# THE GEOMETRIC DISTANCE AND BINARY ORBIT OF PSR B1259−63

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## Summary

**Context**

The pulsar/massive star binary system PSR B1259−63/ LS 2883 is one of the best-studied gamma-ray binaries, a class of systems whose bright gamma-ray flaring can provide important insights into high-energy physics. High-energy GeV and TeV flaring is detected from the system at each periastron passage of the wide, eccentric orbit ($P_{\rm orb} = 1236.9$ days, $e = 0.87$). Although most of the orbital elements of the system are accurately measured with pulsar timing, several key parameters remained unconstrained, such as the inclination of the orbit and its orientation or the distance to the system.

**Analysis**

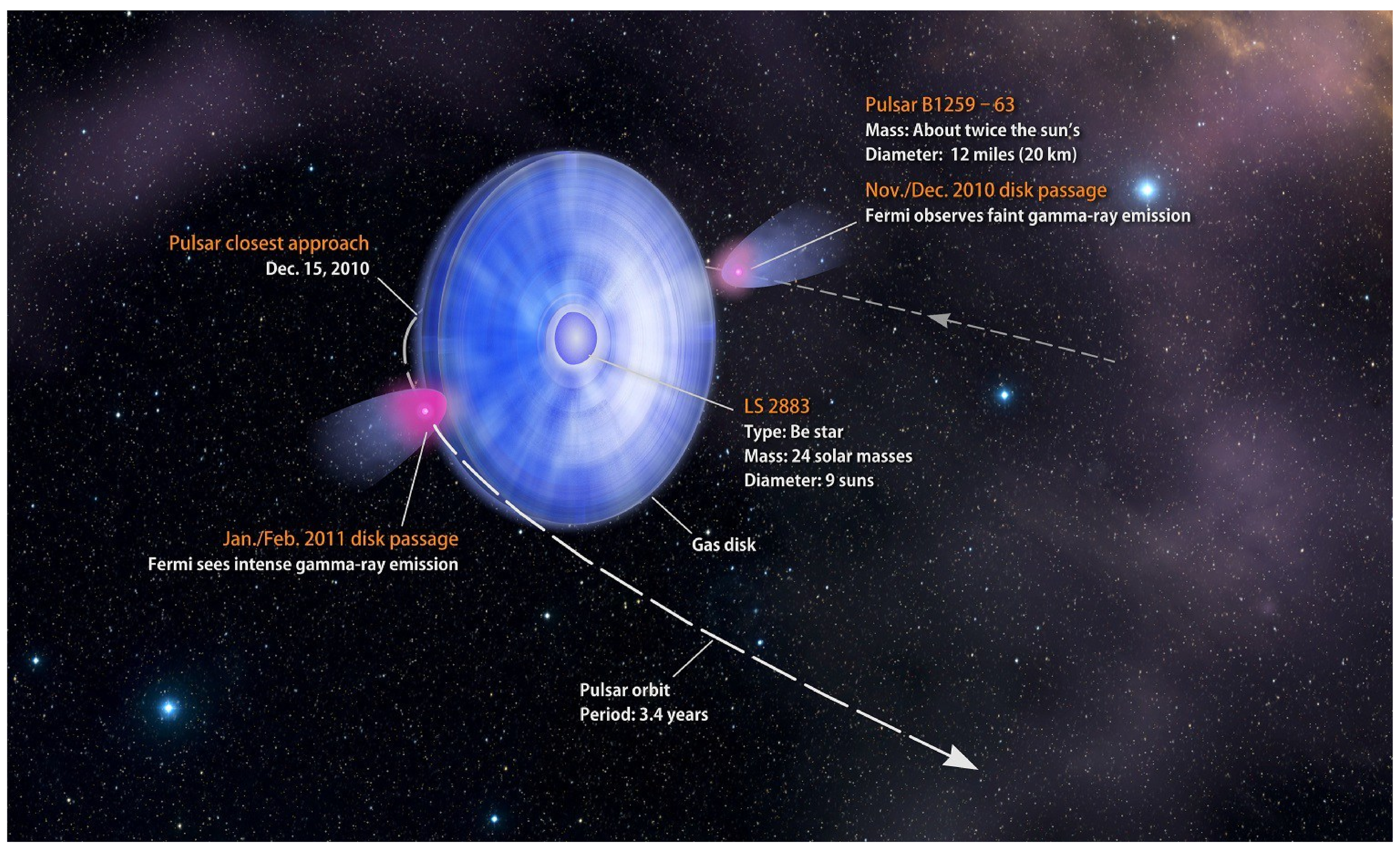
Using the Australian Long Baseline Array we have conducted VLBI observations of PSR B1259−63 over 4.4 years to characterize the pulsar motion around the massive star. From our measured parallax of $0.38 \pm 0.05$ mas we use a Bayesian approach to infer a distance of $2.6^{+0.4}_{-0.3}$ kpc. We find that the binary orbit is viewed at an angle of $154 \pm 3°$ to the line of sight, implying that the pulsar moves clockwise around its orbit as viewed on the sky. Taking our findings together with previous results from pulsar timing observations, all seven orbital elements for the system are now fully determined.

**Conclusions**

We use our measurement of the inclination angle to constrain the mass of the stellar companion to lie in the range 15–31$M_\odot$. Our measured distance and proper motion are consistent with the system having originated in the Cen OB1 association and receiving a modest natal kick, causing it to have moved $\sim 8$ pc from its birthplace over the past $\sim 3\times10^5$ years. The orientation of the orbit on the plane of the sky matches the direction of motion of the X-ray synchrotron-emitting knot observed by the *Chandra X-ray Observatory* to be moving away from the system.

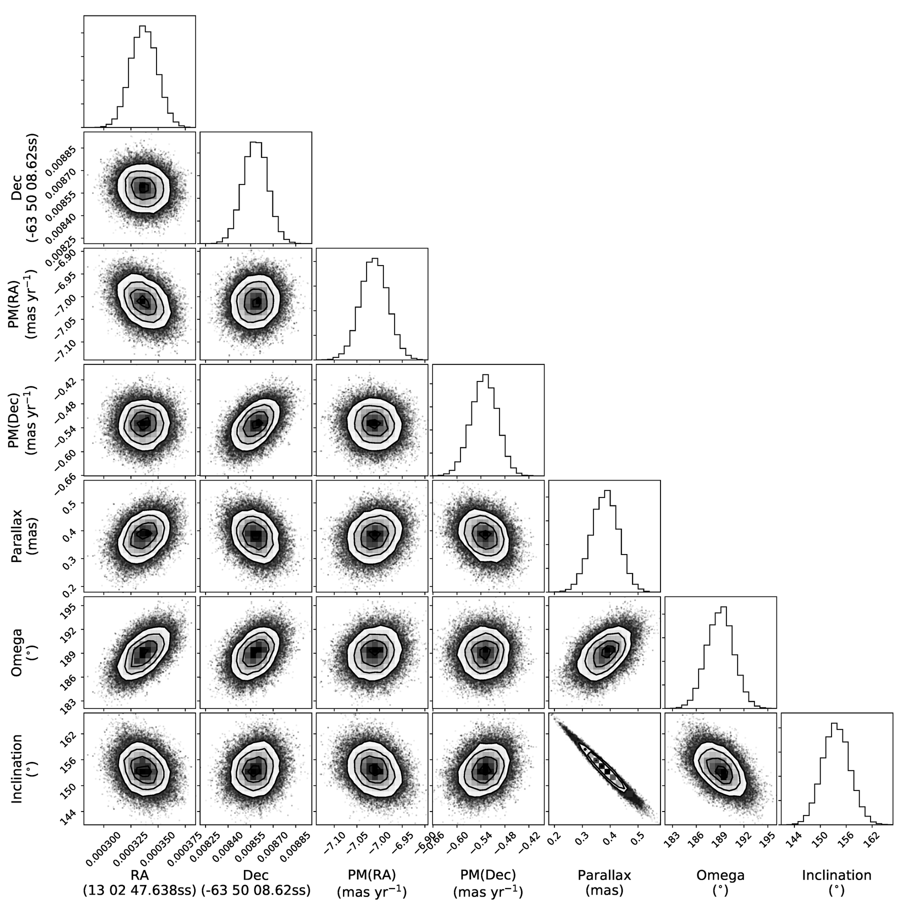
## The gamma-ray binary PSR B1259−63/ LS 2883

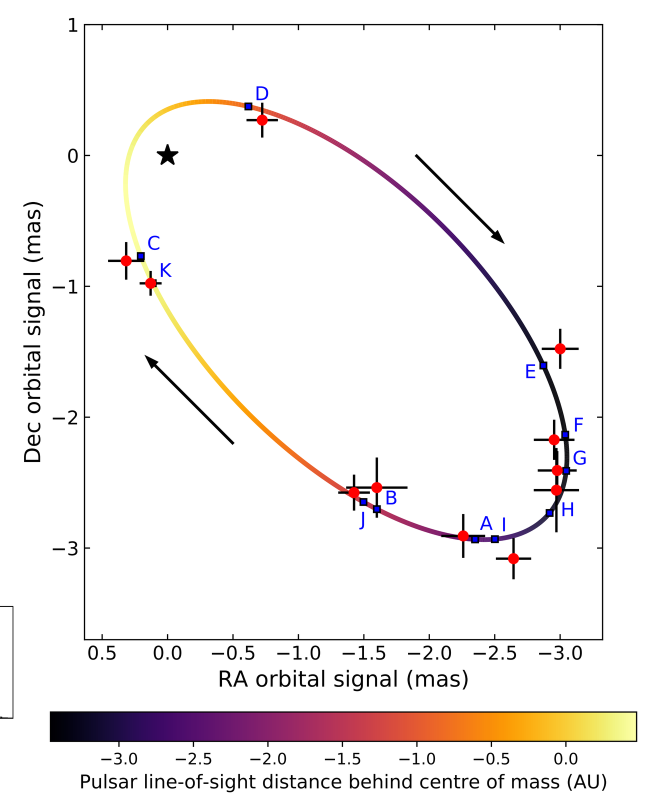
Gamma-ray binaries are systems comprised of a massive star in orbit with a compact object, whose broadband, non-thermal energy output peaks in the MeV–GeV band, with the emission typically being modulated on the orbital timescale. High-energy GeV and TeV flaring is detected from the PSR B1259−63 system every orbit around periastron passage as the pulsar passes through, and possibly disrupts, the circumstellar disk of its O9.5Ve companion star. The gamma-ray production mechanism has been suggested to be inverse Compton upscattering of stellar photons by relativistic electrons, either in the shocked region where the pulsar wind interacts with the stellar wind from the massive companion, or in the unshocked pulsar wind. Such inverse Compton emission depends on the scattering angle between the electrons and the stellar photons, and would thus be subject to relativistic aberration and boosting. Alternatively, it has been proposed that the GeV flares could be attributed to Doppler-boosted synchrotron emission in the bow-shock tail formed as the shocked pulsar wind is collimated by the stellar wind. Regardless of the exact mechanism, the observed emission will depend on the orbital parameters of the system, in particular the inclination to the line of sight.




## Bayesian fit to the orbital elements

We solved for the seven astrometric parameters; reference position ($\alpha_0$, $\delta_0$), proper motion ($\mu_\alpha \cos\delta$, $\mu_\delta$), parallax $\pi$, longitude of the ascending node $\Omega$, and the inclination angle of the orbit to the line of sight $i$. We used a Markov-Chain Monte Carlo (MCMC) algorithm. Left figure shows the covariances of the fitted parameters. All parameters are well constrained, although there is a degeneracy between inclination angle and parallax. Right figure shows the observed orbital motion of PSR B1259−63, after subtracting off the best-fitting proper motion and parallax signatures. The pulsar moves clockwise around its orbit, as shown by the arrows.

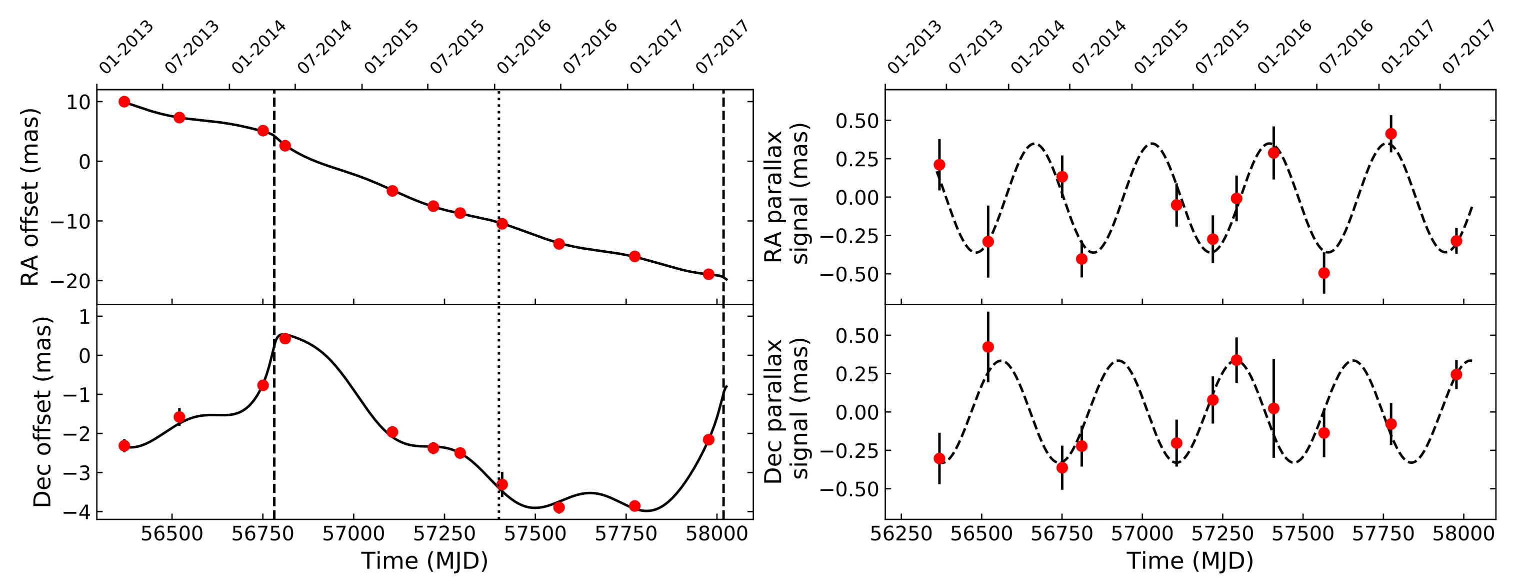



## Observations and parallax signature

Using the LBA, we made eleven observations of PSR B1259−63 over a 4.4-year period. The trajectory of the pulsar on the sky is made up of the proper motion, parallax and orbital signatures, all of which we aimed to sample during our astrometric campaign. We used the DiFX software correlator to provide a pulsar binned dataset with four pulse phase-resolved bins to represent the full pulse profile. Pulsar binning enhances the pulsed emission while allows us to separate pulsed from unpulsed emission.

Left figure shows the motion of PSR B1259−63 on the sky over time, in both R.A. (top) and Dec. (bottom). The black line shows our best fitting astrometric solution. The dashed and dotted vertical lines show the epochs of periastron and apastron, respectively. Right figure: the best-fitting proper motion and orbital signatures have been subtracted to better see the annual parallax signature.




Results of the MCMC fitting to our LBA astrometric data. The fitted parallax of $0.38 \pm 0.05$ mas corresponds to a distance of $2.6^{+0.4}_{-0.3}$ kpc. The five orbital elements derived from long-term pulsar timing (which were held fixed at their best-fitting values from Shannon et al. 2014) are listed in the second section of the table.

| Parameter | Symbol | Value |
|---|---|---|
| Reference position in R.A. (J2000) | $\alpha_0$ | $13^{\rm h}02^{\rm m}47\overset{s}{.}638337 \pm 0.000012$ |
| Reference position in Dec. (J2000) | $\delta_0$ | $-63°50'8.62859'' \pm 0.00008$ |
| Proper motion in R.A. (mas yr$^{-1}$) | $\mu_\alpha \cos\delta$ | $-7.01 \pm 0.03$ |
| Proper motion in Dec. (mas yr$^{-1}$) | $\mu_\delta$ | $-0.53 \pm 0.03$ |
| Parallax (mas) | $\pi$ | $0.38 \pm 0.05$ |
| Inclination angle (°) | $i$ | $154 \pm 3$ |
| Longitude of the ascending node (° CCW from N through E) | $\Omega$ | $189 \pm 2$ |
| Orbital period (days) | $P$ | $1236.724526 \pm 0.000006$ |
| Epoch of periastron (MJD) | $T_0$ | $53071.2447290 \pm 0.0000007$ |
| Eccentricity | $e$ | $0.86987970 \pm 0.00000006$ |
| Projected semi-major axis (lt-s) | $a \sin i$ | $1296.27448 \pm 0.00014$ |
| Argument of periastron | $\omega$ | $138\overset{\circ}{.}665013 \pm 0\overset{\circ}{.}000011$ |

## Conclusions

- We derived the first model-independent measurement of the distance to the system of $2.6^{+0.4}_{-0.3}$ kpc, slightly larger than previous estimates.
- The inclination angle of the binary orbit of $154 \pm 3°$ implies a companion mass of 15–31 $M_\odot$.
- The pulsar rotates clockwise around its orbit, and the orientation of that orbit on the plane of the sky is consistent with the extended X-ray emission moving away in the direction of apastron.
- Our proper motion implies a space velocity of $34 \pm 13$ km s$^{-1}$ relative to Cen OB1, and is consistent with the system having been formed in that association and receiving a natal kick on the formation of the neutron star.
- The increase in the derived distance further increases the inferred gamma-ray luminosity, so these results appear to favour gamma-ray production mechanisms involving Doppler boosting.

## Publication

- The geometric distance and binary orbit of PSR B1259-63
  Miller-Jones et al. (2018), MNRAS, 479, 4849
  `http://adsabs.harvard.edu/abs/2018MNRAS.479.4849M`
- MCMC astrometryfit: `https://github.com/adamdeller/astrometryfit`