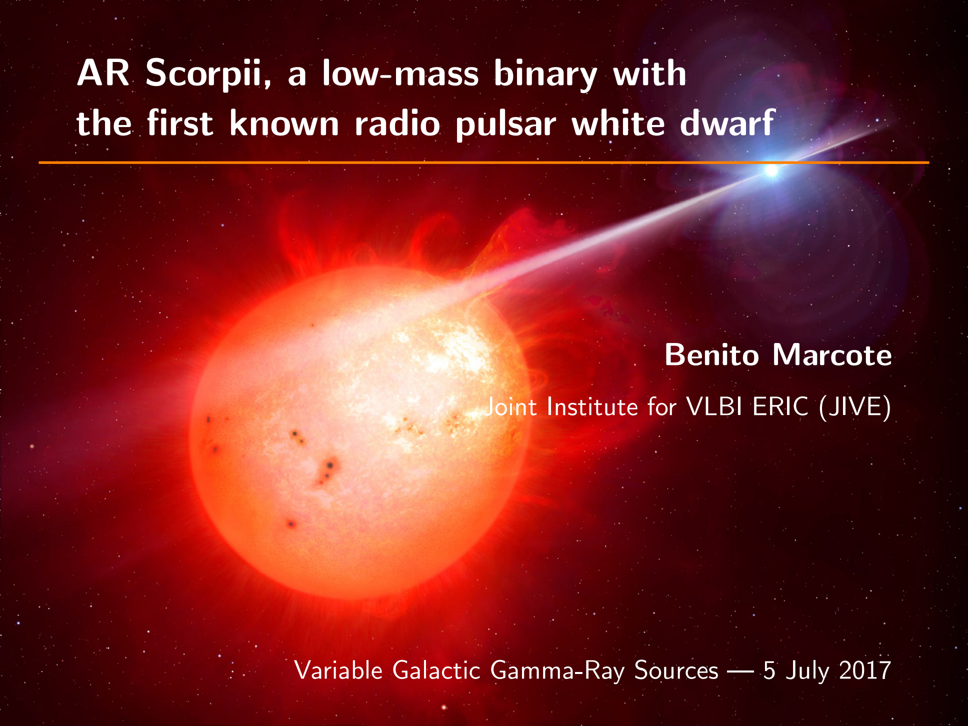
AR Scorpii, a low-mass binary with the first known radio pulsar white dwarf



Benito Marcote

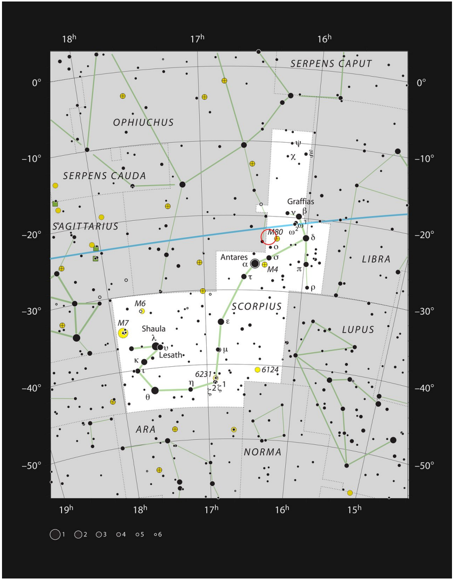
Joint Institute for VLBI ERIC (JIVE)

Variable Galactic Gamma-Ray Sources — 5 July 2017

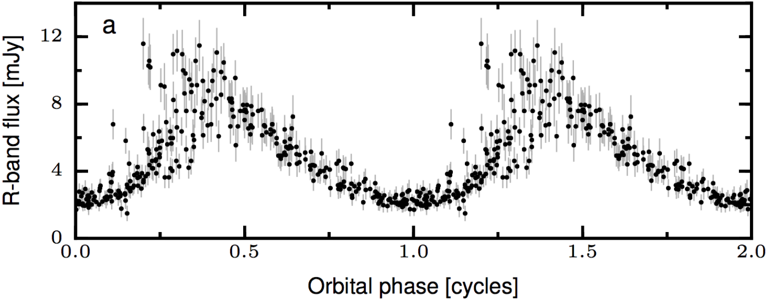
Introducing AR Scorpii

A long time ago. . .

- 14.5–16.5 mag
- 116 pc away
- δ-Scutti star (Satyvaldiev 1971):
  - Pulsations of the star's surface
  - Used as standard candles



Introducing AR Scorpii



AR Sco, a M star + white dwarf binary

- But there is a problem…

  …it is not a δ-Scutti star!

- Light-curve with large scatter

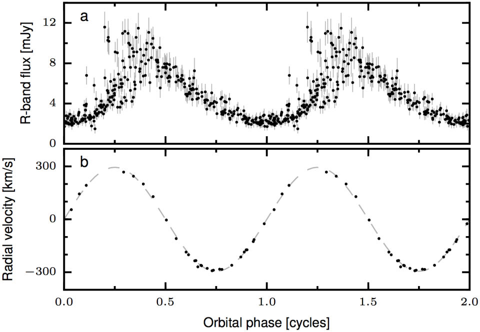
- Binary system

- $P_{\text{orb}} = 3.56$ h

- M star $\approx 0.3\ M_\odot$

  White Dwarf $\approx 1\ M_\odot$

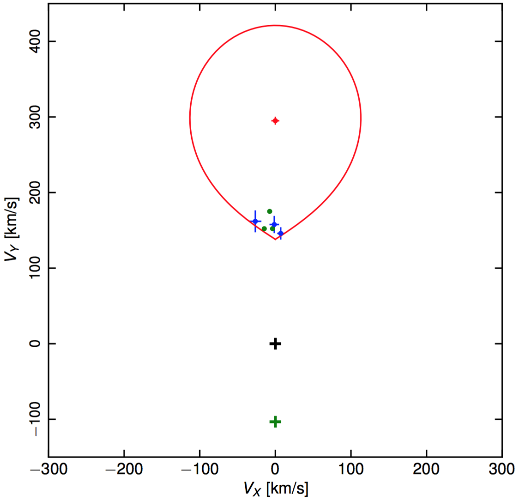
- Emission from radio to X-rays



$\phi = 0.5 \implies$ inferior conjunction

Marsh et al. (2016, Nature, 537, 374)

Origin of the spectral line emission

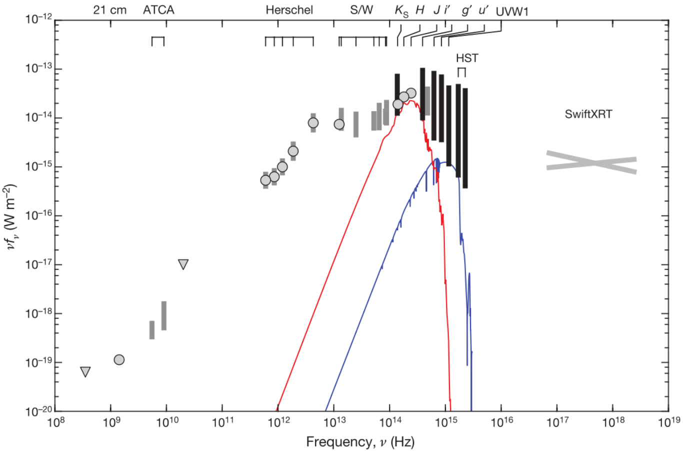


Marsh et al. (2016)

- Roche lobe
- M star
- center of mass
- white dwarf

- SiIV and HeII lines
- Hα, β, γ lines

Spectral Energy Distribution



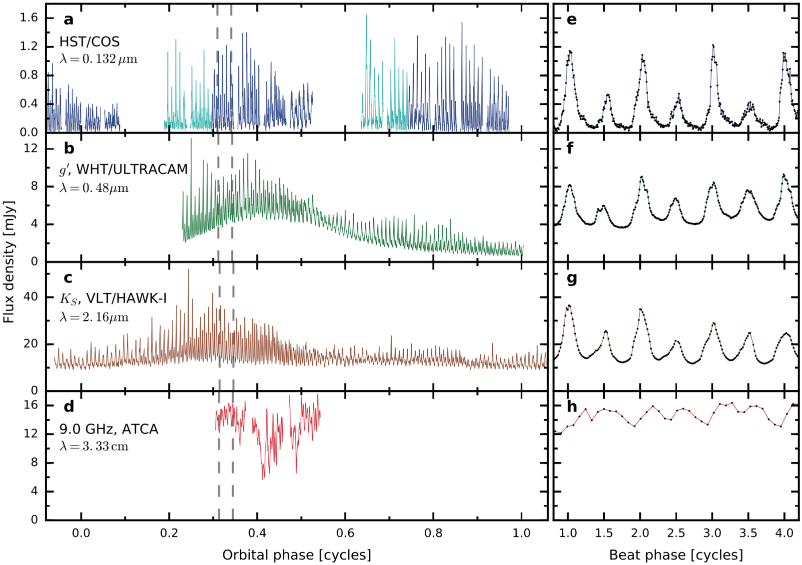
Maximum luminosity $L \approx 6.3 \times 10^{25}$ W

Average luminosity $\bar{L} \approx 1.7 \times 10^{25}$ W

Much larger than the stellar lum. combined: $\sim 4.4 \times 10^{24}$ W

$$L_{0.2\text{–}10\ \mathrm{keV}} \approx 4.9 \times 10^{30}\ \mathrm{erg\ s^{-1}}\ (\sim 4\%\ L_{\mathrm{optical}})$$

AR Sco: light-curves



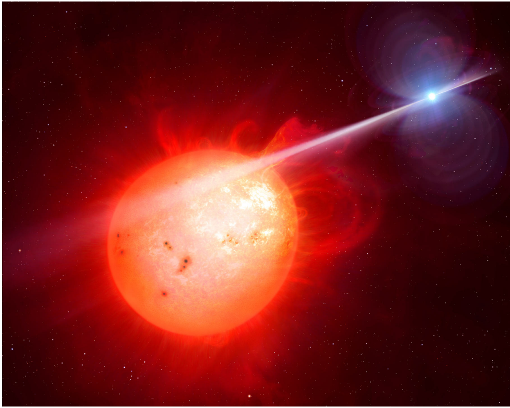
Marsh et al. (2016)

AR Sco: the first pulsar white dwarf

- Orbital period of 3.56 h
- Pulses observed every 1.97 min
- Spin period: 1.95 min
- **AR Sco is the first "so-called" radio pulsar white dwarf**
- Spin-down: $P\dot{P}^{-1} \sim 10^7$ yr

  WD cooling time: $\sim 10^9$ yr

  Spin-up / spin-down cycles?



(Marsh et al. 2016)

A piece of context

- All known binary WD ($\sim$120) but one exhibit flux densities < 1 mJy Barrett et al. (2017)
- Jet outflows are known in some accreting white dwarfs Körding et al. (2008, 2011)
- **AE Aqr** is the exception:
  - Can exceed 10 mJy
  - Rapidly spinning magnetic white dwarf
  - magnetic propeller Wynn et al. (1997), Meintjes et al. (2012)
  - GeV? evidences but no significant (Li et al. 2016)
  - TeV bursts? Meintjes et al. (1994), Bowden et al. (1992), Bowden et al. (1992) and Chadwick et al. (1995) but see (Aleksić et al. (2014)
- **AR Sco**
  - Is also bright ($\sim$10 mJy)
  - No accretion. Propeller system?

The origin of the emission

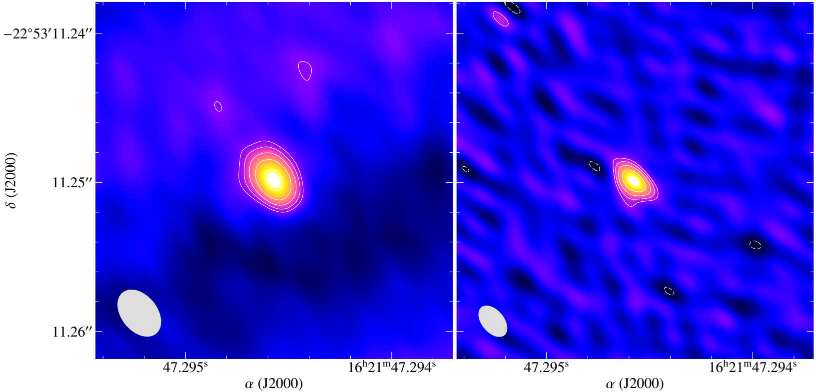
Most of the emission is likely originated in the M star's magnetosphere facing the white dwarf (Marsh et al. 2016, Katz 2017)

How the energy is transferred from the white dwarf to the M star?

Two main possibilities:
(Marsh et al. 2016, Buckley et al. 2017, Katz 2017)

- Collimated relativistic particle outflows
- Direct interaction between the WD magnetosphere and the M star

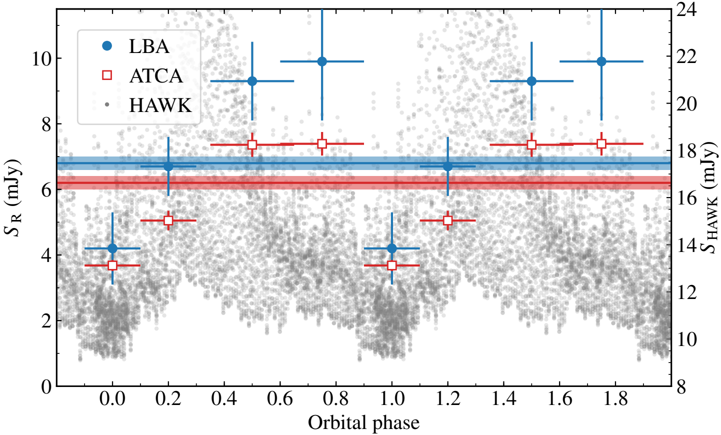
VLBI radio observations with the Australian LBA



Natural weighting (no self-cal.) — vs — zero robust after self-cal.
Contours start at 3σ rms noise level of 0.4 mJy.

Compact emission (< 0.17 mas $= 0.02$ AU $= 4\ R_\odot$)
Marcote et al. (2017, A&A, 601, L7)

VLBI radio observations with the Australian LBA

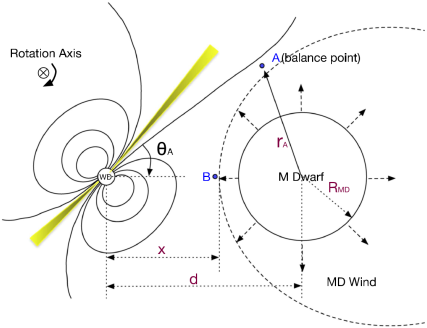


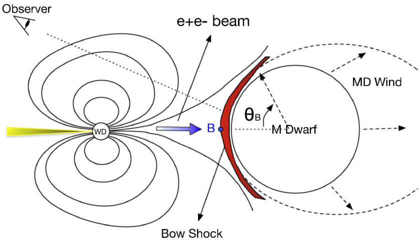
Light-curve of AR Sco from the LBA and ATCA data.
HAWC (IR) data
Marcote et al. (2017, A&A, 601, L7)

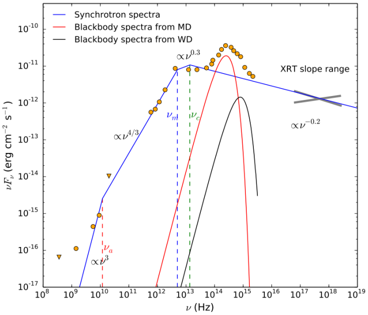
AR Scorpii: a summary

- Luminosity 4–14 times larger than the stellar luminosity combined
- No accretion signatures
- *All* emission is compact (< 0.17 mas $= 0.02$ AU $= 4\ \mathrm{R}_\odot$)
- Non-thermal radio emission ($5 \times 10^9 \lesssim T_b \lesssim 10^{12}$ K)
- Optical emission (Buckley et al. 2017, Nat. Astron, 1, 29):
  - linear polarization up to 40%
  - Circular polarization $\lesssim 5\%$
  - Pulsed emission powered by the spin-down of the WD
  - Highly magnetized ~ 500 MG
- Emission likely to come from the surface of the M star hit by the WD collimated outflow
- Likely to evolve towards a Polar system

AR Scorpii: a summary







Geng et al. (2017, ApJ, 831, L10)

GeV emission from AR Sco?

- In this system, the light-cylinder is $\sim 6 \times 10^{11}$ cm (~ 7.5 times orbital separation)
- At that distance $B \sim 0.4$ G
- $\gamma_e \approx 10^6$ (Buckley et al. 2017)
- No detailed analysis of *Fermi*/LAT data yet
- Flare activity could be expected
- Hints of modulated emission in previous releases?

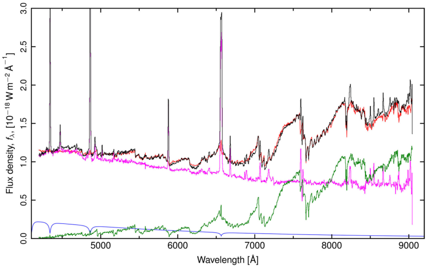
  But no significant enough

Conclusions

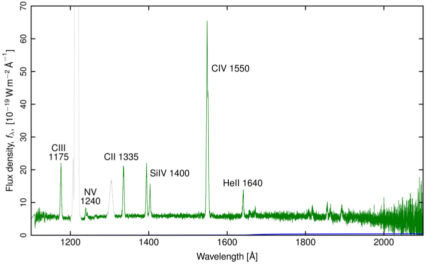
- AR Sco is the first system of its kind
- Contains a pulsing white dwarf with a period of 1.95 min
- Orbiting a low-mass M star
- Emission from the surface of the M star hit by the WD outflow
- New possible γ-ray emitting binary
- Precursors of polar systems?

Thank you!

Optical & ultraviolet spectra



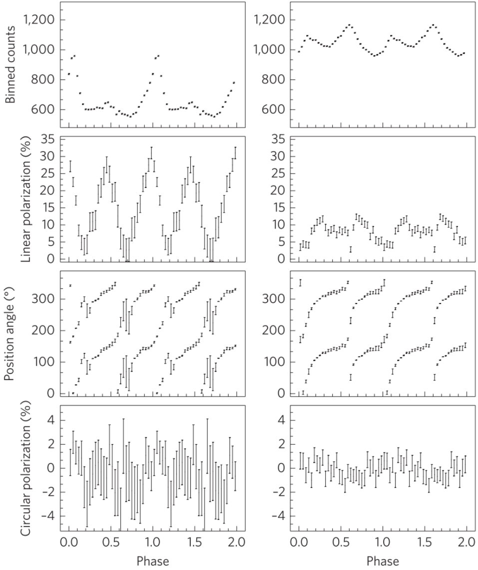
Optical spectrum



Ultraviolet spectrum

Marsh et al. (2016)

Optical polarization



Buckley et al. (2017)