Bow Shock Emission Model For the White Dwarf Pulsar AR Scorpii

Yong-Feng Huang

（黄永锋，南京大学）

Nanjing University, China

Collaboration: Jin-Jun Geng, Bing Zhang

Geng, Zhang & Huang, 2016, ApJL, 831, L10 (arxiv:1609.02508)

Outline

1. AR Scorpii --- introduction
2. Bow shock emission model
3. Conclusions

the AR Scorpii system

A binary system: white dwarf + M star (116 pc)

Orbital period: 3.56 h, nearly circular orbit

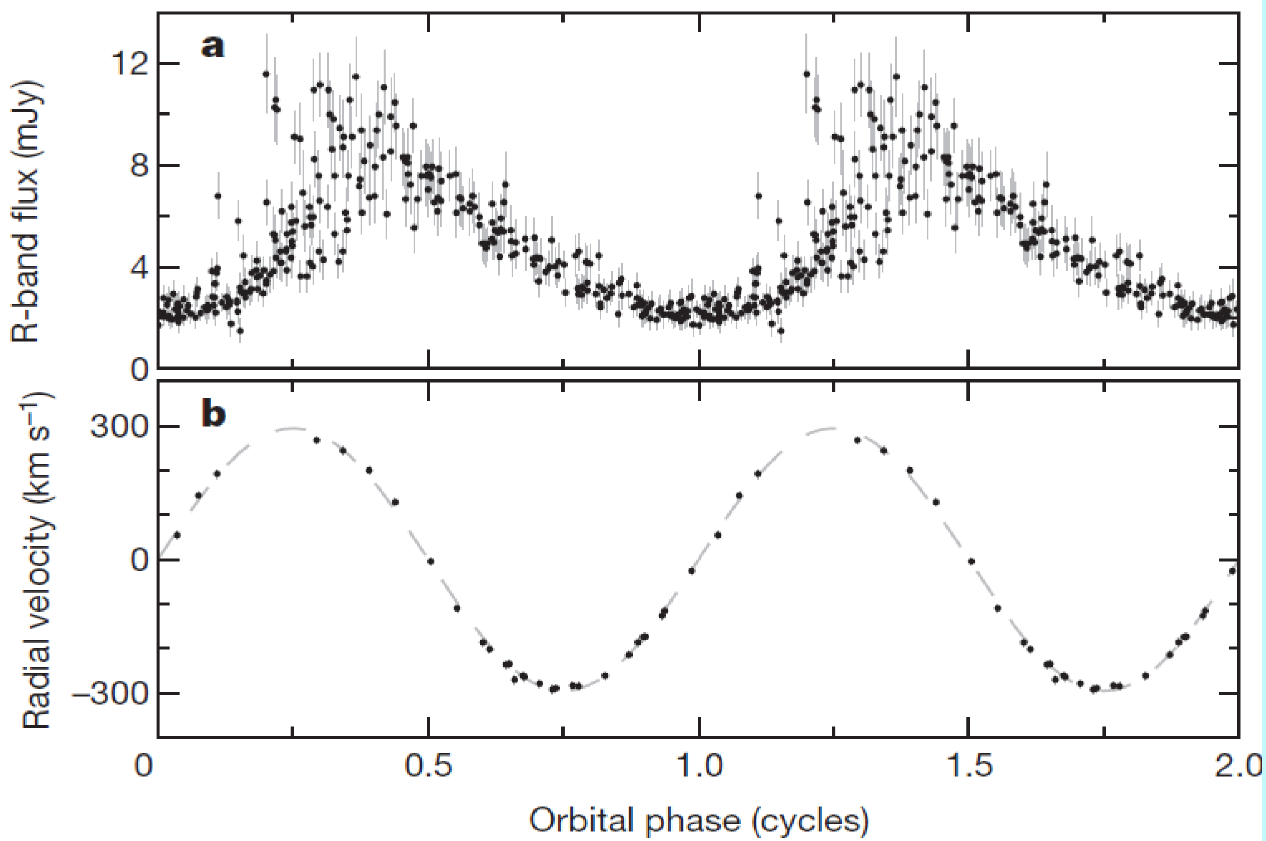
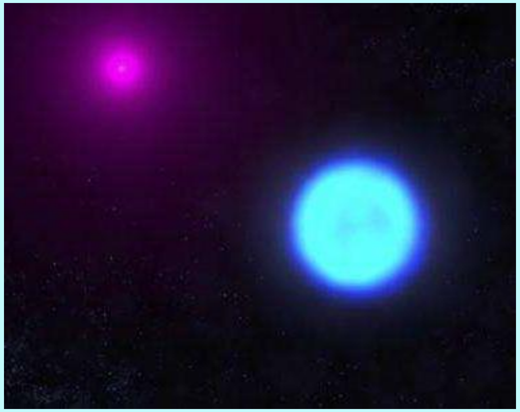
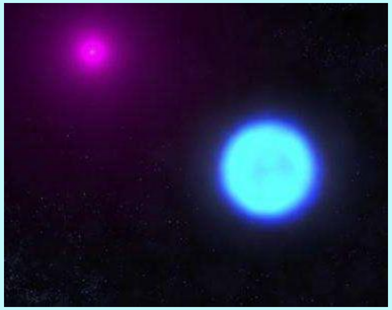


Figure 1 | AR Sco's optical brightness and radial velocity curve.
a, Photometry (30-s exposures) taken over 7 years shows a factor of four



Marsh et al. 2016, Nat

the AR Scorpii system



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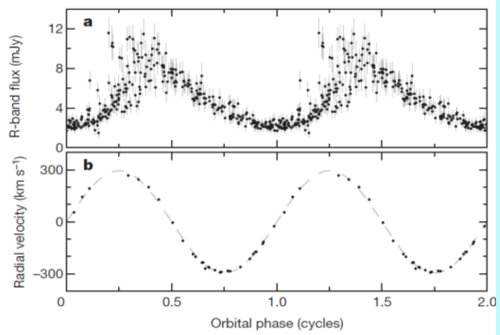
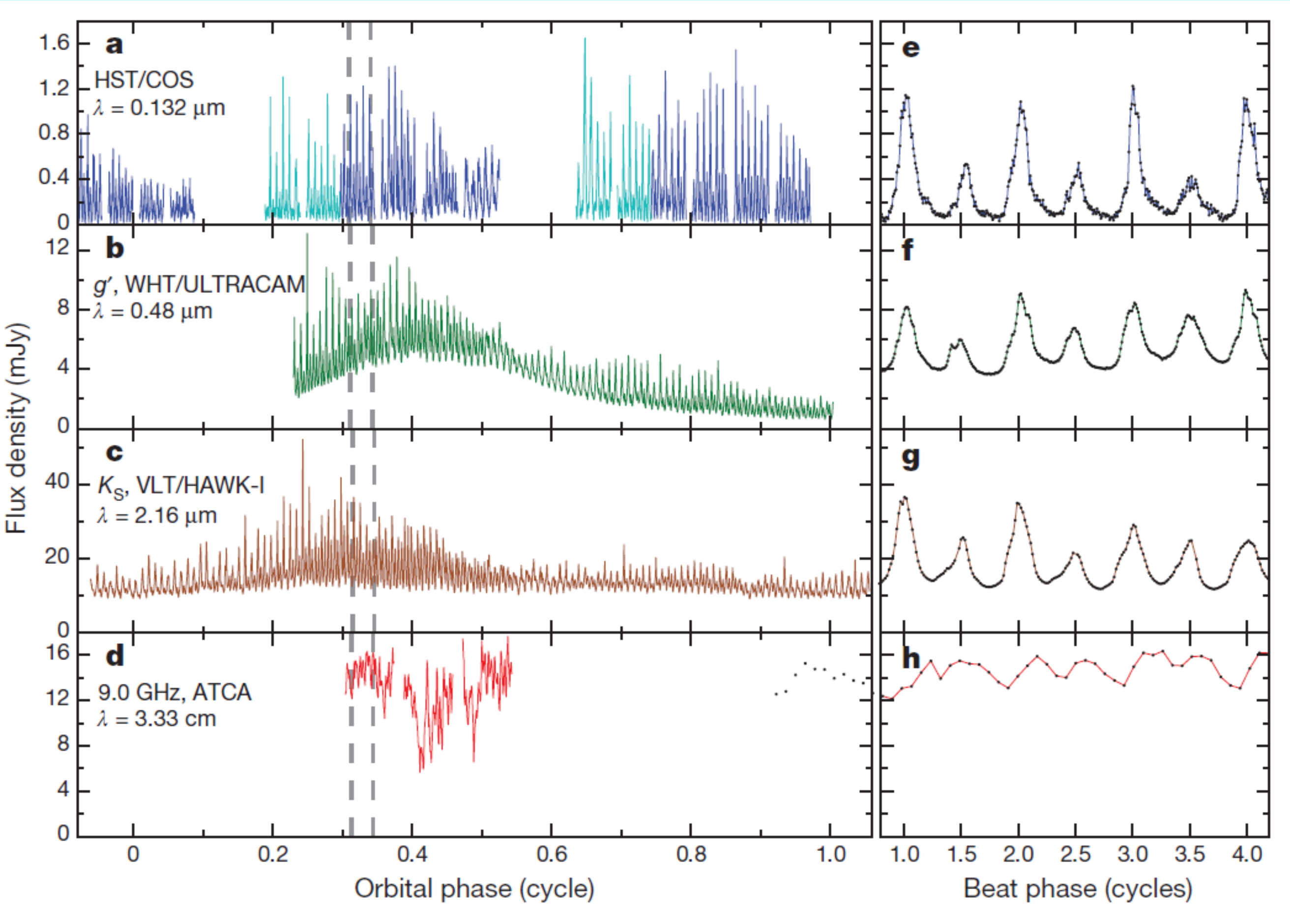


1.97 minutes period



High speed multi-band measurements

Marsh et al. 2016, Nat

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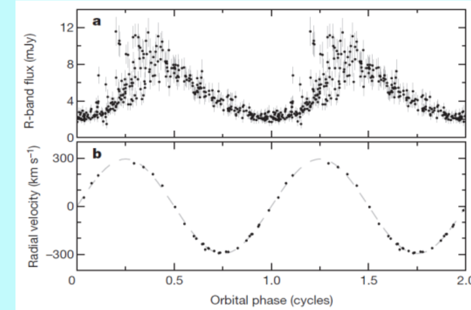

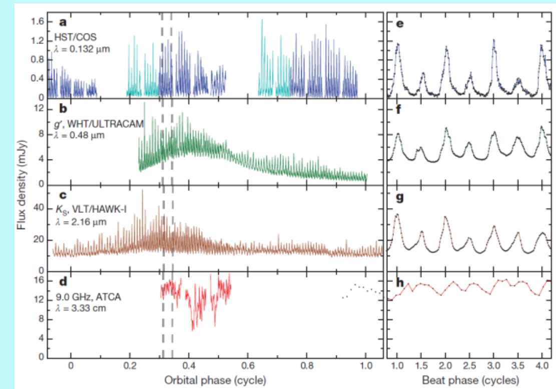

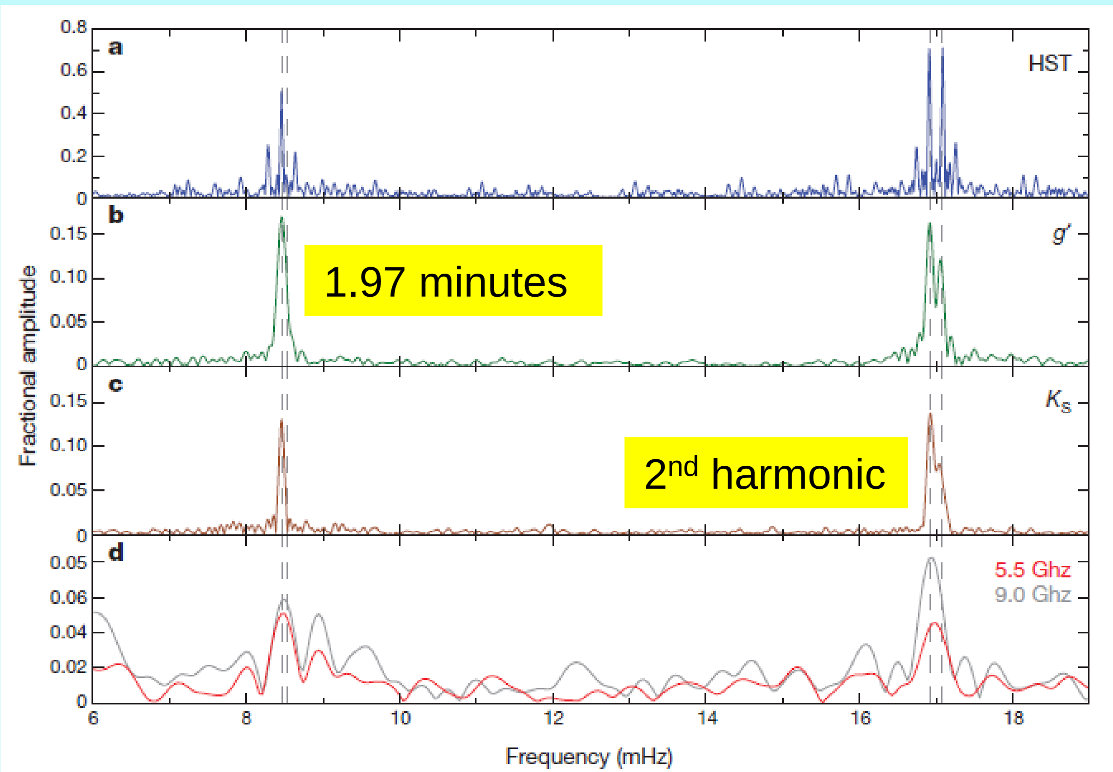

Fourier amplitudes vs. frequency

Marsh et al. 2016, Nat

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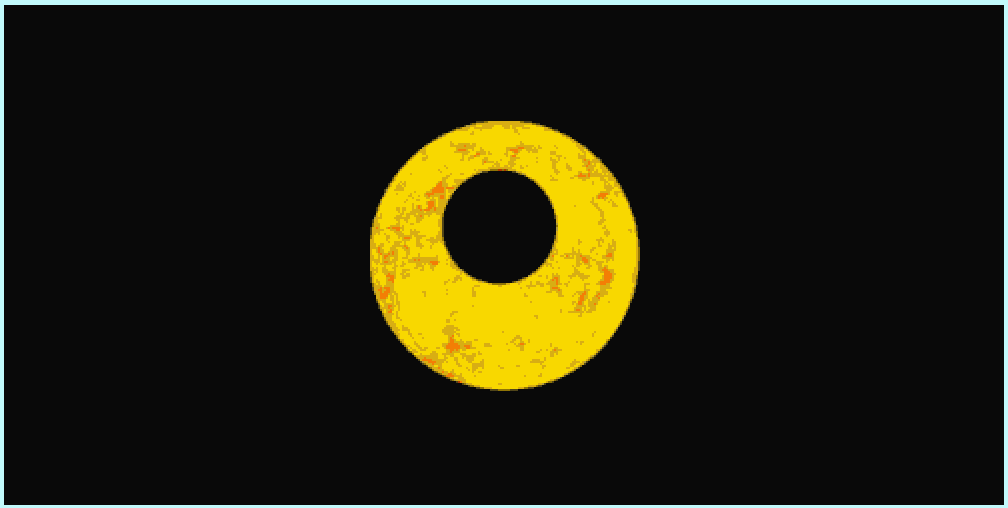

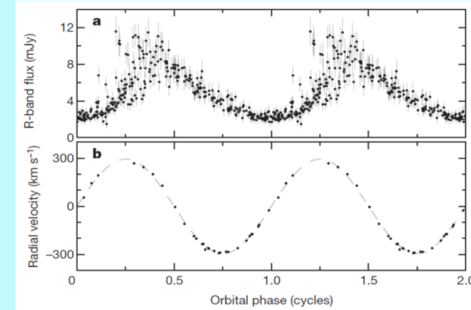

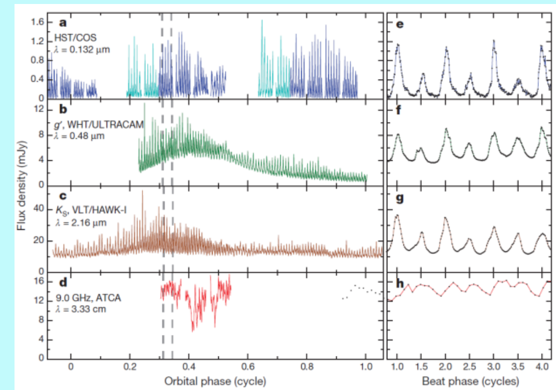

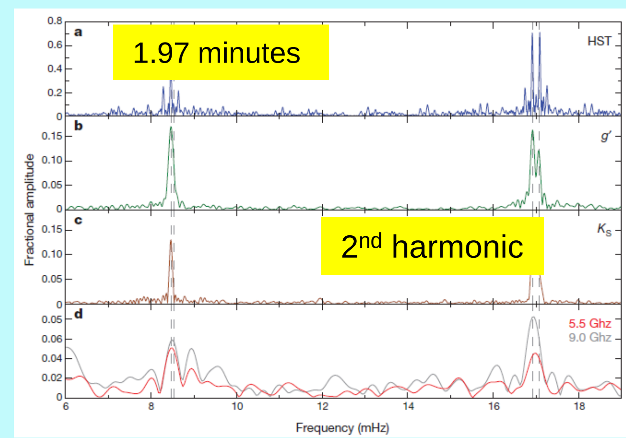

Beat frequency: $\nu_B = \nu_S - \nu_O$

$P_B = 1.97$ min
$P_O = 3.56$ h

WD spin period: $P_S = 1.95$ min

Marsh et al. 2016, Nat

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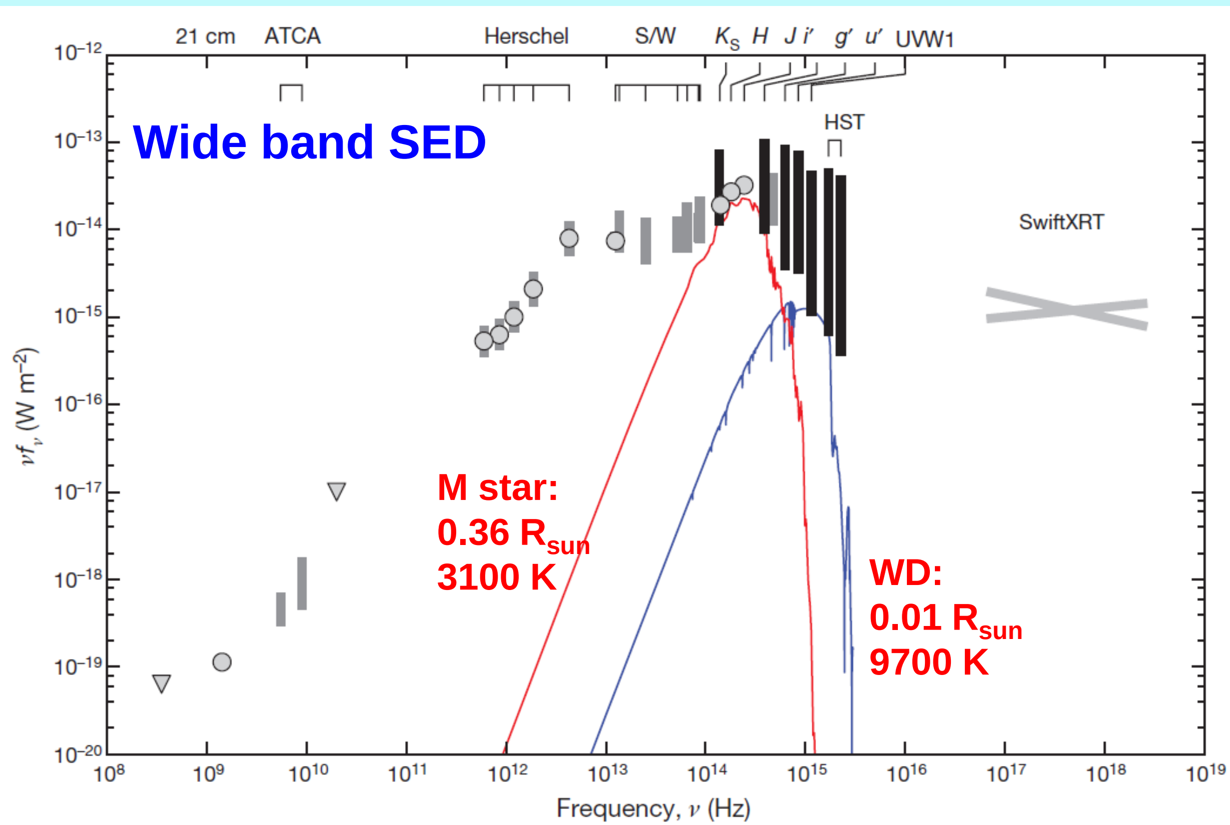
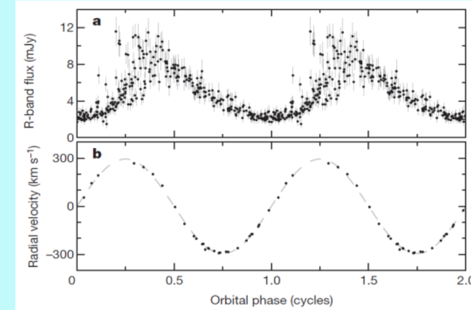
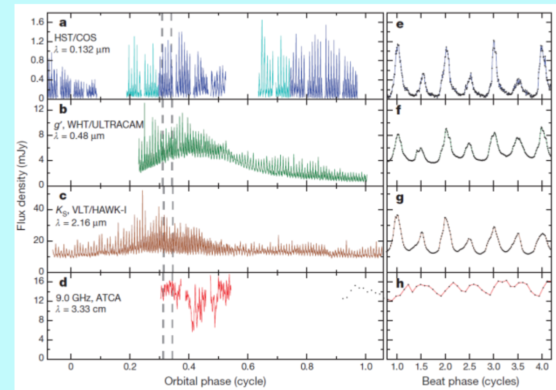
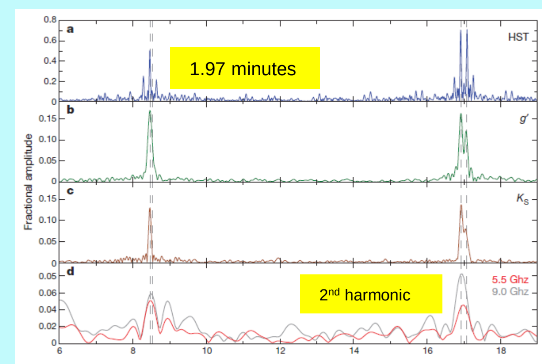








Marsh et al. 2016, Nat

Takata, Yang & Cheng, 2017:

Emission from relativistic electrons trapped by closed magnetic field lines of the magnetic WD

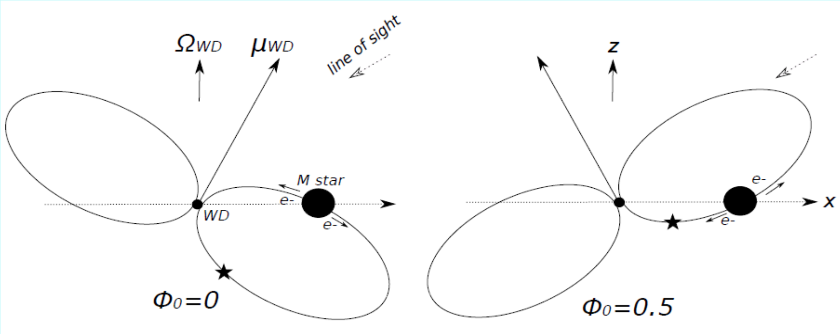


Fig. 1.— Schematic view of the AR Sco system and the coordinate in the study. The observer is located within the plane made by the spin-axis (z-axis) and x-axis. The spin

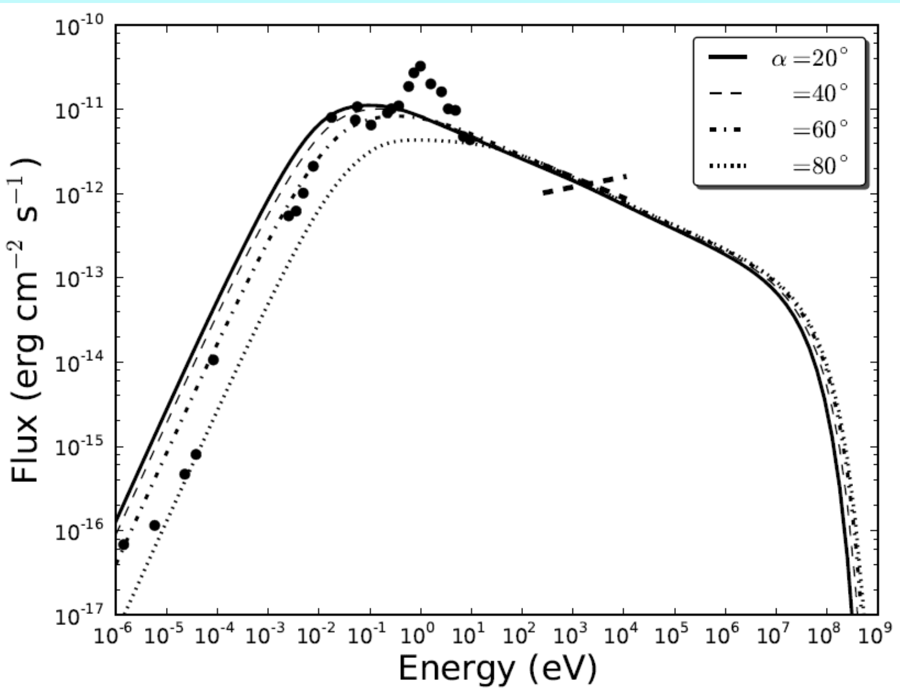
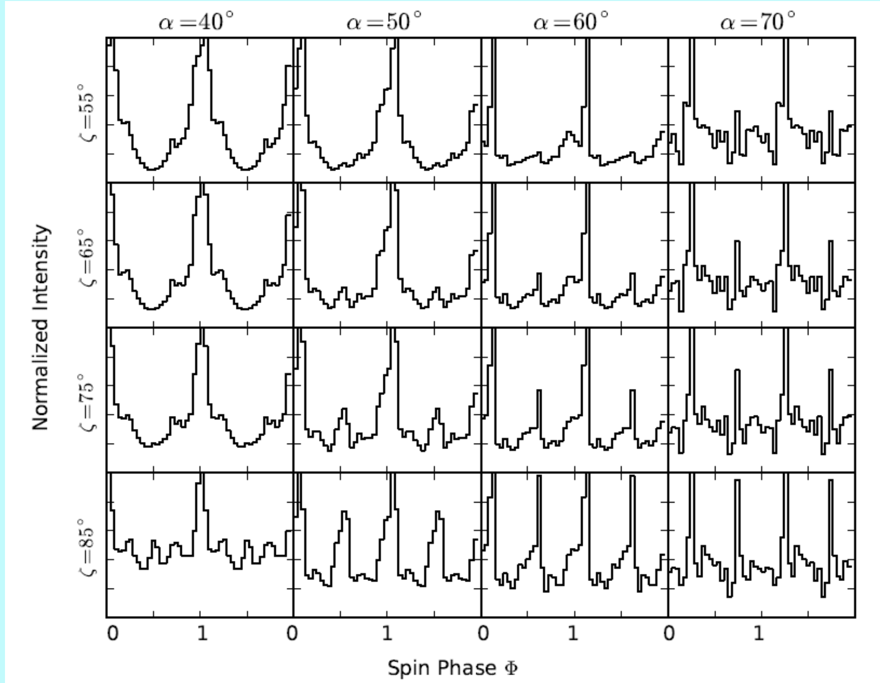


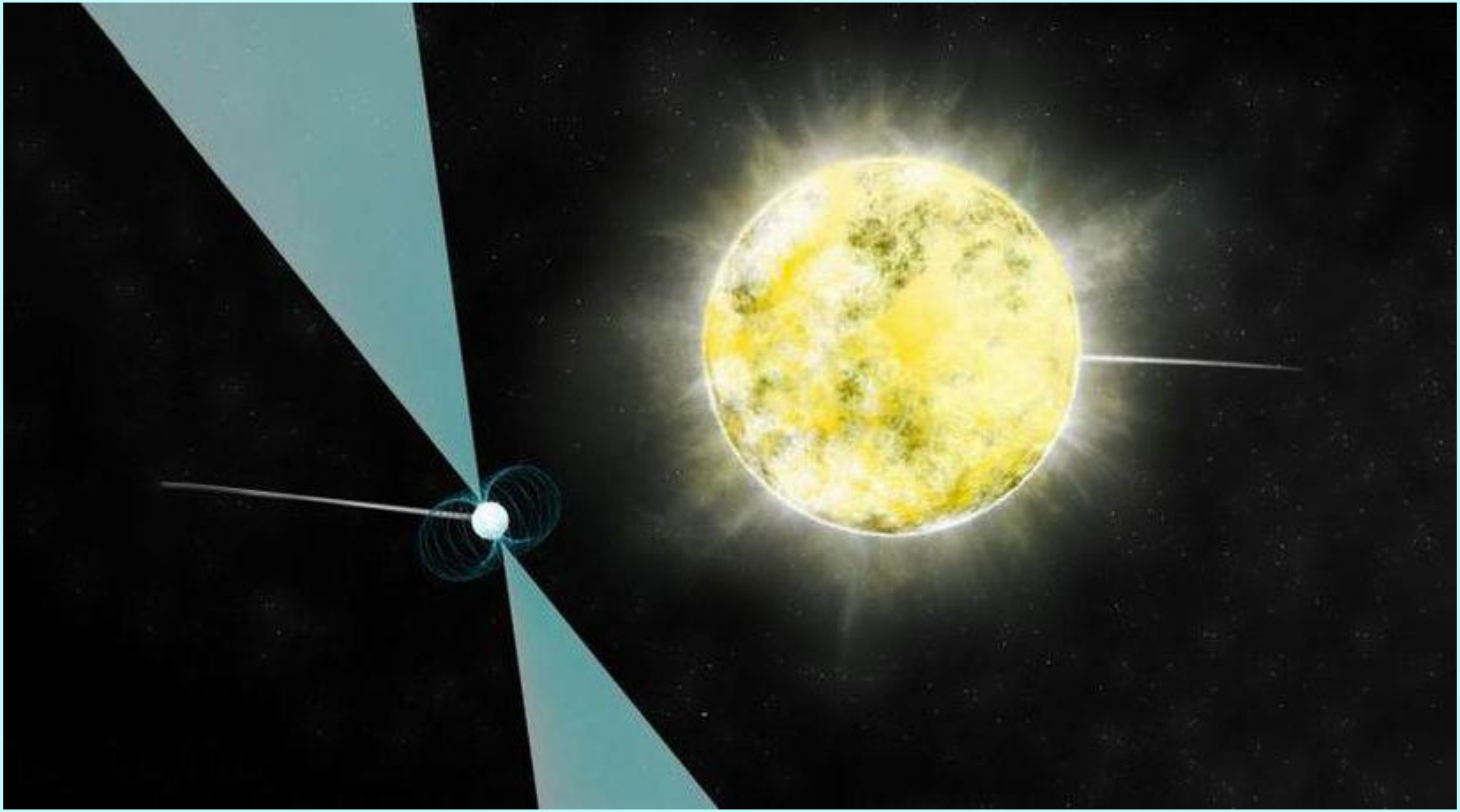
Fig. 10.— Spectrum of ARScorpii. The observational data (filled circles and thick c



ig. 6.— Light curve in 0.1-1eV energy bands as a function of the inclination angle (α)
ie viewing angle (ζ). The companion star is located between the WD and observer (inf

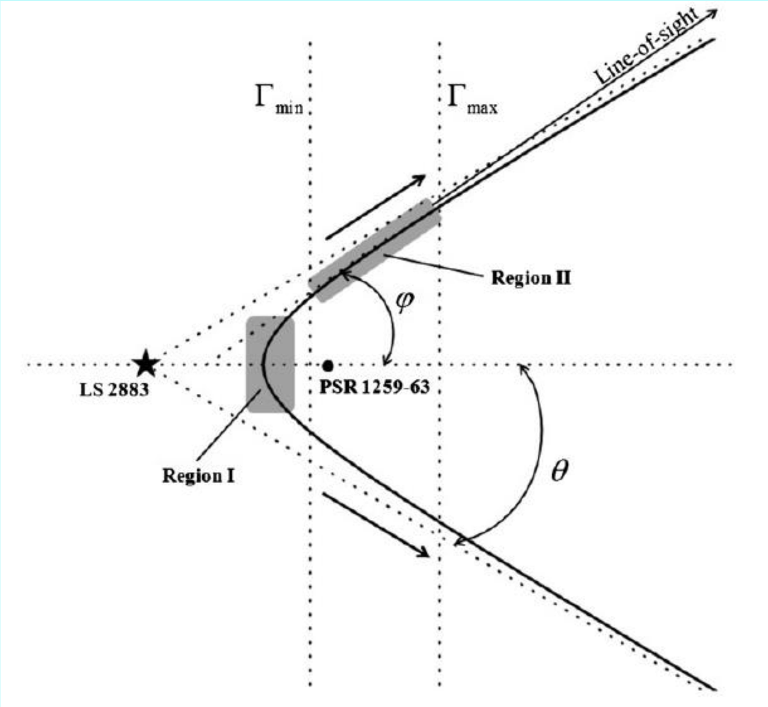
Takata J., Yang H., Cheng K.S. 2017, ApJ

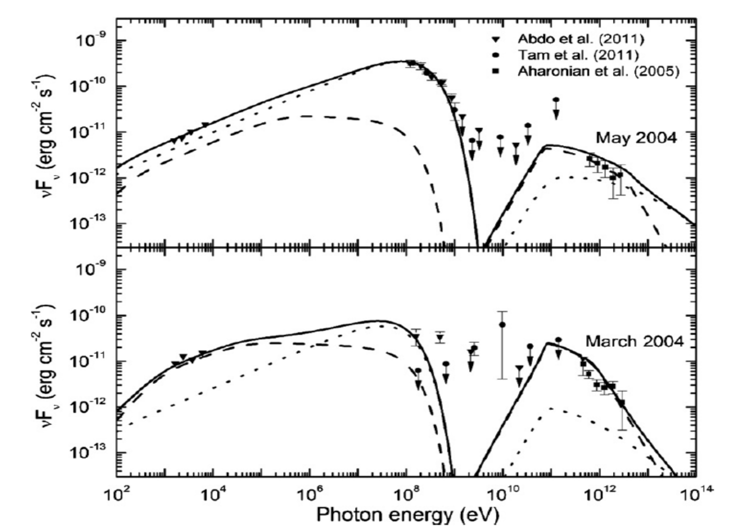
Our model：bow shock emission

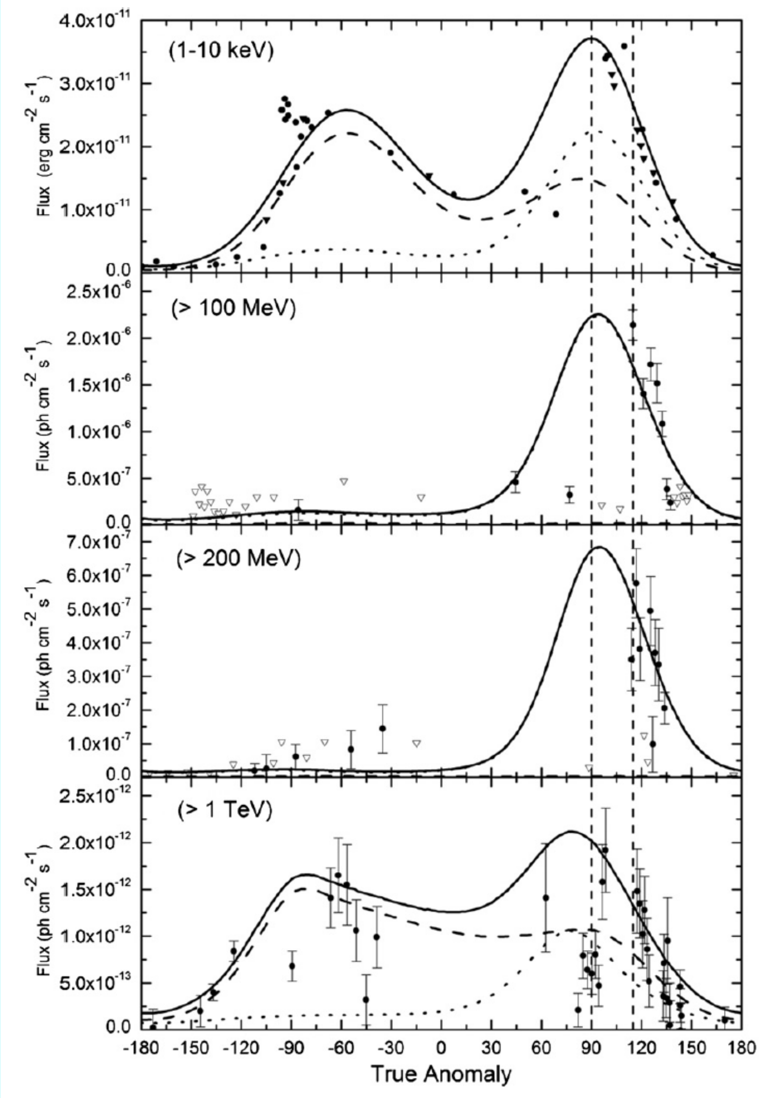


Picture taken from the website:
http://news.52shehua.com/article_img-6499.html

K. S. Cheng et al.: Bow shock in PSR 1259-63 / LS 2883 system







Kong, Cheng & Huang, 2012, ApJ
also see: Kong, Yu, Huang, Cheng, 2011, MNRAS

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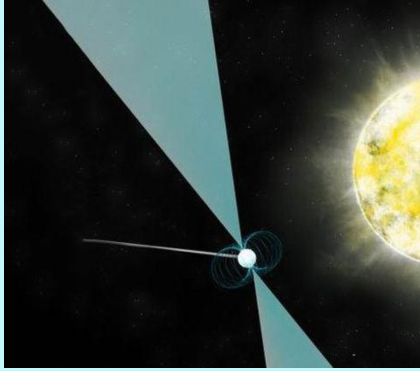
The WD as a pulsar



$M_{\rm WD} = 0.8 M_\odot$ $R_{\rm WD} = 7 \times 10^8$ cm

Marsh et al. 2016

$P = 1.95$ min $\dot{P} = 3.9 \times 10^{-13}$s s^{-1}

Spin down luminosity: $\dot{E}_{\rm rot} = -4\pi^2 I \dot{P} P^{-3} \simeq 3.0 \times 10^{33}{\rm erg\ \ s^{-1}}$

For dipole and wind outflow, magnetic spin down power:

$$\dot{E}_{\rm mag} \simeq \frac{(2\pi)^4 B_p^2 R_{\rm WD}^6}{6c^3P^4}$$

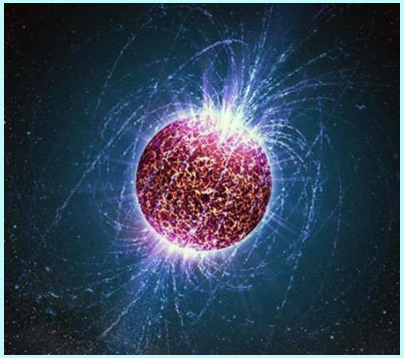
$$B_p \simeq \left(\frac{3M_{\rm WD}c^3}{5\pi^2 R_{\rm WD}^4} P\dot{P}\right)^{1/2} = 7.1 \times 10^8\ {\rm G} \left(\frac{P}{1.95\ {\rm minutes}} \frac{\dot{P}}{3.9 \times 10^{-13}{\rm s\ s^{-1}}}\right)^{1/2}$$

$R_{\rm lc} = cP/2\pi = 5.6 \times 10^{11}$ cm > WD-MD distance: $d \sim 7.6 \times 10^{10}$cm

The MD is in the magnetosphere of the WD.

Geng, Zhang & Huang 2016, ApJL, 831, L10

The WD as a pulsar (Zhang & Gil 2005)



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$$M_{\rm WD} = 0.8 M_\odot$$

$$R_{\rm WD} = 7 \times 10^8\ {\rm cm}$$

$$P = 1.95\ {\rm min}$$

$$\dot{P} = 3.9 \times 10^{-13}{\rm s\ s^{-1}}$$

Polar cap opening angle:

$$\theta_{\rm open} = \left(\frac{R_{\rm WD}}{R_{\rm lc}} \right)^{1/2} = 2^\circ \left(\frac{P}{1.95\ {\rm minutes}} \right)^{-1/2}$$

Polar cap radius:

$$R_{\rm pc} = R_{\rm WD} \left(\frac{R_{\rm WD}}{R_{\rm lc}} \right)^{1/2} = 2.5 \times 10^7 \left(\frac{P}{1.95\ {\rm minutes}} \right)^{-1/2} {\rm cm}$$

Maximum potential drop across the cap:

$$\Phi_{\rm max} = \frac{2\pi^2 B_p R_{\rm WD}^3}{c^2 P^2} \simeq 3.9 \times 10^{11}{\rm statV} \times \left(\frac{P}{1.95\ {\rm minutes}} \right)^{-3/2} \left(\frac{\dot{P}}{3.9 \times 10^{-13}{\rm s\ s^{-1}}} \right)^{1/2}$$

Can accelerate electrons to:

$$\gamma_e = q_e \Phi_{\rm max}/m_e c^2 \simeq 2.3 \times 10^8$$

Geng, Zhang & Huang 2016, ApJL, 831, L10

The WD as a pulsar: polarization observations

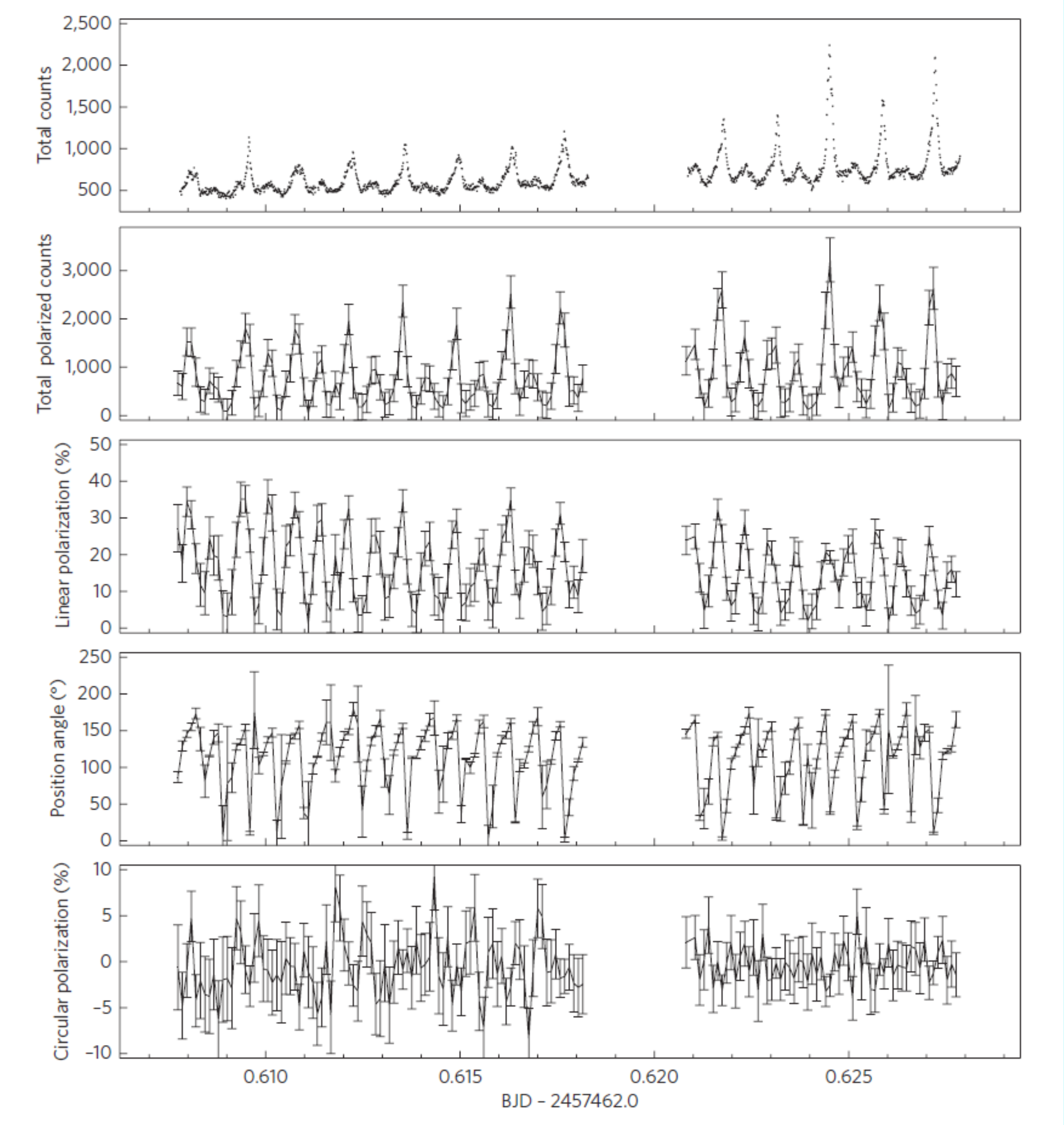
Total counts:

Total polarized counts:

Linear polarization: (up to 40%)

Polarization angle:

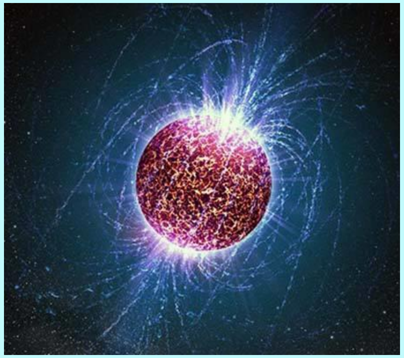
Circular polarization: (up to n%)

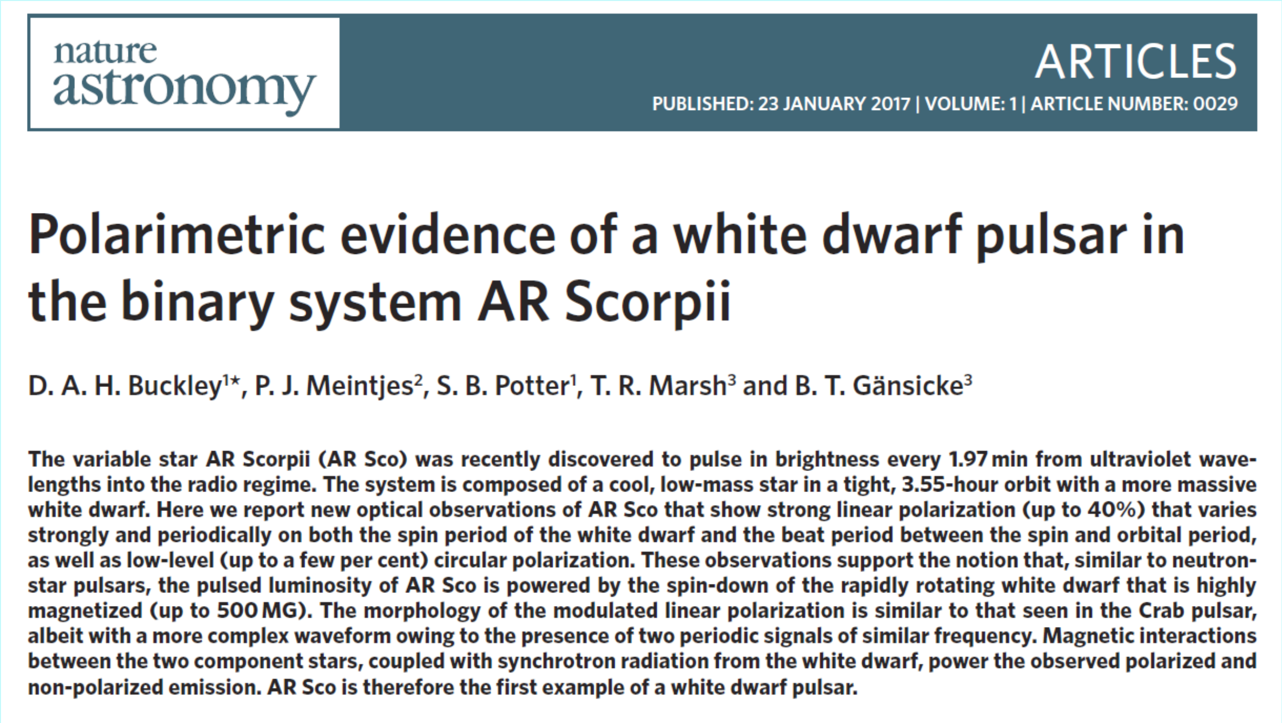


Buckley et al: Polarization behavior is similar to Crab pulsar.

Buckley et al. 2017, Nat Astron.

The WD as a pulsar

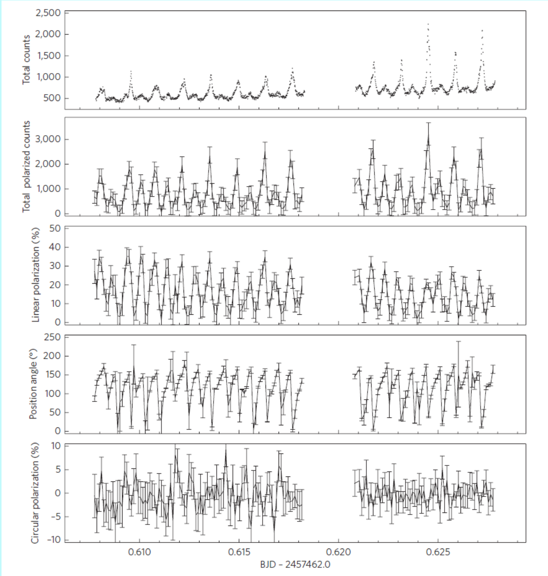



nature astronomy
ARTICLES
PUBLISHED: 23 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0029

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

D. A. H. Buckley[1]*, P. J. Meintjes[2], S. B. Potter[1], T. R. Marsh[3] and B. T. Gänsicke[3]

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.

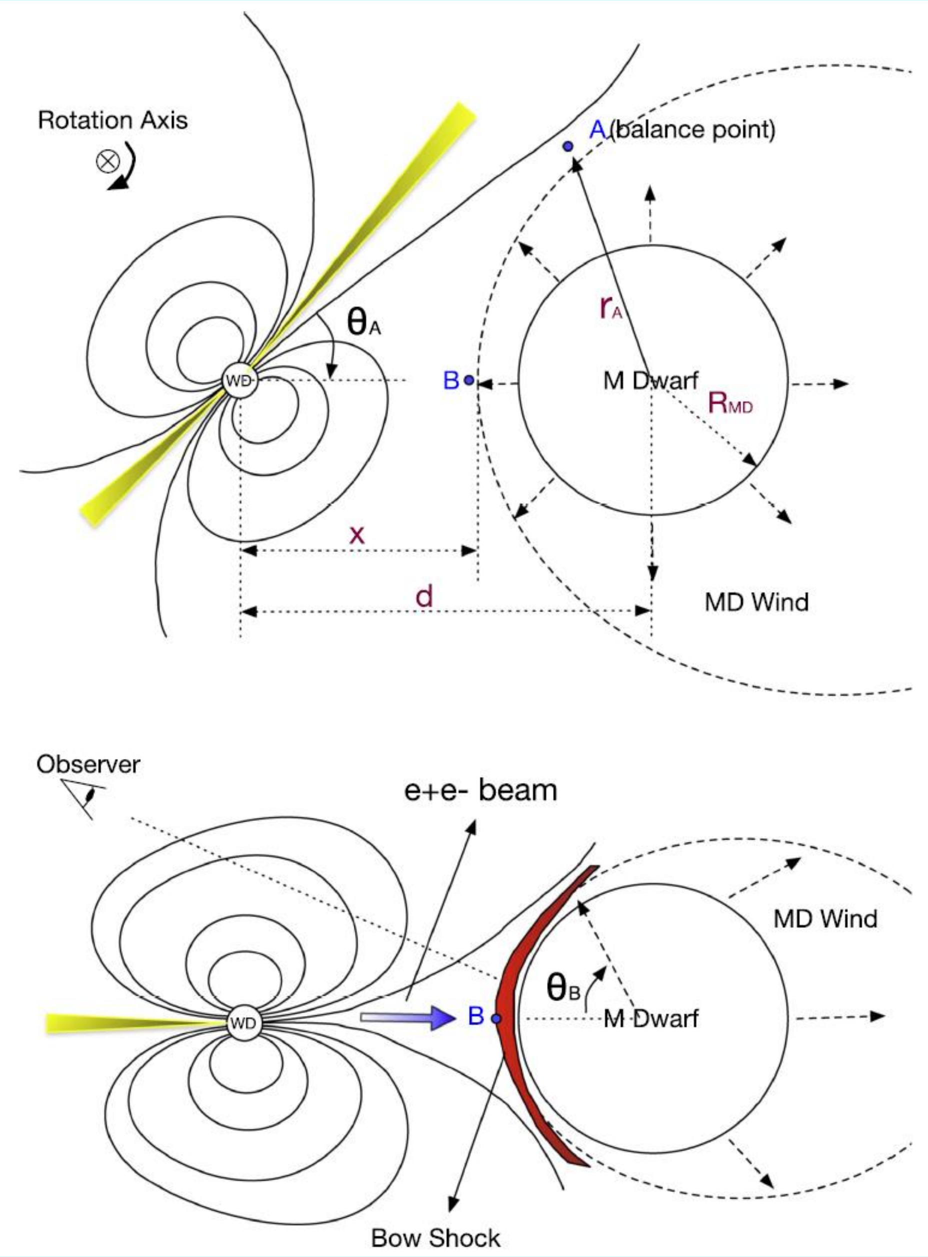


Polarization behavior is similar to Crab pulsar.

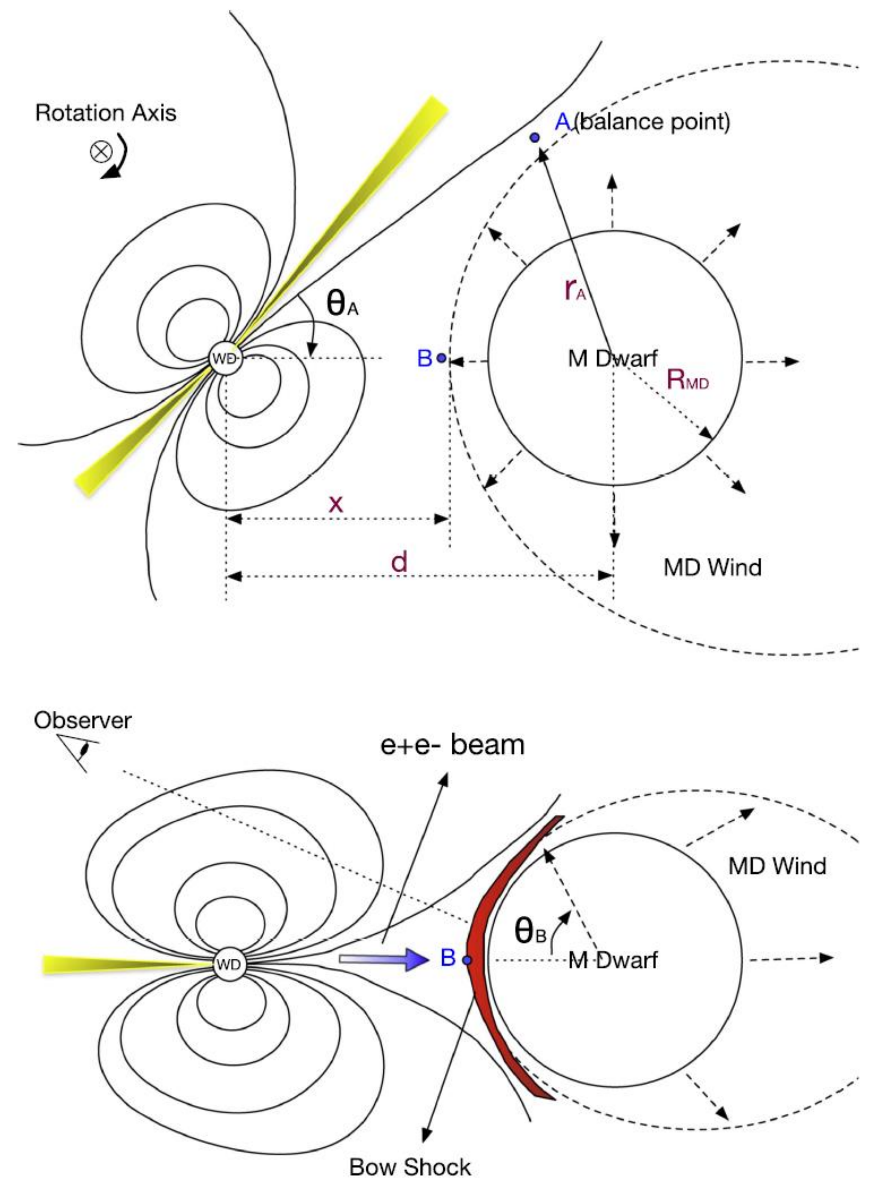
The WD is highly magnetized: ~ 5×10^8 G.

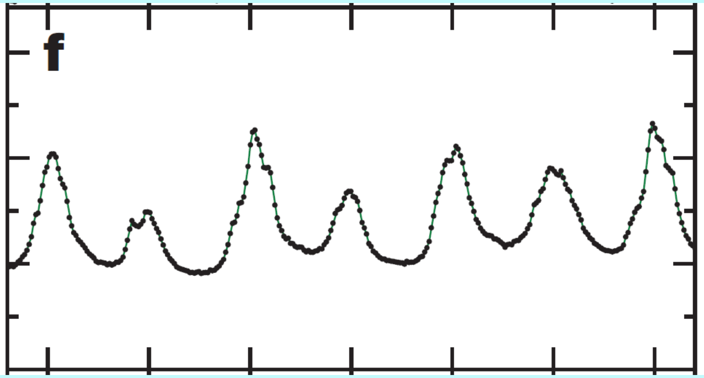
"AR Sco is therefore the first example of a white dwarf pulsar."

Buckley et al. 2017, Nat Astron.



Geng, Zhang & Huang 2016, ApJL, 831, L10





Two peaks, with similar amplitude: a nearly perpendicular rotator

The peaks are wide (duty cycle ~50%):

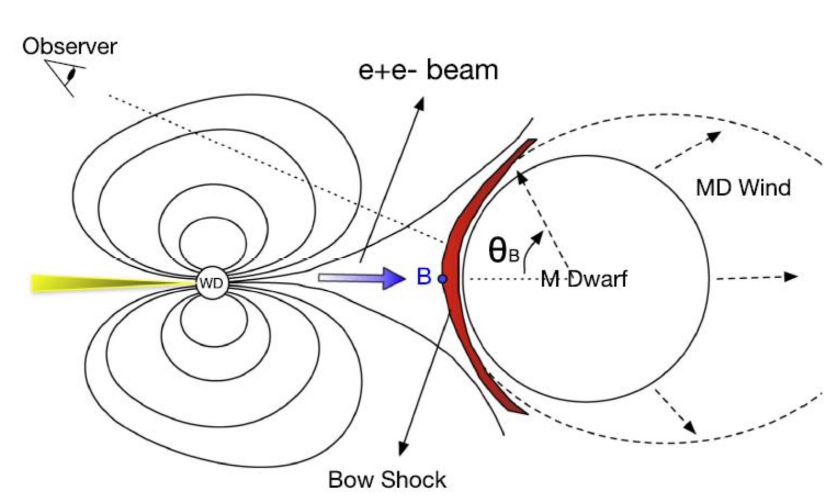
$$\theta_{\rm A} \sim 90^\circ/2 = 45^\circ$$

$$r_{\rm A} = 5.8 \times 10^{10}\ {\rm cm}$$

$$\bar{B} = (B_{\rm A} + B_{\rm B})/2 \simeq 1200\ {\rm G}$$

Geng, Zhang & Huang 2016, ApJL, 831, L10

Synchrotron emission from the bow shock



$$\bar{B} = (B_{\rm A} + B_{\rm B})/2 \simeq 1200\ \rm G$$

Electron distribution:

$$\frac{dn_e}{d\gamma_e} = \begin{cases} C\gamma_e^{-p}, & \gamma_m \leqslant \gamma_e \leqslant \gamma_c, \\ C\gamma_c\gamma_e^{-p-1}, & \gamma_c < \gamma_e \leqslant \gamma_{\max}, \end{cases}$$

Characteristic Lorentz factors:

$$\gamma_m = 45$$

$$\gamma_c = 73\ (P/1.95\ \rm min)^{-1}$$

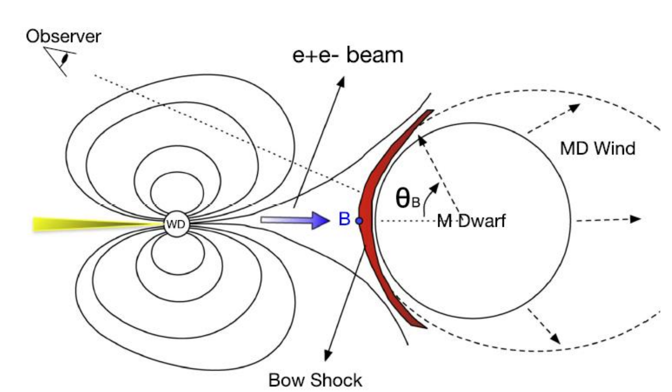
$$\gamma_{\max} = (6\pi q_e/\sigma_T \bar{B})^{1/2} = 3.4 \times 10^6$$

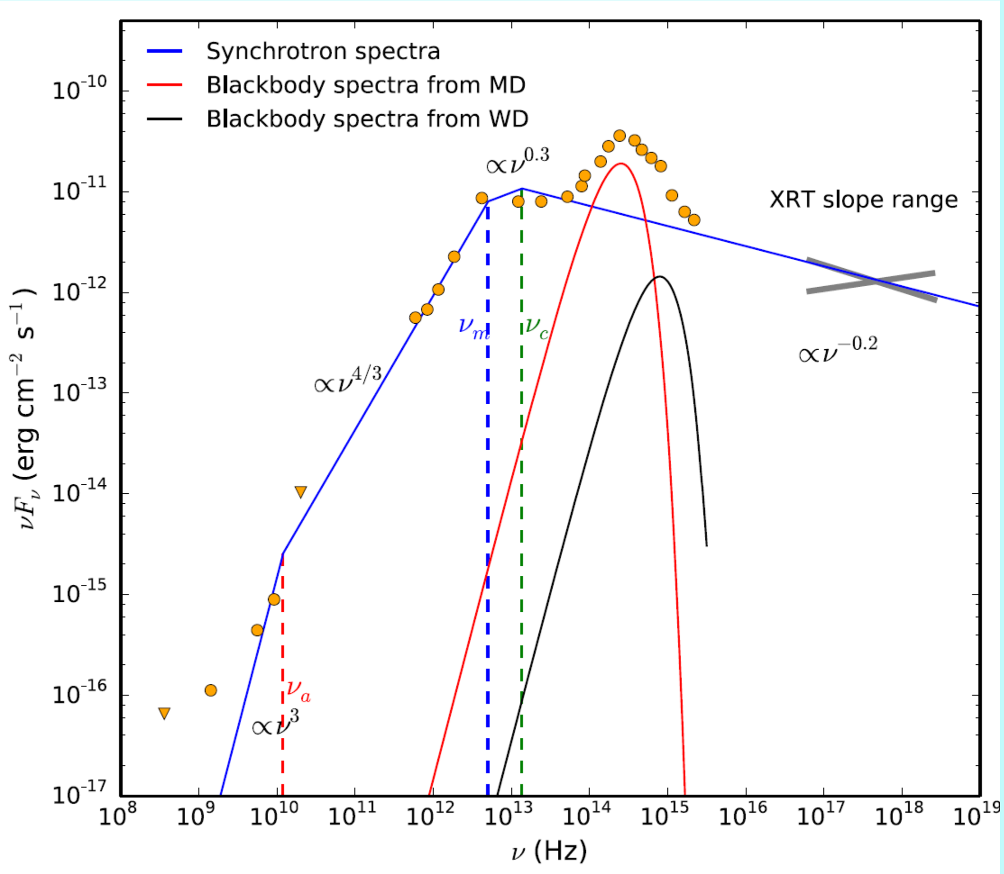
$$F_{\nu,\rm peak} = \frac{\sqrt{3}\, q_e^3 \bar{B}}{m_e c^2} \frac{n_e V}{4\pi D_L^2}$$

$$D_L = 116\ \rm pc$$

Geng, Zhang & Huang 2016, ApJL, 831, L10

Synchrotron emission from the bow shock





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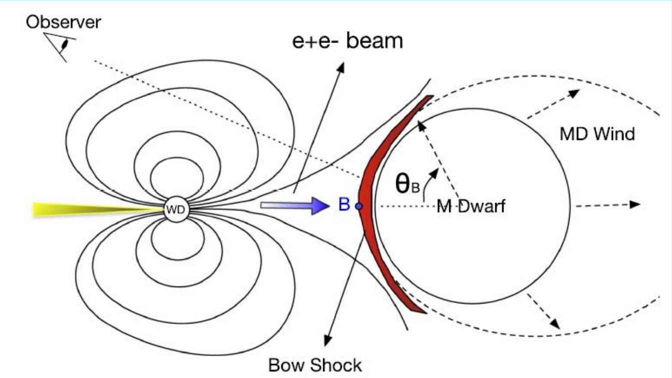
$$p \sim 2.4$$

$$n_e = 3.5\times 10^8\,{\rm cm}^{-3}$$

Geng, Zhang & Huang 2016, ApJL, 831, L10

Origin of the electrons



$$n_e = 3.5\times10^{8}\,\mathrm{cm}^{-3}$$

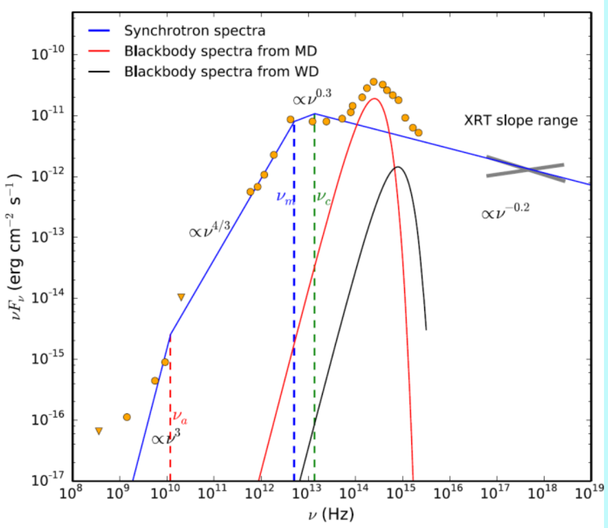
The Goldreich & Julian charge density:

$$n_{\rm GJ} = \frac{\boldsymbol{\Omega}\cdot\boldsymbol{B}_{\rm B}}{2\pi q_e c} = 1.1\ \mathrm{cm}^{-3}$$

The electrons should come from the M-star:

$$\dot{M} = 4\pi R_{\rm MD}^2 v n_e m_p/\zeta$$

$$= 4.1\times10^{-11}(\zeta/0.2)^{-1} M_{\odot}\ \mathrm{yr}^{-1}$$



Note that typical M-star wind is:

$$10^{-15}\text{–}10^{-10} M_{\odot}\ \mathrm{yr}^{-1}$$

Geng, Zhang & Huang 2016, ApJL, 831, L10

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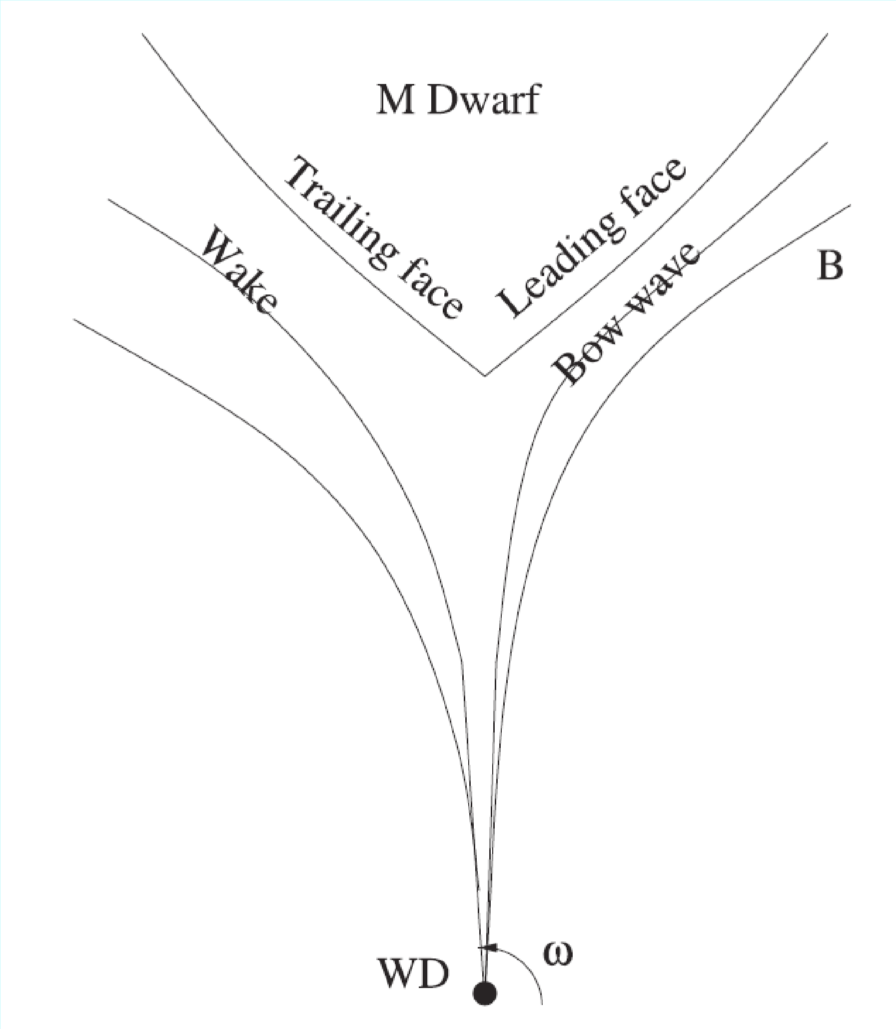
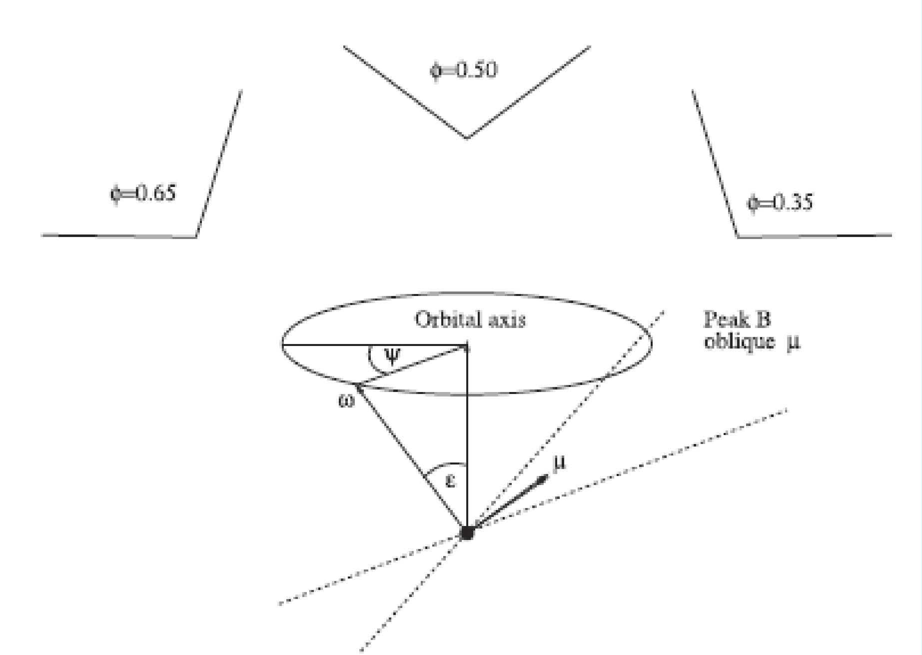
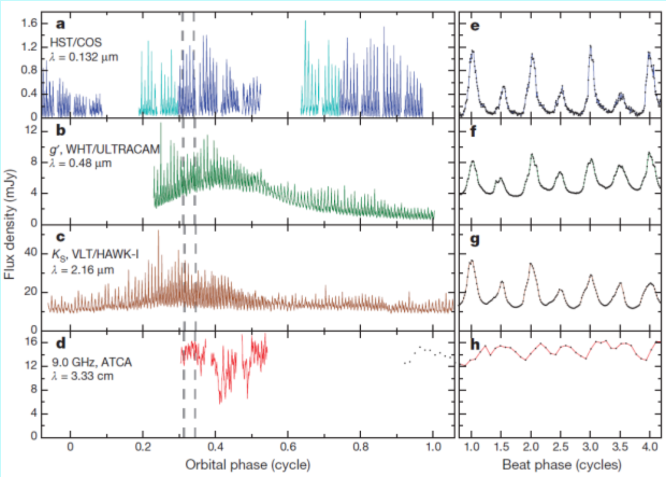
Another similar bow shock explanation:
A Precessing White Dwarf Synchronar?

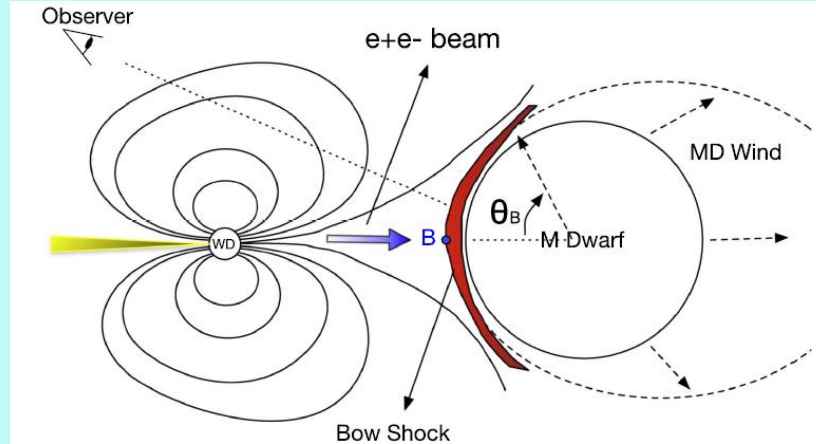


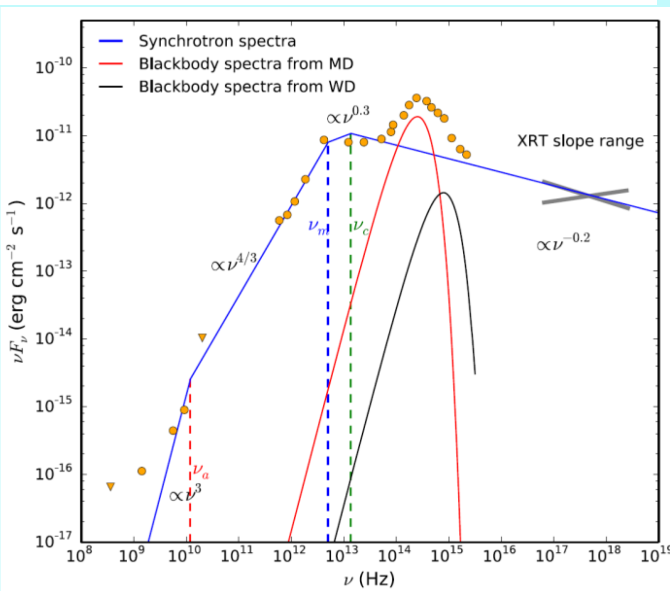


Katz 2017, ApJ

Conclusions







AR Scorpii:

(1) Pulsed emission is observed (radio to UV).

(2) Spectrum is non-thermal.

(3) The WD is a pulsar. A bow shock can be generated due to the interaction between the WD pulsar and the M-dwarf companion.

Thank You!

Geng, Zhang & Huang, 2016, ApJL, 831, L10
arxiv:1609.02508