Phase-resolved Polarimetric Constraints on the White Dwarf Pulsar in AR Sco

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- Marsh et al. (2016) detected optical and radio pulsations from the binary white dwarf (WD) system AR Scorpii
- Orbital period of 3.55 hours and a "pulsar" spin period of 1.95 min
- Constrained the mass of the WD to $\sim 0.8 M_{\odot}$ and the M-dwarf companion to $\sim 0.3 M_{\odot}$
- Stiller et al. (2018) obtained a $\dot{P} = 7.18 \times 10^{-13}\ ss^{-1}$

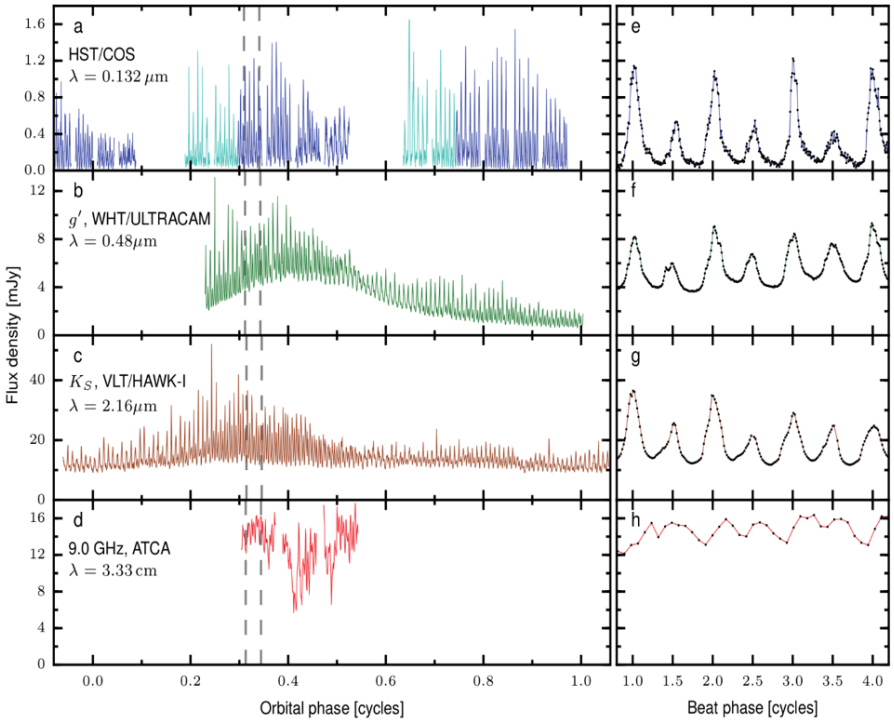

Figure: Light Curve of AR Sco from Marsh et al. (2016) showing ultraviolet to radio bands

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- Optical and UV emission lines show no indication of an accretion disc
- The optical and UV are non-thermal emission and pulsed at the WD spin period
- This gives a light cylinder radius of $R_{\rm LC} = 5.6 \times 10^{11}\ cm$ and an orbital semi-major axis of $a = 8.5 \times 10^{10}\ cm$
- Buckley et al. (2017) found that the system exhibits strong linear optical polarisation (up to $\sim 40\%$) and the WD having a magnetic field estimated to be $\sim 500\mathrm{MG}$

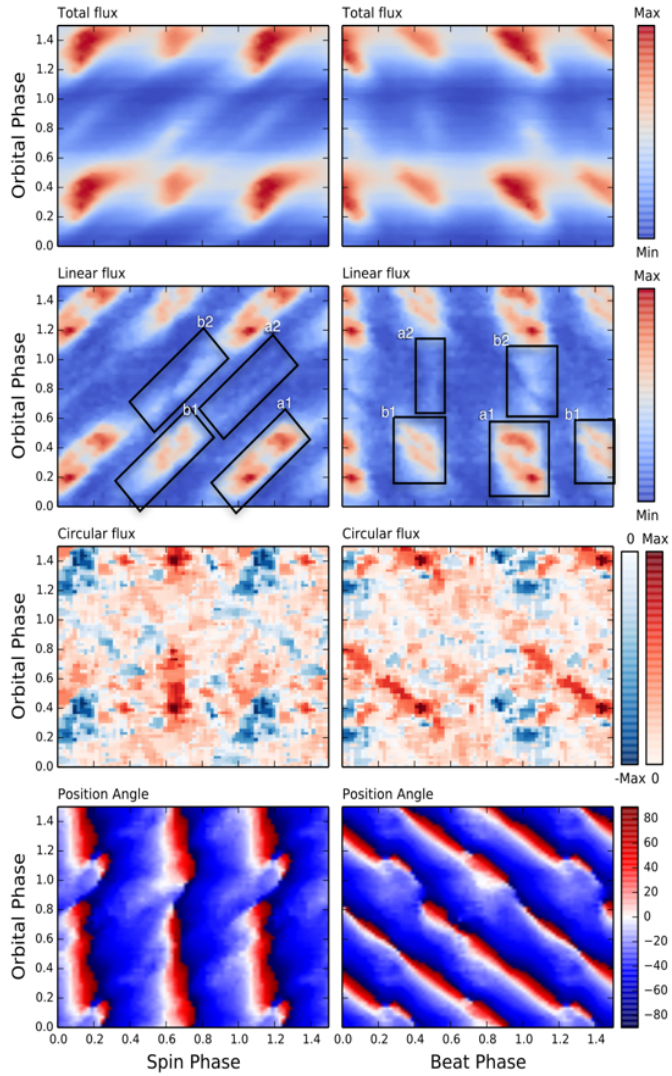

Figure: Extensive observational data from Potter and Buckley (2018)

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- Garnavich et al. (2020) detected two hotspots located at the poles of the WD.
- Garnavich et al. (2020) inferred an upper limit of $100\mathrm{MG}$ for the WD surface field using Zeeman splitting.
- Takata et al. (2020) found a double-peaked structure in the X-rays vs. the single-peaked structure observed in the 2016 and 2018 observations.

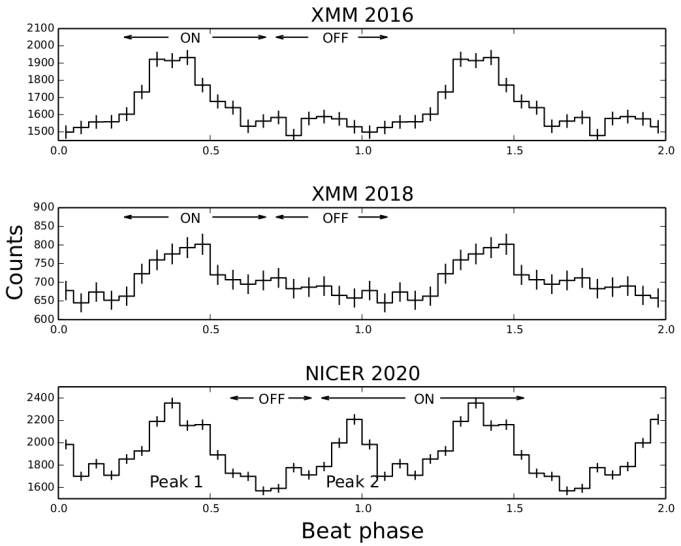

Figure: Takata et al. (2020)

AR Sco Observations

- Takata et al. (2020) created phase maps of the pulse profiles, binned with the beat and spin period, respectively.
- Some components of the emission were found to be coupled to the beat period and others to the spin period.
- *Fermi LAT* analysis done by Kaplan et al. (2019) and Singh et al. (2020) showed a 2σ detection for γ-rays from the source.

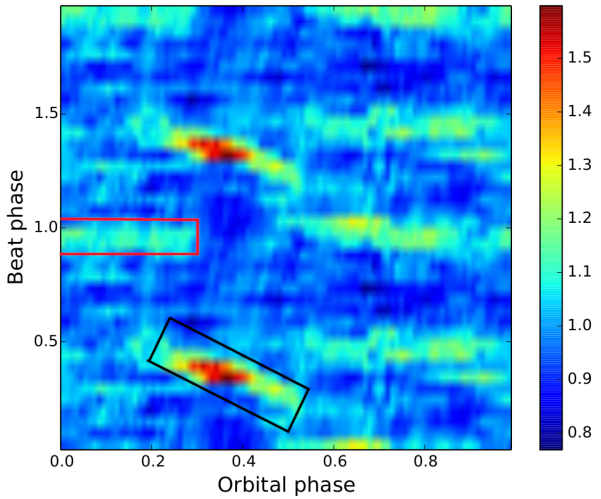

Figure: Takata et al. (2020)

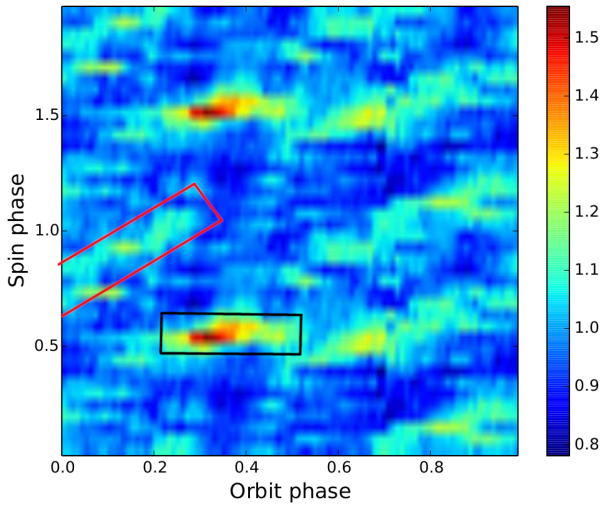

Figure: Takata et al. (2020)

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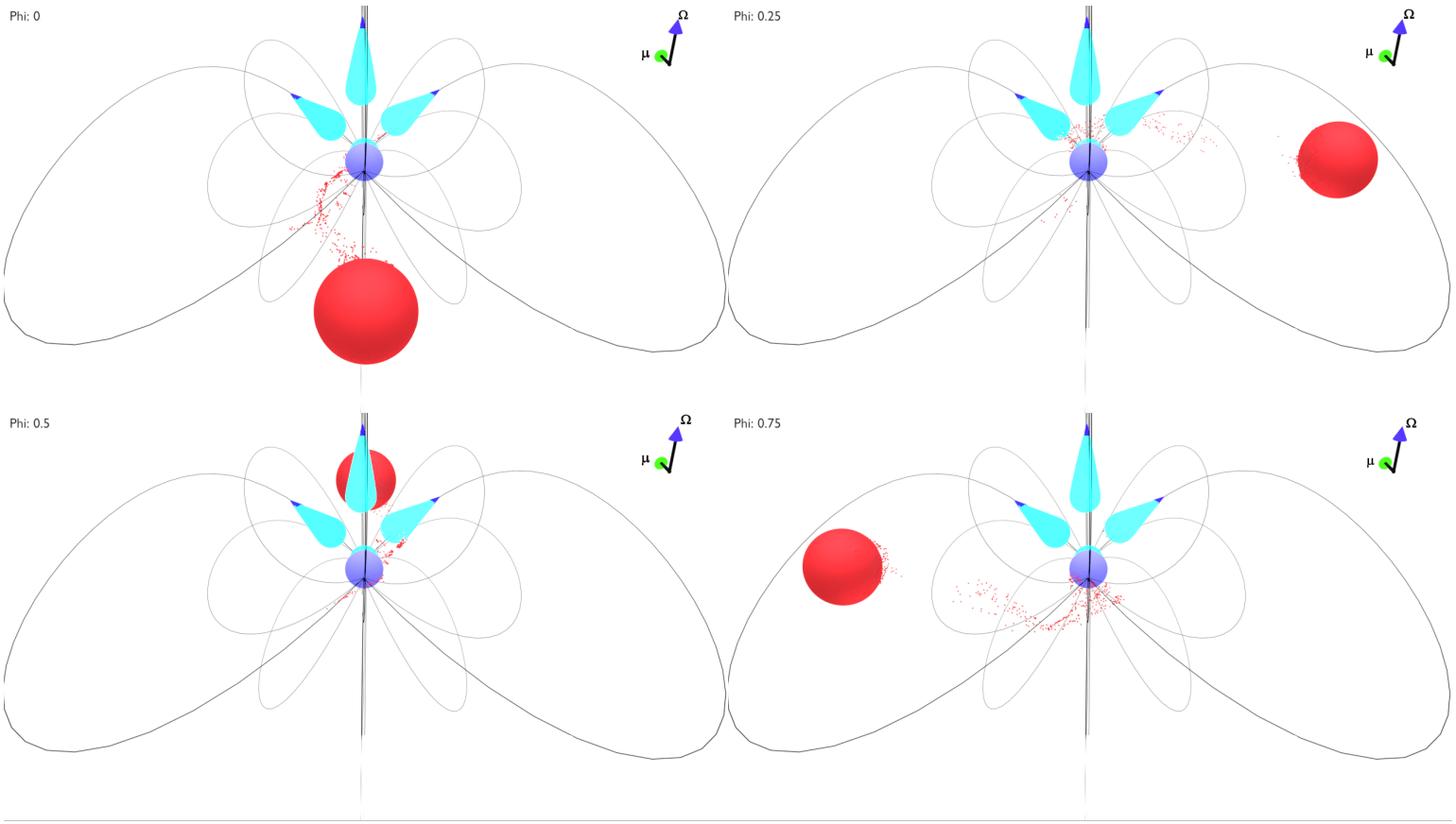

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- **Shock frame emission**
  - Geng et al. (2016) shock accelerated-particles model.
  - Katz et al. (2017) precession model.
  - Garnavich et al. (2018) magnetic reconnection model.
  - Bednarek (2018) hadronic model.
- **WD magnetosphere frame emission**
  - Buckley et al. (2017) Spin down pulsar model.
  - Takata et al. (2017) magnetic mirror model.
  - Potter & Buckley (2018) particle injection model (Geometric).
  - Du Plessis et al. (2019) RVM model (Geometric).
  - Lyutikov et al. (2020) ionised plasma model.

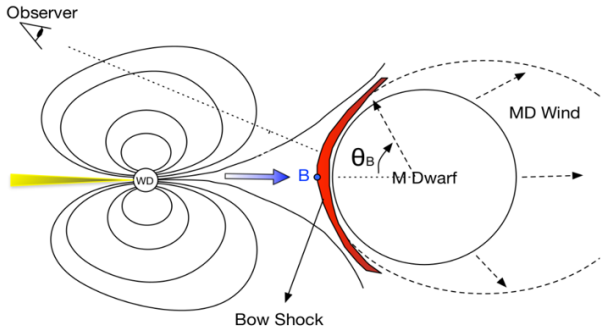

Figure: Geng et al.(2016)

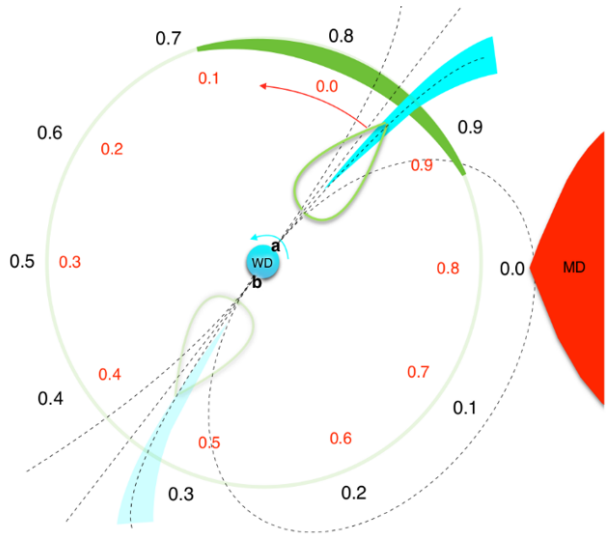

Figure: Potter & Buckley (2018)

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Model

Beam Geometry

- The Rotating Vector Model (RVM) by Radhakrishnan and Cooke (1969) gives the polarisation position angle (PPA) as: $\tan(\psi - \psi_0) = \frac{\sin\alpha \sin(\phi - \phi_0)}{\sin\zeta\cos\alpha - \cos\zeta\sin\alpha\cos(\phi - \phi_0)}$

- Assumptions of RVM:
  - A zero emission height
  - All the emission is tangent to the local magnetic field lines
  - Pulsar co-rotational speed at the emission altitude is non-relativistic
  - The radio emission beams are circular
  - Static vacuum dipole magnetic field
  - The plane of polarisation is parallel to the meridional plane of the local magnetic field

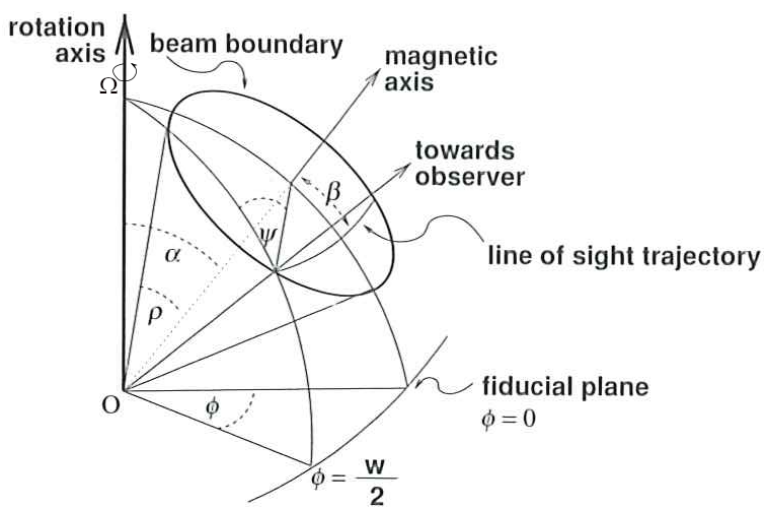
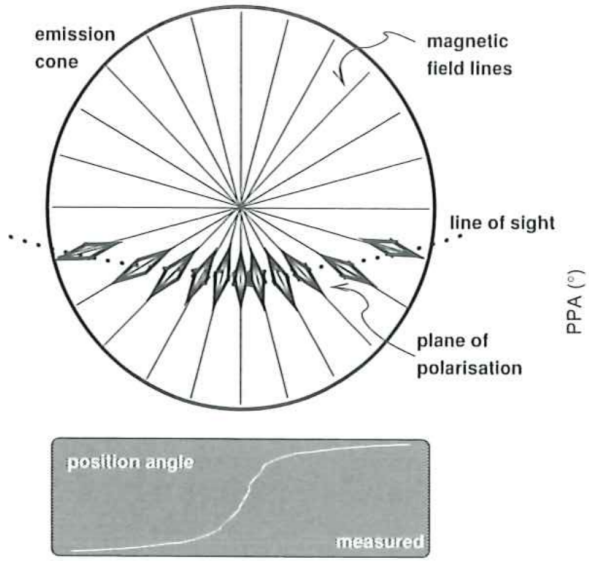


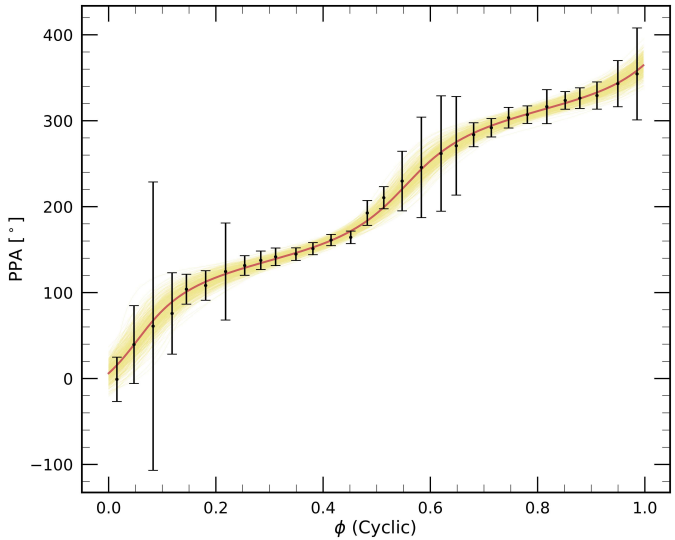
Figure: Lorimer and Kramer (2005)

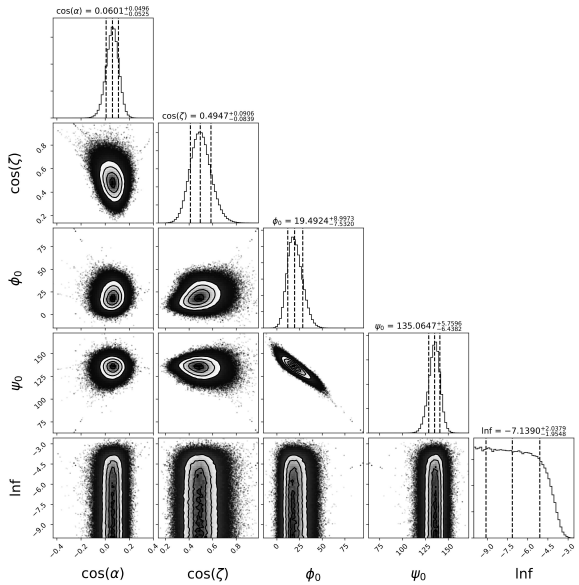


Results

Best Fit

- A Markov-Chain Monte Carlo (MCMC) technique by Foreman-Mackey et al. (2013) was applied to find the best fit
- We used the PPA data from Buckley et al. (2017)
- We found the best fit for the PPA data using the cosine of the angle
- We added a likelihood parameter to correct for the case when errors are underestimated by some fraction f
- We obtained $\alpha = 86.6^{+3.0}_{-2.8}$ and $\zeta = 60.5^{+5.3}_{-6.1}$





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- The potential drop at the polar cap is $\Phi_{\rm max} = 4 \times 10^{11}\,{\rm statvolt}$, yielding $\gamma_{max} = 3 \times 10^8$
- 'Near' is at WD surface ($B_{\rm P} \sim 8 \times 10^8$ G) and 'far' is at the companion ($B_{\rm x} \sim 2 \times 10^3$ G)
- Equating $t_{\rm SR} = t_{CR}$ and solving for pitch angle we find $\eta \sim 10^{-5}$
- SR dominates over curvature radiation (CR) as long as the pitch angle is non-zero
- For more detail see Du Plessis et al. (2019)

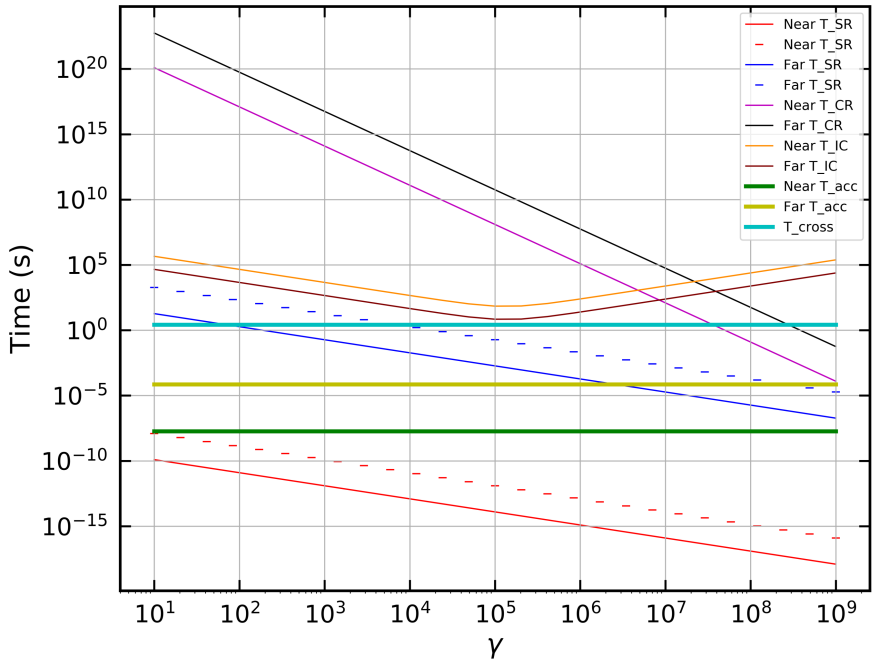

Figure: Acceleration, crossing and radiation (CR, SR and IC) loss timescales for 'far' ($B_{\rm x}$) and 'near' ($B_{\rm p}$) cases. The solid lines for SR represent a pitch angle of $\pi/2$ and the dashed lines represent a pitch angle of 0.1 ($\sim 6^\circ$).

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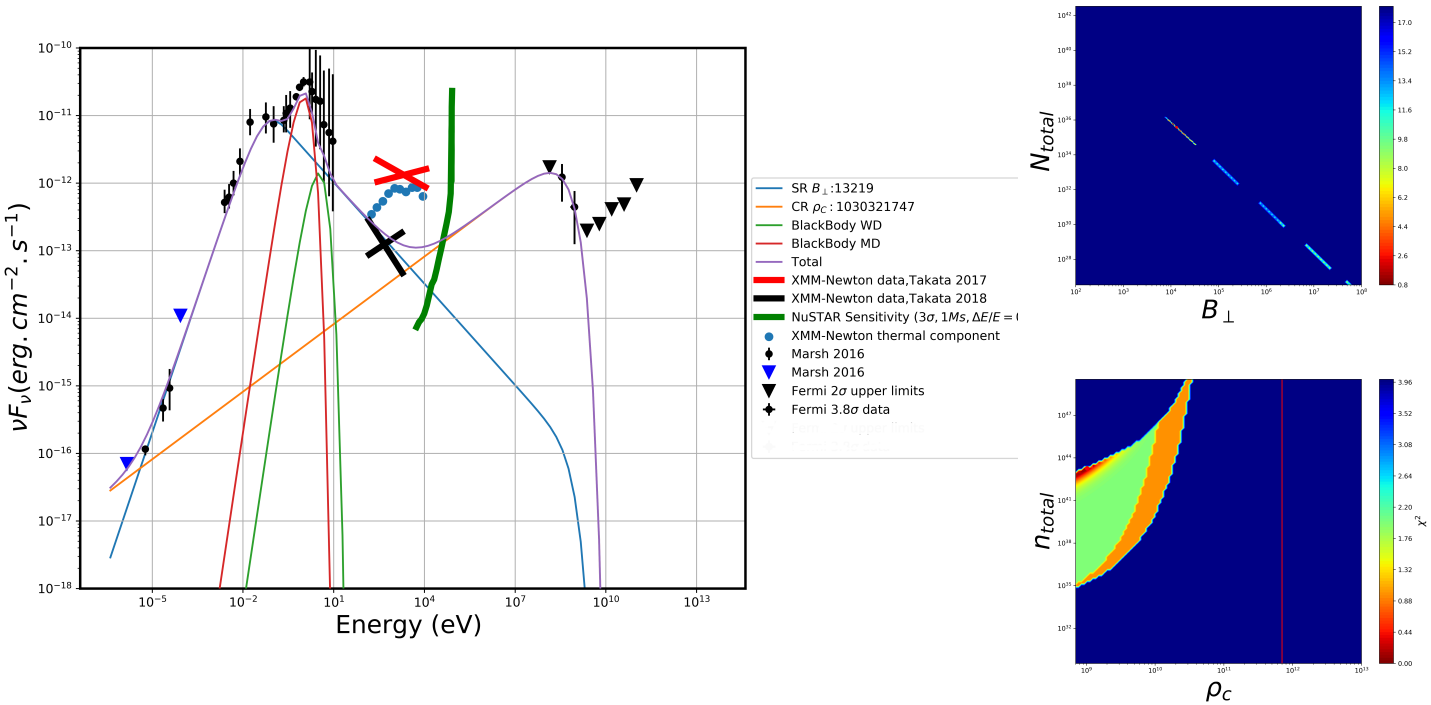

Figure: SED plot showing the optical data from Marsh et al. (2016), the XMM-Newton data from different Takata papers is shown with the red assumed to be the total and black the pulsed flux. The best SR and CR fits with the chosen parameters were plotted and summed together to give a total flux spectrum. The blackbody spectra for the white dwarf and M dwarf is plotted in green and red respectively.

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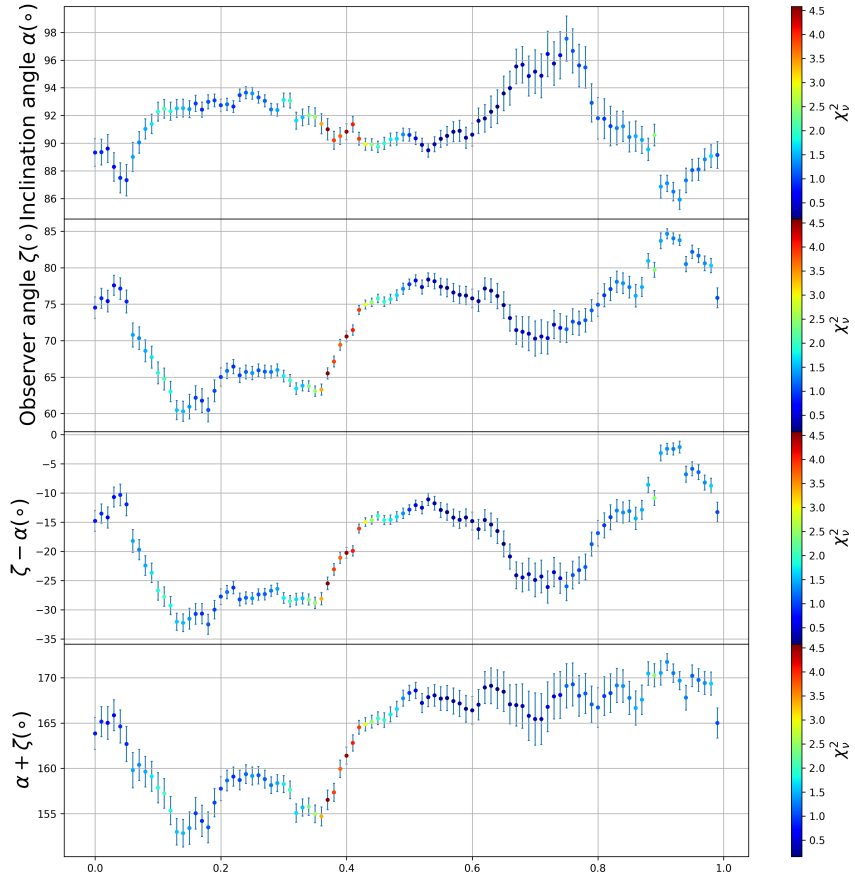
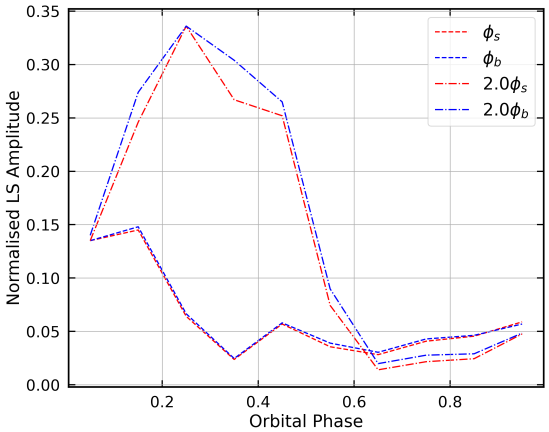
These figures show the best-fit results for all the epoch datasets binned together (Potter and Buckley, 2018)

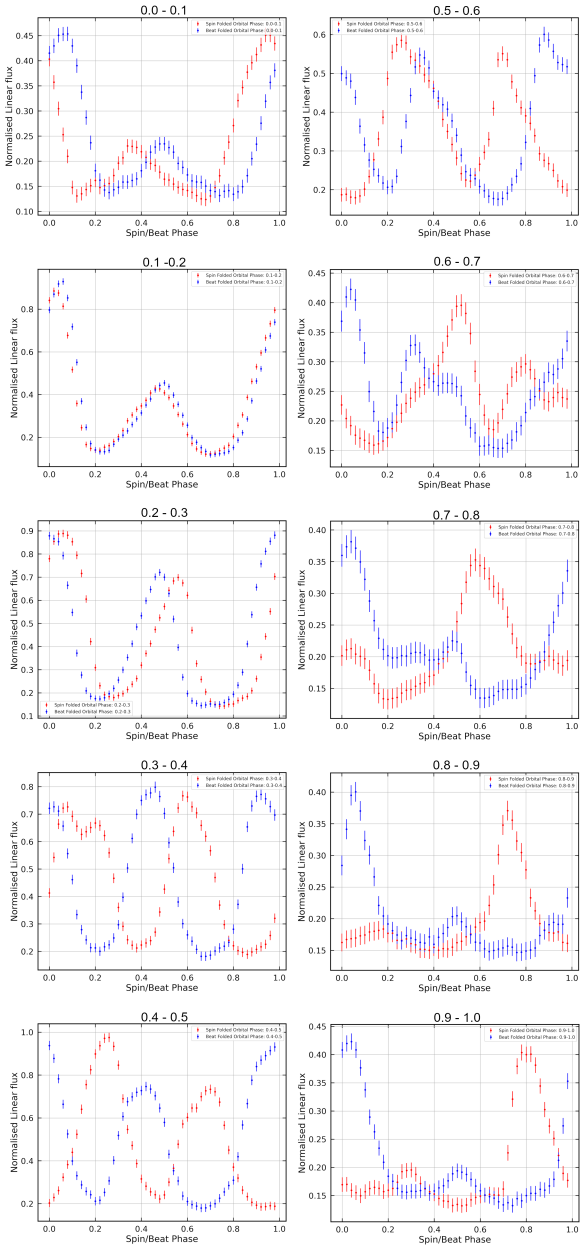


Results

Orbital Variation

- Blue is the beat-folded linear flux
- Red is the spin-folded linear flux
- Linear flux maximum between orbital phase $0.2 - 0.45$
- Mixture of spin- and beat-coupled emission





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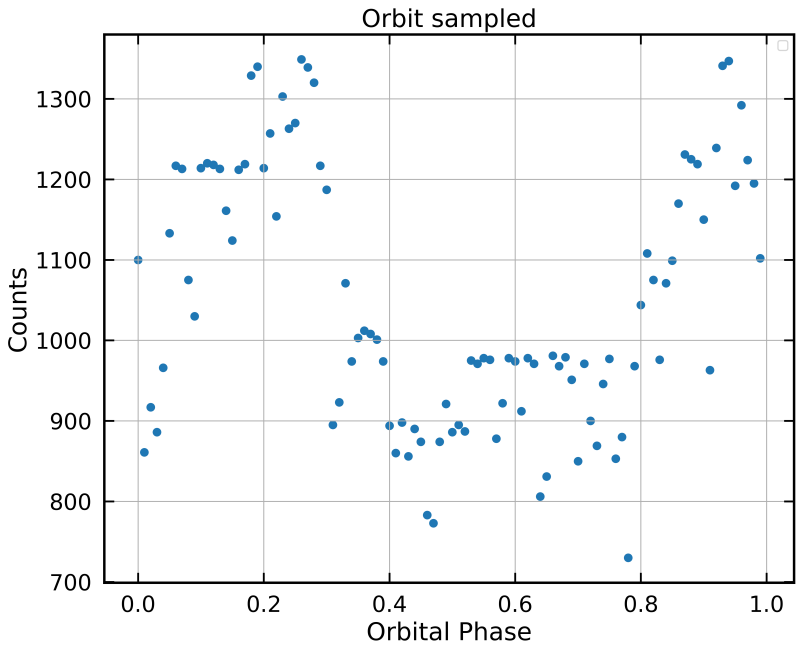
Variation in α and ζ Speculations

- Precession of the WD.
- Biased orbital sampling.
- Asymmetric or wobbling emissions region.
- Different particle pitch angles.
- Different injection regions and rates.
- A mix of WD and companion emission might have an effect on orbitally-dependent depolarization.



Conclusions

- We found that we can model this white dwarf pulsar polarisation using the RVM: emission from the WD is magnetospheric synchrotron emission
- We found $\alpha = \left(86.6^{+3.0}_{-2.8}\right)^{\circ}$ and $\zeta = \left(60.5^{+5.3}_{-6.1}\right)^{\circ}$ and because of the large duty cycle we find small errors compared to radio pulsar fits
- Marsh et al. (2016) found double-peaked light curves, the second harmonic is present in the Fourier analysis and the PPA has a 180° swing suggesting an inclination angle close to 90°
- We constrained the mass of the white dwarf to $M_{WD} = 1.0^{+0.16}_{-0.10}\ \mathrm{M}_{\odot}$ using ζ
- SR dominates as long as the pitch angle of the particles can be maintained

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- Use a more sophisticated emission model and adapt to WD system
- Solve the coupled transport equations from Harding et al. (2005) more generally without assuming $\gamma \gg 1$ and small pitch angles to compare with the Takata et al. (2017) magnetic mirror model were they violated these assumptions.
- Revisit radiation and polarisation calculations and implement syncro-curvature radiation.
- Investigate particle turnaround point, injection scenarios and magnetic field structure.

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