EXTREMELY HIGH PRECISION VLBI ASTROMETRY OF PSR J0437–4715 AND IMPLICATIONS FOR THEORIES OF GRAVITY

A. T. DELLER,1,2 J. P. W. VERBIEST,1,2 S. J. TINGAY,3 AND M. BAILES1

Received 2008 July 8; accepted 2008 August 12; published 2008 August 26

ABSTRACT

Using the recently upgraded Long Baseline Array, we have measured the trigonometric parallax of PSR J0437–4715 to better than 1% precision, the most precise pulsar distance determination made to date. Comparing this VLBI distance measurement to the kinematic distance obtained from pulsar timing, which is calculated from the pulsar’s proper motion and apparent rate of change of orbital period, gives a precise limit on the unmodeled relative acceleration between the solar system and PSR J0437–4715, which can be used in a variety of applications. First, it shows that Newton’s gravitational constant $G$ is stable with time ($\dot{G}/G = (-5 \pm 26) \times 10^{-13}$ yr$^{-1}$, 95% confidence). Second, if a stochastic gravitational wave background existed at the currently quoted limit, this null result would fail ~50% of the time. Third, it excludes Jupiter-mass planets within 226 AU of the Sun in 50% of the sky (95% confidence). Finally, the ~1% agreement of the parallax and orbital period derivative distances provides a fundamental confirmation of the parallax distance method on which all astronomical distances are based.

Subject headings: astrometry — gravitation — pulsars: individual (PSR J0437–4715)

1. INTRODUCTION

PSR J0437–4715 has been observed intensively since its discovery by Johnston et al. (1993). It is the brightest and nearest observed millisecond pulsar, and has also been studied in the optical (Bell et al. 1993), ultraviolet (Kargaltsev et al. 2004), and X-ray (Zavlin et al. 2002) bands. The high rotational stability and close proximity of this pulsar–white dwarf binary system make it an excellent probe of general relativity (GR) and alternative forms of gravitational theories. The measurement of its Shapiro delay by van Straten et al. (2001), where the radio waves from the pulsar are delayed as they pass through the gravitational potential of the companion, is one such test which has shown consistency with GR predictions. The search for the low-frequency stochastic gravitational wave background (GWB) using pulsar timing arrays (e.g., Jenet et al. 2005) is another test of GR which is facilitated in part by timing of J0437–4715.

Although variation of Newton’s gravitational constant $G$ with time is forbidden in GR, this is not required in alternate formalisms of gravity (e.g., Brans & Dicke 1961). Verbiest et al. (2008) have measured the rate of change of orbital period $\dot{P}_b$ in the J0437–4715 system to better than 2% precision and shown that the agreement of the derived kinematic distance with the parallax distance derived from timing limits the time variation of $G$ to less than 3 parts in $10^{11}$. In this Letter, we present a new very long baseline interferometry (VLBI) determination of the position, proper motion, and parallax of PSR J0437–4715 and show that this improves the previously published $G$ limit derived from this system by an order of magnitude, approaching the best published limit [$\dot{G}/G = (4 \pm 9) \times 10^{-13}$ yr$^{-1}$], which is derived from laser lunar ranging (LLR; Williams et al. 2004). Our VLBI observations and results are presented in §§ 2 and 3, respectively, and the limitations on apparent accelerations (due to $G$ or other possible causes such as unseen massive planets) are derived in § 4. In § 5 we investigate the impact of the stochastic GWB on our results and derive an independent limit on the GWB amplitude. We summarize our conclusions in § 6.

2. VLBI OBSERVATIONS

Details of the observational, correlation, and post-processing strategies used are covered in detail in Deller et al. (2008) and only a brief summary is presented here. Four observational epochs (MJD 53868, 54055, 54181, 54416) spanned 1.5 yr, with each epoch lasting 12 hr and utilizing all available antennas from the Australian Long Baseline Array (LBA). These were the three ATNF antennas (ATCA, Parkes, Mopra), the two University of Tasmania antennas (Hobart and Ceduna) and, when available, one of the NASA Deep Space Network (DSN) antennas at the Tidbinbilla station. Observations were made at 8.4 GHz, and four 16 MHz bands were used, quantized at two-bit precision to give a total data rate of 256 Mbps.

Phase referencing was conducted using the International Celestial Reference Frame (ICRF) source J0439–4522, a bright (several hundred mJy flux at 8 GHz) and compact radio source less than 2" from PSR J0437–4715, whose position is known to 1 mas (Ma et al. 1998). A 6 minute target/calibrator cycle was employed, with observing time divided equally between the target and calibrator. The well-studied blazar PKS 0537–441 was used for bandpass calibration.

The data were correlated, using matched filtering (gating) on pulse profiles, with the DiFX software correlator (Deller et al. 2007). Due to the extremely narrow pulse profile of PSR J0437–4715 at 8.4 GHz, this gating improves the output signal-to-noise ratio (S/N) by a factor of 7 compared to un gated data. The pulsar ephemeris used to set gates was taken from Hotan et al. (2006).

Due to the relatively high frequency used for these observations, several of the calibration steps described in Deller et al. (2008) proved unnecessary. Data reduction was performed with and without GPS-based ionospheric correction, and the

1 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H39, P.O. Box 218, Hawthorn, VIC 3122, Australia.
2 Cosupervised through the Australia Telescope National Facility, P.O. Box 76, Epping, NSW 1710, Australia.
3 Department of Imaging and Applied Physics, Curtin University of Technology, Bentley, WA, Australia.

DSS43 (70 m) participated on MJD 54055 and 54181, while DSS34 (34 m) was used on MJD 54416.
small (∼100 µas) corrections which resulted from ionospheric correction gave a poorer parallax fit overall, with double the estimated systematic errors. Given the uncertainty of GPS-based corrections at these southern latitudes, the ionospheric corrections were not applied. In addition, the effect of scintillation was negligible at these higher frequencies, so the scintillation correction detailed in Deller et al. (2008) was not applied.

Attaining single-epoch accuracies of ∼100 µas, as shown in § 3, required postcorrelation corrections to the visibilities due to the proper motion of the pulsar (∼200 µas in each 12 hr observation). In addition, the orbital motion of PSR J0437−4715 causes a peak-to-peak displacement of ∼110 µas. Compensation for this displacement in the single-epoch positions improved the quality of the proper motion and parallax fit, reducing the estimated systematic error contribution by 3%.

3. ASTROMETRIC RESULTS

As discussed in Deller et al. (2008) the optimal weighting for visibility points when imaging the pulsar to fit for position depends on the ratio of thermal noise to residual systematic errors. For strong targets systematic errors dominate the error budget, meaning the use of equally weighted visibilities (as opposed to weighting visibilities by baseline sensitivity) produces superior results. For PSR J0437−4715 the S/N of a typical single-band, single-epoch detection was ∼20, well above the threshold of ∼10 identified in Deller et al. (2008) and thus we would expect equally weighted visibilities to produce superior results. To confirm this, the parallax was determined from two separate data sets, which were produced using sensitivity-weighted and equally weighted visibilities. As expected, the equally weighted data set produced a better fit, with smaller errors on fitted parameters and smaller estimated systematic error contributions.

The data were fitted using an iterative approach designed to estimate and account for systematic errors, described in Deller et al. (2008). The resulting parameter values are shown in Table 1 along with the Verbiest et al. (2008) timing measurements; the VLBI fits to pulsar motion and observed positions are shown in Figure 1. All errors are 1σ unless otherwise stated, and include the covariances between fitted parameters. Over this short timespan, the covariance between parallax and proper motion is significant, and constitutes approximately half of the quoted parallax uncertainty. The average total single-epoch error of 132 µas is the best relative astrometry performed by the LBA to date, and is similar to other recent VLBI astrometric results (e.g., Loinard et al. 2007). By way of comparison, the limiting accuracy for EVN observations at 8.4 GHz has been simulated by Pradel et al. (2006) to be 83 µas with a 1° calibrator-target separation, at a declination of 50°. The EVN has similar sensitivity to the LBA, but somewhat better u-v coverage and longer baselines.

Our derived distance of 156.3 ± 1.3 pc is the most accurate distance measurement (in both absolute and fractional distance) for a pulsar to date and approaches the most accurate distance measurements made of objects outside the solar system (T Tauri, 147.6 ± 0.6 pc: Loinard et al. 2007). Previously, the highest precision VLBI pulsar distance determinations were those made by Brisken et al. (2002) who measured the distance of PSR J0953+0755 to an accuracy of 5 pc, along with eight other northern hemisphere pulsars. The two previous parallax measurements made using a southern array, of PSR J0835−4510 (Dodson et al. 2003) and PSR J1456−6843 (Bai- les et al. 1990), had 1σ distance errors of 19 and 70 pc, respectively.

3.1. Comparison to Timing Astrometry

To compare the VLBI and timing positions, we have refitted the timing data of Verbiest et al. (2008) to obtain the position of PSR J0437−4715 at our reference epoch (MJD 54100). Table 1 shows that the timing and VLBI positions at MJD 54100 differ by over two mas, many times the formal errors shown. However, the formal errors are negligible compared to the 1 mas uncertainty in the VLBI phase reference calibrator position and the potential constant offsets due to phase-referencing errors such as station position errors (known to exist at the cm level for the LBA; Deller et al. 2008). Discrepancies between interferometric and timing positions of even larger magnitudes have been found using the DE200 frame (Bartel et al. 1996), and differences at the mas level still exist for the position PSR J0437−4715 calculated using the newer DE414 solar system ephemeris, as compared to the DE405 ephemeris used by Verbiest et al. (2008). Thus, we conclude that the VLBI and timing position difference is consistent with the uncertainty in the calibrator position and the offset between the solar system frame and the ICRF.

The values obtained for the VLBI proper motion differ by

---

5 The timing positions of Verbiest et al. (2008) have been refitted at the VLBI reference epoch of MJD 54100.

---

**TABLE 1**

**Fitted VLBI Results for PSR J0437−4715 and Comparative Timing Values**

| Parameter Fitted Value and Error | Verbiest et al. (2008) Timing Values |
|---------------------------------|------------------------------------|
| Right ascension (J2000.0)        | 04:37:15.883250 ± 0.000003          |
| Declination (J2000.0)            | −47:15:09.031863 ± 0.000037         |
| μa (mas yr⁻¹)                   | 121.679 ± 0.052                    |
| μb (mas yr⁻¹)                   | −71.820 ± 0.086                    |
| Parallax π (mas)                | 6.396 ± 0.054                      |
| Distance (pc)                   | 156.3 ± 1.3                        |
| Transverse velocity u (km s⁻¹)  | 104.71 ± 0.95                      |
| Reduced χ²                      | 1.0                                |
| Average epoch mean fit error (mas) | 0.059                            |
| Average intra-epoch systematic error (mas) | 0.068                          |
| Average inter-epoch systematic error (mas) | 0.103                          |
| Reference epoch for proper motion (MJD) | 54100.0                           |

* Derived from the kinematic distance obtained from P, not the less precise parallax values.
Fig. 1.—Motion of PSR J0437–4715, with measured positions overlaid on the best fit. Clockwise from top left: Motion in declination vs. right ascension; as before but with proper motion subtracted; right ascension vs. time with proper motion subtracted; and declination vs. time with proper motion subtracted.

∼4σ in both right ascension and declination from the timing values. A likely cause for this discrepancy is small changes in the centroid position of the phase reference source due to intrinsic source variability, which would be absorbed into the proper motion fit. The phase reference source, which is modeled by a ∼1 mas FWHM Gaussian with additional delta components within 5 mas of strength 2% and 0.2% of peak flux, shows no gross evidence of variability (width/positions of primary/secondary components constant to ∼200 μas, and secondary fluxes are constant to ∼1 mJy), but as it is only barely resolved (the beam size is ∼3 mas) variability at the ∼100 μas level would be difficult to detect. Titov (2007) show that some ICRF sources exhibit apparent proper motions of hundreds of μas yr⁻¹ for periods of several years, and while a detailed VLBI history of this source is not available, calibrator measurements from ATCA show that the flux density has declined by a factor of 3 over a 5 yr period, implying some variability. The higher proper motion precision obtained with the timing data (a factor of 5–7 times better than the VLBI results) reflects the fact that the timing data spans a time baseline 7 times longer than the VLBI data set.

The parallax value obtained from VLBI is consistent with that derived from timing, and yields a distance which is consistent with the kinematic distance of 157.0 ± 2.4 pc derived from the orbital period derivative \( P_\nu \). However, the VLBI parallax measurement is an order of magnitude more precise than the timing measurement, and yields a distance which is a factor of 2 more precise than the kinematic distance.

### 4. LIMITS ON ANOMALOUS ACCELERATIONS

The newly measured parallax of \( \pi = 6.396 ± 0.054 \) mas allows an improved measurement of any anomalous acceleration of either the solar system or PSR J0437–4715. Specifically, the apparent acceleration due to time variability of Newton’s gravitational constant \( G \) and the mass of an undetected trans-Neptunian planet near the line of sight to the pulsar can be limited.

#### 4.1. Constraints on \( \dot{G} \)

As first described by Damour & Taylor (1991) a precise measurement of a binary pulsar’s orbital period derivative, \( P_\nu \), can be used to constrain a variation of the gravitational constant, \( G \). However, as Bell & Bailes (1996) pointed out, for PSR J0437–4715 a precise distance needs to be known in order to correct \( P_\nu \) for the Shklovskii acceleration caused by its proper motion (Shklovskii 1970). This analysis has been performed, based exclusively on timing data, by Verbist et al. (2008), whose limit was dominated by the uncertainty in their parallax measurement. Our VLBI parallax value, however, improves this limit by a factor of nearly 10 down to \( \dot{G}/G = (-5 ± 26) \times 10^{-11} \) yr⁻¹ at 95% certainty. This value compares...
well to the most stringent limit currently published: \((4 \pm 9) \times 10^{-13}\) yr\(^{-1}\), derived through lunar laser ranging (Williams et al. 2004). Since \(\pi\) and \(P_0\) are now both measured to similar precision, both measurements will have to be improved for a further significant increase in \(\dot{G}\) sensitivity. Additional VLBI observations and continued timing could see this limit improve on the existing LLR limit early in the next decade.

### 4.2. Acceleration due to Massive Bodies

An alternative source of anomalous acceleration is heavy planets in a wide orbit around the Sun or the pulsar. Building on the initial analysis of Zakamska & Tremaine (2005) our parallax measurement can be combined with the timing results from Verbiest et al. (2008) to derive the following result: \(a_{\odot}/c = (3 \pm 16) \times 10^{-20}\) s\(^{-1}\) at the 2 \(\sigma\) level. This improves the limit published in Verbiest et al. (2008) by an order of magnitude and makes PSR J0437–4715 a more sensitive solar system accelerometer than PSR J1713+0747, the most precise pulsar listed by Zakamska & Tremaine (2005). From this, the limit for \(50\%\) of the sky\(^6\) can be calculated as \([a_{\odot,0.04\mu}\,/c] \leq 3.9 \times 10^{-19}\) s\(^{-1}\) (95\% certainty). This acceleration limit can be used to exclude massive bodies within a given radius of the Sun; for example, at Kuiper Belt radii (50 AU) it excludes a planet more massive than Uranus over \(50\%\) of the sky, while Jupiter-mass planets are excluded within 226 AU over \(50\%\) of the sky.

### 5. IMPACT OF THE STOCHASTIC GWB

Using tools recently developed by Hobbs et al. (2008) we have simulated the effect of a GWB with spectral index \(-2/3\) (as predicted for GWBs caused by black hole–black hole mergers) and dimensionless amplitude \(1.1 \times 10^{-14}\) (the best published GWB limit; Jenet et al. 2006) on the observed value of \(P_0\) from pulsar timing. The simulated GWB causes the kinematic distance to be inconsistent with the VLBI parallax distance at the 2 \(\sigma\) level in \(\sim 50\%\) of trials. Thus, although these observations cannot improve on the present GWB limit, they are consistent with it. Simulations with a GWB with amplitude of \(1.1 \times 10^{-15}\) show inconsistencies between the kinematic and VLBI distances at the 2 \(\sigma\) level in \(95\%\) of trials, providing an independent exclusion of a GWB with an amplitude at or above this value.

It is also interesting to note that the precise limit on \(\dot{G}\) presented in § 4.1 would be impossible in a universe with a strong GWB. In the simulations with GWB amplitude \(1.1 \times 10^{-15}\), the observed \(\dot{G}\) value is inconsistent with 0 in \(99\%\) of cases, merely due to the GWB-induced corruption of the timing measurements. Thus, the stochastic GWB must eventually limit the accuracy of measurements of \(\dot{G}\) in the fashion outlined in this Letter.

### 6. CONCLUSIONS

We have observed PSR J0437–4715 using the LBA and obtained the most precise pulsar distance determination to date, with an error <1.5 pc. Combined with accurate timing data, this has enabled us to confirm that \(|\dot{G}/G| < 3.1 \times 10^{-12}\) yr\(^{-1}\), the most stringent limit not obtained through solar system tests. Alternatively, assuming an unchanging gravitational force, the results can be interpreted as excluding any unseen Jupiter-mass planets within 226 AU of the Sun in \(50\%\) of the sky. Finally, the agreement between VLBI and timing results in this single case implies an upper limit to the stochastic GWB amplitude which is within an order of magnitude of the best limit derived from observations of ensembles of pulsars.

This work has been supported by the Australian Federal Government’s Major National Research Facilities program. A. T. D. is supported via a Swinburne University of Technology Chancellor’s Research Scholarship and a CSIRO postgraduate scholarship. The Long Baseline Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

### REFERENCES

Bailes, M., Manchester, R. N., Kesteven, M. J., Norris, R. P., & Reynolds, J. E. 1990, Nature, 343, 240
Bartel, N., Chandler, J. F., Ratner, M. I., Shapiro, I. L., Pan, R., & Cappallo, R. J. 1996, AJ, 112, 1690
Bell, J. F., & Bailes, M. 1996, ApJ, 456, L33
Bell, J. F., Bailes, M., & Bessell, M. S. 1993, Nature, 364, 603
Brans, C., & Dicke, R. H. 1961, Phys. Rev., 124, 925
Briska, W. F., Benson, J. M., Goss, W. M., & Thorsett, S. E. 2002, ApJ, 571, 906
Damour, T., & Taylor, J. H. 1991, ApJ, 366, 501
Deller, A. T., Tingay, S. J., Bailes, M., & Bell, J. F. 2007, PASP, 119, 318
Deller, A. T., Tingay, S. J., & Briska, W. F. 2008, ApJ, submitted (arXiv: 0808.1598)
Dodson, R., Legge, D., Reynolds, J. E., & McCulloch, P. M. 2003, ApJ, 596, 1137
Hobbs, G. B., et al. 2008, MNRAS, submitted
Hotan, A. W., Bailes, M., &Ord, S. M. 2006, MNRAS, 369, 1502

Jenet, F. A., Hobbs, G. B., Lee, K. J., & Manchester, R. N. 2005, ApJ, 625, L123
Jenet, F. A., et al. 2006, ApJ, 653, 1571
Johnston, S., et al. 1993, Nature, 361, 613
Kargaltsev, O., Pavlov, G. G., & Romani, R. W. 2004, ApJ, 602, 327
Loinard, L., et al. 2007, ApJ, 671, 546
Ma, C., et al. 1998, AJ, 116, 516
Pradel, N., Charlot, P., & Lestrade, J.-F. 2006, A&A, 452, 1099
Shklovskii, I. S. 1970, Soviet Astron., 13, 562
Titov, O. A. 2007, Astron. Lett., 33, 481
van Straten, W., Bailes, M., Britton, M., Kulkarni, S. R., Anderson, S. B., Manchester, R. N., & Sarkissian, J. 2001, Nature, 412, 158
Verbiest, J. P. W., et al. 2008, ApJ, 679, 675
Williams, J. G., Tsyganov, G. G., & Boggs, D. H. 2004, Phys. Rev. Lett., 93, 261101
Zakamska, N. L., & Tremaine, S. 2005, AJ, 130, 1939
Zavlin, V. E., Pavlov, G. G., Sanwal, D., Manchester, R. N., Trümper, J., Halpern, J. P., & Becker, W. 2002, ApJ, 569, 894