Gaia DR2 Distances and Peculiar Velocities for Galactic Black Hole Transients

Poshak Gandhi,1,⋆ Anjali Rao,1 Michael A.C. Johnson,1,2 John A. Paice,1,3 Tom J. Maccarone4

1Department of Physics & Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK
2Electronics and Computer Science, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
3Inter-University Centre for Astronomy and Astrophysics, Pune, Maharashtra 411007, India
4Department of Physics, Box 41051, Science Building, Texas Tech University, Lubbock, TX 79409-1051, USA

Submitted 2018 April 26

ABSTRACT

We report distance estimates for Galactic black hole X-ray binaries with the second data release (DR2) of Gaia, concentrating on sources that are dynamically-confirmed transients or are strong candidates for hosting black holes. While DR1 did not provide parallaxes and proper motions for any of the confirmed black hole binaries, DR2 provides the five-parameter astrometric solutions, including position, parallax and proper motions, for 11 out of a sample of 24 systems, albeit with large uncertainties in some cases. Distance estimates are derived by parallax inversion as well as using Bayesian inference. DR2 distances largely agree with previous estimates. The biggest potential surprise is BW Cir, which DR2 places at a naive (parallax-inversion) distance of \( \sim 0.6 \pm 0.2 \) kpc, possibly making it the nearest dynamically-confirmed black hole transient. However, Bayesian estimates do allow somewhat larger distances and we caution that correlations between the astrometric parameters need to be accounted for, and that the nearby distance estimate creates problems for the physical interpretation of the properties of the donor star. Under similar caveats, the super-bright hard-state transient MAXI J1820+070 lies at a likely distance of \( \approx 3 \) kpc. Thus, some care is needed for estimating distances to black hole binaries which typically lie in the faint regime. Peculiar velocities are also computed for 10 sources, and BW Cir could potentially be a new high peculiar-velocity Galactic black hole X-ray binary.

Key words: stars: black holes – stars: distances – parallaxes – proper motions – accretion, accretion discs

1 INTRODUCTION

Black hole X-ray binaries (BHBs) are key sources for studying accretion in the strong gravitational regime. About 60 low mass BHBs are known in the Galaxy, though only about 20 of these have been confirmed to host black holes, based upon dynamical measurements of the companion star about the primary (Casares & Jonker 2014, Corral-Santana et al. 2016, Tetarenko et al. 2016).

Distances to most BHBs remain highly uncertain. The most reliable distances come from geometric estimates based upon measurements of trigonometric parallax shifts relative to background sources. However, such measurements require exquisite precision, which has not been generally available except for a handful of very long baseline interferometric measurements in the radio: e.g. Cyg X-1 (Reid et al. 2011), V404 Cyg (Miller-Jones et al. 2009a) and GRS 1915+105 (Reid et al. 2014). In the absence of geometric distances, estimates become reliant upon emission- and evolutionary-dependent model assumptions (cf., review by Jonker & Nelemans 2004), but it is not uncommon for such estimates to be uncertain by 50% or much more. The lack of accurate distances is a severe handicap for modelling source luminosities, determining line-of-sight absorption columns, estimating source inclination (hence masses and spins), and understanding the origin and evolution of the sources.

The Gaia mission (Gaia Collaboration et al. 2016) is expected to play a crucial role in the measurement of geometric parallax for targets as faint as G-band (330-1050 nm) magnitude 21, along with providing highly accurate positions and proper motions for more than 1 billion stars (Gaia Collaboration et al. 2016). It is expected to revolutionise our knowledge of the structure of the Galaxy and its constituents. This is expected to include BHBs.

A significant new data release (DR2, Gaia Collaboration et al.
2018) occurred on 2018 April 25, and here, we present the results of a cross-match between the positions of 24 Galactic BHBs and DR2. DR2 is based upon data gathered over 22 months from July 2014 to May 2016. We report on distance estimates from the parallaxes and compare these estimates with previous measurements. We also present estimates of the peculiar velocities of the sources based upon three-dimension kinematics.

2 GAIA COUNTERPART SEARCH AND ASSOCIATION

We queried the DR2 public release on 2018 April 25. A search radius of 2″ was used to search for DR2 entries around each of the 24 targets, though we also experimented with larger radii in individual ambiguous cases as detailed later. In order to assign Gaia counterparts, we used the J2000 ICRS coordinates from SIMBAD, but also cross-checked sources individually against the BlackCAT catalogue (Corral-Santana et al. 2016) which is based upon optical, infrared or radio identifications. The coordinates of MAXI J1820+070 were taken from Kennea (2018). We also included Cygnus X–1 amongst our list of targets. Though a fairly persistent high mass X-ray binary, this source is amongst the best studied of black hole systems, and serves as a useful comparison source.

The associated Gaia counterpart coordinates are listed in Table (1). The offset from the BlackCAT position is also noted and is found to be less than 1″ for most of the sources. Two sources, GX 339-4 and V404 Cyg had multiple possible counterparts and Gaia in individual ambiguous cases as detailed later. In order to assign Gaia counterparts, we used the J2000 ICRS coordinates from SIMBAD, but also cross-checked sources individually against the BlackCAT catalogue (Corral-Santana et al. 2016) which is based upon optical, infrared or radio identifications. The coordinates of MAXI J1820+070 were taken from Kennea (2018). We also included Cygnus X–1 amongst our list of targets. Though a fairly persistent high mass X-ray binary, this source is amongst the best studied of black hole systems, and serves as a useful comparison source.

An astrometric goodness-of-fit statistic (gof) flag (astrometric_gof_al) was provided in the Gaia release, and is also provided in Table (1). This parameter represents the gaussianized χ² and is expected to have zero mean and unity scatter. Values exceeding ±3 indicate a bad fit.

We assigned an overall quality flag of counterpart association in DR2: (A) being secure counterparts; (B) being possible counterparts which may not be trustworthy and should be treated with caution; (C) being likely unrelated associations, and (D) are non-detections. This quality flag is also listed in Table (1).

3 DISTANCE ESTIMATION WITH GAIA

If a parallax σr is known for a system, a simple distance estimate is obtained by inversion \( r_{\text{par}} = 1/\sigma r \). In a detailed work, Bailer-Jones (2015) has demonstrated that this serves as a poor approximation, particularly when the uncertainty on σr is more than 20%. This uncertainty is expected to be higher for fainter objects, which constitute a large fraction of the sources that Gaia will observe in its mission. This is especially important for the sources studied in this paper, several of which have quiescent magnitudes of \( G > 19 \).

Treating the problem as a Bayesian inference problem can help improve the estimate, but this is subject to appropriate cross-checking of a priori distribution of expected distances. As suggested in Bailer-Jones (2015) and Astraatmadja & Bailer-Jones (2016a,b), we have adopted a prior based on exponential decrease of density with distance, which warrants a length scale as an input parameter. We have considered a length scale of \( L = 1.35 \text{kpc} \) (Ibid.) to define the exponentially decreasing space density prior, and compute the posterior distribution of distance \( r_{\text{exp}} \) by combining the prior with a Gaussian likelihood function, as described in the above works.

As in Astraatmadja & Bailer-Jones (2016), we also tested a different prior based upon the expected distribution of sources in the Milky Way. This Milky Way prior was calculated using the same method as for the exponential prior, except for the volume density of stars, \( P(V) \). The Milky Way counterpart to \( P(V) \) was composed of a Galactic low mass X-ray Binary (LMXB) density, as described by Equations (4), (5) and (6) of Grimm et al. (2002) which represent the density of LMXBs in the bulge, disk, and sphere of the Milky Way, respectively. All constants used to calculate the Galactic LMXB density were from Table (4) of Grimm et al. (2002), except for the scale length, where a slightly smaller value of 3 kpc was used Astraatmadja & Bailer-Jones (2016). The LMXB density was the multiplied by \( r^2 \) to construct the Milky Way prior which was then combined with Equation (1) from Bailer-Jones (2015) in order to calculate the posterior.

We have used the mode of the posterior as the distance estimator and the uncertainties represent the difference between \( r_{\text{mode}} \) and the two values for \( r_{\text{mode}} \) corresponding to a 0.5 normalized probability, i.e. a measure of the width at half-maximum. Each posterior was examined by eye, and we also quote the 5% and 95% quantiles from the posterior distribution function.

We have not considered the systematic uncertainty in our calculation as recommended in Gaia Collaboration et al. (2016). Systematic astrometric uncertainties have not been corrected for individually in DR2, though generic corrections are included (Gaia Collaboration et al. 2018; Lindegren et al. 2018). Residual zero-point systematics are expected to be only \( \approx 0.03 \text{ mas} \), much smaller than the statistical uncertainties (Ibid.). Global systematics may be as large as 0.1 mas, but the Collaboration recommendation at present is to not combine these with statistical uncertainties, but rather keep them in mind for the interpretation (Ibid.).

Table (1) lists all 24 black hole binaries and summarizes the values of parallax, proper motion and G-mag from Gaia DR2, where available.

4 PECULIAR VELOCITIES

If black holes originate in a supernova explosion, symmetric as well as asymmetric natal kicks could potentially recoil and scatter sources into new trajectories (Blaauw 1961; Brandt & Podsiadloowski 1995). Studying the distribution of space velocities and positions can thus shed light on their origins. Two black hole binaries for which there is evidence of strong scattering are XTE J1118+480 and GRO J1655-40 (Mirabel 2017). But such measurements require full astrometric and kinematic information: i.e. parallaxes (σr), proper motions (μα, μδ in RA, Dec) and radial velocities (γ), and thus exist for only a handful of sources which have been studied typically with the accuracy of very long baseline interferometry in the radio. DR2 now provides measurements of (μα cosδ, μδ, γ), in addition to σr. Together with assumptions on previous estimates or plausible ranges of γ, we can estimate source velocities.

We used the formalism of Johnson & Soderblom (1987) to transform the observables into heliocentric space velocities (U, V, W). Peculiar velocities (i.e. relative to Galactic circular rotation) were obtained by removing Solar motion and Galactic rotation according to the formalism and constants of Reid et al. (2009, 2014).
5 RESULTS

DR1 archive included the detection of many of the black hole binaries in our sample, however no parallaxes or proper motions were obtained; only positions and $G$ magnitudes were listed. DR2 is more complete in terms of coverage and also far more complete in terms of number of astrometric visits. Thus, it was anticipated to contain parallaxes for a number of confirmed black hole binaries. DR2 provides potential counterparts with positions and $G$-mag for 21 black hole binaries, but complete astrometric solution consisting of position, parallax and proper motion for 11 systems. All of these 11 systems have secure and/or likely reliable counterparts (quality flags A, B). The brightness distribution has a median of $G = 19.35$ mag and standard deviation 3.18 mag.

The uncertainty on parallax in most of the cases is significant and 9 sources out of 11 show fractional uncertainty >20%. The fractional uncertainty is found to be >1 for 2 sources. Also, the parallax for one of the sources (Swift J1753.5–0127) is found to be negative. The distance to the sources is found by inverting $\sigma$ and the values are reported in the third column of Table (2), except that of Swift J1753.5–0127. As expected, the distance and its uncertainty for the sources with fractional $\sigma$ uncertainty > 1 (and/or negative $\sigma$ values) is unreliable and we need to depend on other methods to find the distance estimates for these sources. Also, the uncertainties on distance are large for the sources with fractional >20%.

Distance estimates based upon the two Bayesian priors are also quoted in Table (2), together with their confidence ranges. There is no case of strong disagreement between these, and Bayesian estimates are possible for the case with negative $\sigma$ also. The two different scale lengths of 1.35 kpc and 3 kpc between the two methods illustrate the impact of the choice of prior. In general, larger $L$ ends up preferring a somewhat larger distance, as expected. We also examined the posterior probability distributions of all sources and found no obvious ill-behaved case.

We make use of the proper motion of 10 black hole binaries to infer peculiar velocities. The magnitude of the proper motions is $\sim 10$ mas yr$^{-1}$, with 9 of them being in the direction of decreasing projected RA. In Fig. 1, the sources are plotted on a Hammer projection of the sky, along with arrows showing the current direction of their proper motion.

Table (2) presents $v_{pec}$ values for the 10 objects, though we note the uncertainty in the counterpart to GS 1124–684. The uncertainties on the $v_{pec}$ were obtained from Monte Carlo sampling of all uncertainties on all parameters of the full three-dimensional positional and kinematic dataset, as well as uncertainties on the Solar position and motion (Reid et al. 2014). The solutions for two sources (XTE J1118+480, 4U 1543–475) showed bimodal error probabilities and should be treated with caution. The solution for Swift J1753.5–0127 was strongly unconstrained. These unreliable solutions are mainly related to the significant parallax uncertainties. Discussion on the individually reliable $v_{pec}$ values can be found in the next section.
Table 1: *Gaia* DR2 astrometric and photometric data for a sample of 24 black hole binaries.

Note: The RA and Dec positions given in the second and third column respectively are the coordinates in J2015.5 epoch obtained from *Gaia*. The offset given in the third column is the angular separation between the position of the sources in *Gaia* and BlackCAT, with the exception of MAXI J1820, which is between *Gaia* and Kennea & Siegel (2018). The quality flags stand for the following:

A: Highly likely that this *Gaia* counterpart is correct.
B: Possibility that this *Gaia* counterpart is not correct
C: Unlikely that this *Gaia* counterpart is correct
D: Source was not found within 2″ *Gaia* DR2.

| Nr. | Source | RA (h:m:s) | Dec (d:m:s) | Offset (arcsec) | Mag | Parallax (mas) | PMRA (mas y⁻¹) | PMDec (mas y⁻¹) | vradial (km s⁻¹) | Ref. | gof | Flag |
|-----|--------|-----------|-------------|----------------|-----|---------------|---------------|----------------|-----------------|------|-----|------|
| 1   | GRO J0422+32 | 04:21:42.72 | +32:54:26.94 | 0.858 | 20.85 | 0.64±0.16 | -0.09±0.25 | -5.20±0.30 | 8.5±1.8 | – | 4.406 | A |
| 2   | 1A 0620–00 | 06:22:44.54 | -00:20:44.37 | 0.681 | 17.52 | – | – | – | – | (1) | 3.026 | A |
| 3   | GRS 1009–45 | 10:13:36.40 | -04:32:52.52 | 0.629 | 17.73 | – | – | – | – | (2) | -0.154 | C |
| 4   | XTE J1118+480 | 11:18:10.77 | +48:02:12.21 | 0.523 | 19.35 | 0.30±0.40 | -17.57±0.34 | -6.98±0.43 | -15±10 | (3) | 4.694 | A |
| 5   | GS 1124–684 | 11:26:26.59 | -68:40:32.89 | 0.346 | 19.57 | 0.61±0.34 | -2.44±0.61 | -0.71±0.46 | 16±5 | (4) | 0.352 | B |
| 6   | SWIFT J1357.2–0933 | 13:57:16.83 | -09:32:38.79 | 0.358 | 20.75 | – | – | – | – | (5) | 0.911 | A |
| 7   | GS 1354–64 | 13:58:09.71 | -64:44:05.29 | 0.514 | 20.53 | 1.83±0.58 | -9.38±2.22 | -5.70±2.26 | 103±4 | (6) | 1.592 | A |
| 8   | 4U 1543–475 | 15:47:08.27 | -47:40:10.37 | 0.702 | 16.48 | 0.04±0.07 | -7.41±0.14 | -5.33±0.10 | -87±3 | (7) | 0.344 | A |
| 9   | XTE J1550–564 | 15:50:58.65 | -56:28:35.31 | 0.412 | 20.90 | – | – | – | – | (8) | 0.123 | A |
| 10  | XTE J1650–500 | 16:50:00.81 | -49:57:43.77 | 1.665 | 20.02 | – | – | – | – | (9) | 0.222 | C |
| 11  | GRO J1655–40 | 16:54:00.14 | -45:04:32.52 | 0.346 | 19.57 | 0.61±0.34 | -2.44±0.61 | -0.71±0.46 | 16±5 | (10) | 4.035 | A |
| 12  | MAXI J1659–152 | – | – | – | – | – | – | – | – | – | – | D |
| 13  | GX 339–4 | 17:02:49.38 | -48:47:23.17 | 0.418 | 16.47 | – | – | – | – | (11) | 2.496 | A |
| 14  | H 1705–250 | 17:08:14.50 | -25:05:30.29 | 0.299 | 20.83 | – | – | – | – | (12) | -0.383 | A |
| 15  | XTE J1752–223 | 17:52:15.11 | -22:20:31.42 | 0.984 | 20.20 | – | – | – | – | (13) | 3.007 | B |
| 16  | SWIFT J1753–0127 | 17:53:28.29 | -01:27:06.31 | 0.092 | 16.70 | -0.01±0.13 | 1.13±0.16 | -5.33±0.15 | 6±6 | (14) | 0.570 | A |
| 17  | XTE J1817–330 | 18:17:43.49 | -33:01:08.80 | 1.164 | 19.86 | – | – | – | – | (15) | 1.900 | C |
| 18  | SXT J1891+3255 | 18:19:21.64 | -25:24:25.84 | 0.063 | 13.57 | 0.15±0.04 | -0.73±0.07 | 0.42±0.06 | 107.4±2.9 | (16) | 0.675 | A |
| 19  | MAXI J1820+070 | 18:20:21.94 | +07:11:07.19 | 0.162 | 17.41 | 0.31±0.11 | -3.14±0.19 | -5.90±0.22 | – | (17) | -0.871 | A |
| 20  | XTE J1859+226 | – | – | – | – | – | – | – | – | (18) | -0.871 | A |
| 21  | GRS 1915+105 | – | – | – | – | – | – | – | – | (19) | -0.871 | A |
| 22  | GS 2000+251 | 20:02:49.52 | +25:14:10.64 | 1.026 | 21.22 | – | – | – | – | (20) | 1.359 | A |
| 23  | GS 2023+338 | 20:24:03.82 | +33:52:01.83 | 1.369 | 17.19 | 0.44±0.10 | -5.77±0.17 | -7.85±0.17 | -0.4±2.2 | (21) | 9.525 | A |
| 24  | Cyg X–1 | 19:58:21.67 | +35:12:05.69 | 0.110 | 8.52 | 0.42±0.03 | -3.88±0.05 | -6.17±0.05 | -5.1±0.5 | (22) | 3.626 | A |

References for the radial velocity: (1) González Hernández, J. I. & Casares, J. (2010); (2) Filippenko et al. (1999); (3) Mirabel et al. (2001); (4) Orosz et al. (1996); (5) Sanchez & Siegel 2015; (6) Casares et al. (2004); (7) Orosz et al. (1998); (8) Orosz et al. (2002); (9) Sanchez-Fernandez et al. (2002); (10) mirabel2002; (11) Heida et al. (2017); (12) Filippenko et al. (1997); (13) Neustroev et al. (2014); (14) Orosz et al. (2001); (15) Corral-Santana et al. (2011); (16) Greiner (2001); (17) Harlaftis et al. (1996); (18) Casares & Charles (1994); (19) Gies et al. (2008).
6 DISCUSSION

6.1 Distance estimates

Fig. 3 shows a comparison of previously published distance estimates (where available) against the DR2 distances based upon the exponentially decreasing prior $r_{exp}$. Of the 10 sources plotted, the two kinds of estimates agree within the plotted 50% uncertainty for 6 objects. There is modest discrepancy for 2 sources: A0620–00 and GS 1124–684. For the latter, we note that the counterpart should be treated with caution. The simple parallax-inversion estimate $r_{inv}$ can only be considered an upper limit for XTEJ1118+480 and 4U 1543-475.

Regarding A0620–00, a previous distance estimate of dynamical model and zero-disk stellar VIH magnitudes comes from Cantrell et al. (2010) who found a distance of 1.06 ± 0.12 kpc. Another distance estimate of 1.0 ± 0.4 kpc by Shahbaz et al. (1994) is close to this value. We note that our simple DR2 $r_{exp}$ value does agree with these within uncertainty, as does $r_{exp}$. Furthermore, examining the full posterior probability distribution for $r_{exp}$, we found agreement within the 5–95% interval (Table 2).

So the message to take away is that the DR2 distances inferred appear to be reliable, though caution is needed in interpretation. As to which distance estimate ($r_{exp}$, $r_{exp}$, $r_{exp}(W)$) should one use, discussion of Bayesian inferences is a detailed problem (e.g. e.g. Bailer-Jones 2015, Astraatmadja & Bailer-Jones 2016, Luri et al. 2018)) and it depends upon the level of priors one is willing to incorporate. Hereafter, we refer to $r_{exp}$ as a good compromise primary distance estimate for discussion, as in Astraatmadja & Bailer-Jones (2016).

Cyg X–1 shows an apparently stronger mismatch in the DR2 distance with respect to the previous radio parallax estimated distance by Reid et al. (2011), at a ≈ 3 σ level. The cause of this discrepancy is currently unclear though it appears to be explainable by systematic uncertainties (see section 6.3 below, where we detail the quality of astrometric fits).

The only case for which there then remains a strong discrepancy between the DR2 and previous estimates is GS 1354–64 (BW Cir), which is also discussed in a dedicated sub-section (6.4) below.

Fig. 2 depicts the location of our sample of BHBs projected onto the plane of the Milky Way using the $r_{exp}$ distances based upon the exponential prior, where available, together with previously published values.

6.2 Peculiar Velocities

The kinematics of GRO J1655–40, V404 Cyg and Cyg X–1 have been published before. Of these, GRO J1655–40 is moving with the highest $v_{pec}$ value. Runaway motion was also inferred for this source by Mirabel et al. (2002), though our DR2 estimate is larger than theirs by about 50% when accounting for the (previous) distance ranges. Our DR2 estimate for V404 Cyg agrees well within uncertainties with the measurement of $v_{pec} = 39.9 \pm 5.5 \text{ km s}^{-1}$ by Miller-Jones et al. (2009). Similarly, for Cyg X–1, Reid et al. (2011) estimate $v_{pec} \approx 21 \text{ km s}^{-1}$, in agreement with the DR2 value. Finally, we also note that a high $v_{pec}$ is inferred in DR2 for XTE J1118+480. Although this measurement has significant uncertainty, it agrees with the inference of this source being a high-velocity black hole first pointed out by Mirabel et al. (2001).

DR2 infers a modest $v_{pec}$ value for A 0620–00 and an intermediate velocity for SAX J1819.3–2525. The inferred values for a few sources show bimodal peaks in the velocity uncertainty distribution and may not be reliable. The highest new reliable $v_{pec}$ value of about 100 km s$^{-1}$ is for GS 1354–64. If correct, this would make it a new high-velocity system (however, see section 6.4). Correlations with black holes masses and updated inferences for linear momentum and natal kicks (Mirabel 2017) will be investigated in future works.

Finally, we also note that the new transient MAXI J1820+070 shows an intermediate $v_{pec} \approx 60 \text{ km s}^{-1}$. A systemic radial velocity is not yet known for this source, so the inference is based upon an assumption of $v = 0 \text{ km s}^{-1}$ (cf. other sources in Table 1). For reference, changing $v$ over the range of $-100$ to $+100 \text{ km s}^{-1}$ changes $v_{pec}$ between $\pm 50$–140 km s$^{-1}$.

6.3 Goodness of Fit and Correlations between Solution Parameters

The goodness-of-fit flag astrometric_gof_al values provided by Gaia, are presented for each of our sources in Table 1. While most flag values are below the value of +3 and thus indicate a reasonable astrometric fit solution, there are a few which are notably above this, e.g. GS 2023+338 (V404 Cyg). Of the 10 sources with previous distance estimates plotted in Fig. 3, 5 have gof > 3. This includes Cyg X–1 (gof = 3.6) which shows an apparent discrepancy in the same figure, but not the most discrepant source BW Cir (gof = 1.6).

So can we explain away the offset seen for Cyg X–1 based upon a bad astrometric fit? This is not obviously the case, because three sources with DR2 $r_{exp}$ values matching previous estimates also have an apparently bad astrometric gof: XTE J1118+480, GRO J1655–40 and V404 Cyg. Of course, a bad astrometric fit could be a necessary but not sufficient condition to explain such distance estimate discrepancies. We also point out that the peculiar velocity inferred from the astrometric solution for Cyg X–1 matches previous estimates (section 6.2).

There then remains the possibility of an effect due to the aforementioned systematic uncertainties. A global systematic error of about 0.1 mas in DR2 (e.g. Luri et al. 2018) would easily bring Cyg X–1 in line with the radio parallax distance of Reid et al. (2011), and this systematic error should be considered before delving into possible physical implications of any real shift between optical and radio. Based upon the Collaboration recommendation, we have not included this systematic within the quoted individual errors (Ibid.). We do note one apparent systematic trend in Fig. 3 that the nearby sources (according to previous distance estimates) all have gof > +3, whereas all distant sources have gof < +3. Whether this indicates a deeper systematic issue, or is simply a result of small number statistics, is not clear. We checked whether there is any correlation between gof and G-mag, as may be expected if there were a distance systematic, but found none (the Spearman rank correlation coefficient between the two parameters is -0.10, with a $p$-value of 0.78). Other tests of systematic effects are currently being carried out by the Collaboration and are beyond the scope of this paper.

In summary, the astrometric fits are broadly reliable for our Galactic BHBs, but goodness of fit and systematic uncertainties need to be kept in mind while interpreting the results.

For the one remaining case of BW Cir with the most discrepant distance estimates, the astrometric gof is not indicative of a significant issue with the fit. Additionally, however, it is possible for the five-parameter astrometric solution values to be significantly correlated with each other (e.g. Lindegren et al. 2018, Luri et al. 2018). The DR2 fit solutions include 10 pairwise correlation coefficients for these; additionally, the DR2 flag
### 6. Gandhi et al. 2018

#### Table 2. The estimates of distance and space velocity obtained using Gaia parallax.

| Nr. | Source | $r_{\text{inv}}$ (kpc) | $r_{\text{exp}}$ (kpc) | $r_5$ (kpc) | $r_{95}$ (kpc) | $v_{\text{pec}}$ (km s$^{-1}$) | Previous Distance (kpc) | Ref. |
|-----|--------|------------------------|------------------------|-------------|--------------|-----------------------------|-----------------------|------|
| 1   | GRO J0422+32  | -                        | -                      | -           | -            | -                           | 2.49 ± 0.30          | (1)  |
| 2   | 1A 0620–00   | 1.57 ± 0.40             | 1.66 ± 0.71            | 1.26        | 3.78         | 1.7 ± 0.81 ± 0.42           | 45.1 ± 11.0          | (2)  |
| 3   | GRS 1009–45  | -                        | -                      | -           | -            | -                           | 3.8 ± 0.3            | (3)  |
| 4   | XTE J1118+480 | 3.34 ± 0.42             | 2.80 ± 3.70            | 1.61        | 8.50         | 3.7 ± 0.12 ± 0.33           | 140 ± 66.5           | (4)  |
| 5   | GS 1124–684  | 1.65 ± 0.93             | 2.04 ± 0.87            | 1.29        | 7.39         | 6.6 ± 1.14 ± 0.45           | 46.7 ± 11.0           | (5)  |
| 6   | SWIFT J1357.2–0933 | -                    | -                      | -           | -            | -                           | 2.33 ± 0.45          | (6)  |
| 7   | GS 1354–64   | 0.55 ± 0.17             | 0.67 ± 2.03            | 0.52        | 5.44         | 0.74 ± 0.15 ± 0.53          | 105 ± 4.6 ± 6.9      | (7)  |
| 8   | 4U 1543–47S  | 24.72 ± 1.15            | 7.02 ± 3.88            | 4.90        | 12.37        | 10.11 ± 0.53 ± 3.53         | 98.3 ± 22.41         | (8)  |
| 9   | XTE J1550–564 | -                        | -                      | -           | -            | -                           | 4.38 ± 0.58          | (9)  |
| 10  | XTE J1650–500 | -                        | -                      | -           | -            | -                           | 2.60 ± 0.70          | (10) |
| 11  | GRO J1655–40 | 3.66 ± 1.01             | 3.51 ± 1.03            | 2.67        | 6.76         | 7.29 ± 1.37 ± 0.34          | 147.7 ± 13.1          | (11) |
| 12  | MAXI J1659–152 | -                      | -                      | -           | -            | -                           | 8.6 ± 3.7            | (12) |
| 13  | GX 339–4     | -                        | -                      | -           | -            | -                           | >6.0                 | (13) |
| 14  | H 1705–250   | -                        | -                      | -           | -            | -                           | 8.6 ± 2.0            | (14) |
| 15  | XTE J1752–223 | -                      | -                      | -           | -            | -                           | 5.75 ± 2.25          | (15) |
| 16  | SWIFT J1753–0127 | -                    | -                      | -           | -            | -                           | 5.5 ± 4.5            | (16) |
| 17  | XTE J1817–330 | -                        | -                      | -           | -            | -                           | 6.0 ± 2.0            | (17) |
| 18  | SAX J1819.3–2525 | 6.62 ± 1.01           | 5.77 ± 1.01            | 4.58        | 9.25         | 7.62 ± 1.13 ± 0.38          | 73.6 ± 14.3           | (18) |
| 19  | MAXI J1820+070 | 3.23 ± 1.14             | 3.11 ± 1.14            | 2.28        | 6.87         | 3.87 ± 1.42 ± 0.29          | 59.6 ± 17.9          | (19) |
| 20  | XTE J1859+226 | -                        | -                      | -           | -            | -                           | -14                  | (20) |
| 21  | GRS 1915+105  | -                        | -                      | -           | -            | -                           | 8.8 ± 2.9            | (21) |
| 22  | GS 2000+251  | -                        | -                      | -           | -            | -                           | 2.7 ± 0.7            | (22) |
| 23  | GS 2023+338  | 2.02 ± 0.02             | 2.04 ± 0.79            | 1.00        | 0.29         | 2.0 ± 0.51 ± 0.20           | 46.8 ± 9.1           | (23) |
| 24  | Cyg X–1     | 2.37 ± 0.18             | 2.31 ± 0.88            | 2.15        | 2.73         | 2.40 ± 0.89 ± 0.24          | 22.1 ± 4.5           | (24) |

Note: $r_{\text{inv}}$ given in the second column of the table are distances estimated by the inversion of parallax, $r_{\text{exp}}$, $r_5$ and $r_{95}$ are the mode, 5% quantile and 95% quantile respectively obtained using the posterior Probability Density Function for exponentially decreasing space density prior. The distance obtained with the Milky Way prior i.e. $r_{\text{exp}}$ are given in sixth column of the table. $v_{\text{pec}}$ are the peculiar velocities relative to Galactic rotation. † indicates a bimodal or unconstrained $v_{\text{pec}}$ distribution which should be treated with caution. *uncertain counterpart. ‡unknown $v_{\text{radial}}$.

References for the previous distances can be found here: (1) Gelino & Harrison (2003); (2) Cantrell et al. (2010); (3) Gelino (2002); (4) Gelino et al. (2006); (5) Hynes (2005); (6) Mata Sanchez et al. (2015); (7) Casares et al. (2009); (8) Jonker & Nelemans (2004); (9) Orosz et al. (2011); (10) Homan et al. (2006); (11) Hjellming & Rupen (1995); (12) Knuijters et al. (2013); (13) Hynes et al. (2004); (14) Jonker & Nelemans (2004); (15) Ratti et al. (2012); (16) Cadolle Bel et al. (2007); (17) Sala et al. (2007); (18) MacDonald et al. (2014); (19) Corral-Santana et al. (2011); (20) Reid et al. (2014); (21) Jonker & Nelemans (2004); (22) Miller-Jones et al. (2009); (23) Reid et al. (2011).

**astrometric_sigmas5d_max** denotes the longest semi-major axis of the 5-$\sigma$ error ellipse when including correlations – a rough single measure of the effect of the covariances. Amongst our sample of sources with five-parameter fits, BW Cir turns out to have the largest value of this flag, indicative of additional covariances.

In order to check the effect of these parameter correlations, we used the code of Bailier-Jones et al. 2017; GAIA-C8-TN-MPIA-CBJ-0813 to infer the distance prior when accounting for covariances between position, parallax and transverse (proper motion) speed. This codes also uses an exponentially decreasing space density prior (we set this to $\rho = 1.35$ kpc) to match our assumptions, and also assumes a beta distribution velocity prior with a maximum transverse speed of 750 km s$^{-1}$. The posterior probability is maximised at a distance of 2 kpc and the distribution tails off significantly beyond $\approx 5$ kpc, again arguing against a much larger distance. This source is discussed in further detail in the following section.

---

6.4 The curious case of GS 1354–64 (BW Cir)

GS 1354–64, or BW Cir, is a dynamically confirmed black hole (Casares et al. 2009). Previous estimates on its distance have placed it at a possible distance of $\sim 25$ kpc (Casares et al. 2004, 2009), on the other side of the galaxy. There are good reasons for such an inference, as discussed in the above papers, including the donor star classification and expected luminosity given its orbital period, as well as the radial velocity match with Galactic differential speed at that distance. However, Gaia apparently disagrees with this estimate strongly, placing it at a likely distance of less than or around 1 kpc. Even the 95% upper interval on distance quoted in Table (2) is much less than 25 kpc. Although previous distance estimates have remained uncertain, this is a puzzling discrepancy given the expected donor star classification and expected intrinsic brightness. The DR2 distance would make the source underluminous in both optical and X-rays.

In order to rule out any systematics related to counterpart identification, we present in Fig. 4 the DR2 counterparts found within a larger search radius of 3″, overlaid on a ground-based (VLT/FORS2) optical image of the field. Despite a potential small systematic astrometric offset relative to the VLT image, Gaia does appear to correctly find BW Cir and its two nearest neighbours, implying no immediate identification issues. We also note that the

3. https://www.mpi-a.de/4287840/3D_astrometry_inference.pdf
Figure 1. Map of the sky, in Galactic Coordinates, using the Hammer-Aitoff projection. The yellow circles represent the locations of the black hole binaries for which we have proper motions from Gaia, while the red circle represents the uncertain association for GS 1124–684. The white arrows show the direction of their proper motion. (Galactic sky image: Mellinger2009)

DR2 flag astrometric_gof_al = 1.59 for this source is not indicative of a significant issue with the astrometric solution.

At its inferred DR2 distance, $v_{pec}$ is dominated by the systemic heliocentric radial velocity $\gamma$. However, we note that if the source identification were correct but the distance were significantly larger, the DR2 proper motions would start pushing up $v_{pec}$ to several hundred km s\(^{-1}\) or more, irrespective of (plausible values of) $\gamma$. While this cannot be ruled out a priori, it adds additional support to a closer distance. We also note that a high proper motion was measured in the Hot Stuff for One Year Catalogue (Altmann et al. 2017), although that is now superseded in terms of precision by DR2.

In summary, the DR2 identification for BW Cir appears reliable, and the parallax and proper motion argue for this source being a nearby black hole. Taking the inferred DR2 $r_{exp}$ at face value would imply this source to be the nearest black hole binary. A nearby distance would also bring the source quiescent X-ray luminosity $L_X$ in line with the $L_X$–$P_{orb}$ (orbital period) trend for black hole binaries (cf. Reynolds & Miller 2014), and also revives the possibilities of the source being associated with Cen X–2 (cf. Casares et al. 2004, 2009).

But we caution that further investigation is definitely warranted in order to (1) carry out other complementary checks on the distance – e.g. with future radio facilities – and, (2) to understand implications for the quiescent (and outburst) source nature. In particular, taking the distance at the low end of the distribution has major implications for the amount of light that can be produced by the donor star, and, in turn the radius of the donor star. The donor star’s period is well established (Casares et al. 2004, 2009) and its classification is unlikely to be subject to significant revision, so changing the donor star distance changes its radius. If the donor star is then also still assumed to fill its Roche lobe, then the mass must be $\sim 25^3$ times smaller for a distance of 1 kpc than for a distance of 25 kpc in order to maintain the same density, and the same optical flux for the donor star. This would yield a donor mass of $\sim 5 \times 10^{-5} M_{\odot}$, unreasonably small. While the donor may, potentially be highly bloated, and overluminous for its mass, it is unlikely to be much less than $\sim 0.1 M_{\odot}$. For such a star to be filling its Roche lobe, the distance could be changed by only a factor of about 2 from the $\sim 25$ kpc estimate of Casares et al. (2009). Some additional flexibility can be derived by allowing the fraction of the optical light coming from the donor star to be a bit smaller than the 30–50 % range for different quiescent fluxes assumed by Casares et al. (2009), but given the detectability of ellipsoidal modulations from the source in the presence of other variability, and the detectability of the stellar absorption lines, the veiling of the donor star by accretion light cannot be too extreme. Similarly, the system could potentially bewind-fed, and underfilling its Roche lobe, but it could only underfill the Roche lobe by a small amount while still having a tidally locked donor star that produces ellipsoidal modulations.

The hypothesis of a large distance creates a different problem: a space velocity that is potentially above the escape velocity from the Galaxy despite the source’s location quite close to the Galactic Plane. This problem is likely to be solved in part by the covariance of $\varpi$ and $\mu$ (see section 6.3), and in part by simple random measurement uncertainties on the parameters. We plan to explore this source in more detail in a future paper, but at the present time, it seems most likely that BW Cir is located a few kpc away, toward the upper end of the distance range acceptable from the parallax estimate, with a large space velocity. In order to solve the problem, one will need to consider the priors not just from the space distribution of stars, but from the reasonable range of space velocities, and the need for the donor star to produce the observed ellipsoidal modulations and the observed rotational broadening of the stellar absorption lines and the need to produce the observed reddening and X-ray neutral hydrogen column absorption. We also suggest
Figure 2. The positions of the black hole binary sample projected onto the plane of the Milky Way. Yellow stars represent positions calculated using Gaia data and $r_{exp}$. Orange stars represent objects for which there were no parallaxes from Gaia and their positions taken from the literature. The numbers correspond to those assigned to the systems in Tables (1) and (2). BW Cir is marked in red due to potential caveats on its distance; see section 6.4 (Milky way image: NASA/JPL-Caltech, ESO, J. Hurt.).

that other high angular resolution measurements (e.g. with future radio facilities, or pushing current sub-mm facilities to deep limits) to corroborate or revise the DR2 parallax and motion should be carried out. Finally, we remind the reader that further data releases from Gaia will help in this regard.

6.5 MAXI J1820+070

MAXI J1820+070 is a new transient detected very recently with MAXI on March 11, 2018 (Kawamuro et al. 2018) following an optical brightening reported by the ASASSN survey (Denisenko et al. 2018). The system peak brightness lay amongst the brightest sources in the extra-Solar X-ray sky, and it has been observed by many observatories across the electromagnetic spectrum. The system is believed to host a black hole based upon a variety of properties and has remained in the hard state throughout the present outburst (e.g., Baglio et al. 2018, Uttley et al. 2018, Gandhi et al. 2018), making this an exceptionally bright hard state. Its optical position is reported to be consistent with a star which appeared in Gaia DR1 with nominal astrometric uncertainty of a few milliarcseconds, but its distance has not previously been determined.

The DR2 distance estimate is $\approx 3 \pm 1$ kpc, irrespective of the estimate used from Table (1) though with a potential tail out to $\approx 7$ kpc at somewhat higher distances. An X-ray flux of several Crab around peak (e.g. Bozzo et al. 2018) would then imply a hard state luminosity of $\sim 10\%$ of the Eddington luminosity.

MAXI J1820+070 illustrates the real power of Gaia, in that geometric distance estimates are now possible for newly discovered transients (with optical counterparts brighter than $G \approx 20.5$ or so), giving an incredibly useful first distance estimate in the absence of detailed spectroscopic follow-up.
Gaia distances to Black Hole Binaries

7 CONCLUSION

We have investigated Gaia DR2 distances for a sample of Galactic black hole transients (and Cyg X–1 included for comparison). We used simple parallax inversion as well as Bayesian estimates. While there is broad agreement between DR2 and previous distance estimates, care should be taken to investigate the full astrometric solution, including fit flags and correlations, before making final inferences.

The DR2 distance apparently disagrees strongly with previous estimates for BW Cir and we do not have a clear explanation for this at present. We advise that more work should be carried out before taking the DR2 result at face value in this case, and suggest a more likely plausible compromise distance of a few kpc.

Since Galactic X-ray transients typically lie in the faint regime for Gaia, the DR2 geometric distances are not necessarily more accurate than previous dedicated studies of individual sources. However, Gaia’s real utility will be in providing immediate estimates for new outbursting binaries in the future, as demonstrated by the case of MAXI J1820+070. Similarly, transverse velocities could be inferred for an even larger subset of sources for which proper motions (but not parallaxes) are inferred.

Since Gaia DR1 and DR2 are intermediate releases, the accuracy of parallaxes and proper motions is expected to improve as the mission matures. This database has the potential to significantly advance our understanding of the distribution, nature and origin of Galactic accreting binaries, but we suggest caution in naive interpretations of the parallax values.

8 ACKNOWLEDGMENTS

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. AR acknowledges a Commonwealth Rutherford Fellowship, JP is part supported by funding from a University of Southampton Central VC Scholarship. We thank J. Casares and P.A. Charles for a discussion on BW Cir, and all coauthors of the BlackCAT catalogue for a useful public resource. This research has made use of observational archival image, including HST/MAST, ESO, 2MASS, PanSTARRS1 and NASA/IRSA.
