

Improving Distances to Binary Millisecond Pulsars with Gaia

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Abstract

Pulsar distances are notoriously difficult to measure, and play an important role in many fundamental physics experiments, such as pulsar timing arrays. Here, we perform a cross-match between International PTA pulsars (IPTA) and Gaia's Data Release 2 (DR2) and Data Release 3 (DR3). We then combine the IPTA pulsar's parallax with its binary companion's parallax, found in Gaia, to improve the distance measurement to the binary. We find seven cross-matched IPTA pulsars in Gaia DR2, and when using Gaia DR3 we find six IPTA pulsar cross-matches but with seven Gaia objects. Moving from Gaia DR2 to Gaia DR3, we find that the Gaia parallaxes for the successfully cross-matched pulsars improved by 53%, and pulsar distances improved by 29%. Finally, we find that binary companions with a $<3.0\sigma$ detection are unreliable associations, setting a high bar for successful cross-matches.

Unified Astronomy Thesaurus concepts: [Millisecond pulsars \(1062\)](#); [Binary pulsars \(153\)](#); [Distance measure \(395\)](#); [Gaia \(2360\)](#)

1. Introduction

Millisecond pulsars (MSPs) are valuable probes in several areas of astrophysics, including gravitational-wave detection with pulsar timing arrays (PTAs; Sazhin 1978; Detweiler 1979; Hellings & Downs 1983), tests of general relativity (e.g., Lazaridis et al. 2009), and dark-matter density mapping (Phillips et al. 2021). First discovered in Backer et al. (1982), many MSPs have microsecond timing precision, making them some of the best clocks in nature.

For these experiments, outcomes are improved by better pulsar distance measurements. Measuring these distances can be difficult since many MSPs are at kiloparsec distances, making precise parallax measurements difficult. For well-timed pulsars (those with timing precision of at least 1 μ s for pulsars \sim 1 kpc away; Toscano et al. 1999), timing parallax can be used to determine distances (Backer & Hellings 1986). Similarly, for pulsars that have been imaged to submilliarcsecond precision, very long baseline interferometry (VLBI) can be used to measure distances (Salter et al. 1979). For some pulsars in binaries, we can estimate their distances by using the so-called kinematic distance measurement (D_k ; Shklovskii 1970; Bell & Bailes 1996).

The distance to a pulsar can also be constrained indirectly: the dispersion measure (DM) of a pulsar is the delay in the arrival of a pulse as a result of its travel through the ionized interstellar medium. These measurements therefore are dependent on the column density of electrons in the model of the galaxy. The two principal models currently in use are those of Cordes & Lazio (2002) and Yao et al. (2017), hereafter referred to as NE2001 and YMW16, respectively. However, there is a great deal of uncertainty in these DM-based distance estimates, conservatively 20%–40% (Cordes & Lazio 2002; Yao et al. 2017).

Binary pulsar companions thus offer a complementary path to making a distance measurement by finding an optical counterpart in, for example, Gaia. While Jennings et al. (2018) carried out a cross-match between pulsars with known companions and Gaia Data Release 2 (DR2), here, as in Mingarelli et al. (2018, hereafter M18), we combine both pulsar-timing-based parallaxes with Gaia-based parallaxes to improve the overall distance measurement. This work includes and supercedes the results of M18, carrying out and reporting the results of cross-matches with Gaia DR2 and Data Release 3 (DR3). We improve on our cross-match statistics by looking at the temperature of the companion in addition to a novel false-alarm probability (FAP) calculation.

Compared with Gaia DR2, DR3 provides measurements of parallax and proper motion for 10% more objects (Arenou et al. 2018). In addition to the millions of new sources, Gaia DR3 also includes updated measurements of proper motion, sky position, parallax, and photometric parameters for over 96% of DR2 sources.

The paper is laid out as follows. In Section 2, we describe how we identify pulsar companions in Gaia, and compute the FAPs of these associations using two approaches: one is a chance association, and the other verifies the match via computing the temperature of the companion and cross-validating it. We report our results in Section 3, and close with a summary of our results and discussion of them in Section 4.

All of the data analysis software used in this work is publicly available on GitHub, written in Python, at <https://github.com/abby-moran/gaiaDR3-pulsars>.

2. Identifying Binary Candidates in Gaia

2.1. Cross-matching IPTA DR2 with Gaia

We cross-referenced the sky positions of MSPs in Perera et al. (2019, hereafter IPTA DR2), with objects in Gaia DR2 and DR3 (Gaia Collaboration et al. 2018, 2023). Using the proper motion and coordinates of each candidate match, we



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Table 1
Summary of the Pulsars for Which Companions Were Identified in Gaia DR2 and DR3 with Previously Published Data.

Pulsar	R.A.	Decl.	P_b (d)	Companion Type	Reference	DR2	DR3
J0437–4715	04:37:15.91	–47:15:09.21	5.741	White dwarf	V08, D08, D16	X	X
J1012+5703	10:12:33.44	+53:07:02.30	0.6046	White dwarf	N95, D16, A18, D20	X	X
J1024–0719	10:24:38.68	–07:19:19.43	~ 10^4	Main sequence	K16, B16	X	X
†J1732–5049	17:32:47.77	–50:49:00.21	5.263	—	R16	X	X
†J1747–4036	17:47:48.72	–40:36:54.78	...	—	...	—	X
† J1843–1113	18:43:41.26	–11:13:31.07	...	—	...	X	X
J1910+1256	19:10:09.70	+12:56:25.49	58.47	—	S05, D16, D23	X	—
*J1949+3106	19:49:29.64	+31:06:03.80	1.950	White dwarf	De12	X	—

Notes. Improved distances for those detected in Gaia DR3 are reported in Table 2. Pulsar positions are from IPTA DR2, while binary periods and the companion types when known are from references cited in the “Reference” column. Unknown companion types are denoted by —. In the last two columns, an X indicates a positive cross-match was found (see Section 2) in the given Gaia data release and — indicates no companion was identified. A † indicates a weak ($<3.0\sigma$) Gaia association in both DR2 and DR3. *J1949+3106 had a companion identified in Gaia DR2 but not in Gaia DR3. We therefore believe this to be a false cross-match result from DR2, and explore the implications of this in Section 3.1.

updated the Gaia objects to the IPTA DR2 epoch. We require that the object’s position is within 3σ of the pulsar’s position in IPTA DR2. We also require that the object has a parallax measurement, and that the proper motion of the object in R.A. and decl. are within 3σ of the pulsar’s IPTA DR2 values.

2.2. False-alarm Probabilities: Chance Association?

It is possible that in certain more crowded parts of the galaxy, pulsar systems have higher FAPs; that is to say, that the Gaia object and the pulsar are in chance alignment rather than a binary system. In order to test the null hypothesis, we calculate the FAP for each potential system. We do this by randomizing the pulsar’s sky coordinates within three arcseconds in both R.A. and decl. This has the added benefit of taking into account the more crowded parts of the sky where the pulsars are more likely to randomly align with a Gaia object. We then search around the pulsar within a radius of $3''$ for Gaia objects and repeat the process at least 10^7 times. The number of trials in which a Gaia object is found divided by the number of total trials gives the FAP. We carry out this test using astrometric data from the relevant Gaia data release; for associations detected in both DR2 and DR3, we report a FAP for each data release.

We set our detection threshold to be 3.0σ , since in a cross-match between PSR J1949+3106 (hereafter J1949+3106) and Gaia DR2, we found a 3.0σ detection of a binary companion that was not found in Gaia DR3. We therefore only claim valid cross-matches for pulsars with $>3.0\sigma$ detections; see Section 3.1 for more details. Systems with higher FAPs indicate tentative matches in need of further verification.

2.3. False-alarm Probabilities: Temperatures

Many IPTA pulsars have known binary companions, and some of these companions have published effective temperatures. In an effort to further validate our Gaia-IPTA cross-matches, we calculate the temperature of each cross-matched Gaia object based on Gaia DR3 photometric data. We find the magnitude for the blue passband, G_{BP} , and for red light, G_{RP} for each source. We calculate the effective temperature as in Jordi et al. (2010):

$$\log(T_{\text{eff}}) = 3.999 - 0.654(C_{\text{XP}}) + 0.709(C_{\text{XP}})^2 - 0.316(C_{\text{XP}})^3 \quad (1)$$

where C_{XP} is given by $G_{\text{BP}} - G_{\text{RP}}$. For objects with $C_{\text{XP}} < 1.5$, Equation (1) has a standard error of $\sigma_T = 0.0046T_{\text{eff}}$. The error introduced by this model increases as we approach $C_{\text{XP}} = 1.5$, which is the case for several of our cross-matches. While Gaia does not report individual uncertainties on the magnitudes used in Equation (1), Gaia Collaboration et al. (2023) estimates that for stars in Gaia DR3 with $G \approx 20$, the G_{BP} error is 180 mmag, and 52 mmag for G_{RP} . Our final error is the quadrature sum of this uncertainty and the uncertainty introduced by Equation (1).

For objects with $C_{\text{XP}} > 1.5$, we explore an alternate route to estimate the T_{eff} . We compare the photometric data of the Gaia DR3 object to the synthetic catalog in Jordi et al. (2010): based on the object’s magnitude in blue (G_{BP}) and red (G_{RP}) as well as its color ($G_{\text{BP}} - G_{\text{RP}}$), we find the synthetic star which is most similar to our Gaia object. We then use the T_{eff} of this similar object as an estimate for the companion’s temperature.

3. Results

We have identified six candidate binary companions to IPTA pulsars in Gaia DR3: these are PSRs J0437–4715, J1012+5307, J1024–0719, J1732–5049, J1747–4036, and J1843–1113 (see Table 1 for more information). We report the FAPs of these detections and distance measurements based on Gaia DR3 parallaxes combined with pulsar-timing-based parallax measurements. Our results are also summarized in Table 2.

We calculate the combined distance to the binary systems by multiplying the posteriors of PTA- and/or VLBI-based parallax measurements with the Gaia DR3 parallax value. We then apply the distance prior (Bailer-Jones et al. 2021) and report the distance as the peak of the combined distance curve, with 16th and 84th percentiles as the distance errors. This distance prior includes a nonzero global parallax offset, though the impact of this on the final distance is negligible. For comparison, we compute combined distances with Gaia DR2 parallaxes using the Bailer-Jones et al. (2018) distance prior (M18).

We do not include kinematic distances when computing combined pulsar distance measurements, since proper-motion errors are correlated between kinematic distance measurements and timing parallax.

Notably, two candidate companions in the Gaia DR2 cross-match do not meet the requirements in DR3: those associated with pulsars J1910+1256 and J1949+3106 (see Table 1;

Table 2
Summary of Results

Pulsar	D_{DM} (pc) NE2001	D_{DM} (pc) YMW16	Previous Parallax (mas)	Gaia DR3 Parallax (mas)	Combined Parallax (mas)	Distance (pc)	Reference
J0437-4715	139	156	6.37 ± 0.09	7.10 ± 0.52	6.40 ± 0.05	$156_{-1.1}^{+1.1}$	D08, D16
J1012+5703	411	805	0.92 ± 0.20	1.74 ± 0.29	1.17 ± 0.02	845_{-14}^{+14}	D16, D20, D23
J1024-0719	383	376	0.86 ± 0.15	0.86 ± 0.28	0.91 ± 0.05	1072_{-49}^{+67}	IPTA DR2, D23
[†] J1732-5049	1411	1875	None	-0.54 ± 2.22	-0.54 ± 2.22	3874_{-1400}^{+4100}	IPTA DR2
[†] J1747-4036 [A]	3392	7152	0.4 ± 0.7	-0.88 ± 0.46	-0.49 ± 0.38	6042_{-1700}^{+3200}	IPTA DR2
[†] J1747-4036 [B]	3392	7152	0.4 ± 0.7	1.83 ± 0.97	0.87 ± 0.55	4028_{-1600}^{+3800}	IPTA DR2
[†] J1843-1113	1697	1705	0.69 ± 0.33	1.06 ± 0.52	0.80 ± 0.28	4568_{-1800}^{+3500}	D16

Notes. The previous parallax measurement is the parallax value from IPTA **DR2**. For PSRs J0437-4715 and J1012+5307 this is a VLBI measurement, and for PSRs J1024-0719, J1747-4036, and J1843-1113 this is a timing parallax. The combined distances take into account the Gaia DR3 parallax measurement and all other available parallax measurements. For J1747-4036, we use the parallax measurement of the specified Gaia object (either Object A or B). The asymmetric errors on these distances represent the 16th and 84th percentiles. Distances based on DMs assume a standard error of $\pm 20\%$ and are for comparison only. A [†] next to a pulsar's name indicates a weak ($< 3.0\sigma$) Gaia association that we hope to verify in future data releases.

M18). A match was found to PSR J1910+1256 in DR3, but was eliminated by our stringent requirements for proper motion and sky location accuracy. We found no object associated with J1949+3106 in DR3 (see Section 3.1) despite finding a 3.0σ association in Gaia DR2. This is the basis of our detection threshold of 3.0σ .

The pulsar companions we identified in Gaia DR3 are shown on a color-magnitude plot in Figure 1. Also on this diagram, in blue, we show a sample of well-measured stars from Gaia Collaboration et al. (2021). Magnitudes in Gaia DR3 include $E(B - V)$ dust corrections (Riello et al. 2021). Using our median distance values and a 3D dust map (Green et al. 2018), we find that this correction is zero for all sources in this study, except for the objects associated with J1024-0719 and J1843-1113, which have $E(B - V) = 40$ and 718 mmag, respectively.

Below, we discuss each binary pulsar system in Table 1, except for PSR J1910+1256. Our results are structured as follows. First, we discuss J1949+3106, which we use to set our FAP threshold with. This is followed by weak Gaia associations with PSRs J1732-5049, J1747-4036, and J1843-1113 (hereafter we omit the PSR prefix). We finish by describing detections of companion Gaia objects to PSRs J0437-4715, J1012+5307, and J1024-0719 (again dropping the PSR prefix from here).

3.1. J1949+3106: False Association

In our Gaia DR2 analysis, we find a companion to J1949+3106 with a FAP of 3.19×10^{-3} , making this a 3.0σ detection. However, in DR3 neither this DR2 candidate companion, Gaia DR2 2033684263247409920, nor any other object meet the criteria to be a candidate for association with J1949+3106 (see Figure 2).

While IPTA **DR2** confirms that a companion should exist, we find it unlikely that Gaia DR2 2033684263247409920 is this companion. In Deneva et al. (2012) this companion is identified as a white dwarf with $M = 0.85 M_{\odot}$. The dimmest objects in Gaia DR3 have $G \sim 21$, and therefore this companion may be too dim for Gaia to detect. In future data releases we will nonetheless continue to monitor J1949+3106. We therefore require potential Gaia companions to be detected at a $>3.0\sigma$ confidence to be called a confirmed companion.

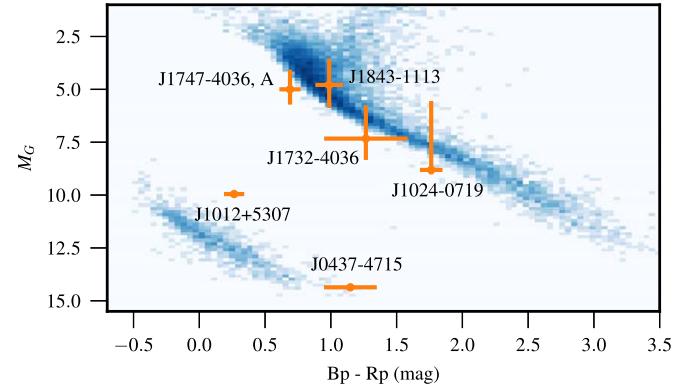


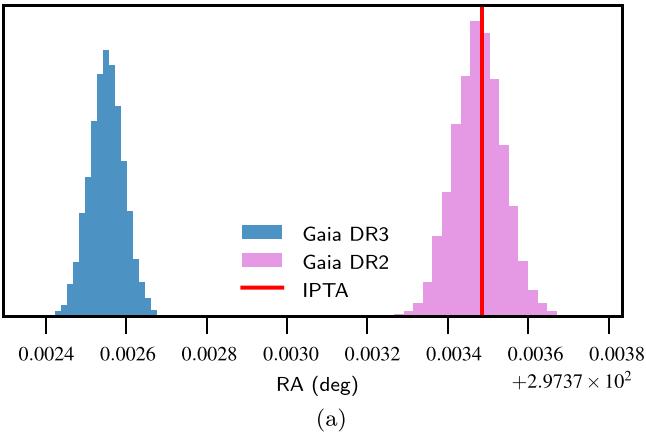
Figure 1. A color-magnitude plot displaying six of the companions to pulsars from this cross-match (orange) against a background of well-measured stars in the Gaia catalog.

3.2. J1732-5049: Weak Association

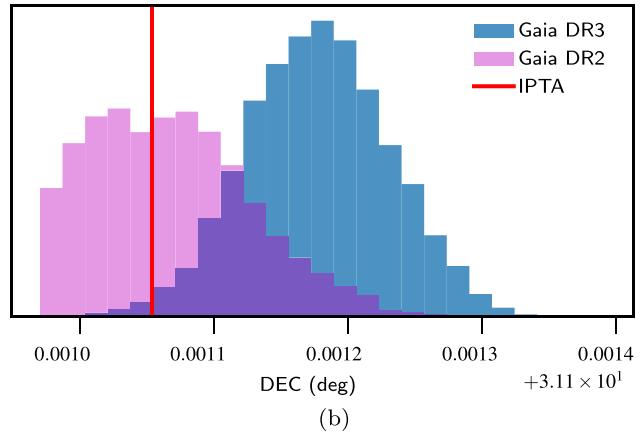
J1732-5049 has a binary companion in IPTA **DR2** with a period of 5.3 days. We tentatively identify this companion as Gaia 5946288492263176704 (M18) in DR2 and DR3. The parallax measurement to this object in DR2 is -1.18 ± 2.84 mas and in DR3 is -0.54 ± 2.22 mas. While negative parallaxes are unphysical, it may be useful to monitor this binary companion in the hopes of obtaining improved parallax measurements.

We find the distance to this object is 3874_{-1400}^{+4100} pc using the DR3 parallax. When we report the 5th and 95th percentiles, this is 3874_{-2500}^{+6200} pc (see Figure 3). Using the Gaia DR2 parallax, the distance is 3980 pc, with the 16th percentile as 4800 pc and the 84th as 11,000 pc. Thus, we see a 42% decrease in the error. Since these distances are derived from negative parallaxes, the measurements are strongly dependent on the distance priors put forth in Bailer-Jones et al. (2018) and Bailer-Jones et al. (2021) for DR2 and DR3, respectively. However, these priors make it possible to yield imprecise but nevertheless meaningful distance measurements from negative parallaxes.

The DR3 identification has a FAP of 3.9×10^{-3} , making this a 2.9σ association. Although this is an improvement from the 2.8σ DR2 association, we have learned that a 3.0σ detection is required for a reliable association, so we cannot yet claim that this is a detection.



(a)



(b)

Figure 2. False association: the sky position of J1949+3106 (red IPTA bar) as compared to the object identified in Gaia DR2 as the pulsar’s companion (pink). The Gaia DR3 data (blue) illustrate that this was a false association. The Gaia object’s position differs from the pulsar’s by 22σ in R.A. and 2.2σ in decl. (a) R.A. of J1949+3106’s former Gaia match, (b) decl. of J1949+3106’s former Gaia match.

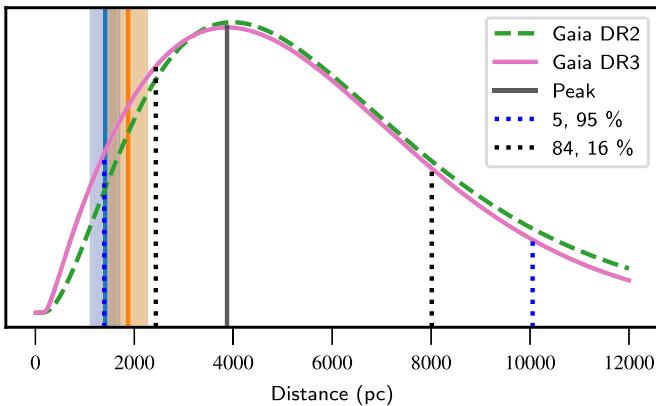


Figure 3. Distances to the system of pulsar J1732–5049 and its candidate binary companion. These Gaia parallaxes are the first potential measurements to the pulsar. Both parallax distances are more than double either DM distance (based on NE2001 in blue or YMW16 in yellow), which assume a standard error of $\pm 20\%$. This may indicate that these models have overestimated the electron density along this line of sight.

We now look to the temperature of the object to help us further understand the validity of the cross-match. With $G_{\text{BP}} = 21.40$ and $G_{\text{RP}} = 19.82$, this object has $C_{\text{XP}} = 1.6$, thus we calculate the temperature using both Equation (1) and via comparison to the synthetic catalog from Jordi et al. (2010). Using the former, we calculate that this companion object has $T_{\text{eff}} = 3104 \pm 1204$ K. However, the error on this is likely underestimated due to the constraints of the model. When the synthetic catalog method is used, we find $T_{\text{eff}} \sim 4000$ K. However, since there is no temperature for this companion in the literature, we are unable to further validate the match.

3.3. J1747–4036: Weak Association

J1747–4036 has been classified as a solitary system (Kerr et al. 2012). Here, we identify two objects in Gaia DR3 that are candidates for association with the MSP. These objects are Gaia DR3 5957827763757710080 and 5957827763757708544, referred to hereafter as Object A and Object B, which are separated by $2''.226$. Either one of these objects may be a binary companion to J1747–4036, but with the current Gaia data we are unable to determine which, if not both, is the false match (see Figure 4).

The Gaia DR3 parallax measurements of Objects A and B are -0.88 ± 0.46 and 1.83 ± 0.97 mas, respectively. These detections thus have signal-to-noise ratios (S/Ns) of -1.91 and 1.89 . In IPTA DR2, J1747–4036 has a parallax of 0.4 ± 0.7 mas. We combine this parallax measurement with the Gaia parallax measurement of Object A and compute a distance of 6042^{+3200}_{-1700} pc. When the IPTA value is instead combined with the parallax of Object B, the distance is 4028^{+3800}_{-1600} pc.

J1747–4036’s companion are colocated, and therefore have the same FAP. We find this FAP to be 1.9×10^{-2} , making these weak, 2.3σ associations. We therefore do not yet claim to have identified a new binary system, since the FAP is below the established threshold.

Although there is no known companion to this pulsar and thus no known temperature to compare our value with, we carry out our false-alarm checks for completeness. We find that Object A has $G_{\text{BP}} = 20.33$ and $G_{\text{RP}} = 19.14$. Using Equation (1), we find that Object A has $T_{\text{eff}} = 4927 \pm 788$ K, a temperature consistent with a cool white dwarf star (Jordi et al. 2010). There is no photometric data for Object B in Gaia DR3.

The two Gaia objects, A and B, have an angular separation of $2''.226$. This translates to a physical separation on the order of 10^3 au using the IPTA DR2 parallax distance. Given the high degree of precision on Gaia DR3 coordinates, it is thus improbable that these two objects are associated with one another. It is more plausible that at least one object, and possibly both, are false match(es), particularly given that the associations are $<3.0\sigma$. Furthermore, timing data for this pulsar point to an isolated system. This would therefore place a limit of $P_b \gtrsim 1$ kyr on this potential binary (Jones et al. 2023). So far, pulsar J1024–0719 appears to be the only pulsar we identify with a companion in an ultralong orbit (Bassa et al. 2016; Kaplan et al. 2016). We are hopeful that future data releases will be able to verify or refute one or both matches.

3.4. J1843–1113: Weak Association

In Gaia DR2 we identify a possible companion to J1843–1113 with 2.5σ confidence (M18). Our cross-match of J1843–1113’s sky position using Gaia DR3 returns the same object, Gaia 4106823440438736384. Its parallax measurement is 1.06 ± 0.52 mas in DR3 and it has a S/N of 2.0, nearly double the Gaia DR2 S/N. The FAP in Gaia DR3 is similarly on the order of 10^{-2} , making this another 2.5σ association.

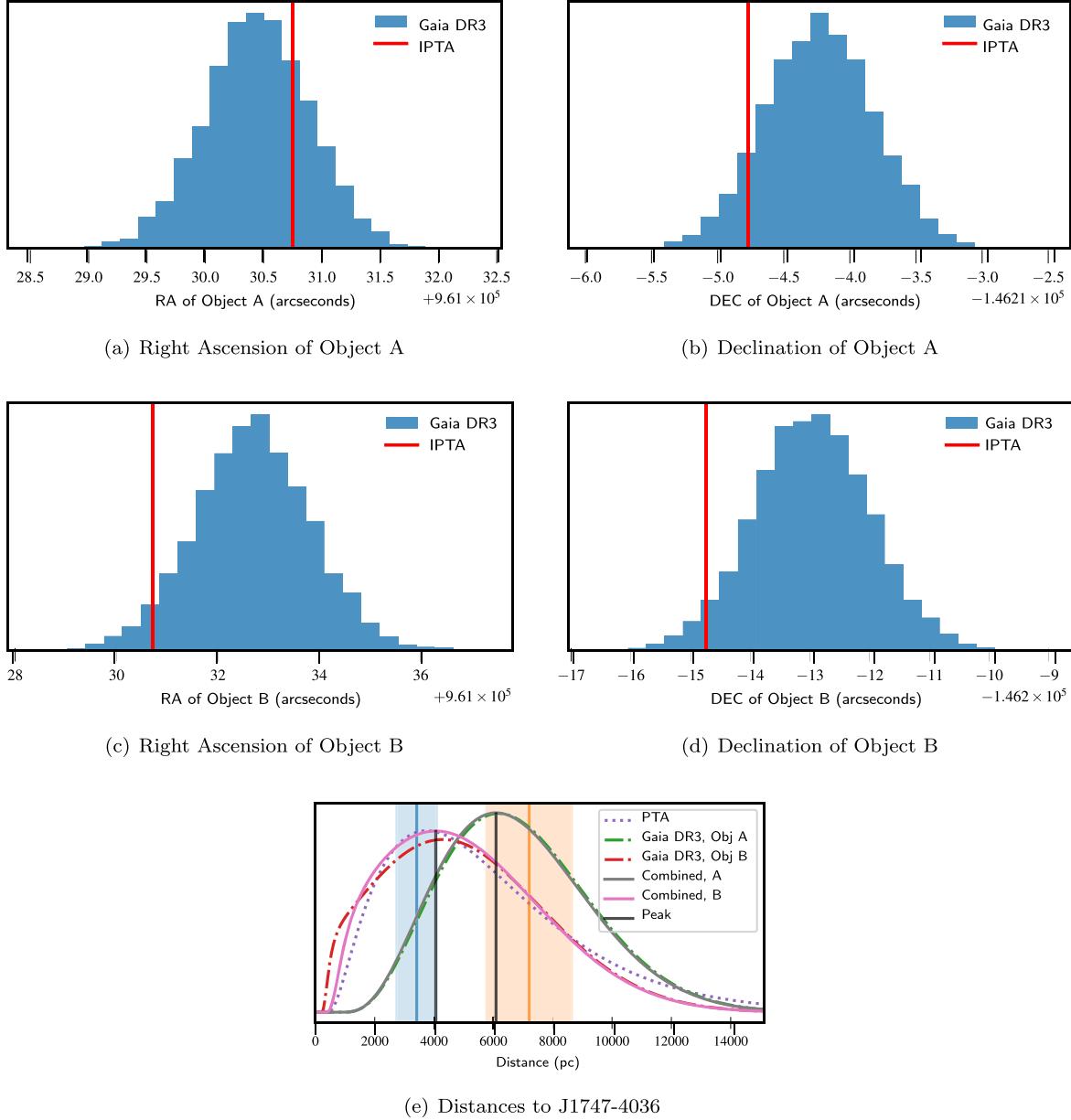


Figure 4. Panels (a) through (d) show comparisons of the location of J1747–4036 (red) and candidate companion objects (blue) after updating the Gaia object positions to the IPTA epoch. Both objects’ positions are consistent with the IPTA position of J1747–4036. Panel (e) shows distances to the system of J1747–4036 in DR3. DM distances from NE2001 (blue strip) and YMW16 (yellow strip) are shown for illustrative purposes and are not included in the combined measurements.

We combine the Gaia DR3 parallax measurement with that from Desvignes et al. (2016) to yield a distance measurement of 4568^{+3500}_{-1800} pc (see Figure 5). The error on this value has increased by $\sim 36\%$ as compared to the DR2 combined distance of 1701^{+3800}_{-105} pc. Although the S/N has doubled from DR2 to DR3, the DR3 parallax is much larger than the PTA-based measurement, resulting in a broader distribution and larger distance errors.

While there is no known companion to this pulsar, but we calculate the Gaia object’s temperature for completeness. The object has $G_{\text{BP}} = 20.85$, $G_{\text{RP}} = 18.89$, and $C_{\text{XP}} = 2.0$, so we use the synthetic catalog and estimate $T_{\text{eff}} \sim 3350$ K.

Given the Gaia object’s high FAP, we emphasize that this is a weak association. J1843–1113 has been studied for decades as a part of PTA experiments with no evidence in timing data to indicate a companion object. However, Jones et al. (2023) find that any pulsar with an unconstrained second frequency

derivative, such as J1843–1113, may host an undetected binary companion with $P_b > 1$ kyr. While unlikely, this may nevertheless be a plausible binary orbit.

3.5. J0437–4715: Strong Association

J0437–4715 is in a 5.7 days orbit with a white dwarf companion, and is one of the closest binary MSPs to Earth (Johnston et al. 1993; Verbiest et al. 2008). Deller et al. (2008) report the system’s parallax as 6.396 ± 0.054 mas based on VLBI, and Reardon et al. (2016) similarly report 6.37 ± 0.09 mas based on timing parallax. We also incorporate the recent timing complementary parallax measurement from Agazie et al. (2023) of 9.70 ± 1.11 mas. Reardon et al. (2016) also report a kinematic distance measurement of 156.79 ± 0.25 pc based on the pulsar’s well-measured orbital period derivative (thus enabling a distance estimate via the Shklovskii effect; Shklovskii 1970).

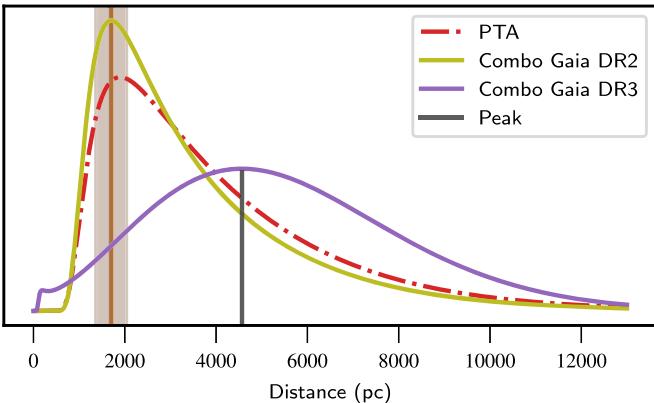


Figure 5. The combined parallax measurements to J1843-1113 and the resulting distances. Despite being a more precise parallax measurement, the Gaia DR3 parallax corresponds to a less precise combined distance than when the Gaia DR2 value is used as a result of its inconsistency with the PTA parallax measurement. The PTA measurement is also consistent with the NE2001 (blue strip) and YMW16 (yellow strip) DM distances. This casts further doubt on the association.

We first identified the binary companion to J0437-4715 as Gaia DR2 4789864076732331648 (M18) and find the same object in DR3. In Gaia DR3, we find that the parallax to this companion object is 7.10 ± 0.52 mas, and thus our detection’s S/N is $7.10/0.52 = 13.5$. In DR2 (M18), the parallax of the associated object is 8.33 ± 0.68 mas, thus DR3 has improved the precision of the Gaia-based parallax by $\sim 25\%$.

We combine the parallax measurements from Gaia DR3, Deller et al. (2008), Reardon et al. (2016), and Agazie et al. (2023). This results in a final distance measurement of $156^{+1.1}_{-1.1}$ pc. The 5th and 95th percentiles of the distance are $156^{+1.9}_{-1.8}$ pc (see Figure 6). Our final combined distance varies very little from the Deller et al. (2008) and Reardon et al. (2016) measurements. This is largely due to errors in the Gaia parallax measurement being much larger than in other sources, thus having little effect on the combined distance measurement. This is also the case in our analysis of Gaia DR2, where we find a distance of $156^{+1.1}_{-1.1}$ pc (M18).

There is a well-known white dwarf companion to J0437-4715 (e.g., Durant et al. 2012). Here, we find $G_{\text{BP}} = 20.73$ and $G_{\text{RP}} = 19.57$, and use Equation (1) to find $T_{\text{eff}} = 5020 \pm 750$ K. Durant et al. (2012) report $T_{\text{eff}} = 3950 \pm 150$ K for the white dwarf companion to J0437-4715, 1.4σ from our value.

We compute the FAP of this association with Gaia DR2 and DR3. In both analyses, we found no positive results in $> 10^7$ trials. This indicates a statistically strong, $\gg 5\sigma$ detection. We are therefore very confident that this companion is indeed the known white dwarf companion to J0437-4715.

3.6. J1012+5307: Strong Association

J1012+5307 is in a binary orbit with a low-mass white dwarf companion (Nicastro et al. 1995). Desvignes et al. (2016) report the parallax of the pulsar as 0.71 ± 0.17 mas, and in Ding et al. (2020) the VLBI-based parallax was found to be 1.17 ± 0.02 mas. Ding et al. (2023) similarly find the timing-based parallax to be 1.17 ± 0.05 mas.

In Gaia DR2, we identify this binary companion as Gaia DR2 851610861391010944 with a S/N = 3.2 (see Figure 7; M18). In Gaia DR3, we again identify this object as the companion to J1012+5307. The parallax measurement to this object is 1.74 ± 0.29 mas with a S/N = 6.0. We combine this with the

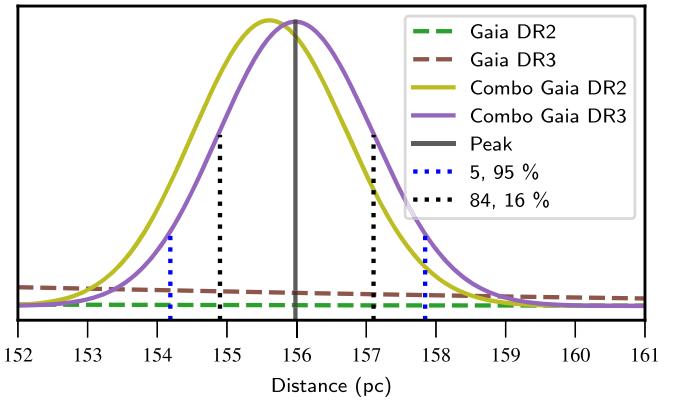


Figure 6. Distances to the system of J0437-4715. The combined curves include parallax-based distances from Deller et al. (2008), Reardon et al. (2016), and Agazie et al. (2023) in addition to the specified Gaia distance. The distances are not significantly impacted by the Gaia parallaxes since the curves are dominated by the ultraprecise VLBI (Deller et al. 2008) and timing (Reardon et al. 2016) parallaxes.

Desvignes et al. (2016), Ding et al. (2020, 2023), and Agazie et al. (2023) measurements and find a combined parallax measurement of 1.17 ± 0.02 mas. This yields a final distance of 845^{+14}_{-14} pc. This is 845^{+24}_{-22} pc when we use the 5th and 95th percentiles. When we calculate the combined distance with the Gaia DR2 parallax, the distance is 841^{+10}_{-12} pc. This distance is marginally more precise than the Gaia DR3 combined distance despite a lower S/N since the DR2 parallax is closer to those reported in Desvignes et al. (2016), Ding et al. (2020), and Ding et al. (2023).

With Gaia DR2, we find a FAP $< 7 \times 10^{-8}$, indicating a $> 5\sigma$ detection. With DR3, we find a FAP of 0 in more than 10^7 tests, indicating a $> 5\sigma$ detection once again. Furthermore, in DR3 this Gaia object has $G_{\text{BP}} = 19.71$ and $G_{\text{RP}} = 19.45$, thus using Equation (1) we find $T_{\text{eff}} = 7407 \pm 1316$ K. Mata Sánchez et al. (2020) study this companion via spectroscopic fits (rather than spectral energy distribution fits) and employ correction functions to properly model the extremely-low-mass companion. They report a temperature of 8362^{+25}_{-23} K, -0.8σ from what we calculate. Therefore it is likely that Gaia DR3 851610861391010944 is indeed the previously identified white dwarf binary companion.

3.7. J1024-0719: Strong Association

J1024-0719 is in an ultrawide binary system ($P_b > 200$ yr) with a low-mass, main-sequence star (Bassa et al. 2016; Kaplan et al. 2016). The spectral type of the companion object was analyzed in Kaplan et al. (2016) and Bassa et al. (2016).

We identify this companion as Gaia DR2 and DR3 3775277872387310208 (M18; see also Antoniadis 2021). In DR2, we find a parallax measurement of 0.53 ± 0.43 (S/N = 1.23), and in DR3 of 0.86 ± 0.28 mas (S/N = 3.08). We combine the DR3 measurement with the pulsar-timing-based parallax measurements from IPTA DR2, Ding et al. (2023), and Agazie et al. (2023) to yield a new distance measurement of 1064^{+67}_{-49} pc. This distance is consistent with the Gaia DR2 combined distance of 1155^{+50}_{-50} pc (see Figure 8).

The FAP of this identification is $< 10^{-8}$ when using Gaia DR2 or DR3, indicating a statistically strong $\gg 5\sigma$ detection in both cases. Since the object has $C_{\text{XP}} = 1.8$ in DR3, we must compare the object to the synthetic catalog to estimate its temperature instead of using Equation (1). We find that this object has $G_{\text{BP}} = 20.08$ and $G_{\text{RP}} = 18.26$, data characteristic of a ~ 3500 K star. Kaplan et al. (2016) and Bassa et al. (2016) report the

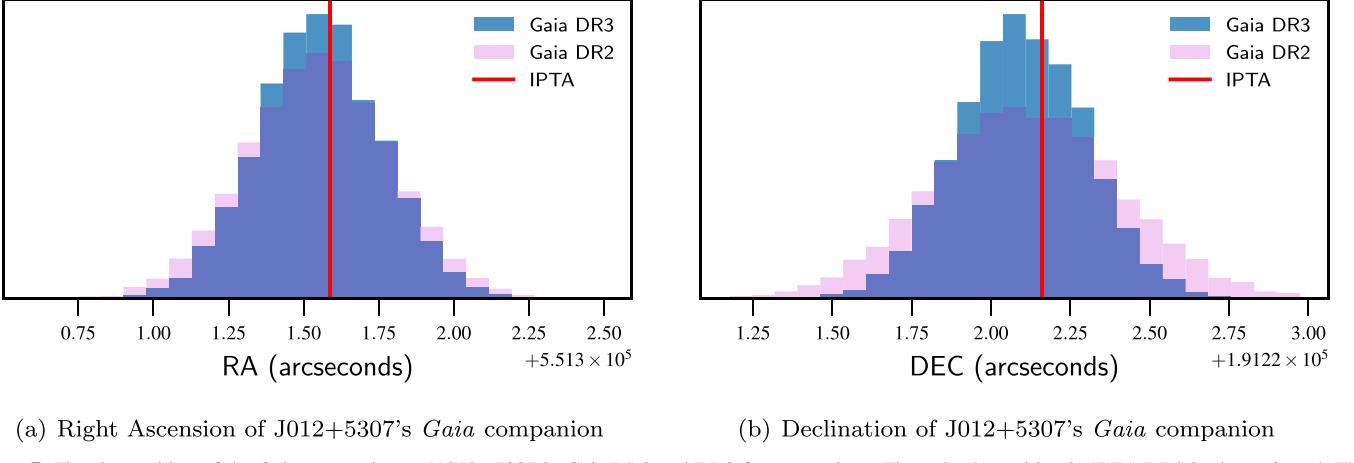


Figure 7. The sky position of the Gaia companion to J012+5307 in Gaia DR2 and DR3 for comparison. The pulsar's position in IPTA DR2 is shown in red. The Gaia R.A. error decreased by 15% from DR2 to DR3, and the decl. error by 33%.

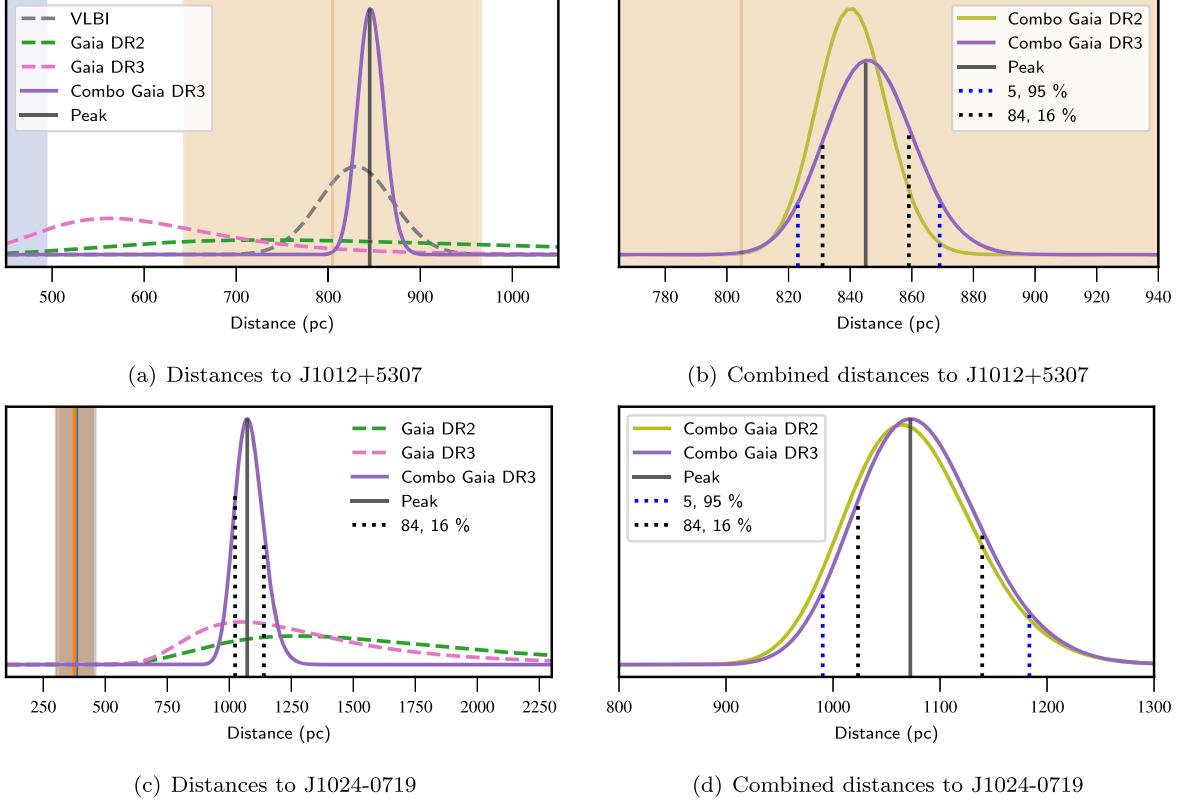


Figure 8. Distances to J1012+5307 and J1024-0719. All DM distances are shown for comparison only and are not used in any distance calculations. The uncertainties in DM distances assume a standard error of $\pm 20\%$. In panels (a) and (b) the combined measurements to J1012+5307 include the Desvignes et al. (2016), Ding et al. (2023), and Agazie et al. (2023) parallax measurements as well as the VLBI distance found in Ding et al. (2020). The combined Gaia DR2 distance is more precise than the combined DR3 distance since the DR3 parallax is very small and therefore results in a broader distribution, even when combined with the other parallaxes. In panels (c) and (d) the combined measurements include the IPTA DR2, the NANOGrav 15 yr data (Agazie et al. 2023), and Ding et al. (2023) parallax measurements. All parallaxes correspond to distances more than double the DM distances, which may indicate that the NE2001 and YMW16 underestimate their errors.

temperature as 3900^{+60}_{-40} K and 4050 ± 50 K, respectively. They classify the object as a cool main-sequence star, which is consistent with our calculated temperature.

4. Discussion and Summary

We have confirmed associations of various credibility to five MSPs in Gaia DR3 as well as identified two new candidates for association with J1747-4036, for a total of six possible

matches. We also identified a false-positive association with J1949+3106 in Gaia DR2, from which we can conclude that detections must have $>3.0\sigma$ confidence to be considered concrete identifications (see Table 3). As a complementary means of verification, we calculated companion temperatures, which can improve detection confidence; see, e.g., J0437-4715.

Looking to the future, parallax errors scale with $T^{-1/2}$, where T is observation time (Jennings et al. 2018). Since the DR3

Table 3
The Strength of Identification for Each Binary System Based on FAP and the Temperature We Calculate for the Gaia Object.

Pulsar	DR2 Detection	DR3 Detection	T_{eff} (K)	Previous T_{eff} (K)	Reference
J0437–4715	$>5\sigma$	$>5\sigma$	5020 ± 750	3950 ± 150	D12
J1012+5307	$>5\sigma$	$>5\sigma$	7407 ± 1316	8362_{-23}^{+25}	S20
J1024–0719	$>5\sigma$	$>5\sigma$	~ 3500	4050 ± 50	B16
[†] J1732–5049	2.8σ	2.9σ	~ 4000	—	—
[†] J1747–4036	N/A	2.3σ	4927 ± 788	—	—
[†] J1843–1113	2.5σ	2.5σ	~ 3350	—	—
[†] J1910+1256	2.4σ	N/A	N/A	—	—
[†] J1949+3106	3.0σ	N/A	N/A	—	—

Notes. Only associations stronger than 3.0σ ($\text{FAPs} < 3.19 \times 10^{-3}$) are considered companion detections and weak associations are denoted by [†]. False associations are denoted by a *. For J1747–4036, the temperature displayed refers to Object A. Companion temperature information from the specified reference is also shown for comparison. When no previous temperature information is available this is indicated with —.

release comes 1 yr after DR2, which was based on 22 months of data, we expect that DR3 parallax errors will be a factor of $(34/22)^{-1/2} \sim 0.6$ smaller. The average increase in S/N from DR2 to DR3 is 53%. The only object for which the S/N did not improve is the companion to J1732–5049, which is in both cases a negative parallax. When this is excluded, the increase in S/N is 74%. Furthermore, the Gaia mission has been extended to 2025, promising a Data Release 4 (DR4) based on 66 months of information.⁴ With an additional 32 months of observations, we therefore expect to see a further improvement in parallax of $(66/34)^{-0.5} \sim 0.7$.

Overall, we find that DM-based distances have underestimated errors. Specifically, the combined distances to J1024–0719, J1732–5049, and J1747–4036 are outside of the assumed DM-based error region of $\pm 20\%$. For J1024–0719, in particular, both NE2001 and YMW16 DM models are less than half as large as the parallax distances. These models may have therefore underestimated the electron density in the localized regions of these pulsar systems.

Compared to the distances from Gaia DR2, the combined distance measurements from DR3 are on average 29% more precise for systems with previously known companions (i.e., excluding the likely false match with J1843–1113; see Table 4). The distances to J0437–4715, J1012+5307, and J1024–0719 are essentially unchanged due to previous parallax measurements that dominate their combined distances. The combined distance to J1732–4026 improved by 30% as expected, since the Gaia measurements are the only known parallaxes.

We also use the Gaia DR3 photometric data to verify our matches. We found that only three Gaia companions are suitable to use with Equation (1) ($C_{\text{XP}} < 1.5$): these are J0437–4715, J1012+5307, and J1747–4036. The latter has no published T_{eff} value, so we focus our attention on comparing the T_{eff} values of J0437–4715 and J1012+5307 to those in the literature. Companions to J0437–4715 and J1012+5307 were identified with $\gg 5\sigma$ confidence. For J0437–4715's companion, Durant et al. (2012) report a temperature 1.4σ from what we calculate and identify the object as a white dwarf. The value we calculate is consistent with this classification. For J1012+5307, Mata Sánchez et al. (2020) report a temperature 0.8σ from our calculated value and identify the companion as a (cool) white dwarf, consistent with the temperature we calculate (see Table 3). This method is therefore good enough to determine

⁴ <https://www.cosmos.esa.int/web/gaia/release>

Table 4
Comparison of Combined Distances Calculated Using the Specified Gaia Parallax Measurements

Pulsar	DR2 Distance (pc)	DR3 Distance (pc)
J0437–4715	$156_{-1.1}^{+1.1}$	$156_{-1.1}^{+1.1}$
J1012+5307	841_{-12}^{+10}	845_{-14}^{+14}
J1024–0719	1155_{-50}^{+69}	1064_{-49}^{+67}
[†] J1732–4036	3980 (4800, 11000)	3874_{-1400}^{+4100}
[†] J1843–1113	1701_{-105}^{+3800}	4568_{-1800}^{+3500}

Notes. Error bars are the 16th and 84th percentiles of the distance measurements, which are in brackets when the 16th percentile is greater than the most probable (peak) distance. Weak Gaia associations in need of further verification are denoted by [†].

if the Gaia object is within the range of temperatures for a given classification, and results in calculated temperatures within 1.5σ of published values.

For the remaining two systems, we compare the Gaia photometric data to the synthetic catalog in Jordi et al. (2010) to estimate temperatures. We find that the estimated temperatures are useful for determining if the Gaia object's photometric data are consistent with expectations for a given classification, although the estimated temperature can only be compared to a previous classification in one case. The temperature of the companion to J1024–0719 is consistent with a main-sequence object, as is its location in Figure 1. This object's photometric data are thus consistent with the classifications made in Kaplan et al. (2016) and Bassa et al. (2016).

Gaia DR4 will report data based on twice as many transits as DR3. Since Jordi et al. (2010) reports that error on photometric color data scales as $C_{\text{XP}} \sim 1/\sqrt{N}$, where N is the number of transits, this photometric data are expected to improve by a factor of $1/\sqrt{2} = 0.7$. Indeed, both methods of temperature measurement may become more useful with data from future Gaia releases as photometric measurements improve. Given this and the expected parallax improvements in Gaia DR4 (Fabricius et al. 2021), we anticipate subsequent improvements in both distance measurements and our verification methods. We will revisit these results again upon the publication of this data release.

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