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Radio Emission from Magnetic Massive Stars

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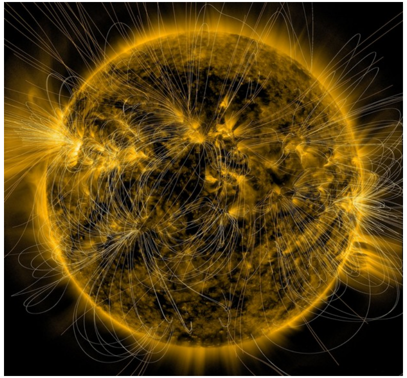
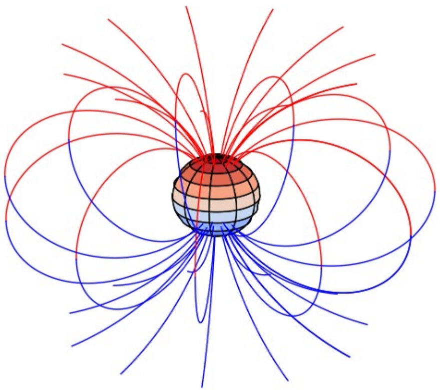
Radio Stars in the era of New Observatories, MIT Haystack Observatory, Westford, MA, USA

I would like to begin by acknowledging the Whadjuk people of the Noongar nation as the Traditional Owners of the land that I live and work, and pay my respect to their Elders past and present.

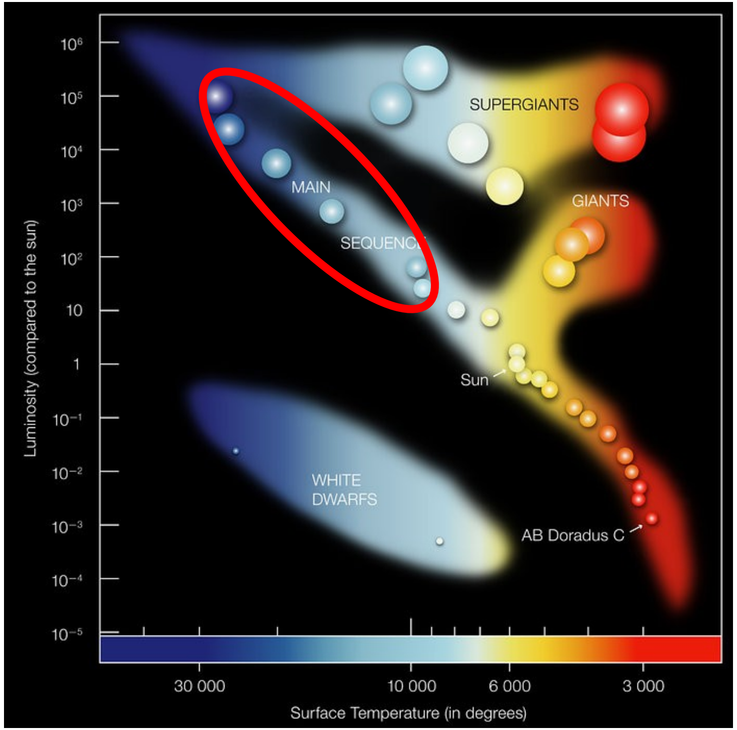
Magnetic massive stars

- Occupy the ‘upper main-sequence’
- ~10% have <u>large-scale</u> (often dipole-like) magnetic fields that are extremely <u>stable</u>





(Credit: NASA/SDO/AIA/LMSAL)



(Credit: ESO)

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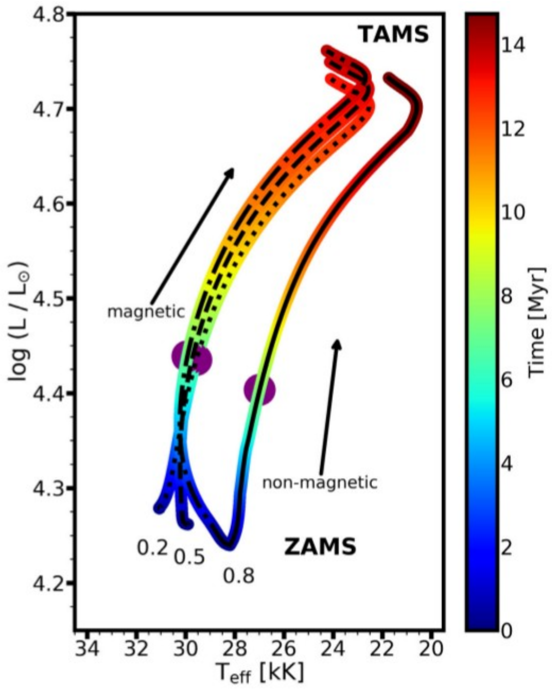
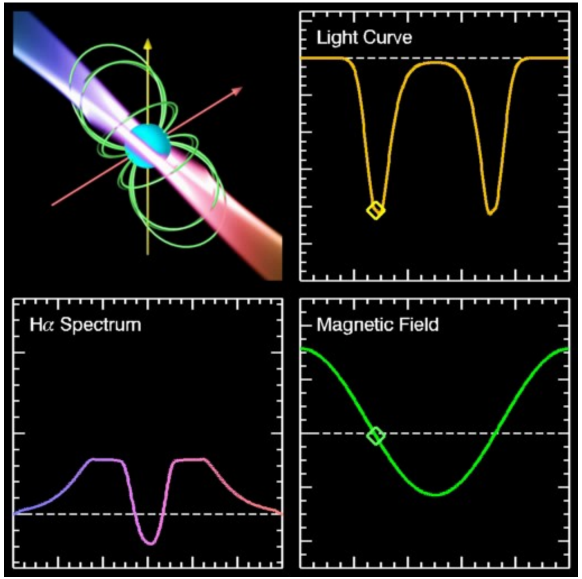
Why are they interesting?



(Keszthelyi et al. 2020)



(Credit: R. Townsend, Townsend & Owocki 2005)

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Radio emission: why should we care?

- Hα, a key probe, is not observed below T_{eff}~15 kK, but radio is observed over a much wider T_{eff} range
  - Allows us to test whether a common scenario exists for all magnetic early-type stars
- Most similarities between magnetic hot and magnetic (ultra)cool objects are observed at radio bands
  - Huge potential for being used as celestial laboratories

Types of radio emission

Quiescent

- Thermal free-free
  - Talk by R. Ignace
- **Gyrosynchrotron**

Periodic pulses

- **Cyclotron maser (Periodic at Rotational timescale)**
- ? (periodic at orbital timescale, see Biswas et al. 2023, MNRAS, 523, 5155)

Flares

- Talk by E. Polisensky

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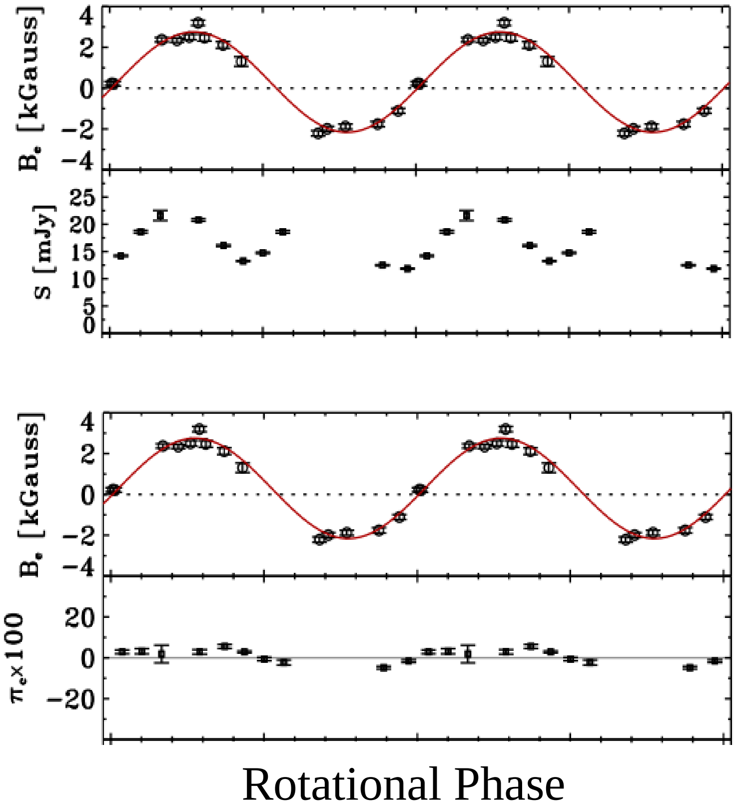
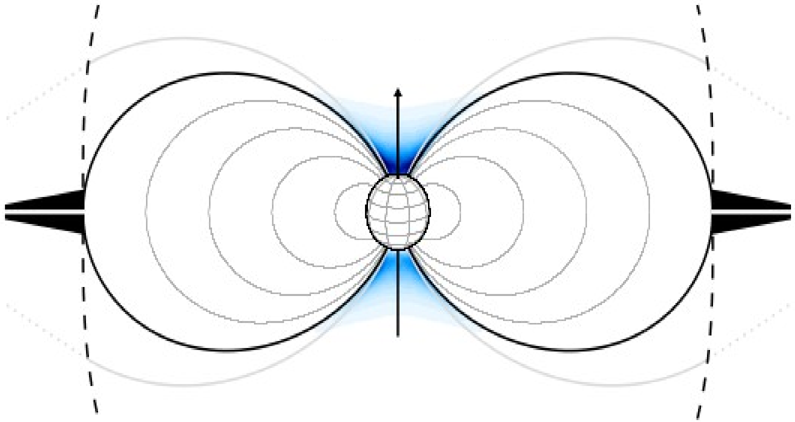
Incoherent radio emission



(Leto et al. 2017)



(Leto et al. 2021)

- Radio emitting sites are located along the magnetic axis (Linsky et al. 1992, Leone & Umana 1993 etc.)
- Violates the GB relation (Leto et al. 2017, 2018)

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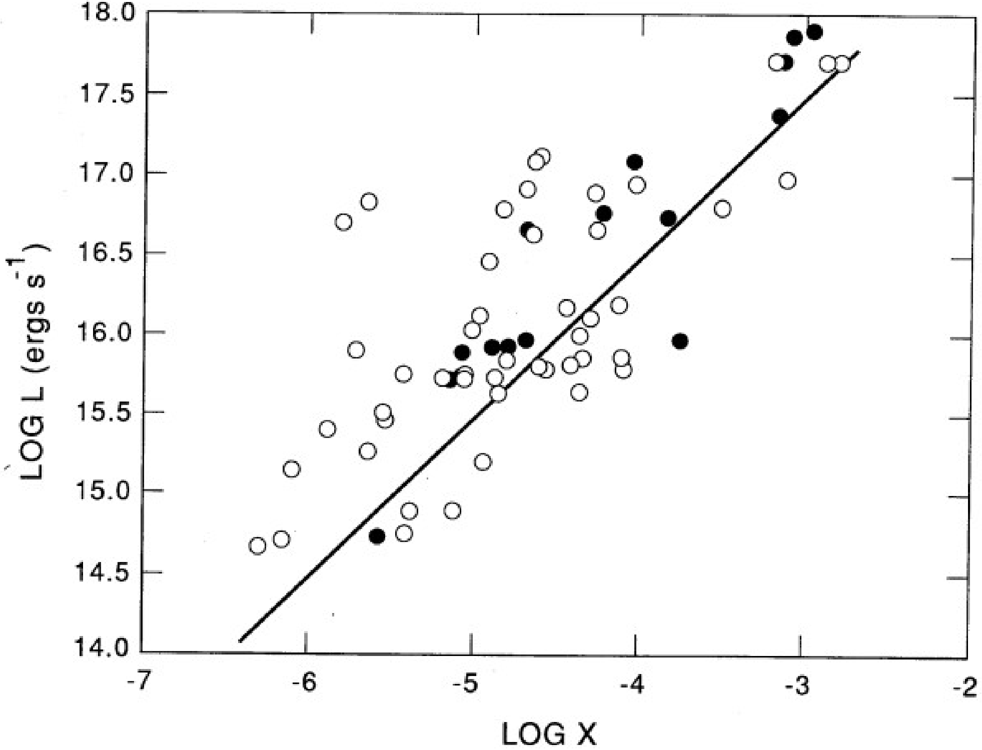
First scaling relation



(Linsky et al. 1992)

$$x = \dot{M}^{0.43} B_{\mathrm{rms}}^{0.97}$$

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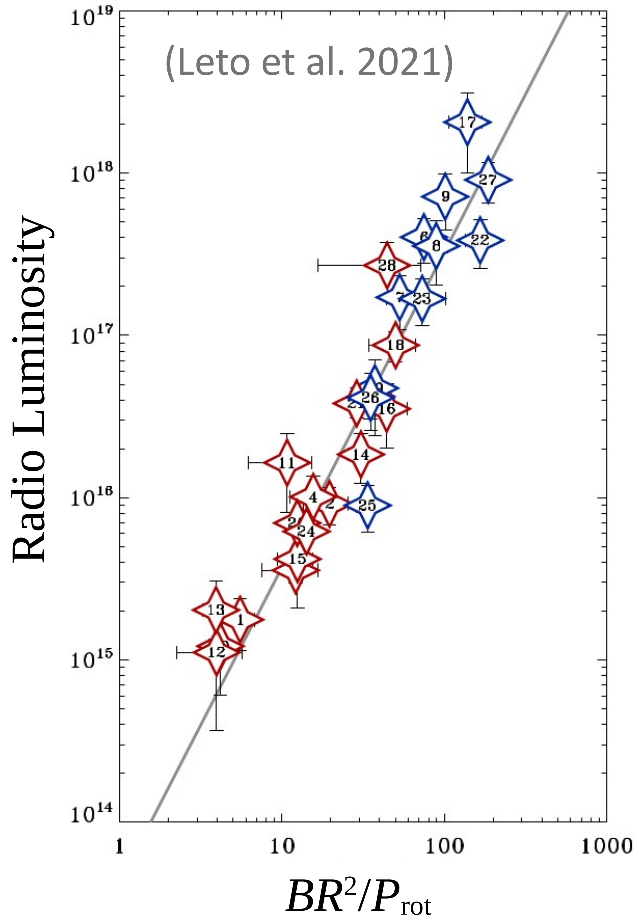
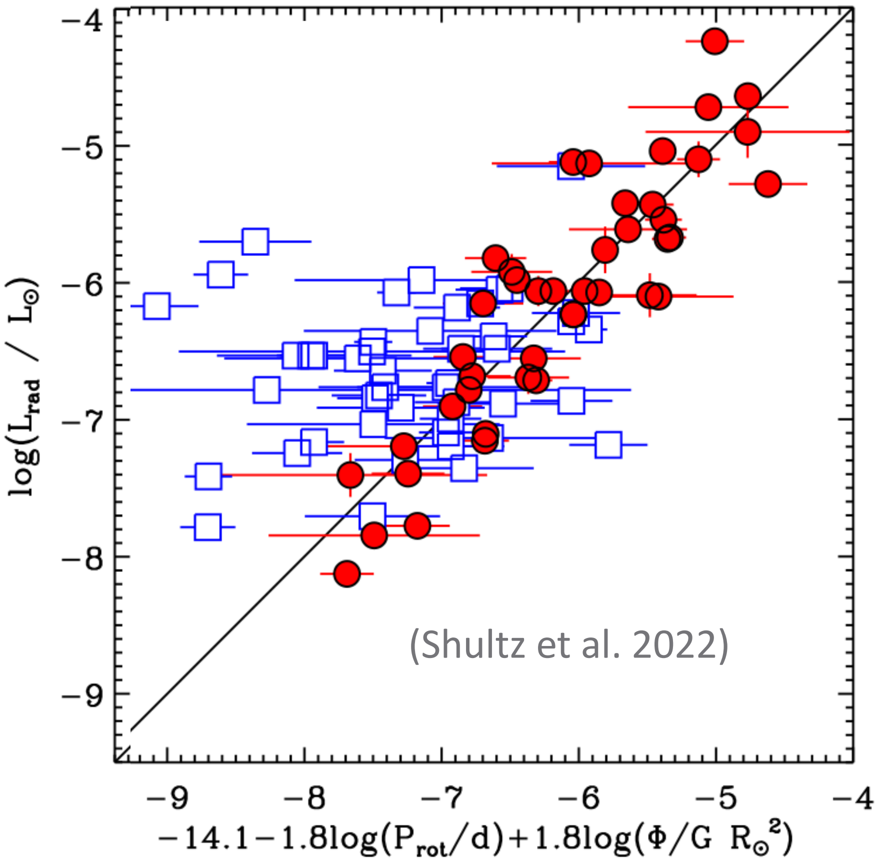
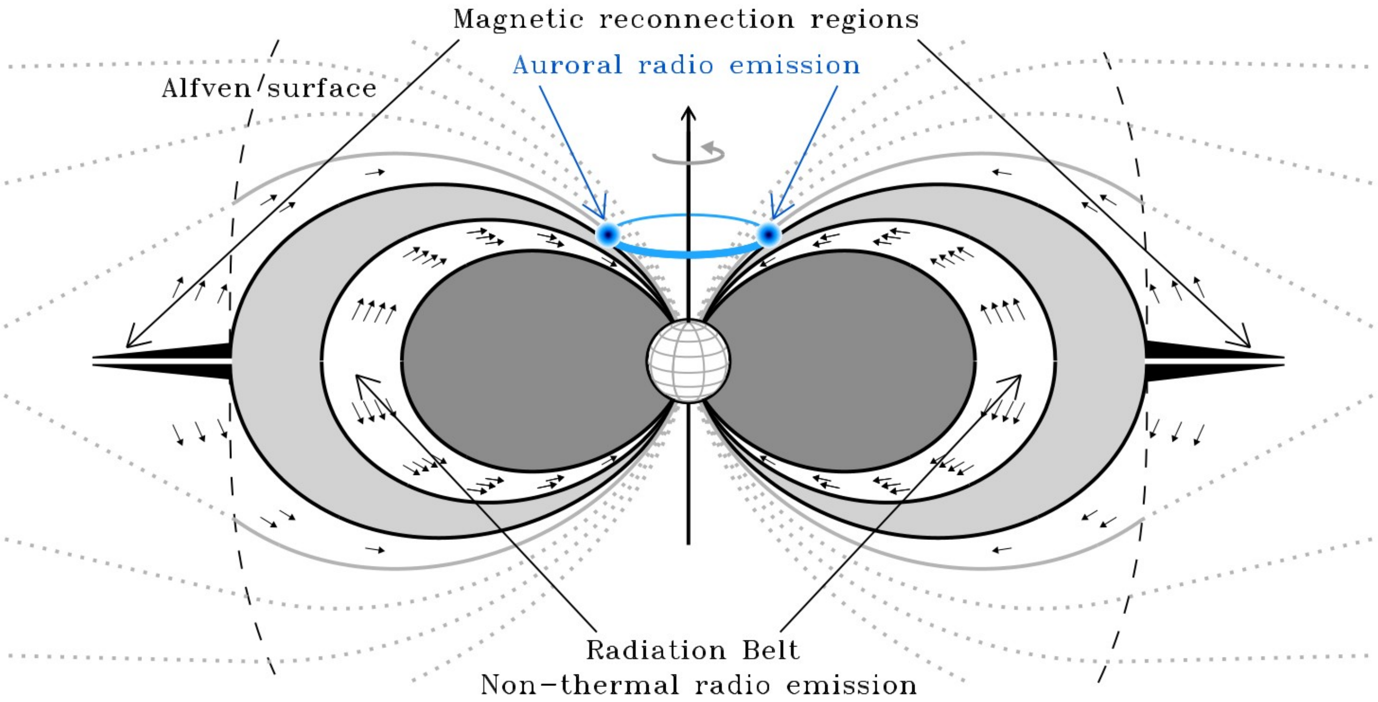
Scaling relation: revisit in 2021-2022





Radiation belt in magnetic massive stars?



(Leto et al. 2021)

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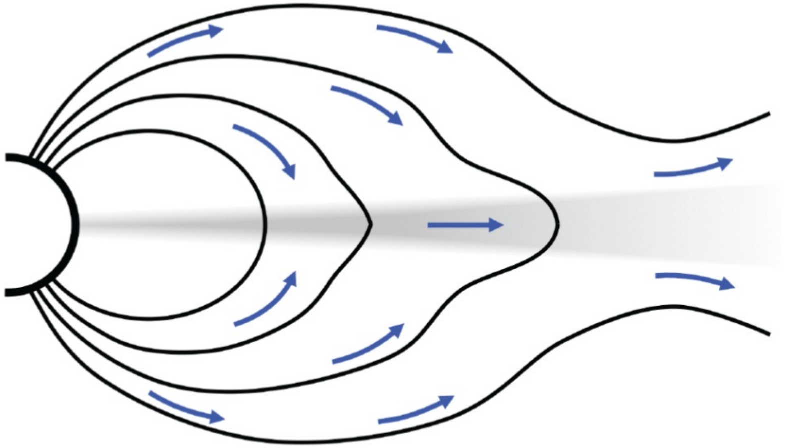
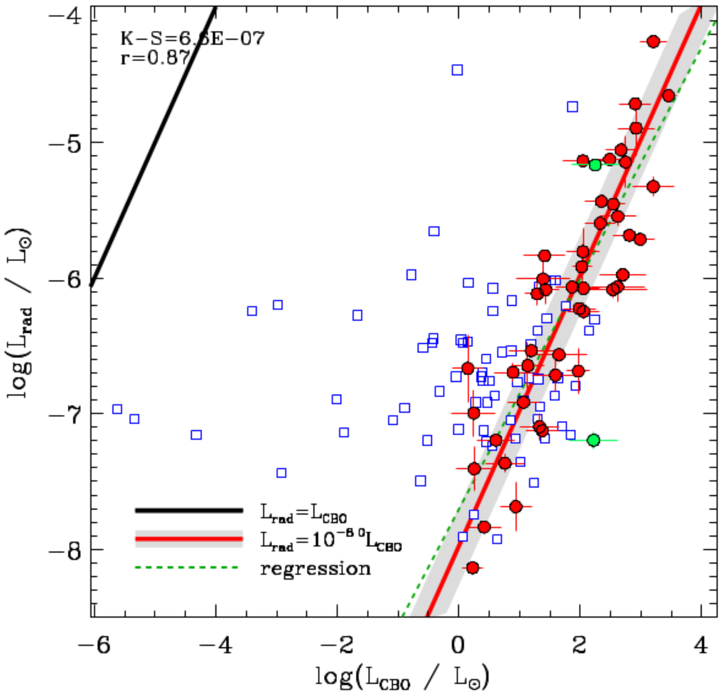
Centrifugal breakout (CBO)





(Shultz et al. 2022,
Owocki et al. 2022)

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Centrifugal breakout (CBO)

$$\boxed{L_{\rm CBO} \approx \dot{M}\Omega^2 R_*^2 \eta_{\rm c}^{1/p}} \, .$$

$$\eta_{\rm c} \equiv \frac{B_{\rm d}^2 R_*^2}{\dot{M} v_{\rm orb}}$$

$$L_{\rm CBO}(p=1) \equiv W\Omega R_*^3 B_{\rm d}^2 \, ,$$

$$L_{\rm CBO}(p=2) = \frac{L_{\rm CBO}(p=1)}{\sqrt{\eta_{\rm c}}} \, .$$

$$\propto \dot{M}^{0.5} B$$

(Owocki et al. 2022)

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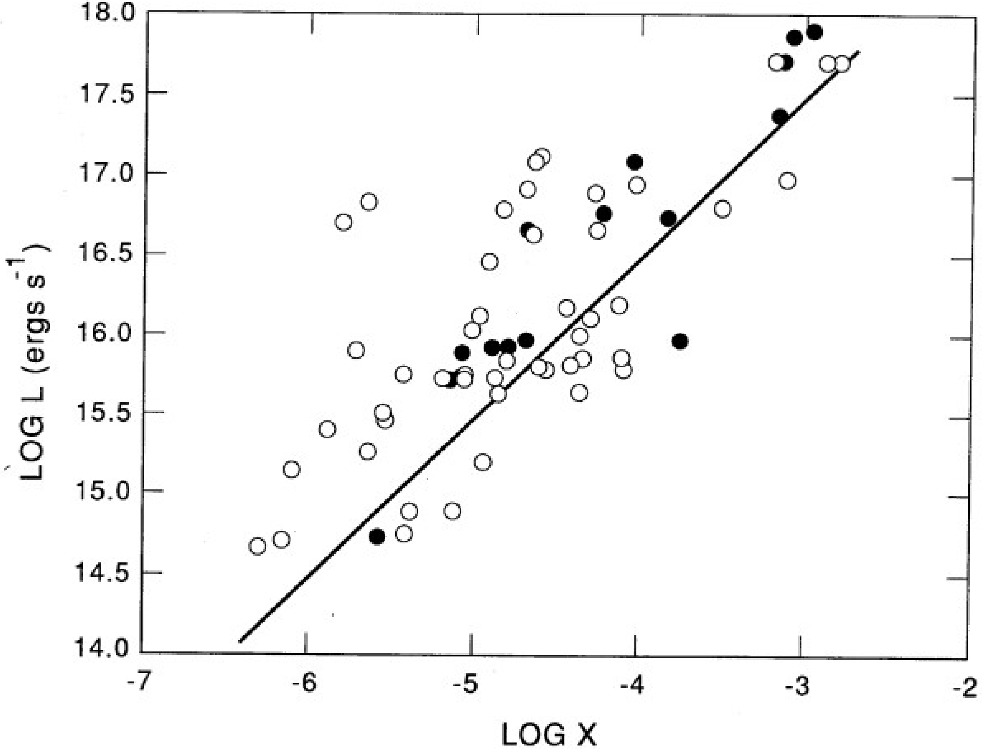
First scaling relation



(Linsky et al. 1992)

$$x = \dot{M}^{0.43} B_{\mathrm{rms}}^{0.97}$$

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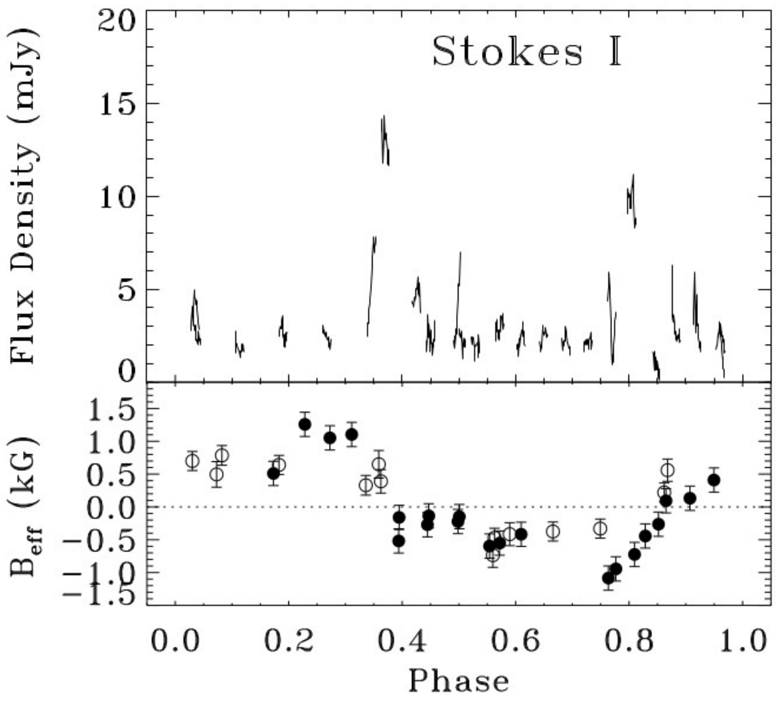
Coherent radio emission

(Trigilio et al. 2000)

- First discovered by Trigilio et al. (2000) from a magnetic late B star CU Vir
- Key properties:
  - Periodic radio pulses with ~100% circular polarization
  - Observed close to the ‘magnetic nulls’



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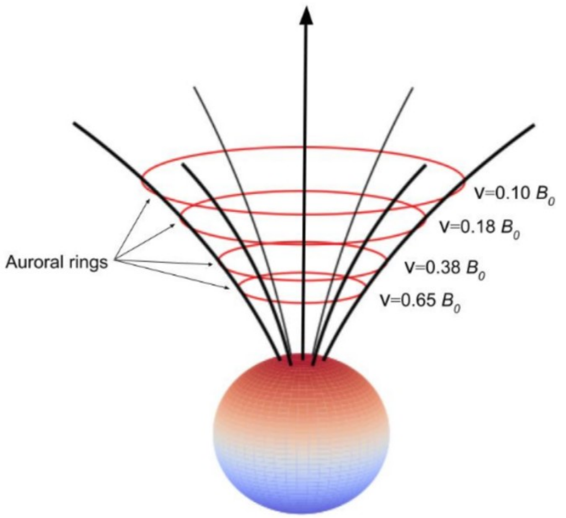
Coherent radio emission

- Mechanism was identified as electron cyclotron maser emission (ECME, Trigilio et al. 2000, 2008)
  - Intrinsically a narrow-band emission
  - Emission frequency is proportional to the magnetic field strength, higher frequencies are produced closer to the star and vice-versa
  - Highly directed emission
- We named them ‘Main-sequence Radio Pulse emitter’ (MRP, Das & Chandra 2021)
- Probably ubiquitous among magnetic massive stars (Das et al. 2022)



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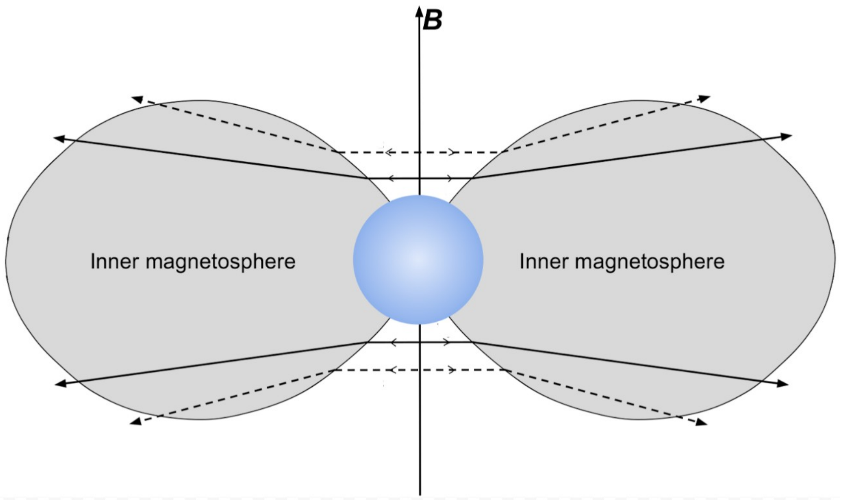
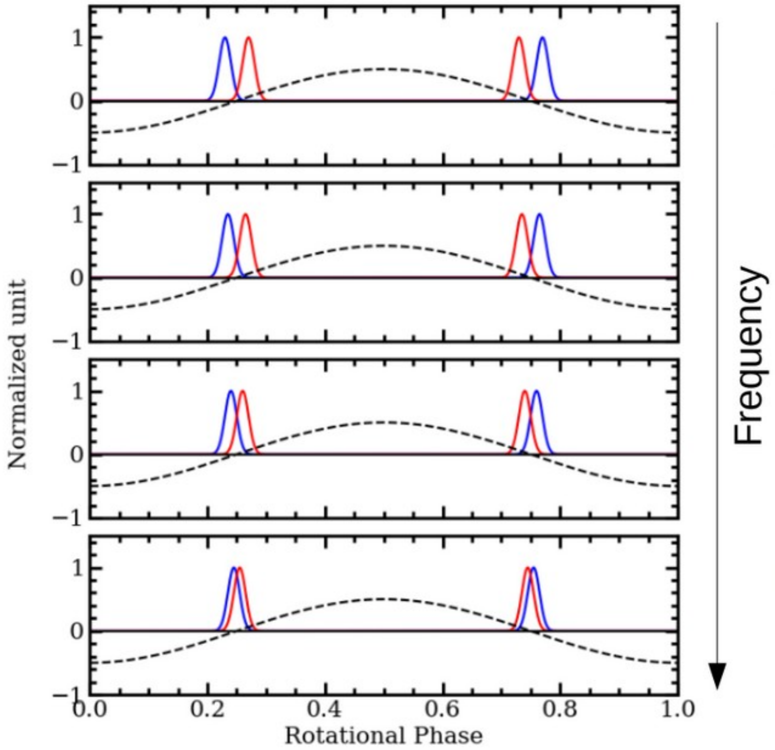
Coherent radio emission over wideband





(Figure made based on Trigilio et al. 2011, Leto et al. 2016)

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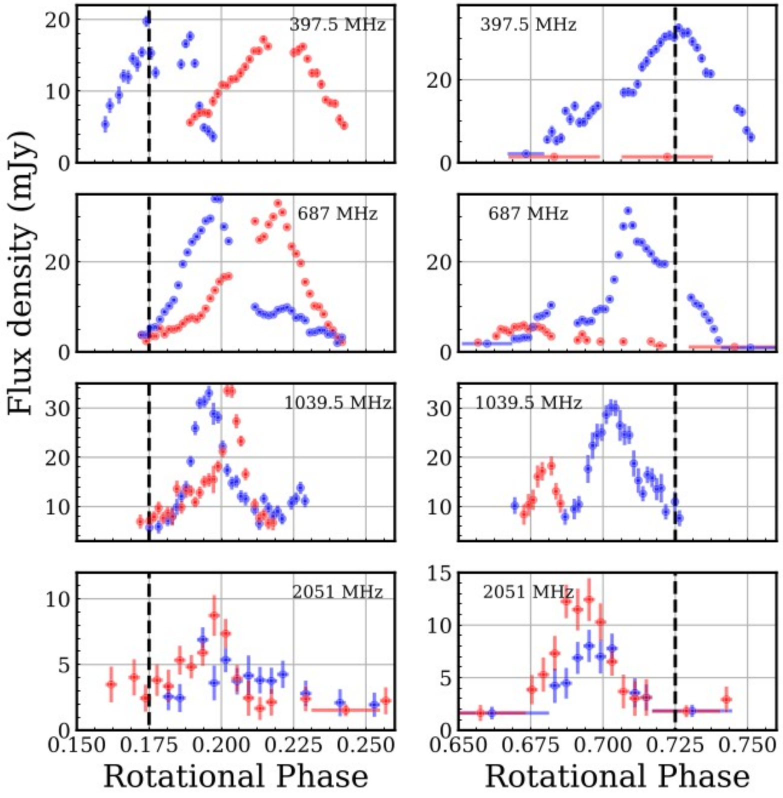
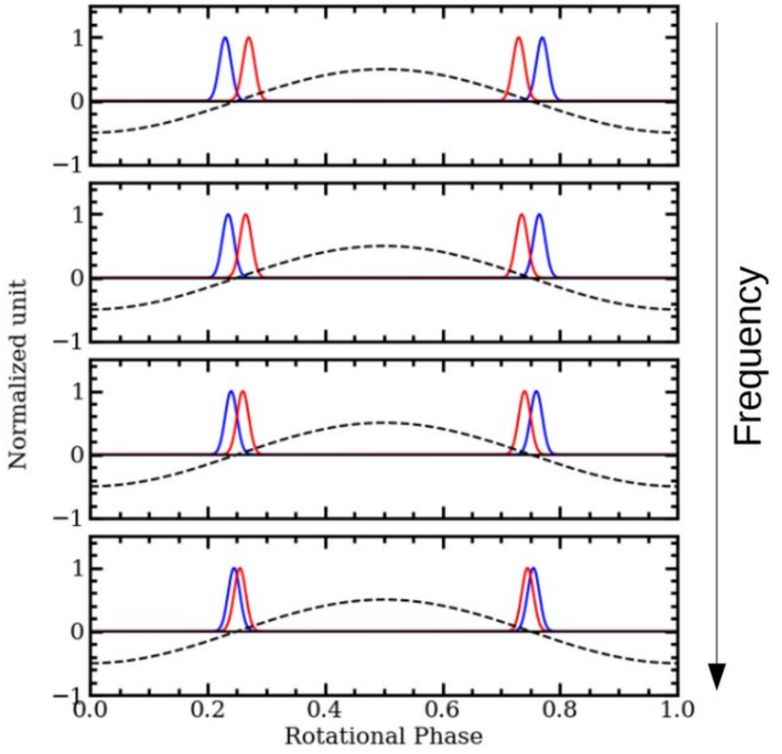
Coherent radio emission over wideband





(Das et al. 2020b)

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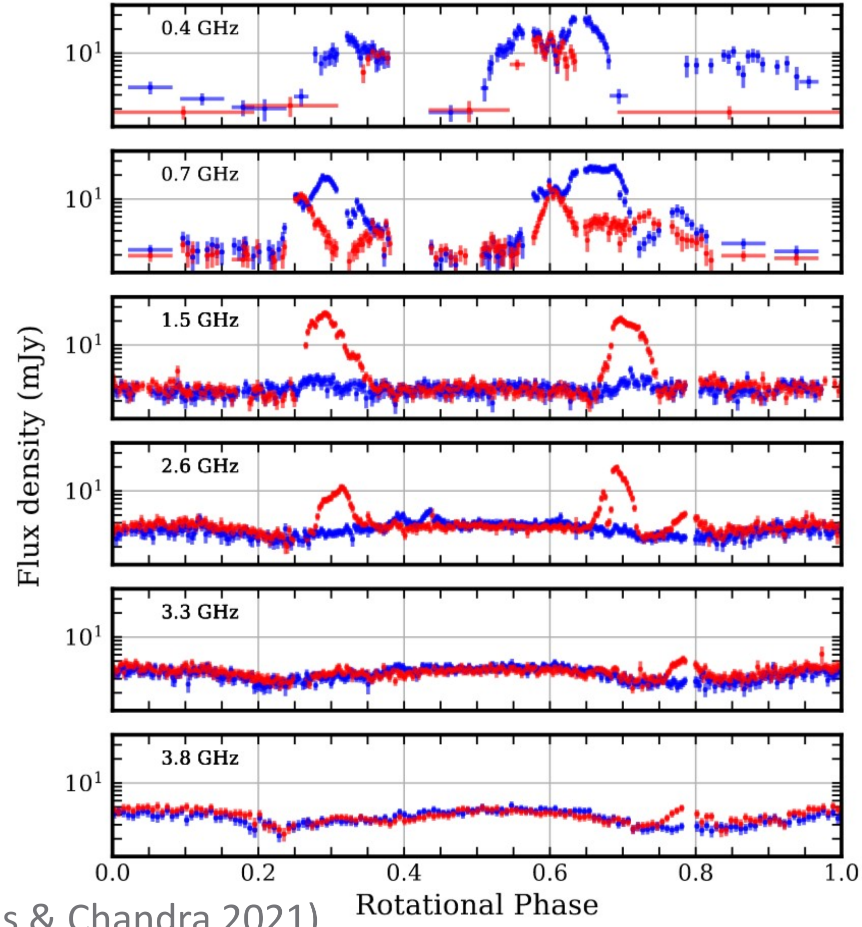
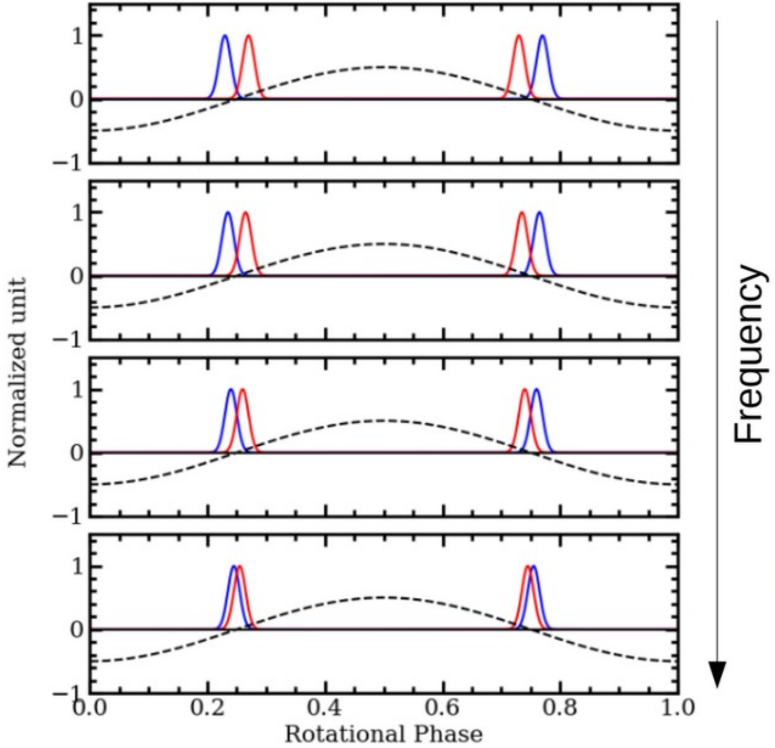
Coherent radio emission over wideband

- Pulse properties observed near different magnetic nulls aren't identical
    - Dependence on stellar orientation w.r.t. the observer

Coherent radio emission over wideband





(Das & Chandra 2021)

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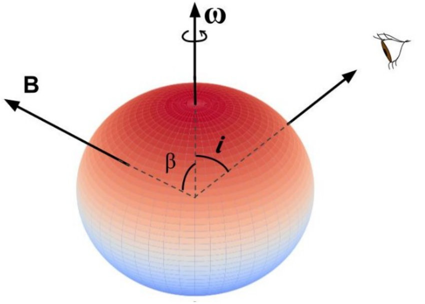
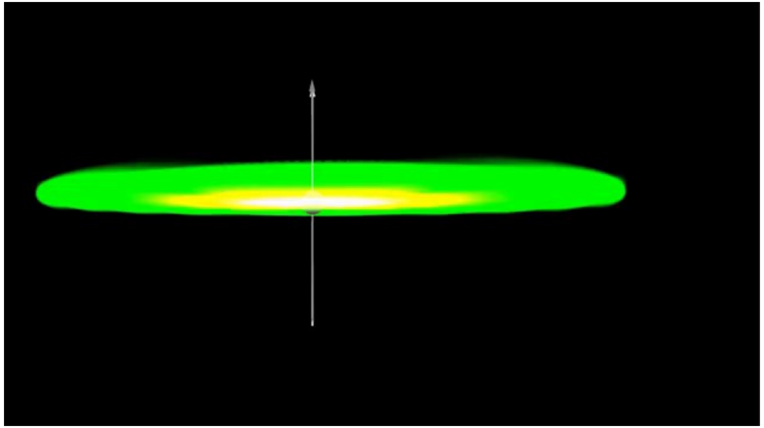
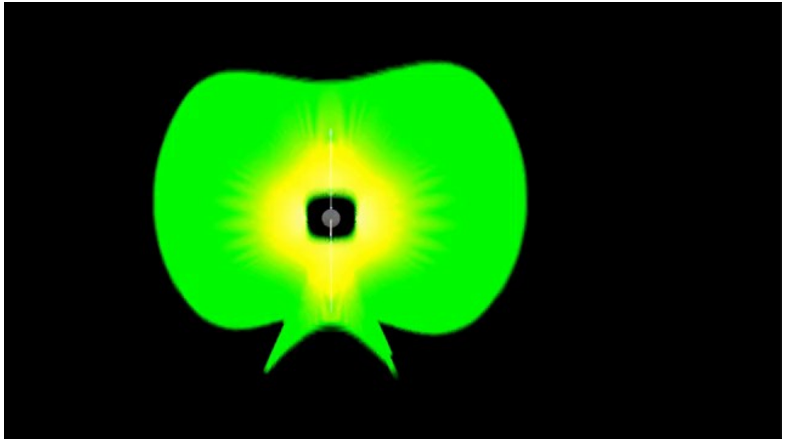
Coherent radio emission over wideband

- Pulse properties observed near different magnetic nulls aren't identical
  - Dependence on stellar orientation w.r.t. the observer
- Pulses can appear significantly away from the magnetic nulls!
- What are we missing?

The importance of obliquity

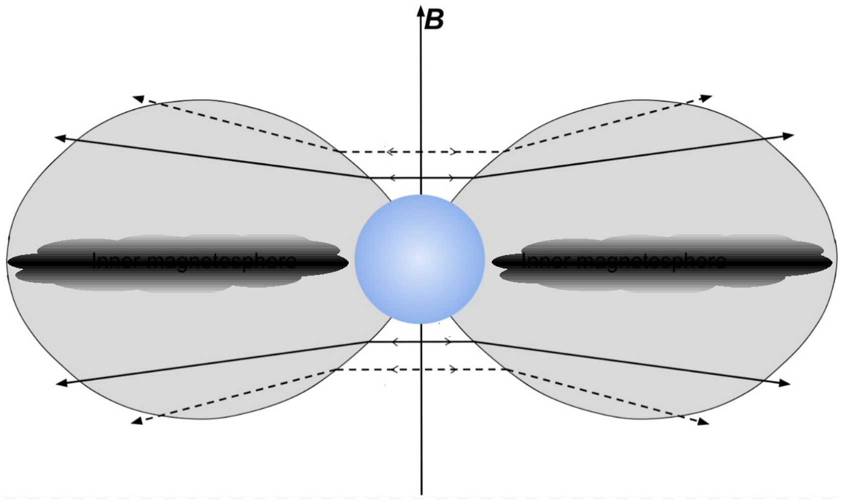


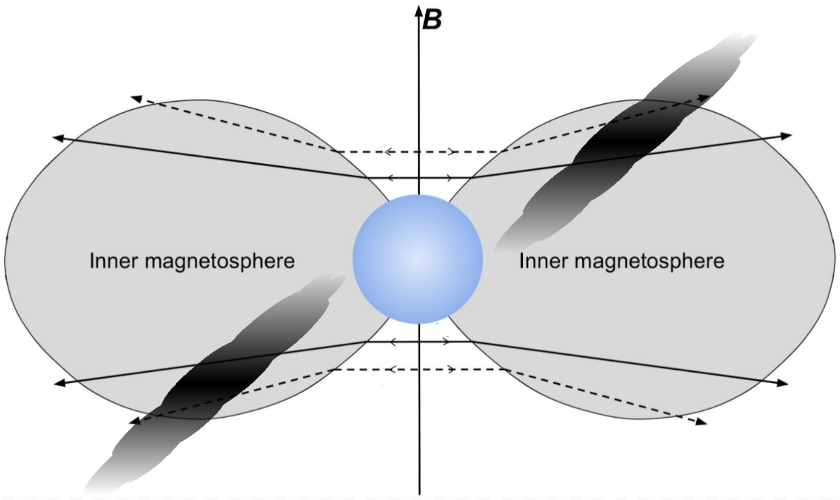




(Video credit: Chris Russell, based on RRM model by Townsend & Owocki 2005, density grid: V. Petit, B. Das)

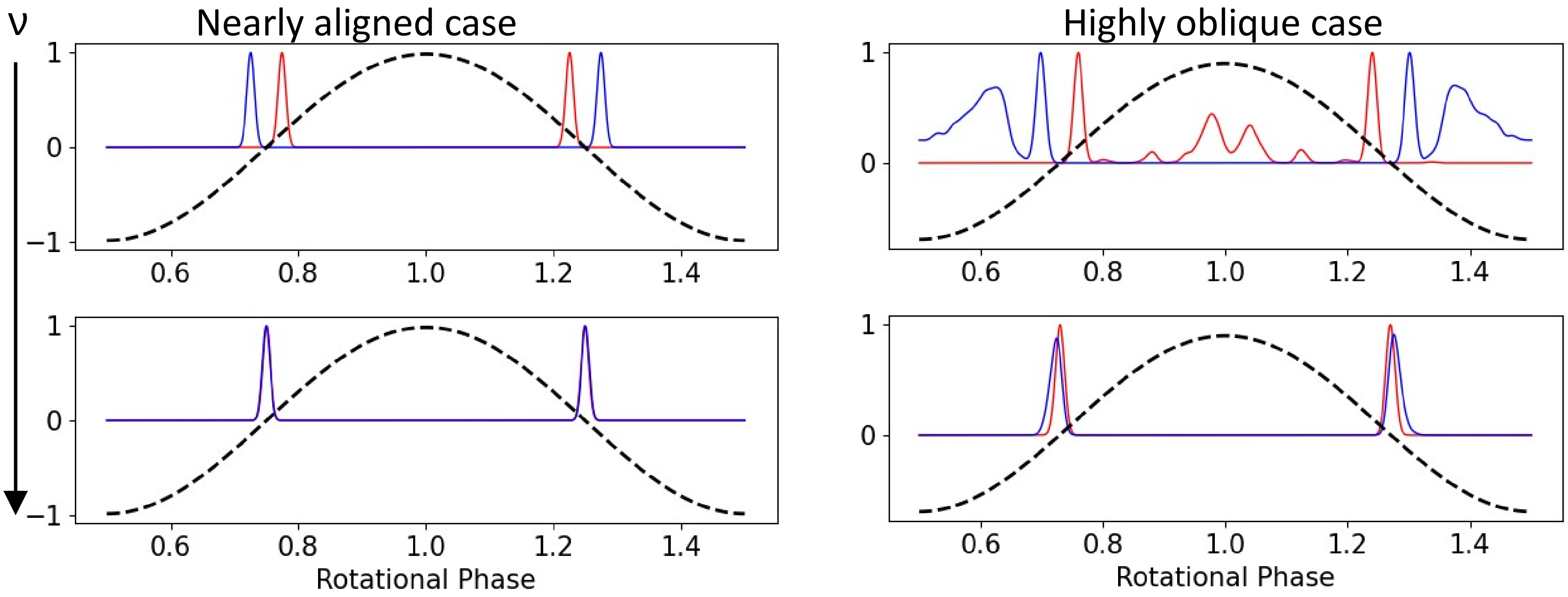
The importance of obliquity





- Both stars have obliquities ~80 degrees!
- We cannot ignore the density gradients in the magnetospheres!

How does obliquity change the ‘expectation’?



(Simulation based on Das, Mondal & Chandra 2020)

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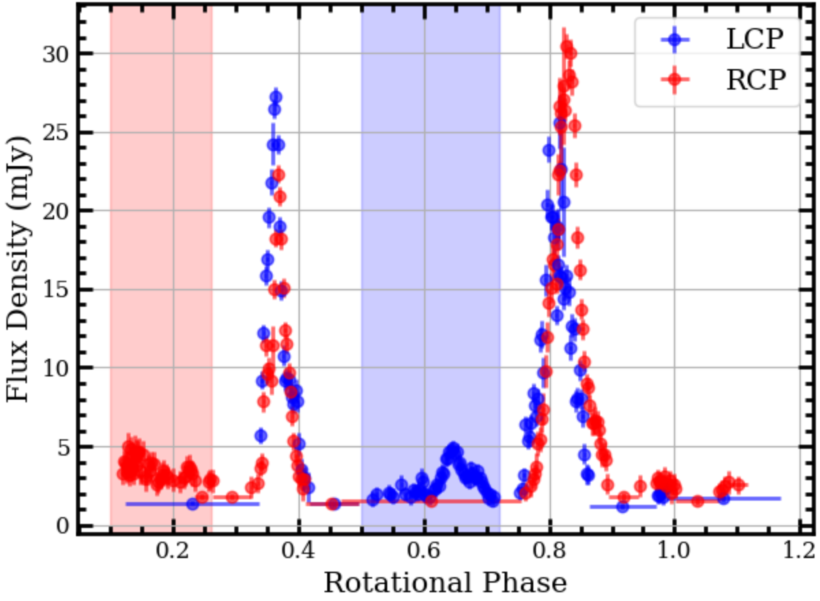
- Can we see some of those non-trivial features in data?

MeerKAT observation of an extreme oblique rotator

- Predicted that there will be secondary pulses based on the known stellar parameters (using the framework of Das, Mondal and Chandra 2020)



(Das et al. in prep.)

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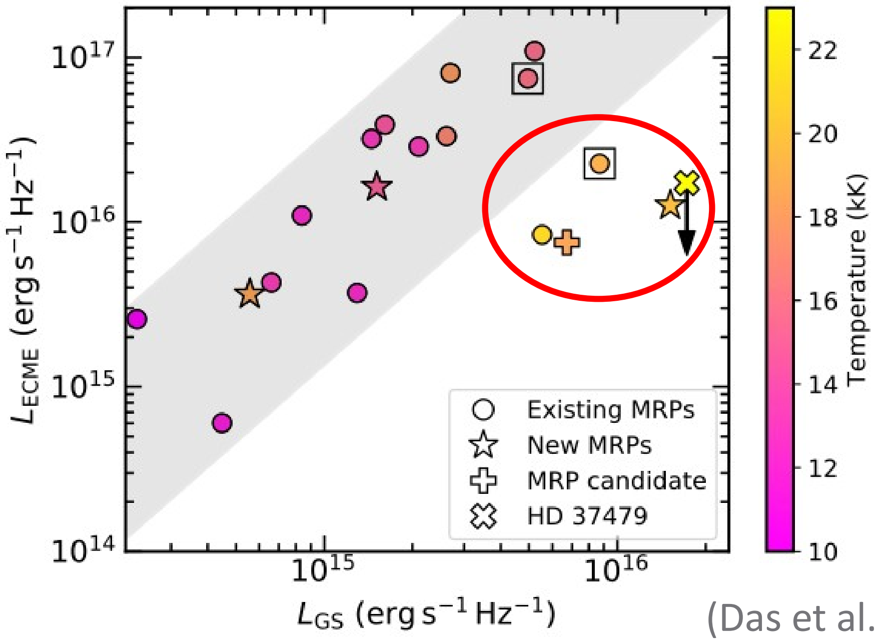
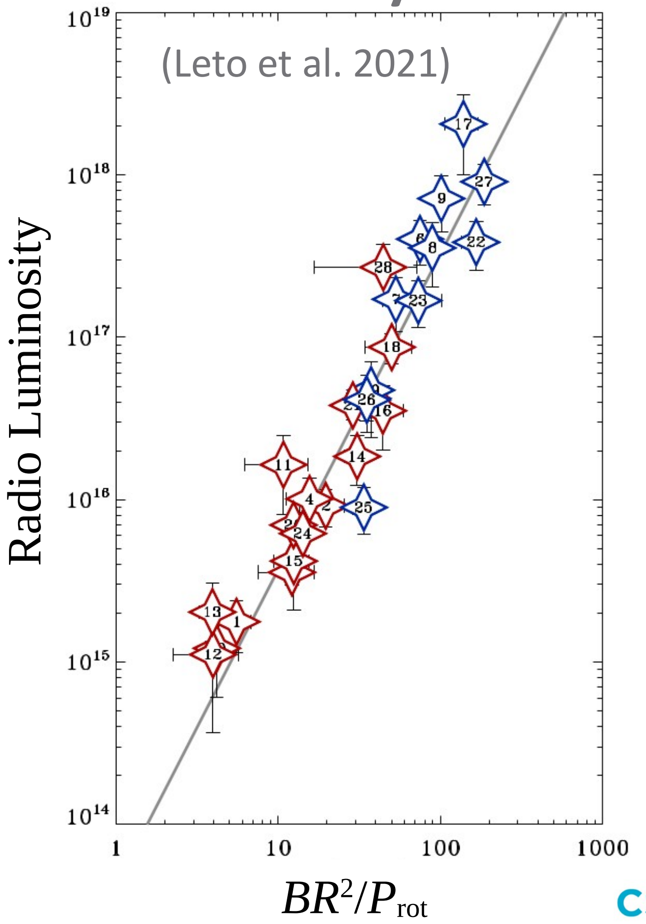
Coherent vs Incoherent Radio Luminosity



(Das et al. 2022b)



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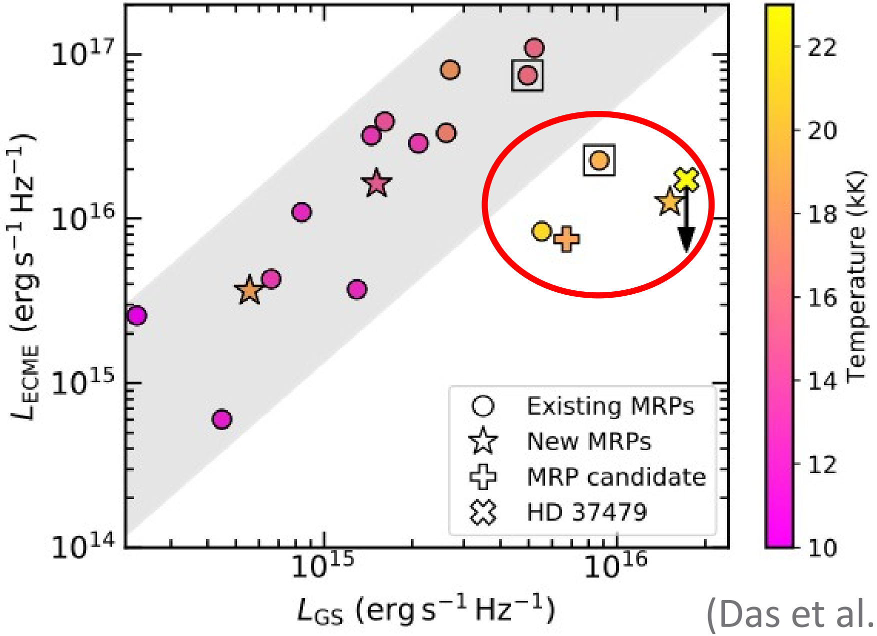
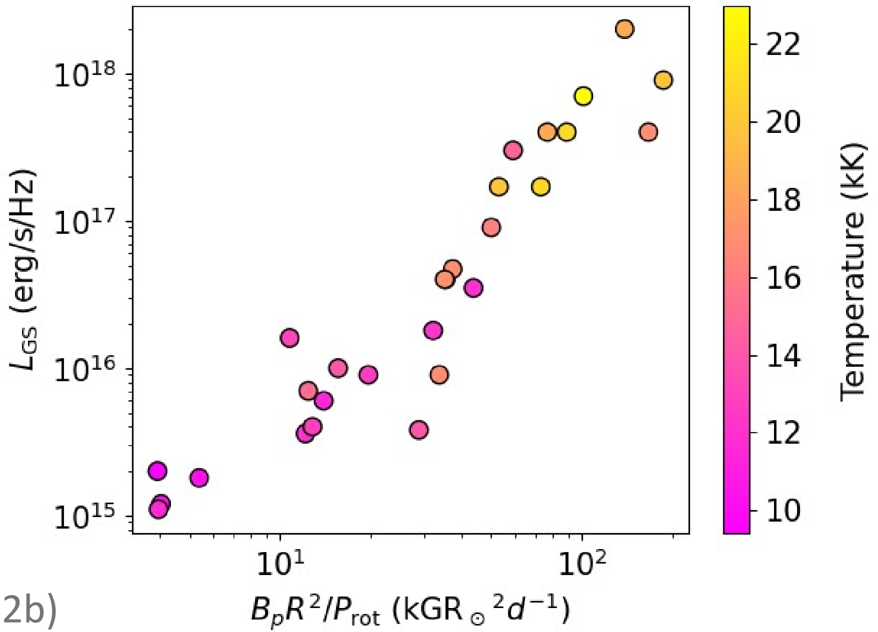
Coherent vs Incoherent Radio Luminosity



(Das et al. 2022b)



(Data from Leto et al. 2021)

Does radio has a dependence on temperature?

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Open questions/unexplored avenues

- Role of T_{eff}/mass-loss rate in radio production/inhibition
  - Expand the sample (use surveys such as VAST, talk by T. Murphy and L. Driessen)
- Stellar parameters controlling properties of coherent radio emission including cut-offs
  - Expand the sample of MRPs, more wideband observation
- MRPs below 400 MHz
  - Lowest frequency detection at 200 MHz (Lenc et al. 2018), but only 1 such MRP
- Magnetic massive stars at mm-band, only 2 stars observed above 50 GHz
- VLBI observations of magnetic massive stars
- Investigation regarding the magnetic hot star-cool star connection!
- And many more...

Need of the hour: more data, more data and more data!!!

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VAST project to study Magnetic Massive Stars (VAST-MeMeS)

Barnali Das, Laura Driessen, Joshua Lee, James Leung, Joshua Pritchard, Kovi Rose,
Matt Shultz, Gregory Sivakoff, Yuanming Wang, Andrew Zic

Current status: 20 new radio-bright hot magnetic stars, 3 MRP candidates

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Magnetic massive stars in the era of new observatories provide one of the widest and most interesting avenues for discoveries!!!

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