Polarimetric Evidence of the first white dwarf pulsar: the binary system AR Scorpii

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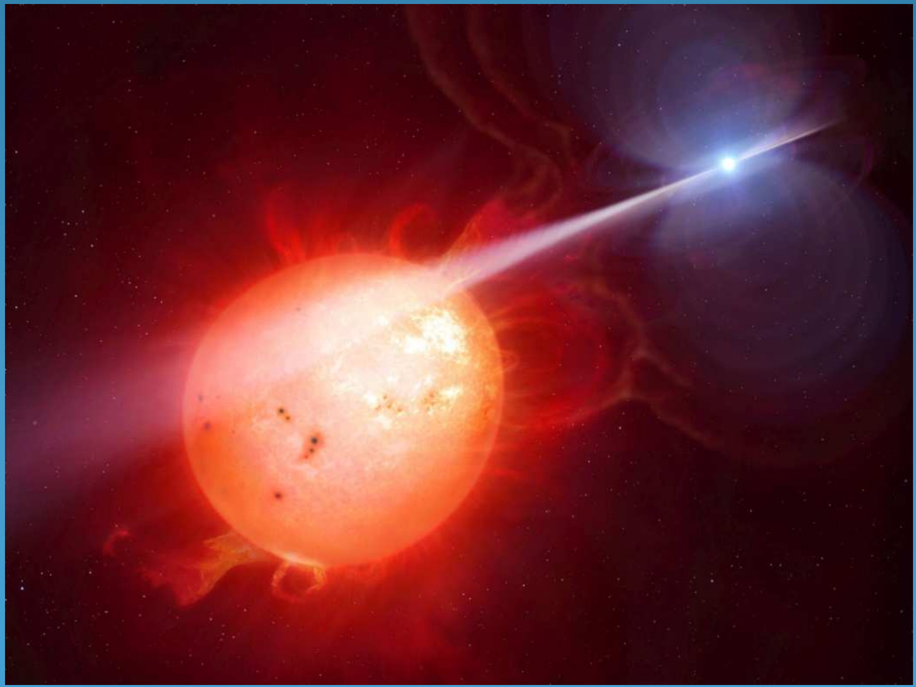
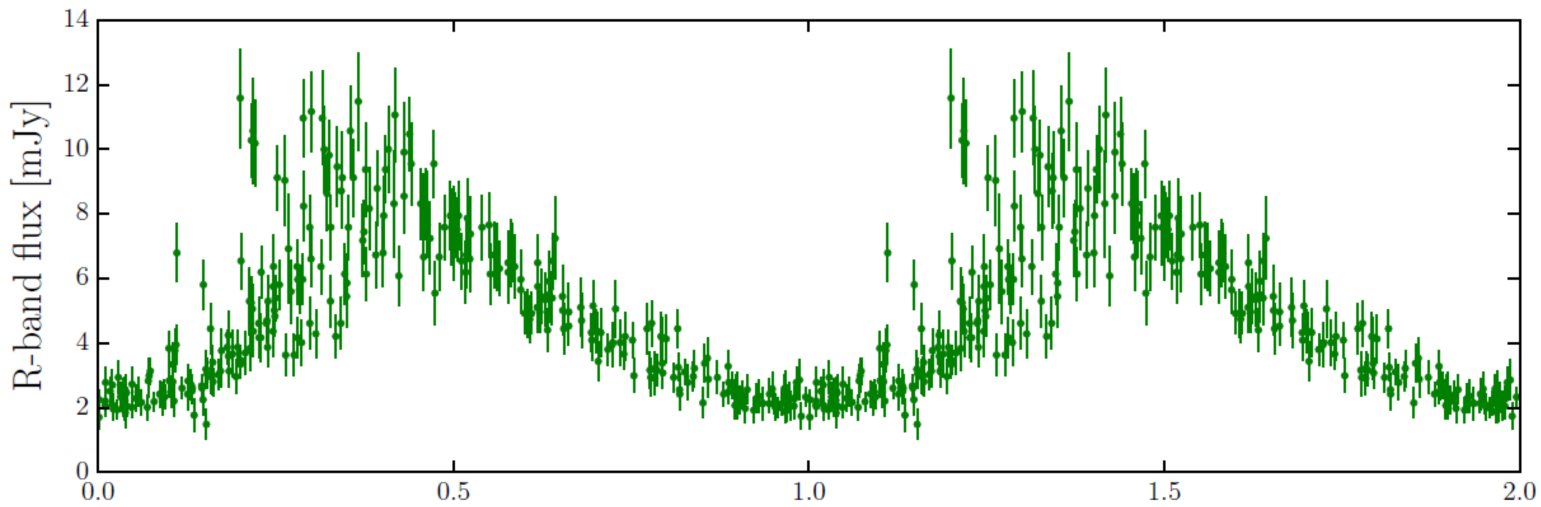


Polarized Emission from Astrophysical Jets: 14 June 2017, Ierapetra, Crete

AR Scorpii: past history

- Originally (mis)classified as a $V = 14$ δ Scuti pulsating star in the 1970s
- Showed ~few hour pseudo-sinusoidal photometric variations
- Alerted by "amateurs" that light curve was "interesting"
  - *Showing short time-scale variablity*
- Follow-up high-speed optical photometry (*Ultracam* on WHT) undertaken in 2015 revealing strong ~ 2 min coherent variations (~50% pulse fraction in optical band)
  - Two periodicities seen, at 117 & 118 sec (spin & beat periods)
- Long term (~7 yr) light curve (from Catalina Real Time Survey):



AR Scorpii: multi-wavelength campaigns

- Following identification of coherent periodicites, intensive multi-wavelength followup observations were conducted during 2015
- Time-resolved photometric observations from radio to UV
  - HST (UV), VLT (*K*-band), Ultracam (optical), ATCA (radio)
  - The short period variability is seen in ALL of the above (to a greater or lesser degree)
- Time-resolve optical spectroscopy
  - WHT (ISIS), INT (IDS), VLT (FORS, X-Shooter)
- *Swift* UV + X-ray observations
- Other multi-wavelength archival observations used to define the SED
  - e.g. 2MASS, Herschel , WISE, Spitzer, FIRST)

Results of this first photometric campaign was published by Marsh *et al*. in *Nature* 537, 374-377 (2016)

Second paper (with polarimetry and interpretations) by Buckley *et al*. will be published in *Nature Astronomy* on 23 Jan (arXiv:1612.03185)

LETTER

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A radio-pulsing white dwarf binary star

(June 2016)

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(Jan 2017)

Polarimetric evidence of a white dwarf pulsar in the binary system AR Scorpii

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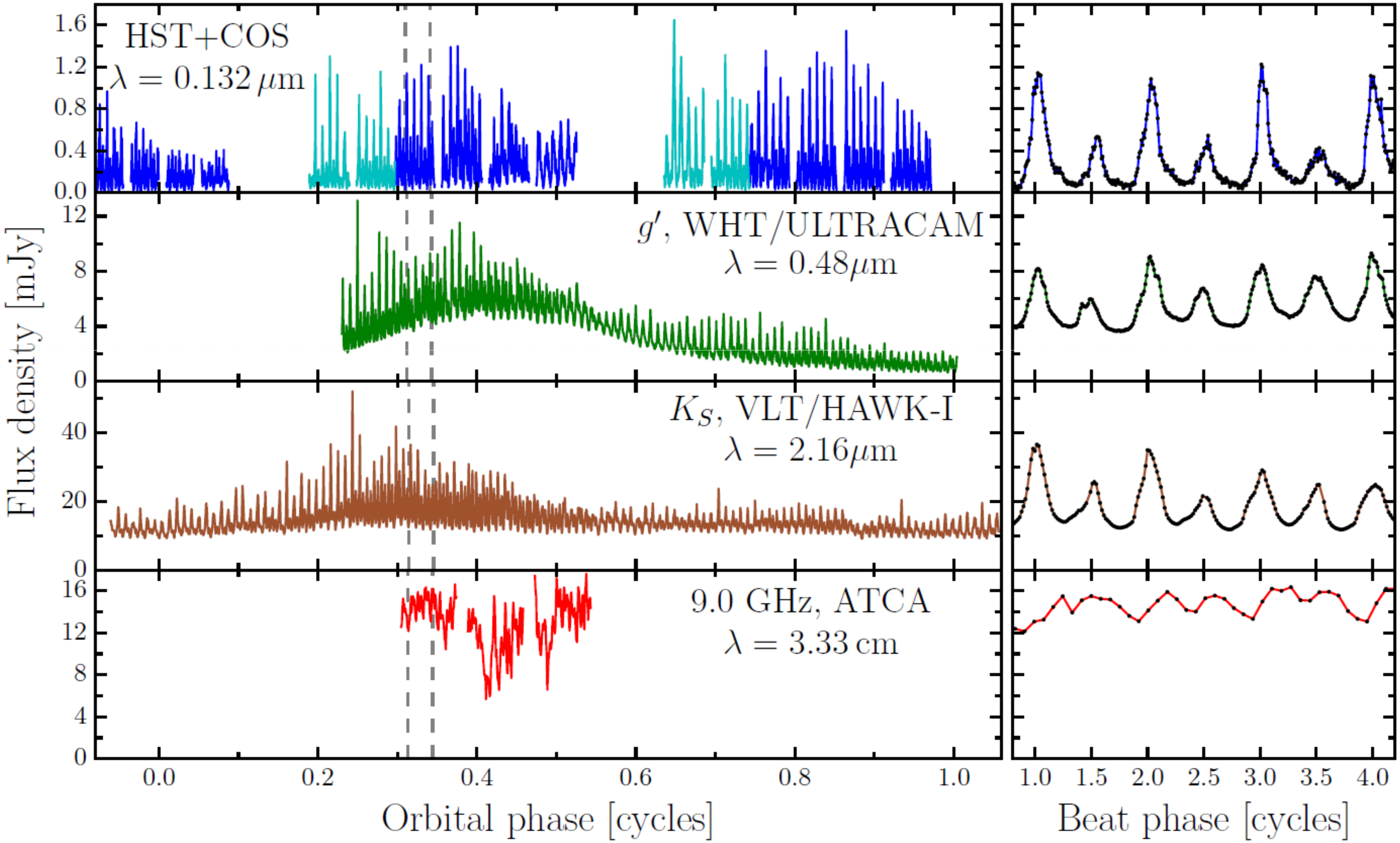
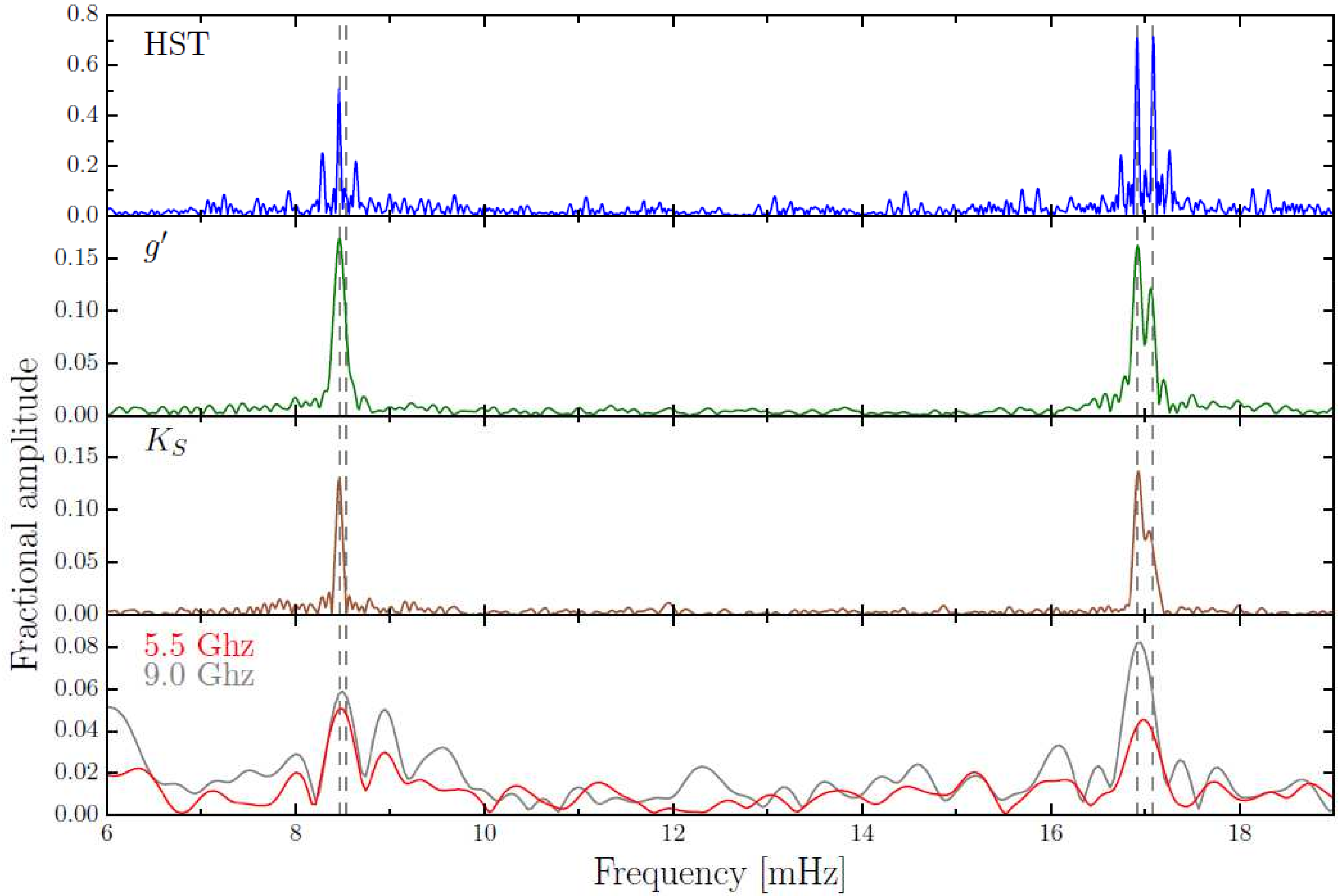
The variable star AR Scorpii (AR Sco) was recently discovered to pulse in brightness every 1.97 min from ultraviolet wavelengths into the radio regime. The system is composed of a cool, low-mass star in a tight, 3.55-hour orbit with a more massive white dwarf. Here we report new optical observations of AR Sco that show strong linear polarization (up to 40%) that varies strongly and periodically on both the spin period of the white dwarf and the beat period between the spin and orbital period, as well as low-level (up to a few per cent) circular polarization. These observations support the notion that, similar to neutron-star pulsars, the pulsed luminosity of AR Sco is powered by the spin-down of the rapidly rotating white dwarf that is highly magnetized (up to 500 MG). The morphology of the modulated linear polarization is similar to that seen in the Crab pulsar, albeit with a more complex waveform owing to the presence of two periodic signals of similar frequency. Magnetic interactions between the two component stars, coupled with synchrotron radiation from the white dwarf, power the observed polarized and non-polarized emission. AR Sco is therefore the first example of a white dwarf pulsar.

The Short Period Pulsations



Power Spectra

- Coherent pulsations detected at two periods (117.12 s spin; 118.20 s) and their harmonics



Pulsations

- Coherent pulsations detected at two periods (117.12 s spin; 118.20 s)
  - The former = spin period of compact object
  - The latter is the beat period between spin and 3.6h orbital period
  - Double peaked profile (strong 1^{st} harmonic)

- Optical pulsation vary from g' = 13.6 – 16.9 (variation by fact of 20×)

- No X-ray pulsations detected (30% pulse fraction upper limit) by *Swift*

- ~7 yrs timebase of Catalina Sky Survey photometry was used to determine period derivative:

$$\dot{P} = 3.92 \times 10^{-13} \ s\ s^{-1}$$

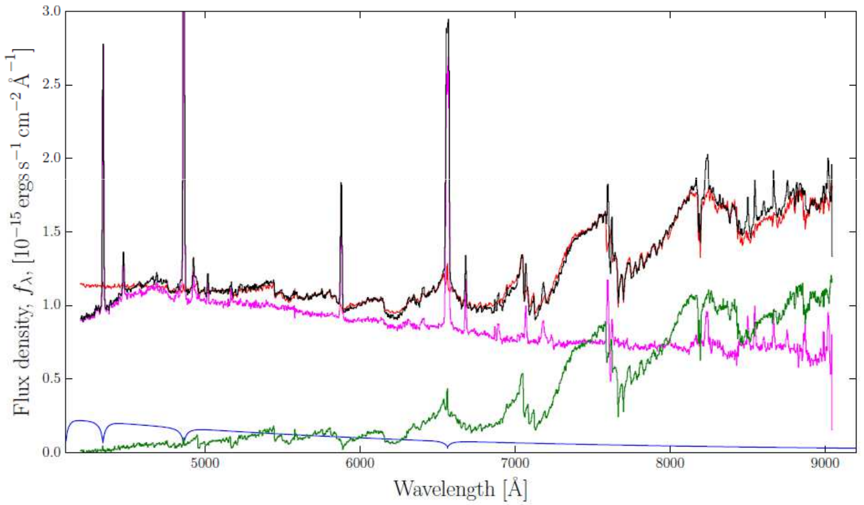
White Dwarf Spin-Down

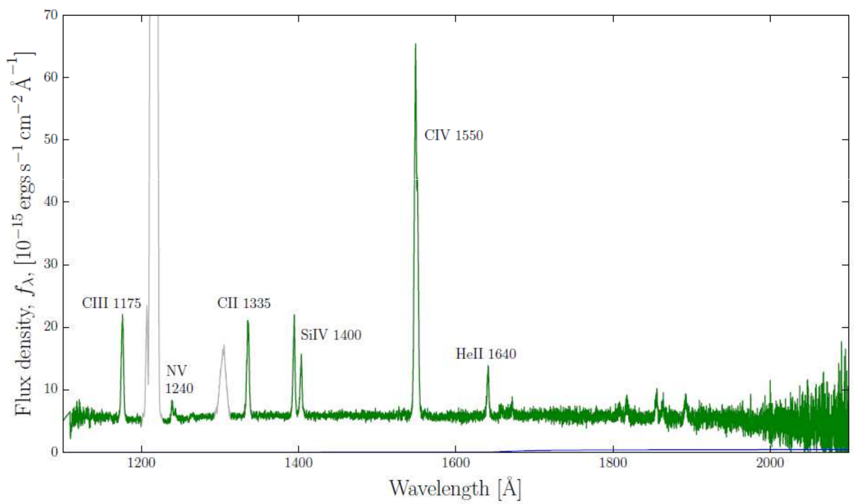
- This implies a spin-down power of $L_{\dot{\nu}_s} = -4\pi^2 I \nu_s \dot{\nu}_s$
  - For a neutron star: $L_{\dot{\nu}}(\mathrm{NS}) = 1.1 \times 10^{21}\ \mathrm{W}$
  - For a white dwarf: $L_{\dot{\nu}}(\mathrm{WD}) = 1.5 \times 10^{26}\ \mathrm{W}$
- The *observed* mean luminosity of the system is $\sim 1 \times 10^{25}$ W (peaking at $\sim 4 \times 10^{25}$ W).
- The sum of stellar components is only $\sim 4 \times 10^{24}$ W, implying the bulk of the luminosity of the system is *not* coming from the stellar components and that it varies from $L_{excess} = 0.6 - 3.6 \times 10^{25}$ W
- **Therefore *if* this luminosity is powered by spin-down, *only a WD* can delivery the required power.**

The spectral components

- **The optical & UV spectra:**

  Observed optical spectrum (black; orbital minimum), M5 V template (green); WD model limit(from *HST*; blue), the difference between observed and summed stellar components (magenta), *characterised by a power law*.





- HST spectrum shows no evidence of WD features, but FUV flux constrains $T_{eff} <$ 9750*K (model in blue)*
- Narrow emission lines in optical/UV come from irradiated face of secondary
- Distance estimate from M-star (spectrum & IR colours) = 116 ± 16 pc

The Non-Stellar Optical Luminosity

- **Accretion cannot explain the additional luminosity:**
  - If this additional *L* were due to accretion, implies $\dot{M}_{\rm WD} = 1.3 \times 10^{-11}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$,
    - But no sign of mass transfer or accretion (stream or accretion disk emission lines, or flickering)
  - But the clincher is the low X-ray luminosity from *Swift*:

    $L_X \;=\; 4.9 \times 10^{23}\,{\rm W}$

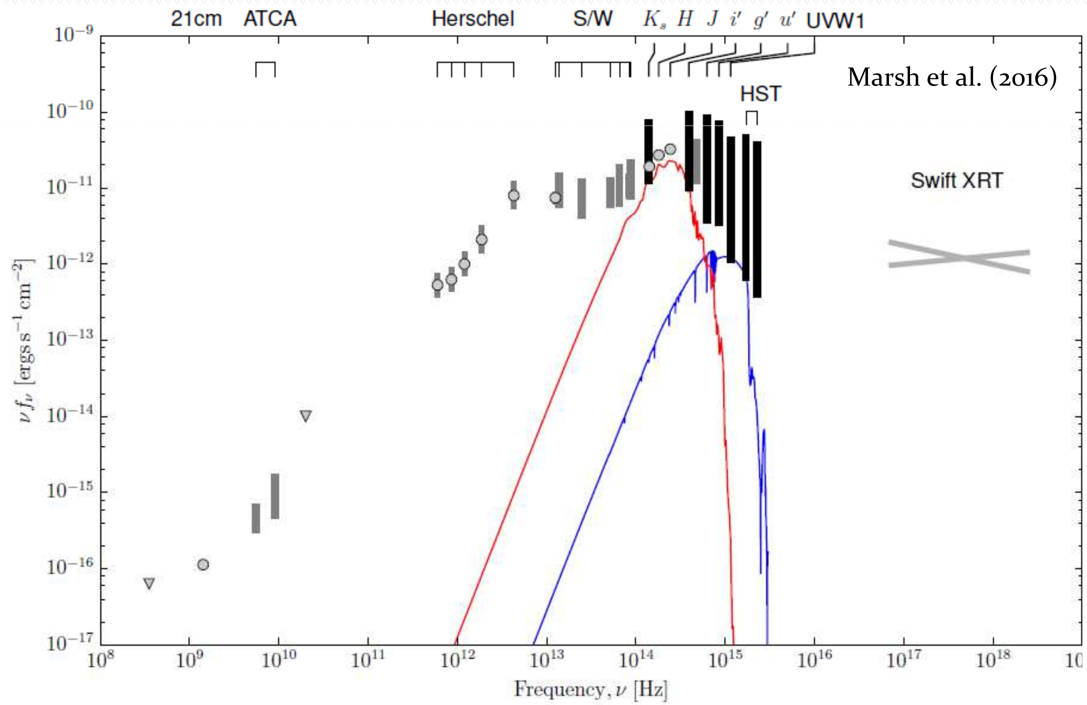
  This is <1% of typical asychronous accreting magnetic CVs (i.e. intermediate polars)
  - And only 4% of the non-stellar luminosity of the system (i.e. residual power law component)

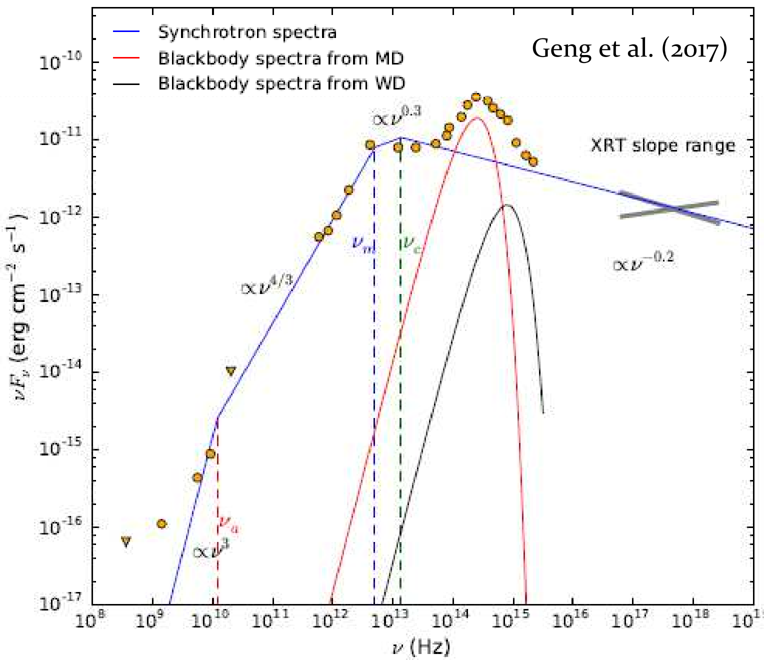
- **Only spin-down can power the system, and *only if the spinning object is a White Dwarf***

[*Other arguments against a neutron star:*
- *Distance of 116 pc (order of mag closer than the nearest accr. N.S. (Cen X-4)*
- *L_X is only 4% of L_{opt} whereas N.S. systems have typically $L_X \sim 100 \times L_{opt}$*]

Spectral Energy Distribution

- Other archival observations have contributed to an overall SED
- $S_\nu \propto \nu^\alpha$ ($\alpha \leq 1$); self-absorbed non-thermal spectrum from radio up to ~10^{13} Hz
- Possible super-position of synchrotron flares in radio regime
- Two main synchrotron components
  - $<10^{13}$ Hz (radio-IR)) from pumped coronal loops
  - $> 10^{13}$ Hz (IR-optical-UV-X-ray) from particle acceleration from high *E*-field.

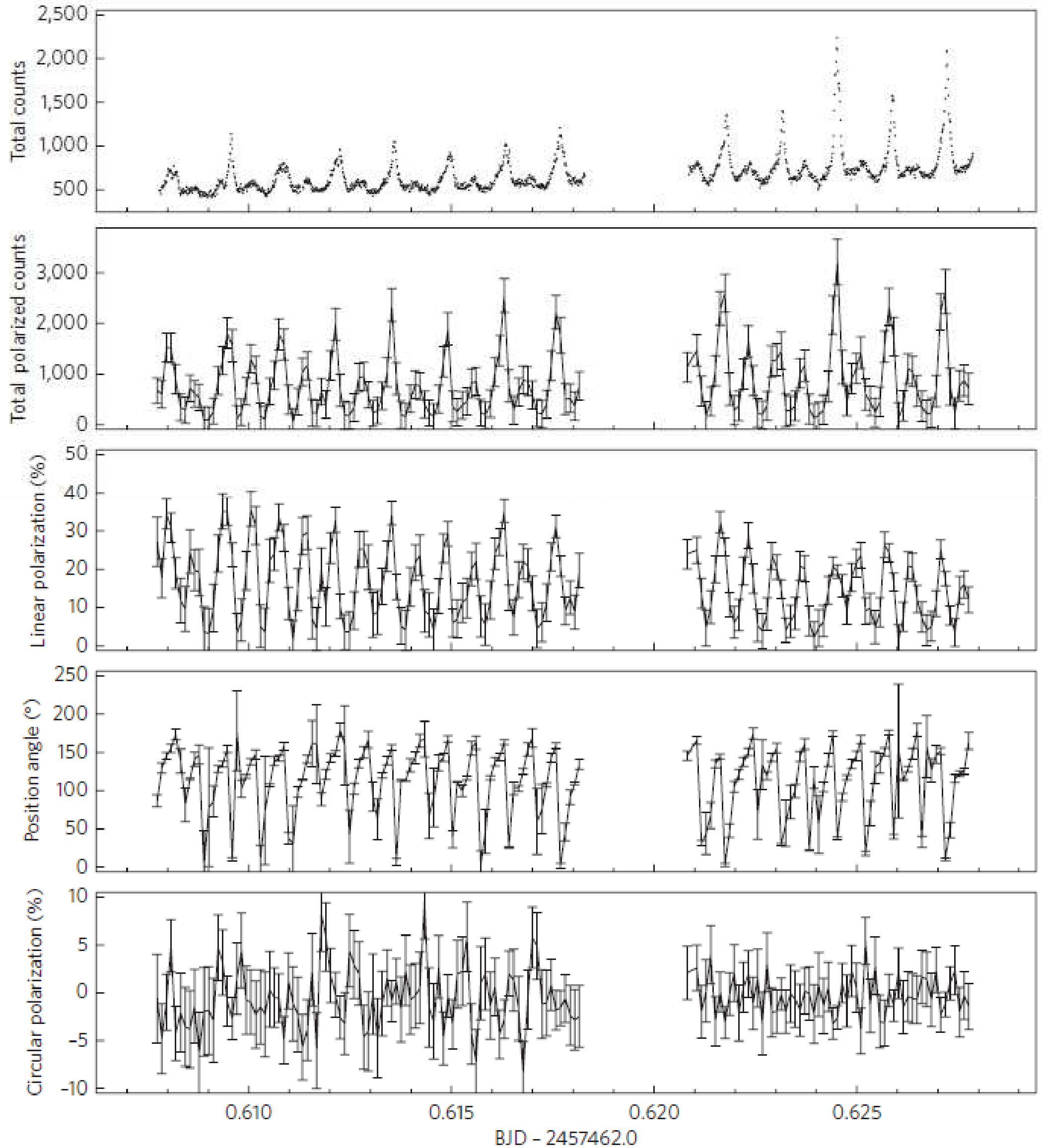




Polarimetric Observations

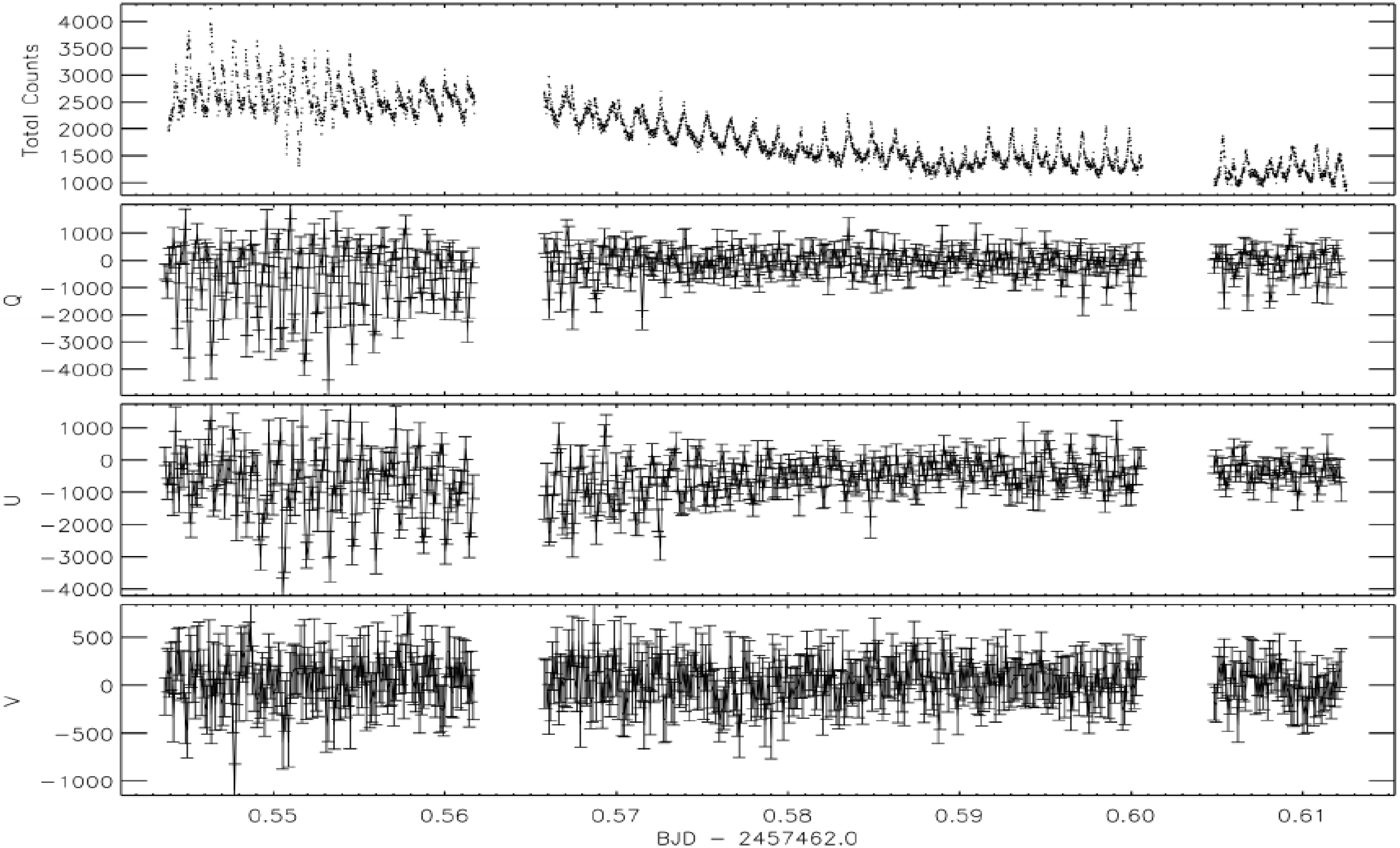
As reported in Buckley et al. 2017:

- All-Stokes (linear + circular) polarimetry conducted on 14 & 15 Mar 2016 at SAAO with 1.9-m + HIPPO (2-channel PMT)
  - 1 milli-sec sampling
  - binned to 1 (*I*) & 10 sec (*Q,U,V*)
- Discovery of strong pulsed linear polarization modulated at both spin & beat *and* their harmonics
- Linear polarization varies from 0-40% with a 90% pulse fraction
- P.A. of E-vector rotates through ~180°
- Consistent with rotating magnetic dipole



14 Mar 2016: 0.55 h data

- Pulsations show variations from night to night, due to orbital phase dependence (*I, Q, U, V*)



15 Mar 2016: 2.28 h data

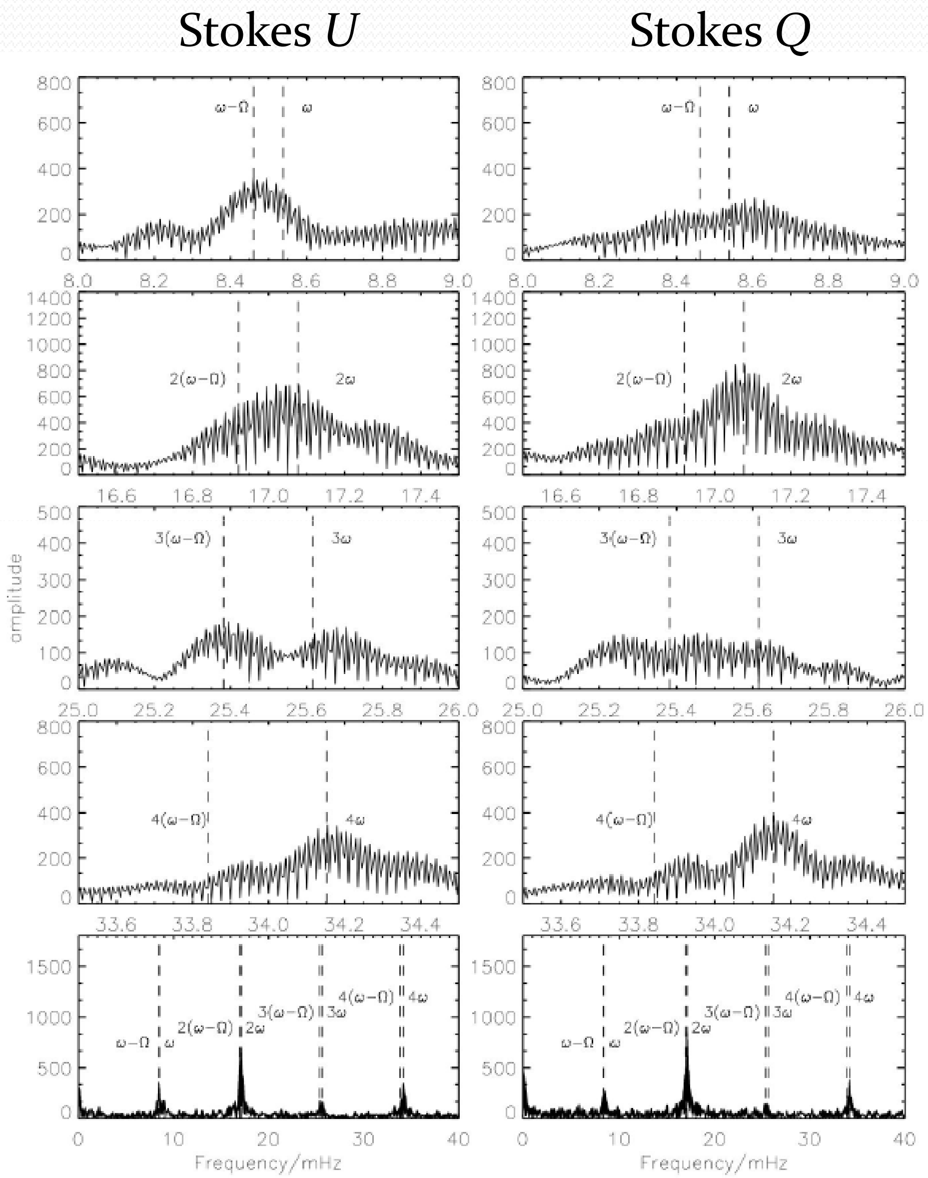
Polarimetric periodicities

- Linearly polarized flux = $(Q^2 + U^2)^{1/2}$ varies dominantly at the harmonic of the *spin* period

- *I* (total intensity) varies dominantly at the beat

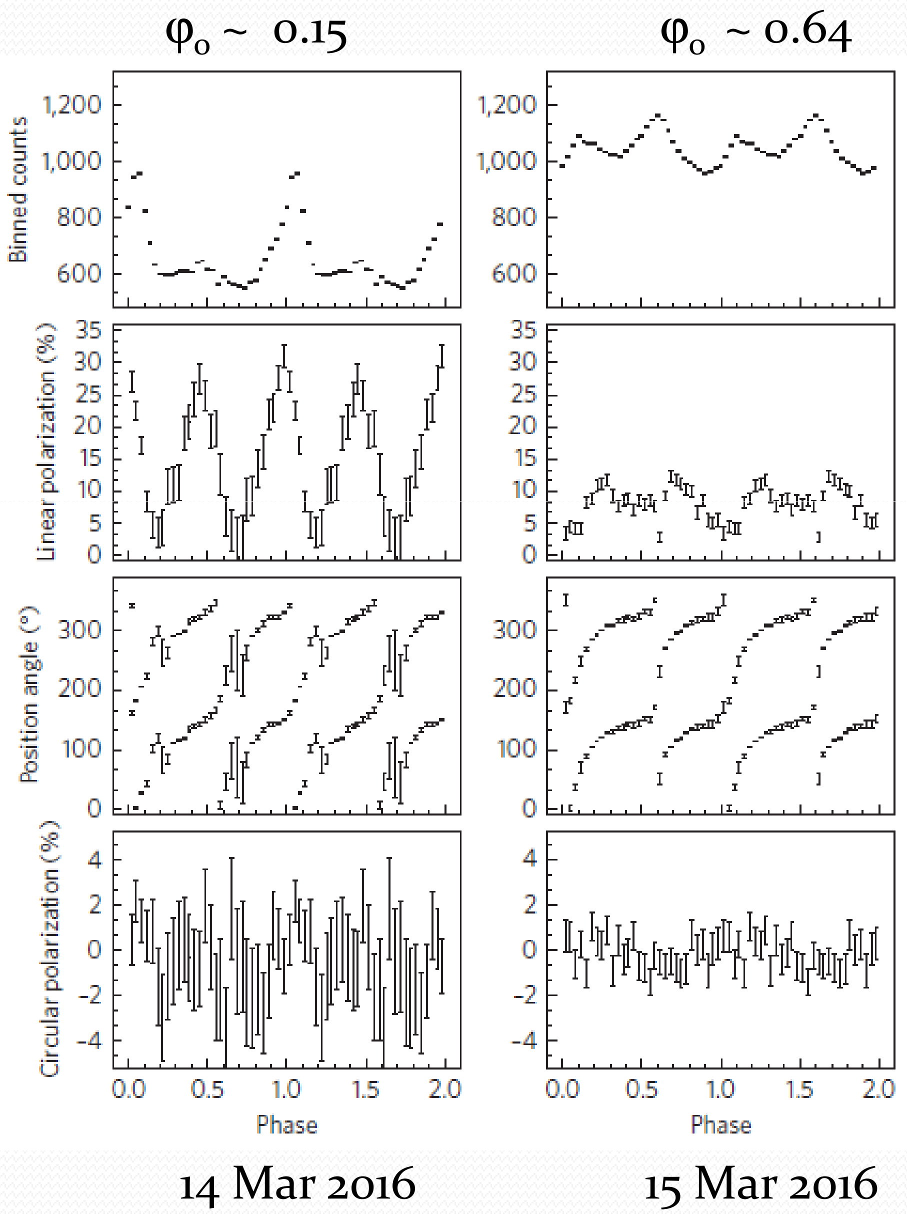
- High level of linear polarization (40%) and lower level of circular polarization (-5% to 5%), consistent with synchrotron emission (de Búrca & Shearer 2015).

- Periodic variations of circular polarization can sometimes be seen, when linear variations have high amplitude.



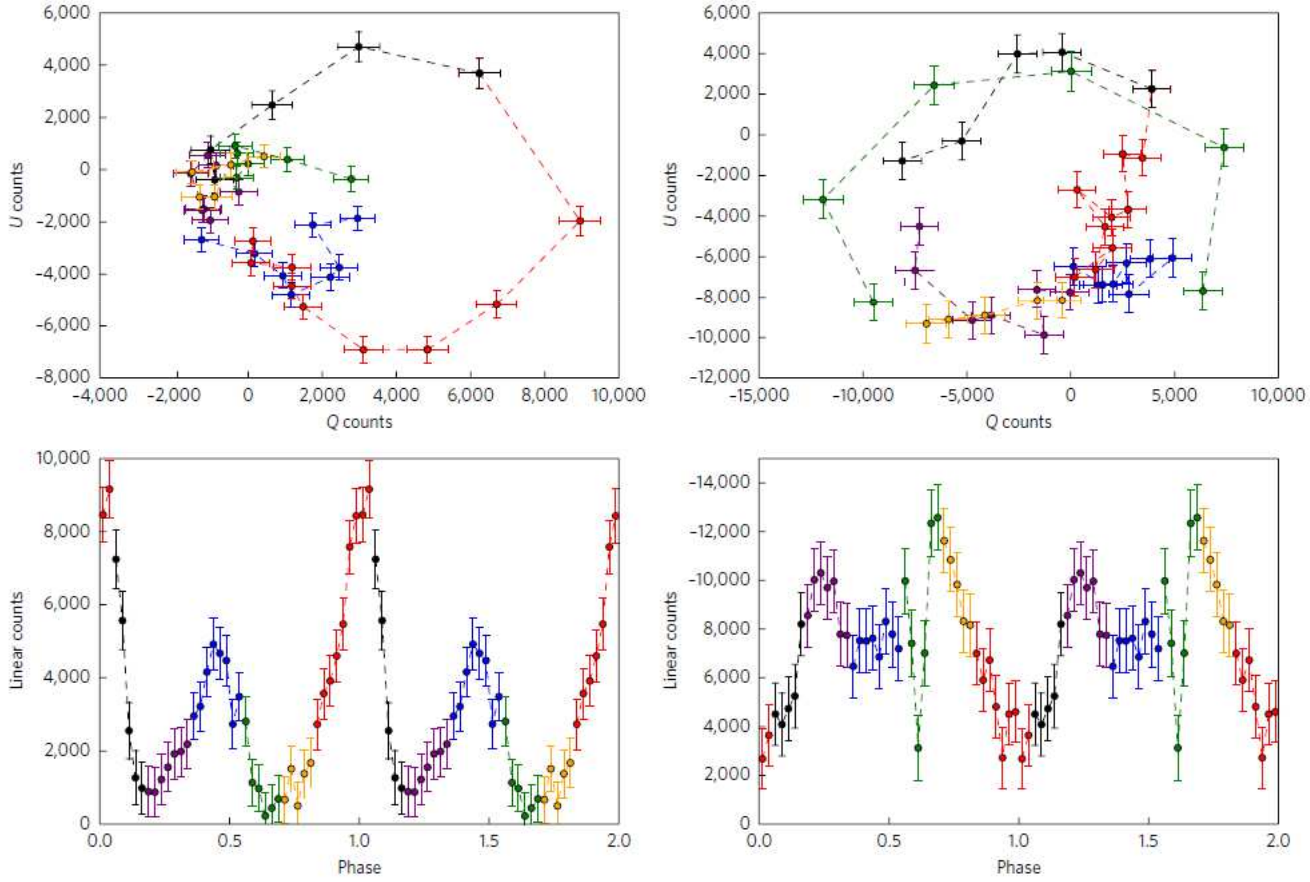
Phase-folded polarization variations

- Fold on the spin period
- Changes from one night to another
- Orbital phase dependency
  - Different aspect of M-star
  - Beat & spin periods interact to modulate waveform



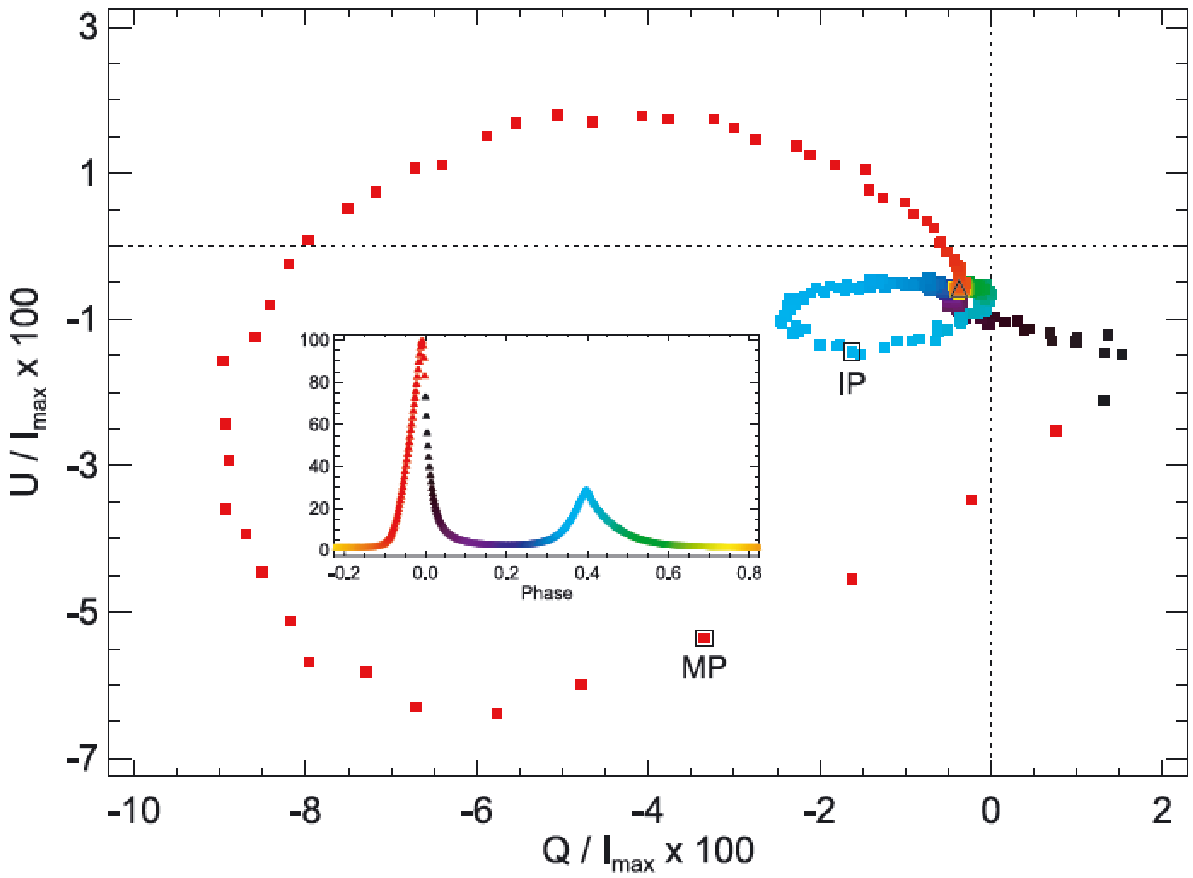
Interpreting the spin modulation

- Looks very like what is expected from a rotating dipole
- Look at *Q, U* plane: points execute counter-clockwise loops



Interpreting the spin modulation of polarization

- Where has this been seen before? Optical polarimetry of the Crab pulsar!
- Interpretation in term of RVM (rotating vector model) for neutron star pulsars
- Many magnetic stars also show similar *Q, U* loops



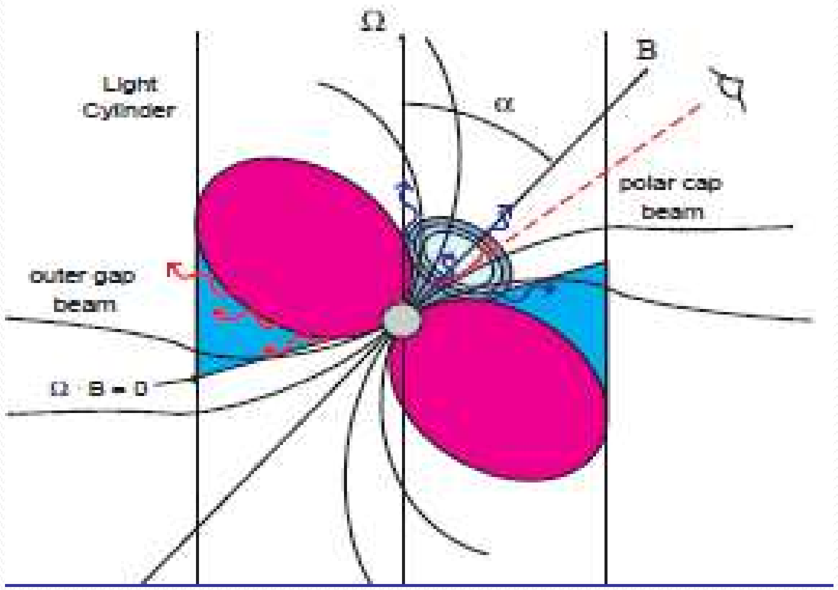
Models and Interpretation

- Large spin-down energy loss from magnetic dipole radiation (Poynting flux) and MHD interactions

$$L_{\rm m-d} = \frac{2B_{1,*}^2\Omega_{\rm rot}^4 R_{\rm wd}^6 \sin^2\chi}{3c^3} \quad \text{which leads to} \quad B_{1,*}\sin\chi = \left(\frac{3c^3 L_{\dot{\nu}_s} P_{\rm wd}^4}{2(2\pi)^4 R_{\rm wd}^6}\right)^{1/2}$$

- Implies *upper limit* of 500MG for WD field *if all the loss is powered by dipole radiation*

$$B_{1,*} \approx 500 \left(\frac{L_{\dot{\nu}_s}}{1.5\times10^{33}\,\text{erg s}^{-1}}\right)^{1/2}\left(\frac{P_{\rm rot}}{117\,\text{s}}\right)^2\left(\frac{R_{\rm wd}}{5.5\times10^8\,\text{cm}}\right)^{-3}\,\text{MG}$$

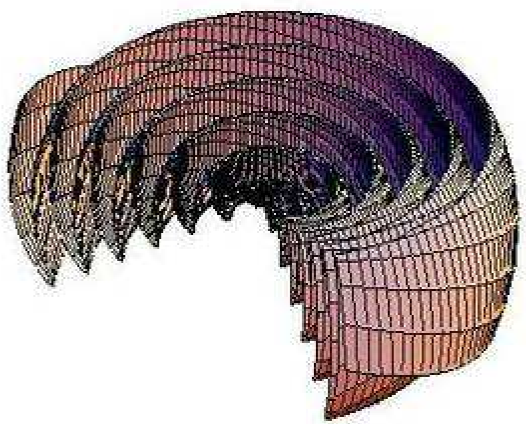


Models and Interpretation

- Polarized flux from WD dipole will be modulated at the spin period
- WD field interactions with M-star coronal loops will generate low ν (<10^{13} Hz) synch at beat period (as seen in radio)
- Spin-down also can be driven by MHD interactions between the WD and M-star, causing “MHD pumping” in the surface layer resulting in B-reconnection and Ohmic diffusion
- High *E*-fields (10^{12} V) can be generated at the light cylinder (~8 × orbital separation) accelerating particles to $\gamma_e \sim 10^6$ leading to polarized synchrotron emission

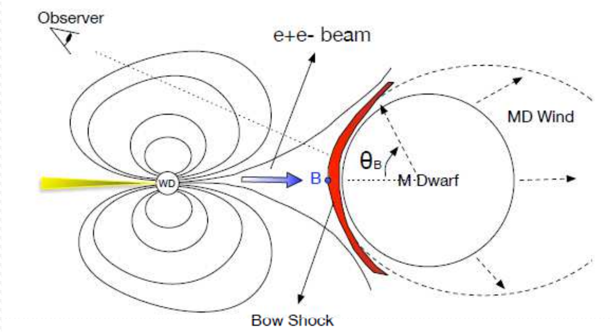
$$\Delta V \approx 10^{12}\left(\frac{P_{\rm wd}}{117\ {\rm s}}\right)^{-5/2}\left(\frac{\mu}{8\times 10^{34}\ {\rm G\ cm}^3}\right)\left(\frac{R_*}{5.5\times 10^8\ {\rm cm}}\right)\ {\rm V}$$

- Oblique dipole will generate relativistic out-flowing MHD “striped” wind, with alternating regions of polarity (e.g. Coroniti 1990) outside the light cylinder



Models and Interpretation

- Another suggestion of a magnetic stand-off shock near the secondary led to an estimate of ~100 MG for WD field strength(Katz 2016; arXiv: 1609.07172v1)
- A bow-shock also suggested by Geng et al. 2016 (arXiv:1609.02508v2)



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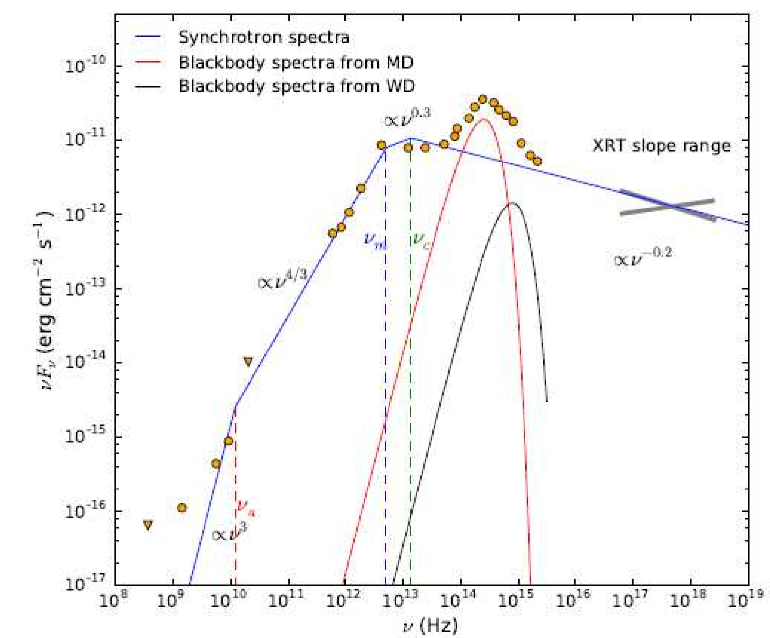
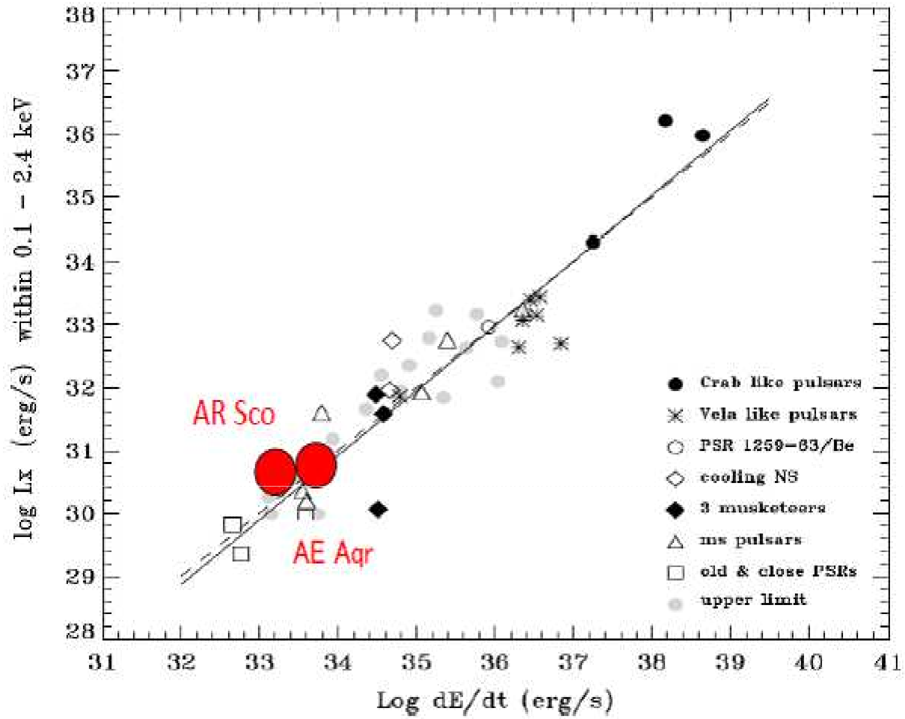
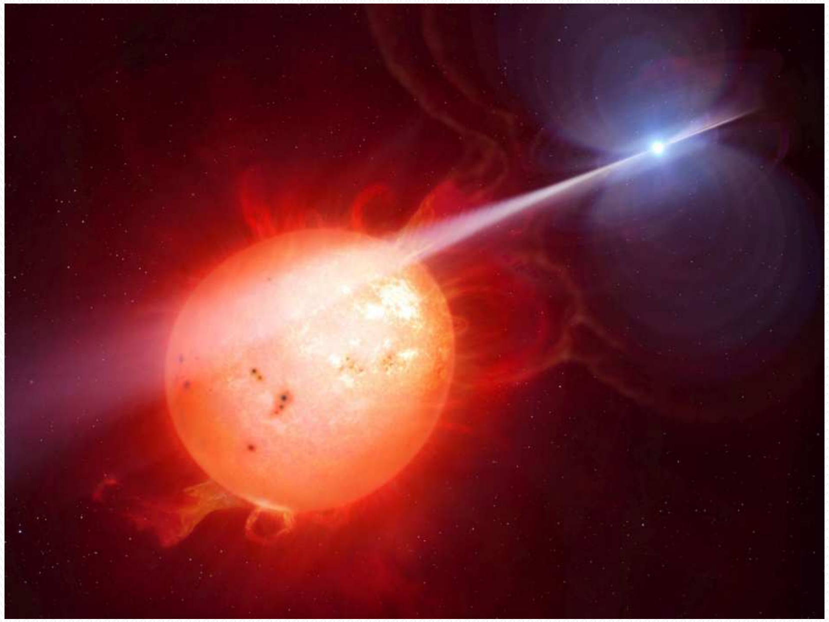
  - <10¹³ Hz (radio-IR)) from pumped coronal loops
  - > 10¹³ Hz (IR-optical-UV-X-ray) from particle acceleration from high *E*-field.



Why call it a White Dwarf Pulsar?

- Spin-down powered
- Dominant synchrotron emission
- Spin modulated magnetic dipole
- Detected from radio to X-rays
- Beamed radiation
- Lorentz factors of ~ γ_e ~400 - 10^6 → relativistic
- electron/proton to be acceleration (strong E-M field and no accreted plasma)

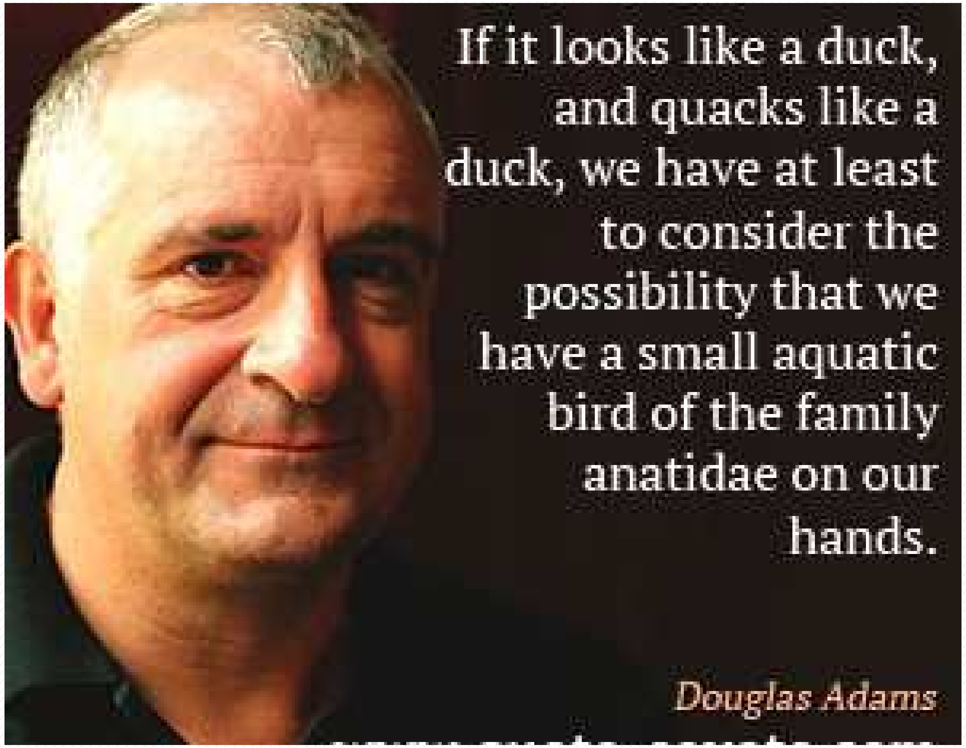




- $L_X / L_{spindown} = 3.3 \times 10^{-3}$
- Same as for pulsars

Ducks and Pulsars

- If it looks like a pulsar….
- Only difference is its not a neutron star



Current & Future Work

Other observations:

- *VLA & VLBI* observations undertaken
  - Varies from 6 – 15 mJy at 9 GHz (VLA)
  - No pulsations at 21 cm
  - Unresolved to a limit of 0.3 milliarcsec ($\Rightarrow < 8R_{\odot} < 4R_{L\text{-}C}$)
- *XMM-Newton* observations in Sep 2016
  - X-rays modulated at the beat period
- *ASTROSAT* observation (50,000 sec) scheduled 29 June – 1 July
- Explore VHE emission possibilities (*HESS)*
- More optical campaigns in 2017 (Apr/May/June/July)
  - ESO, SAAO…
- *Future MeerKAT observations ?*

The End