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

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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

![Graph showing R-band flux vs. Orbital phase]
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

$\phi = 0.5 \quad \Rightarrow \quad$ inferior conjunction

Marsh et al. (2016, Nature, 537, 374)
Origin of the spectral line emission

Marsh et al. (2016)
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

$L_{0.2-10 \text{ keV}} \approx 4.9 \times 10^{30}$ erg s$^{-1}$ ($\sim 4\% \ L_{\text{optical}}$)
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: $P \frac{\dot{P}}{-1} \sim 10^7$ yr
- WD cooling time: $\sim 10^9$ yr

Spin-up / spin-down cycles?

(Marsh et al. 2016)
• All known binary WD (∼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 (∼10 mJy)
  • No accretion. Propeller system?
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:

- 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 $= 4 R_\odot$)

Light-curve of AR Sco from the LBA and ATCA data.

HAWC (IR) data

AR Scorpii: a summary

- Luminosity 4–14 times larger than the stellar luminosity combined
- No accretion signatures
- *All* emission is compact ($< 0.17 \text{ mas} = 0.02 \text{ AU} = 4 \ R_\odot$)
- Non-thermal radio emission ($5 \times 10^9 \lesssim T_b \lesssim 10^{12} \text{ K}$)
- 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 $\sim 500 \text{ MG}$
- 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

GeV emission from AR Sco?

- In this system, the light-cylinder is $\sim 6 \times 10^{11}$ cm ($\sim 7.5$ 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)