Untangling the spider's web: determining the masses of pulsars in binary systems

M. R. Kennedy, R. P. Breton, C. J. Clark, D. Mata-Sanchez, J. Stringer, G. Voisin
Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, The University of Manchester, Manchester M19 9PL, UK
Email: kennedy.mark@manchester.ac.uk

European Research Council
Established by the European Commission

MANCHESTER 1824
The University of Manchester

Abstract

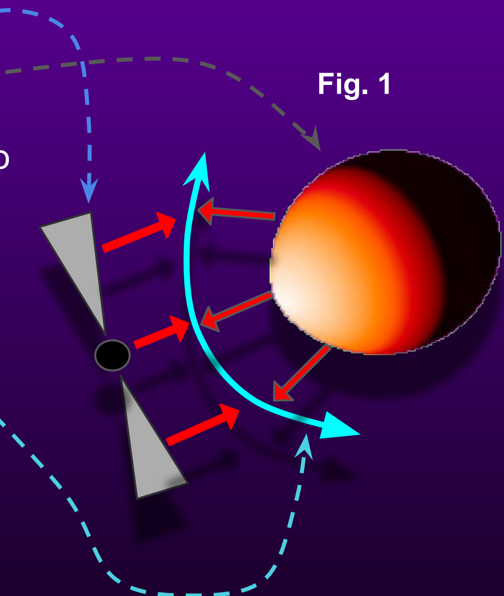
One of the most important challenges in modern astrophysics is to determine the equation of state for neutron stars. An obvious method of narrowing which equations may be valid is by looking for exceptionally heavy neutron stars (> 2 $M_\odot$). For this purpose, the redback and black widow "spider" systems have become increasingly important in recent years, as recent results suggest they contain heavier neutron stars than their other neutron star binary cousins. However, these mass measurements are plagued by observational and methodological biases.

Spiders

A "spider" binary is a system which hosts a millisecond pulsar primary that is ablating its nearby companion star. This behaviour of destroying their companions is what gives rise to the "redback" and "black widows" monikers (Roberts, M., 2011).

At radio and γ-ray frequencies, the pulsar dominates. An intra-binary shock forms where the pulsars and the companions winds meet, and emits at X-ray wavelengths. The companion star is responsible for the majority of the optical light.

Fig. 1



Measuring the masses (M_1 and M_2) requires solving equations 1 and 2. For this, the orbital period of the system (P_o), the projected radial velocities of both the pulsar (K_1) and companion star (K_2), and the systems inclination (i) must be measured. These parameters require a multi-wavelength approach.

Mass Measurements

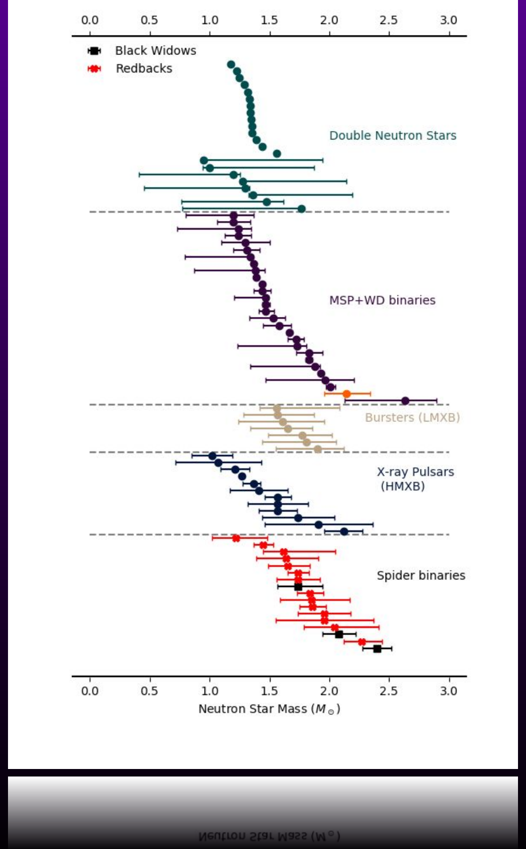
$$q = \frac{M_2}{M_1} = \frac{K_1}{K_2} \quad (1)$$

$$\frac{M_1 \sin^3 i}{(1+q)^2} = \frac{P_o K_2^3}{2\pi G} \quad (2)$$

P_o and K_1 can be obtained from radio timing of the pulsar. K_2 can be obtained from optical spectroscopy of the secondary. i can be measured using optical light curves and binary modelling software.

Fig 2 shows neutron star masses measured for a variety of systems, and shows that spider binaries seem to have a higher median mass, coupled with 2 of the heaviest measured masses.

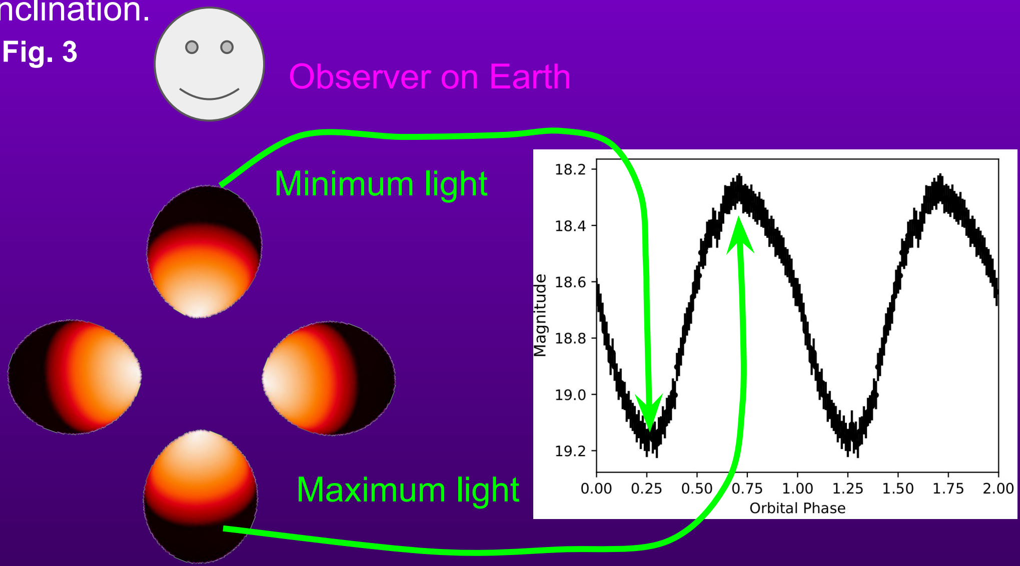
Fig. 2



Untangling the spider's web: determining the masses of pulsars in binary systems

In order to measure the masses, the inclination of the binary must be estimated. This is done by modelling the optical light curve of the binary. We observe different parts of the companion star as it orbits the pulsar, leading to variations in the systems brightness (Fig.3). These light curves can be modelled using binary synthesis tools such as Icarus (Breton et al. 2012) to estimate the inclination.

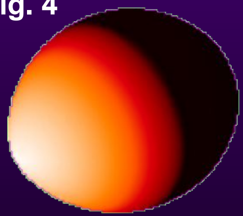
Fig. 3



The Conventional Approach

Until recently, the conventional approach to modelling the light curves of "spiders" assumed that the companion star is uniformly illuminated by the pulsar (as shown by the star in Fig 4.

Fig. 4



When a slight asymmetry is present is the systems light curve, the correct system inclination is no longer recoveredusing a direct heating model, leading to an overestimate of the pulsars mass. As such, asymmetries **must** be accounted for in order to correctly estimate the pulsar mass.

Accounting for Heat Redistribution

$$\vec{J}_{\parallel} = -\kappa \vec{\nabla}_{\parallel} T_* + T_* f(\theta) \sin\theta \vec{u}_r \quad (3)$$

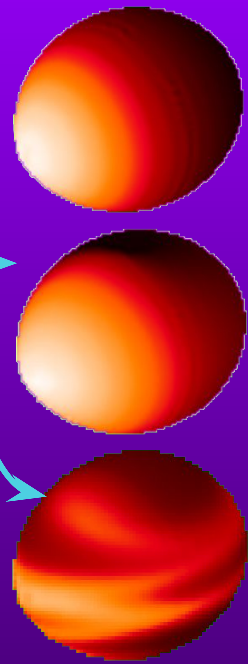


Fig. 5(a)

Fig. 5(b)

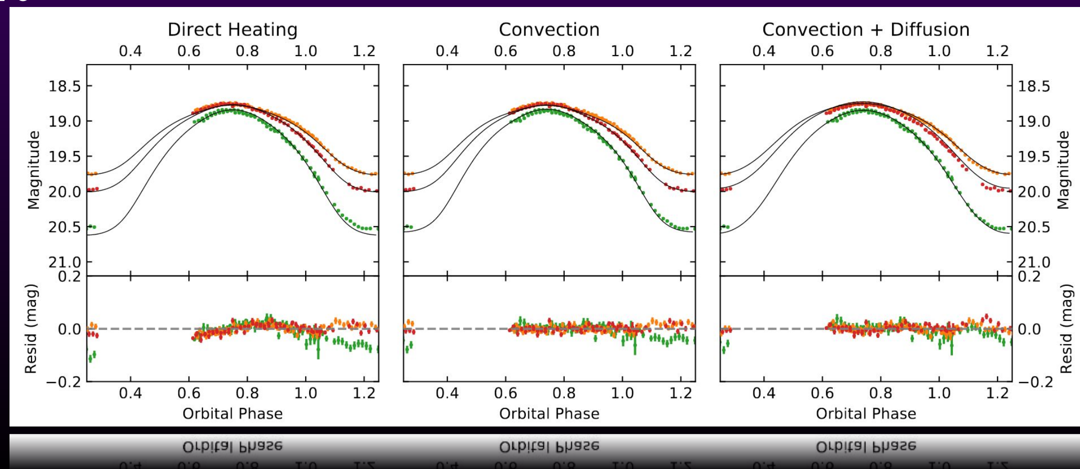
Fig. 5(c)

Equation 3 allows for energy transport across the companions surface (Voisin et al. 2020). The first term allows for surface diffusion of energy.

The second term allows for convection around the star following some profile f(θ). Figure 5(b) shows a simple Gaussian profile, while Figure 5(c) shows a more complex Gauss Hermite.

These heating patterns can be used to model the asymmetries in "spider" light curves, such as those in the redback PSR J2215+5135. Fig 6 shows the light curve of this source in 3 different optical bands alongside direct heating, convection, and convection+diffusion models. The inclusion of these asymmetric components lowers the mass from the published value of (2.27±0.1) $M_\odot$ (Linares et al. 2018) to (1.65±0.1) $M_\odot$.

Fig. 6



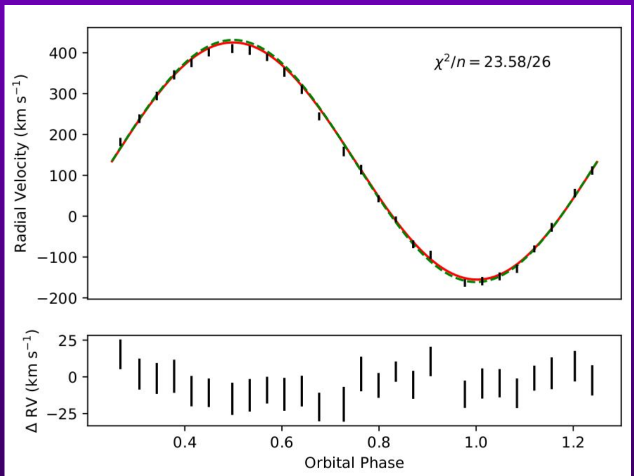
Untangling the spider's web: determining the masses of pulsars in binary systems

The other important parameter which can give rise to serious issues is the projected radial velocity of the companion star, K_2. Optical spectra of the binary systems are dominated by absorption features coming from the companion star.

The Conventional Approach

Normally, the radial velocity of a subset of absorption lines such as Hβ, Si II, or the Ca II triplet will be measured, and the radial velocity of these lines fit as shown in Figure 7.

Fig. 7



These lines are incredibly temperature dependant. Since the temperature difference between the night and day side of the companion can be ~3000 K, different lines may be emitted from different parts of the star.

As such, some lines are associated with the hotter, inner face of the star. Using these as a proxy for the radial velocity will then underestimate the true value of K_2 as this part of the star is moving slower than its centre of mass.

Work to correct this has relied on using absorption lines associated with the colder parts of the star if they are visible. This can lead to an accuracy of 1% in measuring K_2. This can only be done if these cool features can be seen.

Even worse, all other information contained in the flux calibrated spectra which could be used for estimating the companion's temperature and distance to the source is wasted.

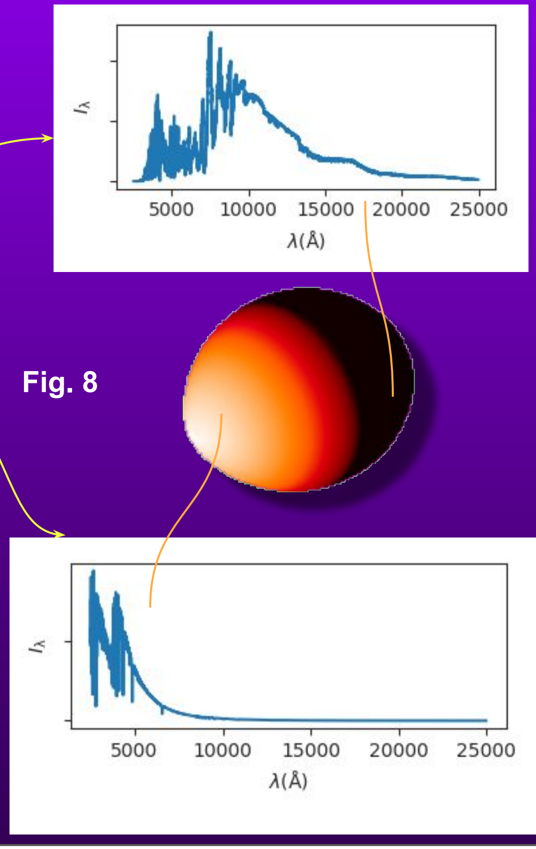
Synthesising the spectra

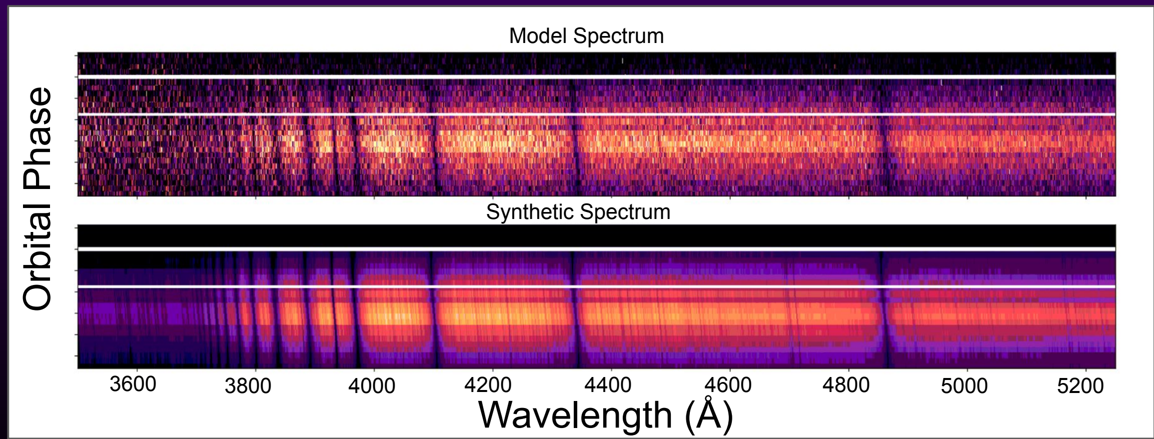
We have developed code which assigns every cell on our model stars the correct emergent spectrum (Fig 8). These can then be integrated over the surface to give a composite synthetic spectrum of the companion.

These model spectra can then be compared to the observed spectra to measure K_2, alongside giving accurate temperature and distance estimates for the system.

Preliminary results suggest we can measure K_2 to 0.2%, the temperature to 0.5%, and the distance to 5%.

Fig. 8





Untangling the spider's web: determining the masses of pulsars in binary systems

Looking forward

- Measuring pulsar masses is very difficult, but possible when no asymmetries are present and spectral features can be easily identified from cold and hot parts of star.
- Models exist to account for these asymmetries, but which one is appropriate is far from clear.
- The correlations between parameters when using asymmetric models are not well understood, and exploring this parameter space takes a long time.
- Deployment of next level spectroscopy modelling is nearly here - just need to figure out best optimisation methods and how to distribute.

References

Breton, R., et al., 2012, ApJ, 748, 115
Linares, M., Shahbaz, T., Caseres, J., 2018, ApJ, 859, 54
Linares, M., 2019, arXiv:1910.09572
Voisin, G., Kennedy, M.R, et al., 2020, arXiv:2006.06552

Acknowledgments

I would like to thank the support of the rest of the "Spiders" research group - Rene Breton, Colin Clark, Daniel Mata Sanchez, Guillaume Voisin, and James Stringer - in the University of Manchester when preparing this poster. I would also like to thank Alexandra Bonta for allowing me to use her neutron star mass diagram, which she created for her third year BSc dissertation.

This work has been funded by the European Research Council, under the European Union's Horizon 2020 research and innovation program (grant agreement No. 715051; Spiders). Part of the work presented here is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme 0103.D-0878(A)."