results ($\chi^2_v = 1.02$ for 21 degrees of freedom) but requires an implausibly steep power-law photon index ($\Gamma \approx 6.5$). A blackbody model yields a temperature of $kT = 0.15 \pm 0.02$ keV, an effective radiation area that is $10^{44} \text{cm}^2$, and an unabsorbed flux of $1.07 \pm 0.15 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–10 keV range, and $\chi^2_v = 0.70$ for 21 degrees of freedom. Fitting a hydrogen atmosphere model assuming a neutron star with mass $1.4 M_\odot$, radius 12 km, and distance 270 pc resulted in a best fit with a redshift-corrected effective temperature $T_{\text{eff}} = 7.8 \pm 1.5 \times 10^5$ K, an emitting area that is $0.60 \pm 0.08\%$ of the total neutron star surface area, an unabsorbed 0.3-10 keV flux of $(1.15 \pm 0.17) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, and $\chi^2_v = 0.84$ for 21 degrees of freedom. The soft thermal spectrum of PSR J1400–1431 is typical of the sample of MSPs detected in X-rays (Bogdanov et al. 2006; Zavlin 2006; Forestell et al. 2014). This thermal radiation likely originates from the magnetic polar caps of the pulsar, which are heated to ~10^7 K by a return flow of relativistic particles from the open field region of the magnetosphere (e.g., Harding & Muslimov 2002).

6. Discussion

With pulsar timing, we have measured J1400–1431’s parallax and find that $P_{\text{deriv}}$ and $\dot{P}/P$ values place an upper limit on the pulsar’s distance, which further constrains parallax and intrinsic spin-down. Combining these priors with another that accounts for the Lutz–Kelker bias, we find 95% confidence intervals on parallax ($\varpi = 3.7^{+1.6}_{-1.2}$ mas) and distance ($d = 270^{+130}_{-80}$ pc). Furthermore, astrometric parameter measurements imply $P_{\text{Shklov}} = 7(2) \times 10^{-21}$, limiting intrinsic spin-down to $P_{\text{int}} \lesssim 2.2 \times 10^{-21}$; only four other MSPs in the Galactic field (excluding those in globular clusters) have $P_{\text{int}}$ values this low (Manchester et al. 2005). For J1400–1431, this has interesting implications for other derived parameters such as characteristic age, $\tau > 22$ Gyr. The fact that $\tau > \tau_{\text{Hubble}}$ is not particularly concerning since it is well known that characteristic age derived in this fashion is a poor predictor of a recycled pulsar’s true age (e.g., Camilo et al. 1994b; Lorimer et al. 1995). Using WD cooling models (Bergeron et al. 2011; Tremblay et al. 2011), we find more realistic cooling timescales, $5 < \tau_{\text{cool}} < 9$ Gyr for assumed WD masses between 0.2 and 0.4 $M_\odot$. Since the WD is born as the recycling process concludes, $\tau_{\text{cool}}$ is a better indicator of the system’s true age. Assuming the true age of the pulsar is inside this range and magnetic dipole braking is entirely responsible for its spin-down (i.e., its braking index, $n = 3$), J1400–1431’s post-recycling birth period was likely between 2.4 and 2.7 ms, given a value of $P_{\text{int}}$ close to the limit shown in Table 2. This result is insensitive to the choice of $n$; braking indices $1 < n < 3$ produce nearly identical ranges for the birth period. Since $P_{\text{int}}$ is proportional to the intrinsic spin-down luminosity ($E_{\text{int}}$), J1400–1431’s low $P_{\text{int}}$ value likely also affects its high-energy emission. Typically, the X-ray and $\gamma$-ray luminosities, $L_X$ and $L_{\gamma}$, are expressed as a fraction of $E_{\text{int}}$ with corresponding efficiencies, $\eta_X \equiv L_X/E_{\text{int}}$ and $\eta_{\gamma} \equiv L_{\gamma}/E_{\text{int}}$; values for these efficiencies have been found in the ranges 0.001% $< \eta_X < 0.1\%$ (see Figure 8 of Forestell et al. 2014) and 1% $< \eta_{\gamma} < 100\%$ (Guillemot et al. 2016). Contours within these ranges are highlighted in Figure 10. After correcting for...
the Shklovskii effect, J1400−1431’s spin-down luminosity is \(E_{\text{int}} < 3.0 \times 10^{33} \text{ erg s}^{-1}\) (see Table 2).

Using a nominal distance of 270 pc and assuming a beaming factor \(f_0 = 1\), the \(\gamma\)-ray luminosity \(L_\gamma = 4\pi f_0 \dot{f}_\gamma d^2 F_\gamma = 8.9 \times 10^{31} \text{ erg s}^{-1}\) (see Equation (15) from Abdo et al. 2013, and description therein), where \(\dot{f}_\gamma\) is the measured \(\gamma\)-ray energy flux from Table 4. Based on the implied \(\gamma\)-ray efficiency of \(\eta_\gamma \gtrsim 3\%\)—on the low end of efficiencies found for MSPs in 2PC—the pulsar produces plenty of energy to power the \(\gamma\)-ray source. We also note that \(E_{\text{int}}/d^2 = 7.4 \times 10^{33} \text{ erg s}^{-1} \text{ kpc}^{-2}\), which is very high owing to the small distance. Over 75% of radio MSPs with \(E_{\text{int}}/d^2 > 1.5 \times 10^{34} \text{ erg s}^{-1} \text{ kpc}^{-2}\) have LAT-detected \(\gamma\)-ray pulsations (Guillemot & Tauris 2014). Evidently, as observed from Earth, J1400−1431 is relatively inefficient at converting spin-down luminosity into \(\gamma\)-ray emission, and given the flux of the \(\gamma\)-ray emission, the modulation is more difficult to detect than for most other MSPs.

The \(\gamma\)-ray luminosity of \(1 \times 10^{29} \text{ erg s}^{-1}\) (0.3–10 keV; \(d = 270\) pc) makes J1400−1431 the least \(\gamma\)-ray luminous rotation-powered MSP detected to date. For reference, it is more than an order of magnitude fainter than other nearby MSPs—PSRs J0437−4715, J2124−3358 (Zavlin 2006), and J0030+0451 (Bogdanov & Grindlay 2009)—all of which have luminosities of \(10^{30}\) erg s\(^{-1}\) or higher. This striking efficiency can be attributed to J1400−1431’s much lower spin-down luminosity (\(E\)); the implied conversion efficiency from spin-down to \(\gamma\)-ray luminosity for J1400−1431 is \(\eta_\gamma > 3.3 \times 10^{-5}\), consistent with \(10^{-5} < \eta_\gamma < 10^{-3}\) typically found for MSPs. On the other hand, if \(E_{\text{int}}\) is close to the derived upper limit, the low \(X\) luminosity might be an indication that the polar cap heating mechanism operates less efficiently in J1400−1431 for reasons that remain to be understood.

PSR J1400−1431 is in a nearly circular 9.5-day orbit around its WD companion, which has a minimum mass of \(m_{c,\text{min}} = 0.26 \text{ M}_\odot\) (assuming \(m_p = 1.35 \text{ M}_\odot\)). Interestingly, this value is in remarkable agreement with the predicted \((P_n, m_{\text{WD}})\)-relationship (see Figure 11). The correlation between \(P_n\) and WD mass is an expected result of the relationship between the He-core mass and radius of a low-mass red giant donor star, regardless of the mass present in its outer envelope (Savonije 1987; Tauris & Savonije 1999). Most WDs with measured masses follow this expected relationship (see Figure 11). The WD companion of PSR J1640+2224 is the most obvious exception, but was removed from Figure 11 due to inconsistent conclusions about its mass based on pulsar timing and astrometric follow-up (S. Vigeland 2017, private communication). Otherwise, only two \(m_{c,\text{min}}\) values are inconsistent with predicted curves. Istrate et al. (2016) show that the \((P_n, m_{\text{WD}})\)-relationship has some width, depending on the metallicity of the progenitor of the WD companion. By allowing a range of \(m_p\), \(i\), and WD progenitor metallicities for J1400−1431’s companion, we find a narrow range of \(m_{c,\text{min}}\) is \(0.24−0.27 \text{ M}_\odot\) for \(P_n = 9.5\) days (see Figure 11). The WD mass inferred from the \((P_n, m_{\text{WD}})\)-relationship is quite close to \(m_{c,\text{min}}\) (for \(m_p = 1.35 \text{ M}_\odot\)), suggesting the system is...
highly inclined. However, there is considerable uncertainty in the \((P_b, m_{\text{WD}})\)-relationship not only as a function of metallicity (as plotted), but due to the unknown history of the system, so it is also worth considering alternate constraints on the inclination.

For MSPs in highly inclined orbits, a Shapiro-delay signature is sometimes detectable in its timing residuals as a function of orbital phase. The maximum delay occurs at superior conjunction (orbital phase, \(\phi_{\text{orb}} = 0.25\)), when the pulsar’s signal must travel directly through its companion’s gravitational well along our line of sight. If J1400–1431 were as highly inclined as discussed above, we would expect a Shapiro delay, \(\Delta_{\text{SB}} = 11\) \(\mu\)s at superior conjunction (for \(m_c = 0.27\ M_\odot\) and \(i = 80^\circ\), which we do not see (Figure 12). However, going to the median expected inclination of 60\(^\circ\) results in a qualitatively similar companion mass, 0.31 \(M_\odot\), with a significant reduction in the Shapiro delay to 6 \(\mu\)s, which would not be detectable with the current data. Note that a lower pulsar mass could also reduce the significance of any Shapiro delay by moving to a lower implied inclination angle to match the \((P_b, m_{\text{WD}})\)-relationship. We expect to be able to place better constraints on range and shape parameters after analyzing data from an upcoming targeted Shapiro-delay observing campaign.

We can further constrain the WD companion’s mass using models (e.g., Althaus et al. 2013) that provide mass–radius relationships for low-mass WDs, photometry results from Section 3, and the posterior PDF for distance (see Figure 3), derived from pulsar timing. Figure 10 (right panel) shows the conversion between WD mass and distance, which could further be expressed as a prior in \(m_c\)-space; taking into account the low-significance parallax detection and additional priors mentioned in Section 2.2, a similar conversion effectively sets an upper limit on \(m_c \lesssim 0.4\ M_\odot\).

Figure 10 (left panel) shows the remarkable agreement between the mass range predicted by the \((P_b, m_{\text{WD}})\)-relationship, our distance posterior (taking into account a significant

\[ P_{\text{Shklovskii}}, \text{photometry results, and estimated X-ray and } \gamma\text{-ray efficiencies. The significant proper motion measured for J1400–1431 suggests that } P_{\text{int}} < 2.2 \times 10^{-21} \text{ s}^{-1}, \text{ which is low, but still consistent with known values for other MSPs in the Galactic field whose intrinsic } P \text{ values have been corrected for the Shklovskii effect. Figure 10 (right panel) shows that the } m_c = 0.24–0.27\ M_\odot \text{ range is mostly excluded, simply based on } m_{c,\text{min}} \text{ (assuming } m_p = 1.35\ M_\odot\), derived from timing results. The lack of detectable Shapiro delay implies a slightly higher companion mass and lower inclination angle. Despite the slight inconsistency with the mass range implied by the \((P_b, m_{\text{WD}})\)-relationship, our data suggest that J1400–1431’s companion mass is likely \(\sim 0.30\ M_\odot\) and the system is \(\sim 230\) pc away, with an orbital inclination angle, \(i \gtrsim 60^\circ\).

\[ P_{\text{int}} < 2.2 \times 10^{-21} \text{ s}^{-1}. \]

The Shklovskii effect provides an additional prior for the system’s parallax and in turn, better constraints on distance, \(d = 270^{+130}_{-80}\) pc. This range agrees nicely with distances estimated using electron density models (270–500 pc; Taylor & Cordes 1993; Cordes & Lazio 2002; Yao et al. 2017).

Using the Goodman Spectrograph on the 4.1 m SOAR Telescope and later the LRIS on the 10 m Keck I Telescope for deeper imaging, we detected J1400–1431’s WD companion for

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25 We use orbital phase interchangeably with eccentric anomaly, since J1400–1431’s orbit is nearly circular.
the first time. Photometry suggests that the companion is a cool DA-type WD (hydrogen atmosphere) with $T_{\text{eff}} = 3000 \pm 100$ K and $R/R_\odot = (2.19 \pm 0.03) \times 10^{-2} (d/270$ pc). Combined with WD cooling models, the effective temperature measurement suggests that the system’s age is in the range 5–9 Gyr, which is consistent with the relatively low upper limit we place on $P_{\text{min}}$ after correcting for the Shklovskii effect and the corresponding characteristic age. Using WD mass–radius models from Althaus et al. (2013) and photometric $R/d$, we find implied mass and distance ranges completely consistent with $m_{c,\text{min}} = 0.26 M_\odot$ and $d = 270^{+130}_{-80}$ pc measurements.

Finally, with high-energy detections of J1400–1431 with XMM-Newton and Fermi, we measured X-ray and γ-ray luminosities, $L_X = 1 \times 10^{39}$ erg s$^{-1}$ and $L_\gamma = 8.9 \times 10^{31}$ erg s$^{-1}$, respectively. Given the upper limit on $P_{\text{min}}$ (and therefore $E_{\text{int}}$), we find efficiencies $\eta_X > 3.3 \times 10^{-5}$ and $\eta_\gamma \leq 0.03$, consistent with expected ranges for the respective wavelength regimes. Although measured high-energy luminosities depend on the assumed nominal distance ($d = 270$ pc), corresponding efficiencies provide additional consistency checks on $P_{\text{min}}$, distance, and photometry constraints determined with various methods.

This information presents a consistent picture; combined, it suggests PSR J1400–1431 has an intrinsic spin-down $P_{\text{int}} \approx 2 \times 10^{-21}$ s s$^{-1}$, a distance $d \approx 230$ pc, WD companion mass $m_c \approx 0.30 M_\odot$, and orbital inclination $i \approx 60^\circ$. These conclusions are slightly inconsistent with WD evolution models (e.g., Istrate et al. 2016) and depend on an assumed pulsar mass ($m_p = 1.35 M_\odot$), but our results are relatively insensitive to $m_p$. Even for low orbital inclination angles ($i \approx 60^\circ$), we expect a Shapiro-delay signature to be detectable ($\Delta_{\text{SB}} = 6 \mu$s) with data from an upcoming targeted observing campaign, which will provide further clarity on the results presented here.

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Facilities:GBT (GUPPI), Fermi LAT, XMM-Newton (pn, MOS1/2), Keck I:10 m (LRIS), SOAR: 4.1 m (Goodman Spectrograph), LOFAR, LWA.

Software:libstempo, astropy (Astropy Collaboration et al. 2013), scipy (Jones et al. 2001), TEMPO, TEMPO2 (Hobbs et al. 2006), PSRCHIVE (Hotan et al. 2004h), IRAF/DAOPHOT, LPIPE, SExtractor (Bertin & Arnouts 1996), Fermi Science Tools.

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Erratum: “A Multiwavelength Study of Nearby Millisecond Pulsar PSR J1400–1431: Improved Astrometry and an Optical Detection of Its Cool White Dwarf Companion” (2017, ApJ, 847, 25)

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In the analysis for the published paper, a bug in the fermi plugin for TEMPO2 resulted in incorrect photon phase calculations. Specifically, the plugin did not correctly handle pulsar timing models with the astrometric information in ecliptic coordinates when the model included proper motion. This bug has been recently identified and corrected in the TEMPO2 repository as of 2020 April 8. Reprocessing the data set from the paper yields a strong detection of gamma-ray pulsations (see Figure 7). The resulting weighted H-test value is 327.3, corresponding to a significance of 16.5σ—a very strong detection.

We also updated Figure 8. The pulsed detection of J1400–1431 is now fully in line with other LAT-detected millisecond pulsars (MSPs). Discussions of the low pulsed fraction in the original text should be ignored. The LAT pulse profile (see Figure 13) and other properties of the gamma-ray pulsations from this pulsar will be presented in the Fermi LAT Third Pulsar Catalog (2020, Fermi LAT Collaboration 2020, in preparation).

15 https://bitbucket.org/psosoft/tempo2/src/master/
Figure 7. Weighted $H$-test vs. time computed both forward (blue) and backward (red) in time. The final $H$-test is 327.3, corresponding to a detection significance of 16.5σ.

Figure 8. Weighted $H$-test statistic vs. Test Statistic for the DC $\gamma$-ray source for the sample of MSPs in 2PC (Abdo et al. 2013). The red star shows J1400–1431.
Figure 13. Fermi LAT pulse profile and phaseogram using the corrected Tempo2 plugin, based on weighted counts above 100 MeV.

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