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J. P. W. Verbiest

D. R. Lorimer

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# Why the distance of PSR J0218+4232 does not challenge pulsar emission theories

J. P. W. Verbiest[1,2⋆] and D. R. Lorimer[3,4]
[1] *Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany*
[2] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*
[3] *Department of Physics & Astronomy, West Virginia University, Morgantown, WV 26506, USA*
[4] *National Radio Astronomy Observatory, Green Bank, WV 24944, USA*



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**ABSTRACT**
Recent VLBI measurements of the astrometric parameters of the millisecond pulsar J0218+4232 by Du et al. have suggested this pulsar is as distant as 6.3 kpc. At such a large distance, the large $\gamma$-ray flux observed from this pulsar would make it the most luminous $\gamma$-ray pulsar known. This luminosity would exceed what can be explained by the outer gap and slot-gap pulsar emission models, potentially placing important and otherwise elusive constraints on the pulsar emission mechanism. We show that the VLBI parallax measurement is dominated by the Lutz-Kelker bias. When this bias is corrected for, the most likely distance for this pulsar is $3.15^{+0.85}_{-0.60}$ kpc. This revised distance places the luminosity of PSR J0218+4232 into a range where it does not challenge any of the standard theories of the pulsar emission mechanism.

**Key words:** pulsars:general – pulsars:individual (PSR J0218+4232) – astrometry

## 1 INTRODUCTION

The millisecond pulsar (MSP) J0218+4232 was discovered by Navarro et al. (1995) and immediately stood out as a particularly bright MSP with a relatively high dispersion measure (DM). This DM placed it at a distance of 5.7 kpc based on the Galactic electron density model used at the time (Taylor & Cordes 1993). Subsequently, Verbunt et al. (1996) detected the pulsar in both X-rays and $\gamma$-rays and showed that the luminosities at these high frequencies were very high, though not impossibly so. Furthermore, these authors commented that the derived $\gamma$-ray efficiency was 10% and could only be predicted by the outer gap model for pulsar emission, not by the polar cap model. This situation changed, however, with the advent of a new electron density model for the Galaxy (Cordes & Lazio 2002), which dramatically changed the derived distance down to 2.7 kpc, in close agreement with the distance range of 2.5 to 4 kpc derived from optical observations of the pulsar's white dwarf companion (Bassa et al. 2003). At this distance, the pulsar's luminosity in $\gamma$-rays is still high, but no longer extreme. As noted by Kramer et al. (2003), this large variability in distances derived from electron density models, implies that care must be taken in deriving consequences from $\gamma$-ray luminosities based on such distances, in particular for PSR J0218+4232.

The debate on the distance (and thereby $\gamma$-ray luminosity) of PSR J0218+4232 changed again, when Du et al. (2014) recently presented the first VLBI measurements of this pulsar's astrometric parameters. They determined a total proper motion of $6.53 \pm 0.08$ mas/yr and, more importantly, a parallax of $0.16 \pm 0.09$ mas, translated into a distance of $6.3^{+8.0}_{-2.3}$ kpc. These results are significant because they make PSR J0218+4232 by far the most luminous $\gamma$-ray pulsar. Furthermore, the VLBI distance and proper motion imply a transverse speed of $195^{+249}_{-71}$ km/s, which is also extreme for the class of MSPs. (Hobbs et al. 2005, derive an average transverse speed of $87 \pm 13$ km/s for this class of pulsar.)

In this paper, we demonstrate that the parallax value reported by Du et al. (2014) is dominated by the statistical Lutz-Kelker bias. We demonstrate that correction for this bias provides a distance that is more in line with the distance derived from the white-dwarf cooling models of Bassa et al. (2003) and with expected pulsar $\gamma$-ray fluxes and transverse velocities. Our analysis is given in Section 2, the implications for the pulsar velocity and $\gamma$-ray luminosity are detailed in Section 3 and our conclusions are summarised in Section 4.

⋆ E-mail: verbiest@physik.uni-bielefeld.de

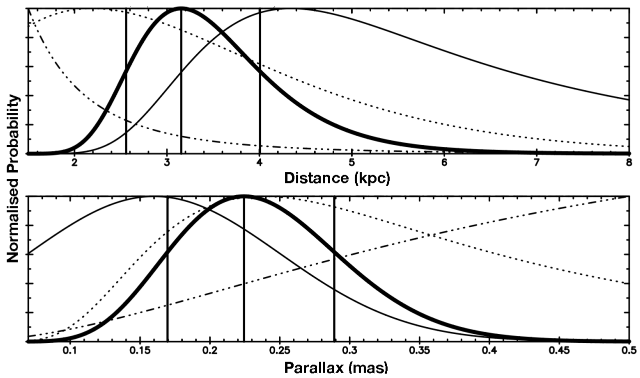


**Figure 1.** The probability distributions for the parallax and distance of PSR J0218+4232. The combined probability distribution is indicated by the thick line; the probability distribution derived from the VLBI parallax measurement is given by the thin, continuous line; the dotted line shows the probability distribution derived from the Galactic distribution of pulsars (the so-called "volumetric" probability); and the triple-dot-dashed line shows the probability distribution derived from the pulsar's published flux at 1.4 GHz. The most likely value and its 1-$\sigma$ uncertainties are indicated by the vertical lines.

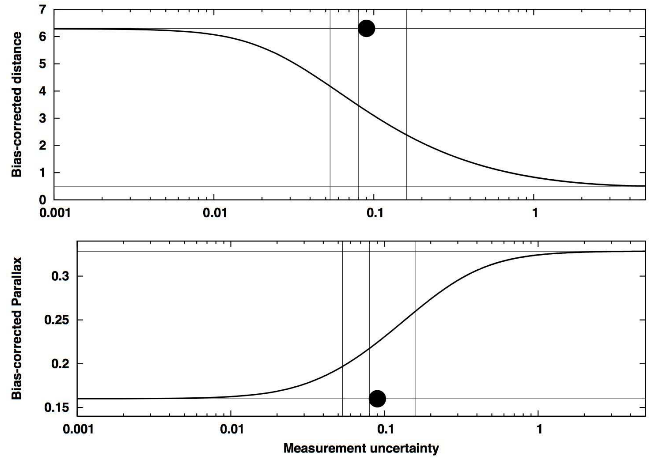


**Figure 2.** The strength of the bias as a function of the measurement uncertainty. For a parallax measurement of 0.16 mas, the thick line shows the bias-corrected distance (top) or parallax (bottom) as a function of the measurement uncertainty. The two horizontal lines are at the distance and parallax values proposed by Du et al. (2014) and as derived from our analysis. The vertical lines indicate 1, 2 and 3-$\sigma$ measurements (from right to left) and the recently published VLBI parallax measurement of Du et al. (2014) is shown by the black dot.

## 2 CORRECTING BIASES IN PARALLAX MEASUREMENTS

The most important statistical bias that affects pulsar parallax measurements with limited measurement precision, is the Lutz-Kelker bias (Lutz & Kelker 1973). Because of the non-linear scaling of volume with parallax, the error volume on the lower-parallax end is larger than on the higher parallax end, resulting in anomalously large parallax measurements. This effect was investigated by Verbiest et al. (2010), who found that parallax measurements with significance below 2-$\sigma$ are likely dominated by this bias.

Applying the bias-correction code of Verbiest et al. (2012), we find that the 1.8-$\sigma$ measurement of Du et al. (2014) is indeed dominated by the Lutz-Kelker bias. The bias-corrected parallax value (see Figure 1) is $0.22^{+0.07}_{-0.05}$ mas, corresponding to a distance of $3.15^{+0.85}_{-0.60}$ kpc[1]

With improved measurement precision, the impact of these biases will decrease, as shown in Figure 2. This indicates that, in order to reduce the effect of bias to within $0.5\,\sigma$, a parallax precision of better than 0.3 mas would be needed, requiring a factor three improvement in the published parallax value. This effort would be worthwhile, though our analysis suggests (as demonstrated in Verbiest et al. 2010), that it would be more likely that the measured parallax value would gradually increase as the measurement precision improved.

Figure 2 also demonstrates how this bias would worsen in case the Du et al. (2014) parallax uncertainty is underestimated. For example, if their measurement precision was underestimated even by only 33%, the bias-corrected distance would become as low as 2.7 kpc.

[1] Note that due to the non-linear character of the parallax-to-distance conversion, the most likely distance estimate is not the inverse of the most likely parallax value, unless in the absence of measurement uncertainties.

## 3 CONSEQUENCES OF THE BIAS-CORRECTED PARALLAX VALUE

Du et al. (2014) derive two significant results from their astrometric measurements. Firstly, they combine their proper motion and parallax measurements to derive a transverse speed for the pulsar of $195^{+249}_{-71}$ km/s. This value is well above the mean MSP transverse speed of $87 \pm 13$ km/s (Hobbs et al. 2005). Redetermining the transverse speed of PSR J0218+4232 with our bias-corrected parallax value, we obtain 98 km/s, which lies well within the scatter inherent to the population.

More importantly, the VLBI distance was used to determine the $\gamma$-ray luminosity of PSR J0218+4232. This resulted in $L_\gamma = 2.2 \times 10^{35}$ erg/s, which places it more than a factor of three above the next most luminous $\gamma$-ray MSP, implying a $\gamma$-ray efficiency in excess of 90%. Our bias-corrected distance of 3.15 kpc, however, results in a $\gamma$-ray luminosity of $5.4 \times 10^{34}$ erg/s, which lies well inside the range of $\gamma$-ray luminosities for MSPs and a $\gamma$-ray efficiency of 23%, also comparable to the population at large (Abdo et al. 2013).

## 4 CONCLUSIONS

We have quantified and corrected biases present in the recent VLBI parallax to PSR J0218+4232. Our results are collated in Table 1 and are as follows. For the parallax we obtain a most-likely value of $0.22^{+0.07}_{-0.05}$ mas and for the distance $3.15^{+0.85}_{-0.60}$ kpc. We have demonstrated that these bias-corrected values result in a transverse velocity of 98 km/s, which is comparable to values obtained for the rest of the MSP population; and in a $\gamma$-ray luminosity of $5.4 \times 10^{34}$ erg/s, also in line with values obtained for other MSPs. The $\gamma$-ray emission of this pulsar, therefore, does not

**Table 1.** Summary of results. Shown are the parallax and distance from the Du et al. (2014) VLBI measurements (1), from our standard bias-correction code described in Verbiest et al. (2012) (2) and from the volumetric and luminosity information alone (i.e. the prior information excluding the parallax measurement; 3).

| Method | Parallax (mas) | Distance (kpc) |
|---|---|---|
| (1) VLBI | $0.16 \pm 0.09$ | $6.3^{+8.0}_{-2.3}$ |
| (2) Bias-corrected | $0.22^{+0.07}_{-0.05}$ | $3.15^{+0.85}_{-0.60}$ |
| (3) vol. & lum. priors | $0.3^{+0.3}_{-0.1}$ | $0.5^{+0.8}_{-0.3}$ |

challenge the outer gap or slot-gap models for pulsar emission, as claimed by Du et al. (2014).

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