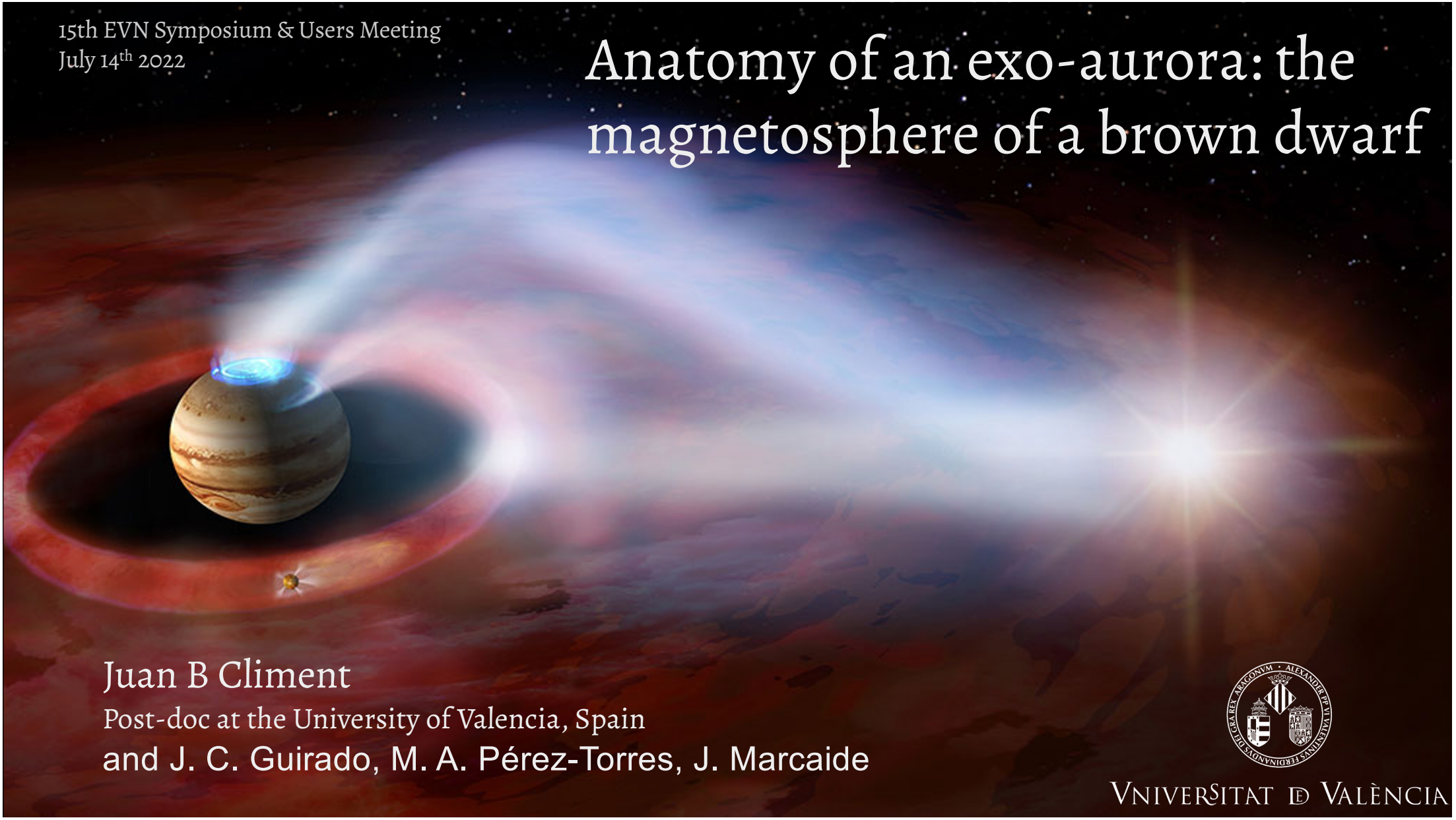
15th EVN Symposium & Users Meeting
July 14th 2022

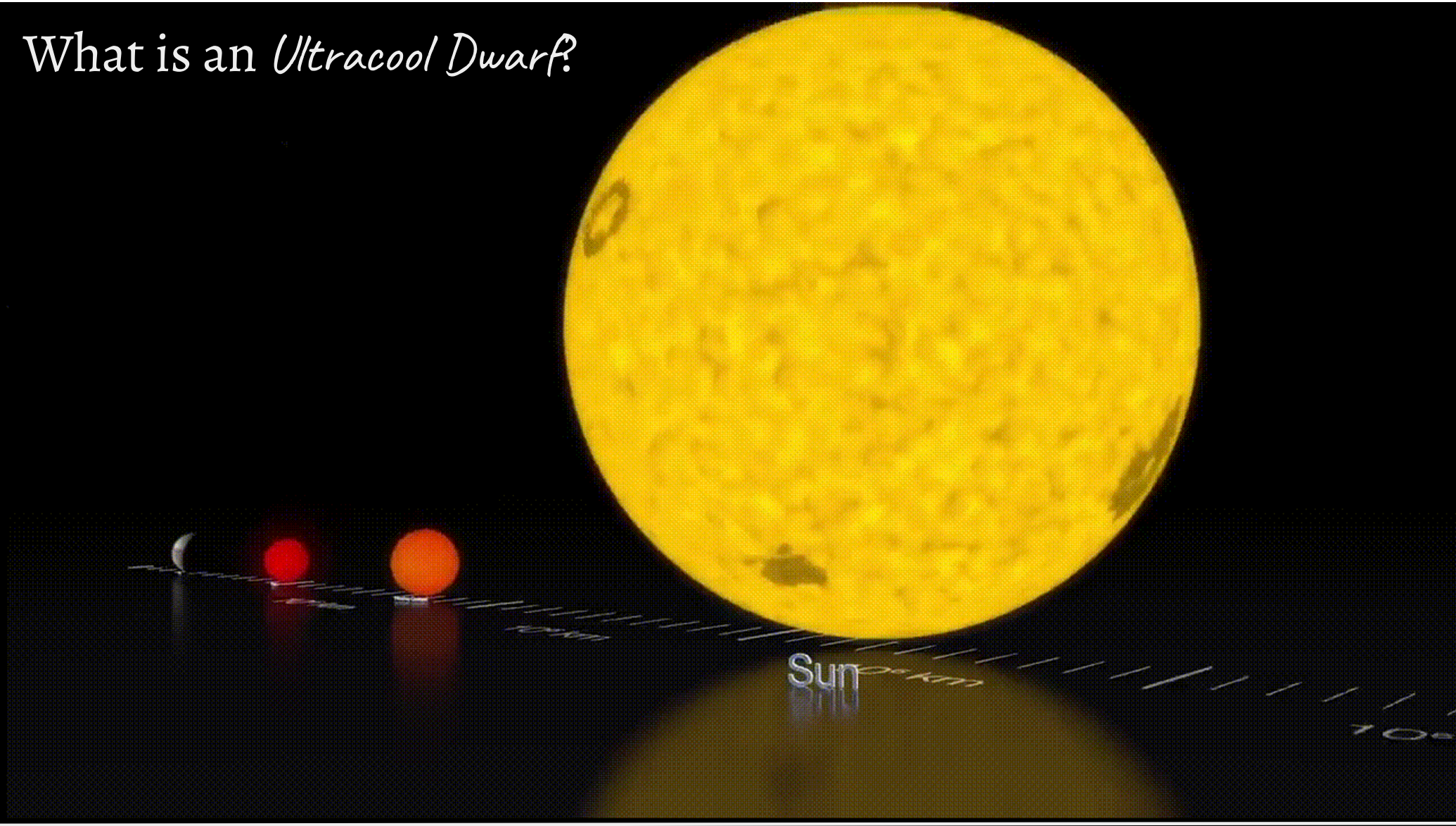
Anatomy of an exo-aurora: the magnetosphere of a brown dwarf



Juan B Climent
Post-doc at the University of Valencia, Spain
and J. C. Guirado, M. A. Pérez-Torres, J. Marcaide

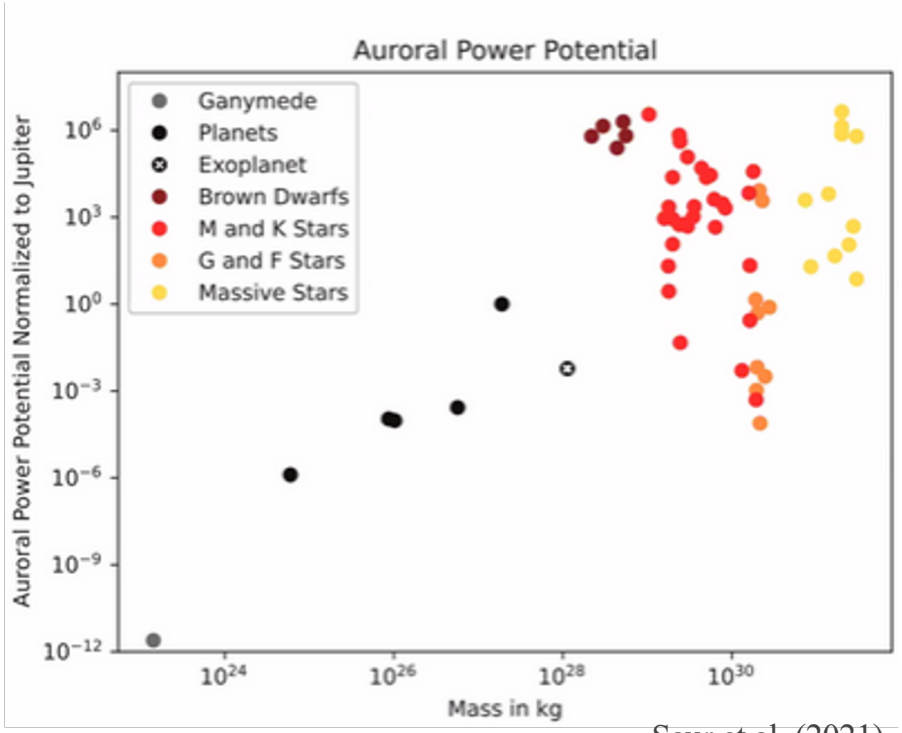
VNIVERSITAT DE VALÈNCIA

What is an *Ultracool Dwarf?*



Why study them at *radio* frequencies?

★ They are extremely interesting by themselves (aurorae, powerful magnetic fields, fast rotators, etc)

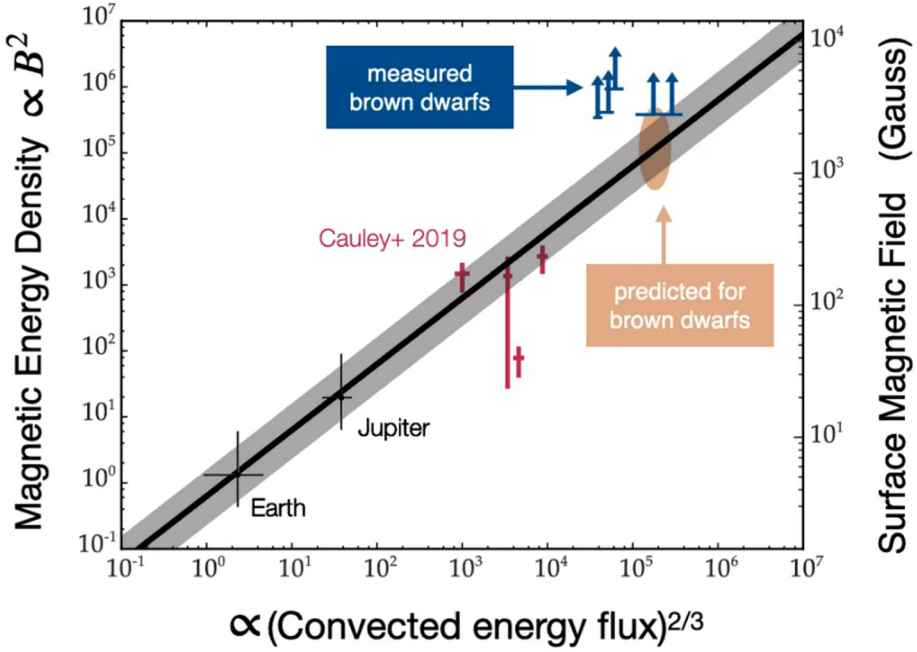


Saur et al. (2021)

Why study them at *radio* frequencies?

- ★ They are extremely interesting by themselves (aurorae, powerful magnetic fields, fast rotators, etc)
- ★ As we'll see, aurorae occur at ν(MHz) ≈ 2.8 B(Gauss), so detection = B determination → test dynamo models.

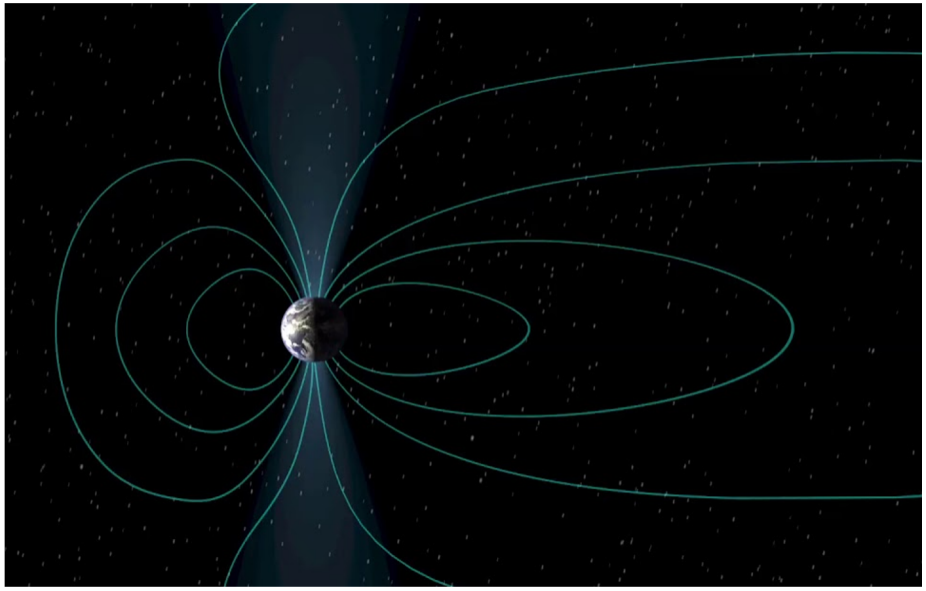
  SPOILER: the seminal scaling law relating thermal energy convected in deep interiors to B strengths (Christensen et al. 2009) is not sufficient in UCDs!



Adapted from M. Kao

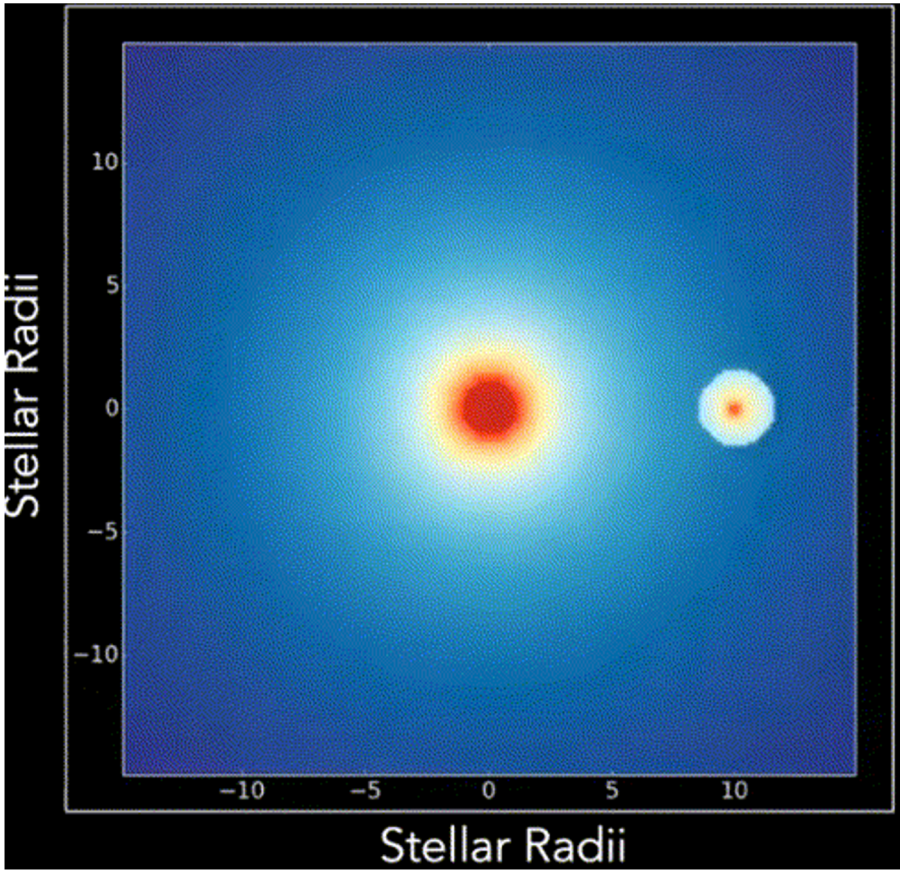
Why study them at *radio* frequencies?

- ★ They are extremely interesting by themselves (aurorae, powerful magnetic fields, fast rotators, etc)
- ★ As we'll see aurorae occur at ν(MHz) ≈ 2.8 B(Gauss), so detection = B determination → test dynamo models
- ★ The knowledge gathered may lead to a direct detection of exoplanetary radio emission.



Why study them at *radio* frequencies?

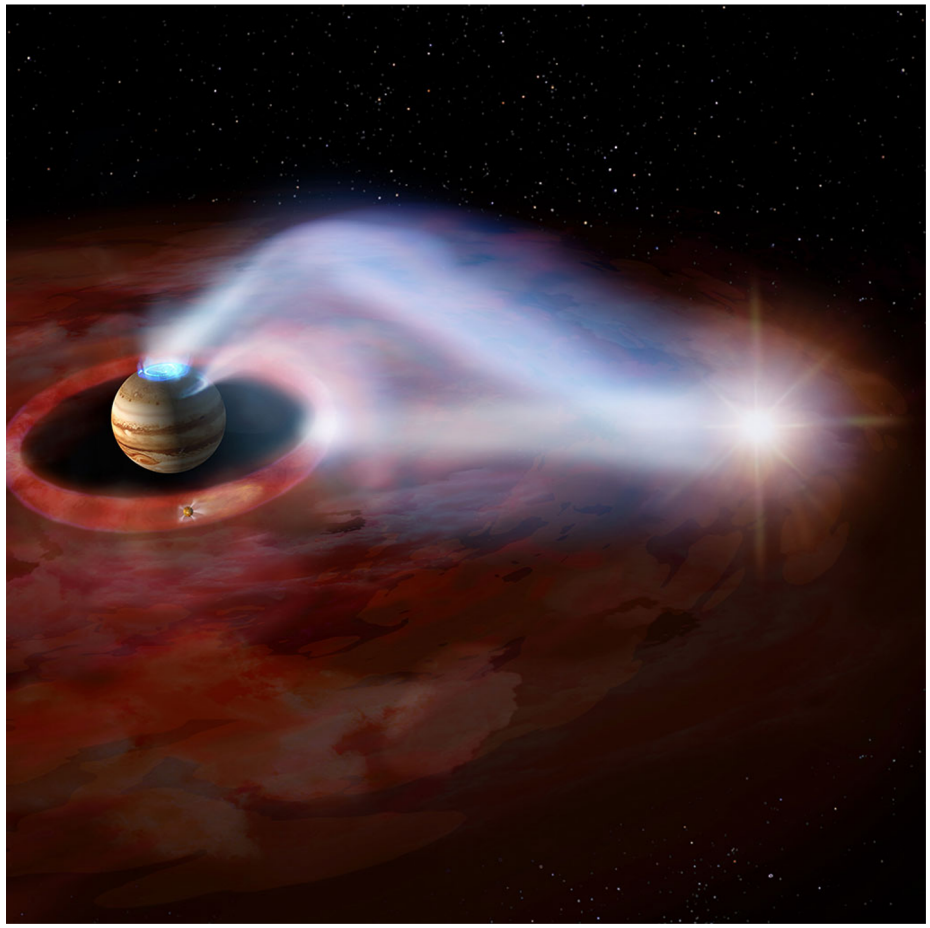
- ★ They are extremely interesting by themselves (aurorae, powerful magnetic fields, fast rotators, etc)
- ★ As we'll see aurorae occur at ν(MHz) ≈ 2.8 B(Gauss), so detection = B determination → test dynamo models
- ★ The knowledge gathered may lead to a direct detection of exoplanetary radio emission.
- ★ A new way of detecting and characterizing exoplanets based on star–planet interaction (SPI).
  - Optical spectroscopy (Cauley et al. 2019)
  - Proxima Cen (Pérez-Torres et al. 2021).
  - B of exoplanets! → Exoplanets interiors and exteriors



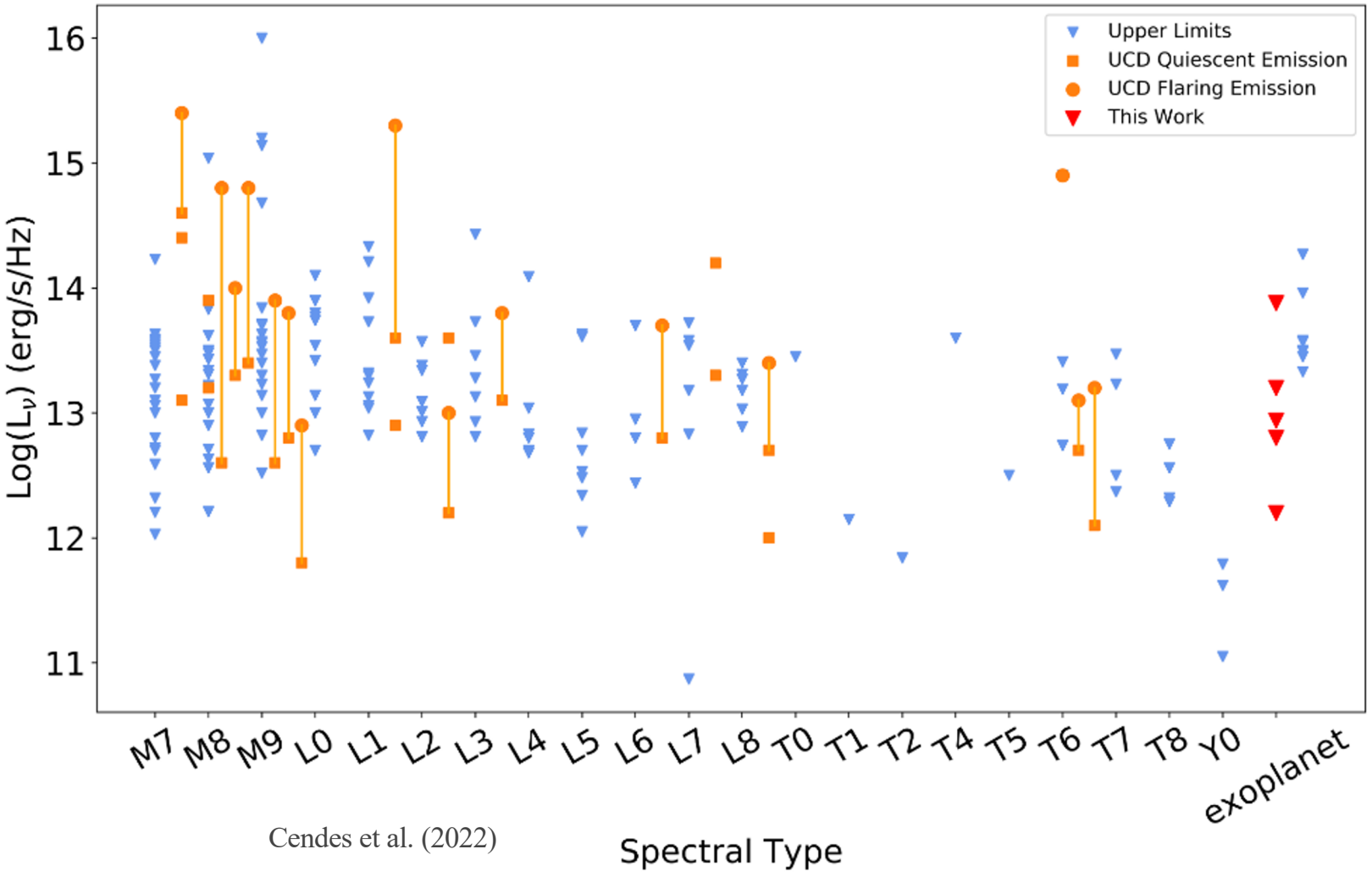
Masakos et al. (2015)

Why study them at *radio* frequencies?

- ★ They are extremely interesting by themselves (aurorae, powerful magnetic fields, fast rotators, etc)
- ★ As we'll see aurorae occur at ν(MHz) ≈ 2.8 B(Gauss), so detection = B determination → test dynamo models
- ★ The knowledge gathered may lead to a direct detection of exoplanetary radio emission.
- ★ A new way of detecting and characterizing exoplanets based on star–planet interaction (SPI).
- ★ Allow us to start looking into magnetosphere plasma conditions. What is the origin of this plasma?
  - Flares from UCD
  - Satellites (Io-Jupiter case)
  - Combination



Past *detections* and *non-detections*



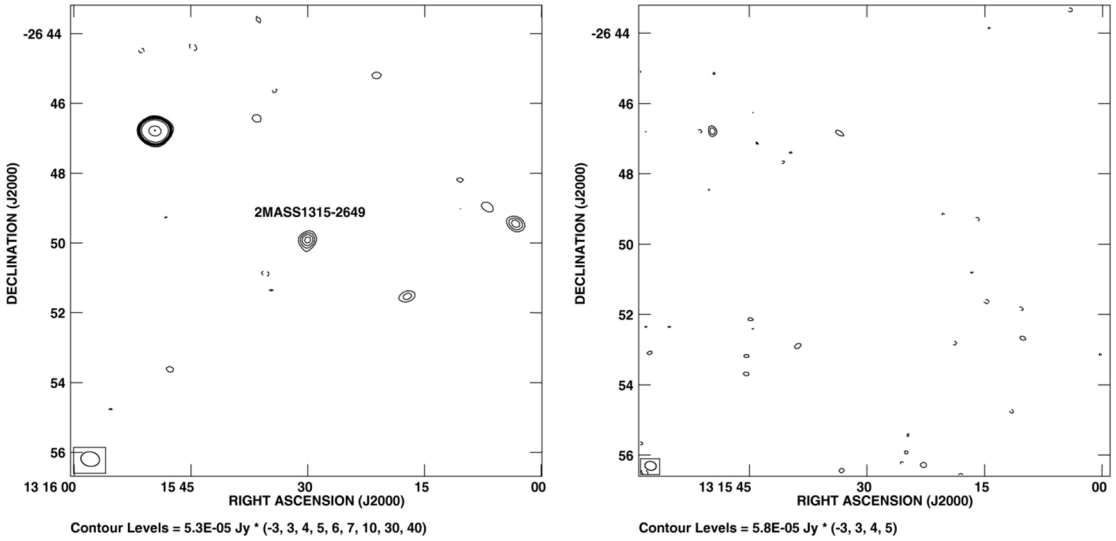
Cendes et al. (2022)

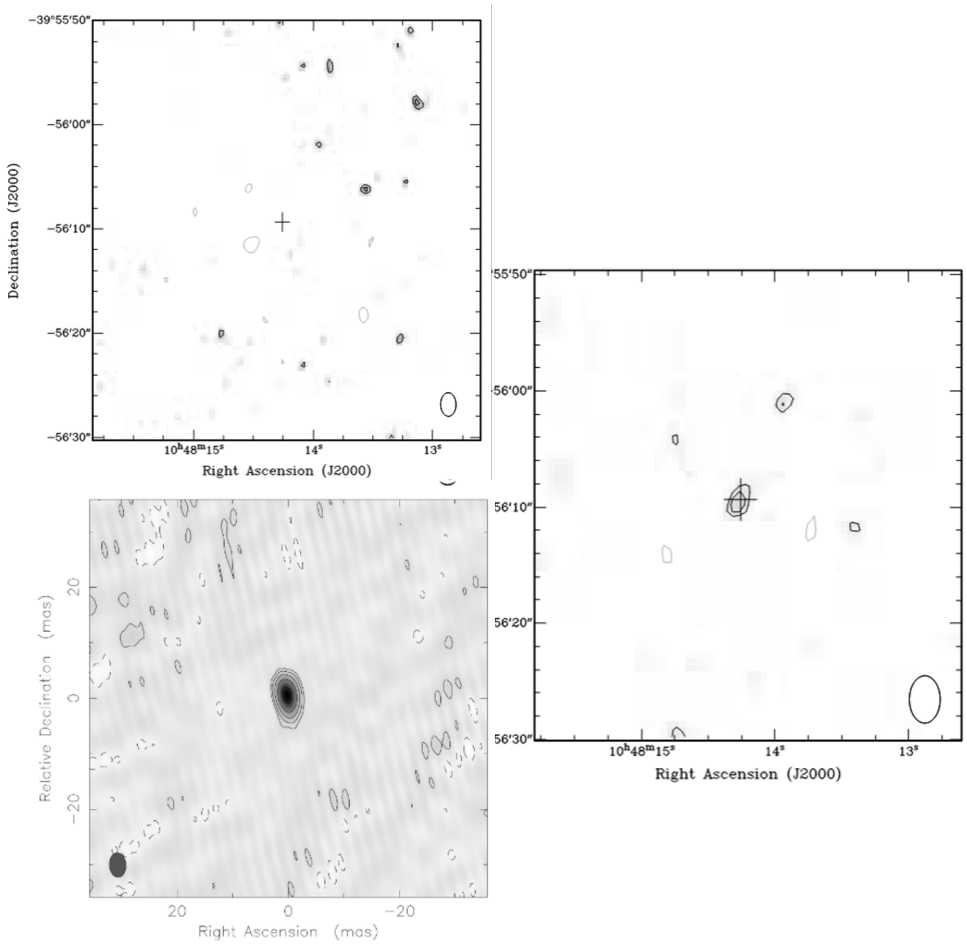
28 at GHz (Williams 2018 and references therein; Guirado et al. 2018; Richey-Yowel et al. 2020; Kao & Pineda 2022)

1 at MHz (Vedantham et al. 2020)

Radio emission in *UCD*

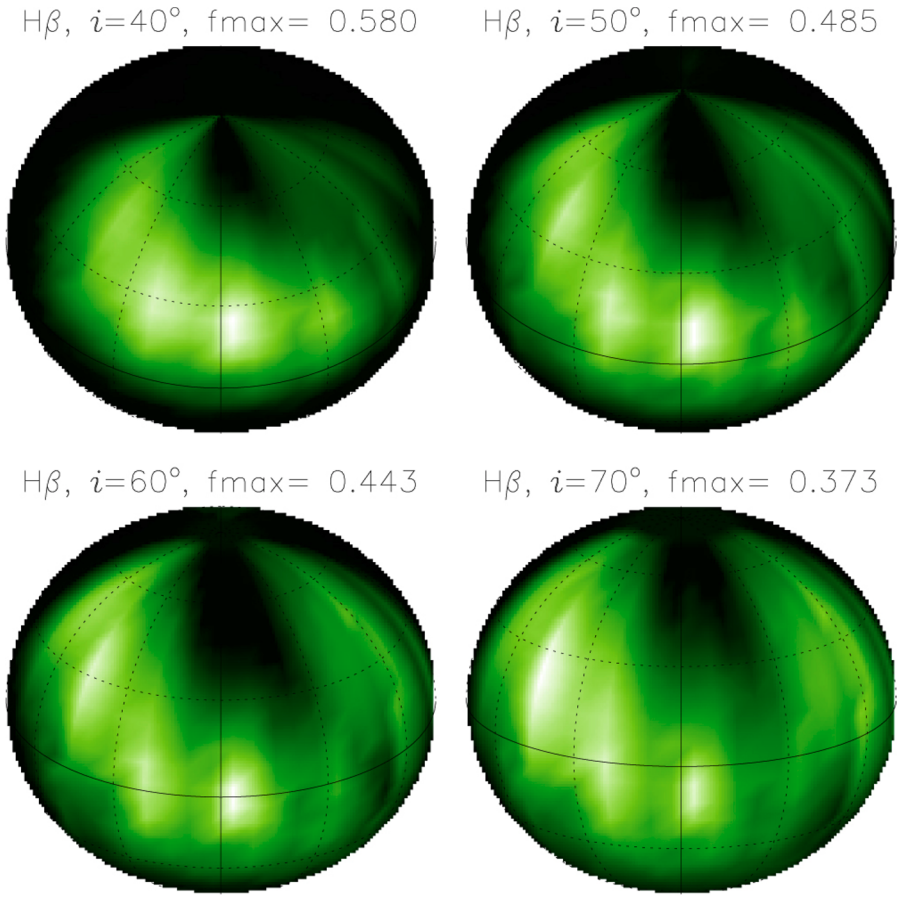
- ★ Up to 10% exhibit radio emission at 1-10 GHz (Route & Wolszczan 2016).
- ★ Perhaps up to 50% for fast rotators (vsin i >20 km/s; McLean et al. 2012).





Radio emission in *UCD*

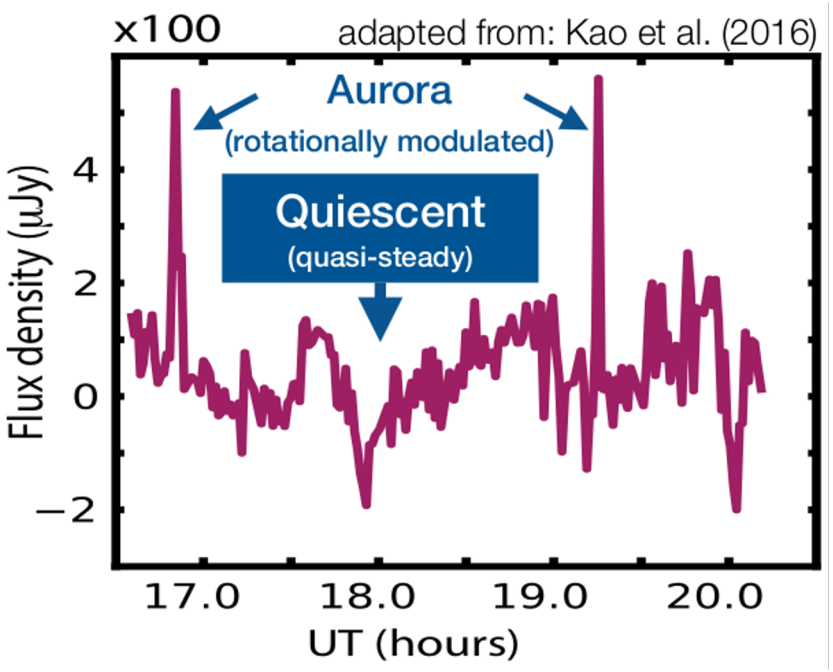
- ★ Up to 10% exhibit radio emission at 1-10 GHz (Route & Wolszczan 2016).
- ★ Perhaps up to 50% for fast rotators (vsin i >20 km/s; McLean et al. 2012).
- ★ They can possess strong magnetic fields of up to a few kG (e.g., Berdyugina 2017).



Hβ emission maps of LSR J1835+2359 (Berdyugina et al. 2017)

Radio emission in *UCD*

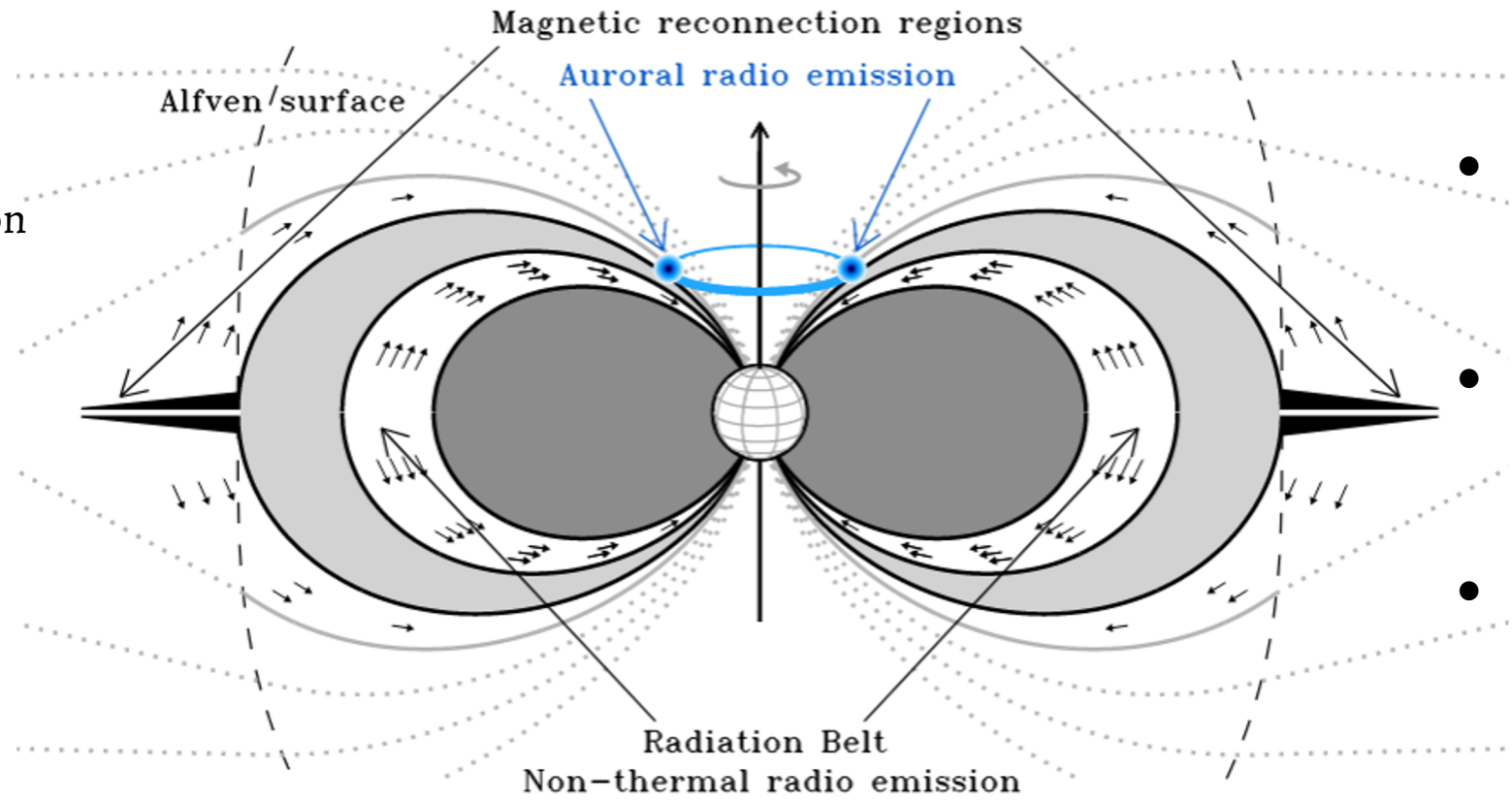
- ★ Up to 10% exhibit radio emission at 1-10 GHz (Route & Wolszczan 2016).
- ★ Perhaps up to 50% for fast rotators (vsin i >20 km/s; McLean et al. 2012).
- ★ They can possess strong magnetic fields of up to a few kG (e.g., Berdyugina 2017).
- ★ Low/moderate polarized quiescent emission + a highly polarized, rotationally modulated bursting emission: (gyro)synchrotron + ECMI.



Radio emission in *UCD*

Quiescent:

- Polar?
- Radiation belts?
- Both?



Leto et al. (2021)

Bursts:

- Flaring magnetic reconnection on the surface?
- ECMI due to precipitating e^- from middle magnetosphere?
- Satellite induced ECMI?

VLBI observations of *UCD*

- ★ Only three published detections (Forbrich & Berger 2009, Zhang et al. 2020, Forbrich et al. 2016) but extremely useful:
  - Determine dynamical masses
  - Resolve whether the emission originates in one or both components
  - Provide precise Parallax and proper motion
  - Investigate the presence of exoplanets around them by astrometric campaigns. (Curiel et al. 2020)

New VLBI observations of *UCD*

- ★ Only three published detections (Forbrich & Berger 2009, Zhang et al. 2020, Forbrich et al. 2016) but extremely useful:
  - Determine dynamical masses
  - Resolve whether the emission originates in one or both components
  - Provide precise Parallax and proper motion
  - Investigate the presence of exoplanets around them by astrometric campaigns. (Curiel et al. 2020)

- ★ 5 GHz EVN campaign shows promising results with 4 detections.

- ★ Rotation period < 4 hours

Name	Spectral Type
EQ J1122+2550	T6
LSR J1835+3259	M8.5
LSPM J0036+1821	L3.5
LP 349-25	M8+M9

New VLBI observations of *UCD*

- ★ Only three published detections (Forbrich & Berger 2009, Zhang et al. 2020, Forbrich et al. 2016) but extremely useful:
  - Determine dynamical ma
  - Resolve whether the emis n components
  - Provide precise Parallax a
  - Investigate the presence of exoplanets around them by astrometric campaigns. (Curiel et al. 2020)

The coolest UCD detected with VLBI: a T6 object with 30 M_{jup}.

- ★ 5 GHz EVN campaign shows promising results with 4 detections.

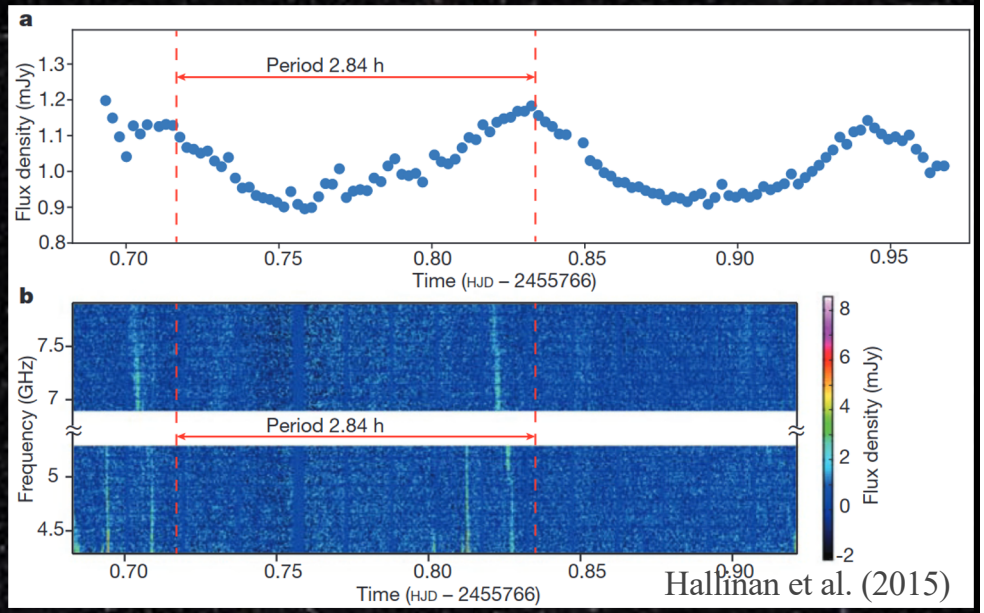
3 epochs: two double detections, one single detection

The coolest UCD with pulses detected with VLBI arrays

Name	Spectral Type
EQ J1122+2550	T6
LSR J1835+3259	M8.5
LSPM J0036+1821	L3.5
LP 349-25	M8+M9

LSR J1835+3259

- ★ M8.5 object at only 5.7 pc
- ★ Rotation period of 2.845 ± 0.003 hr (Harding et al. 2013)
- ★ First object where exo-aurorae where proposed (Hallinan et al. 2015)

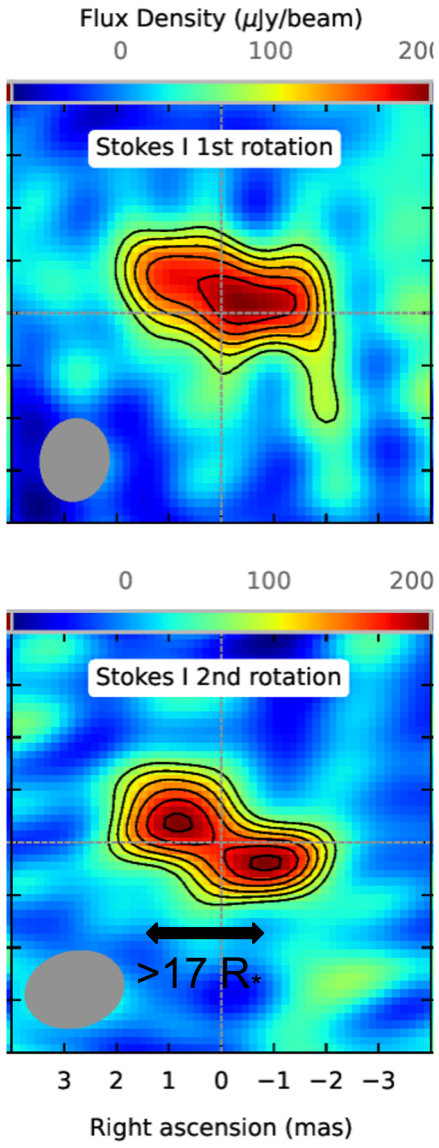


Hallinan et al. (2015)

LSR J1835+3259

6-hour observation in 2021 → two complete rotations!

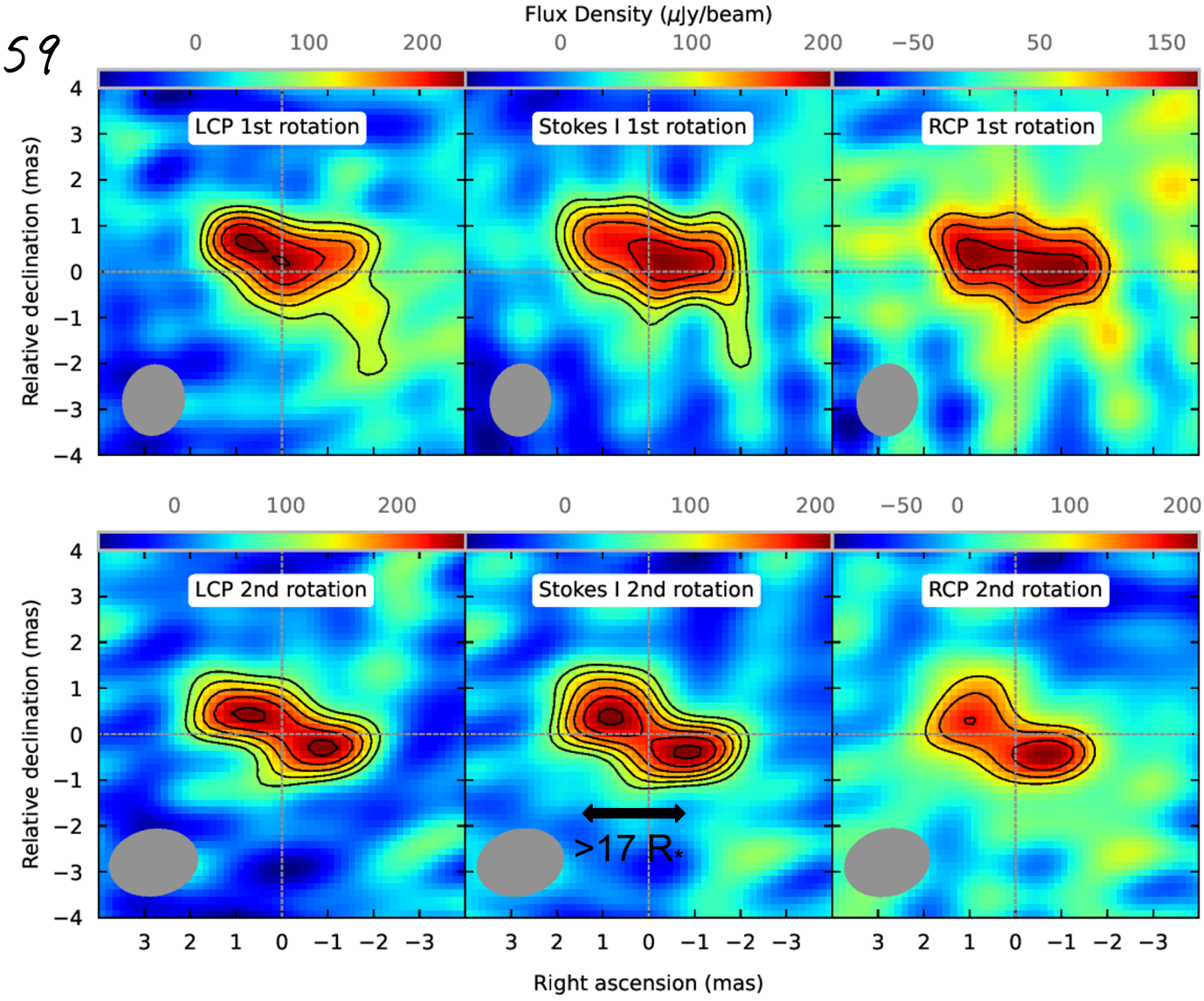
EVN = great signal to noise



LSR J1835+3259

6-hour observation in 2021 → two complete rotations!

Rotation average LCP and RCP are different. But they are averaged!



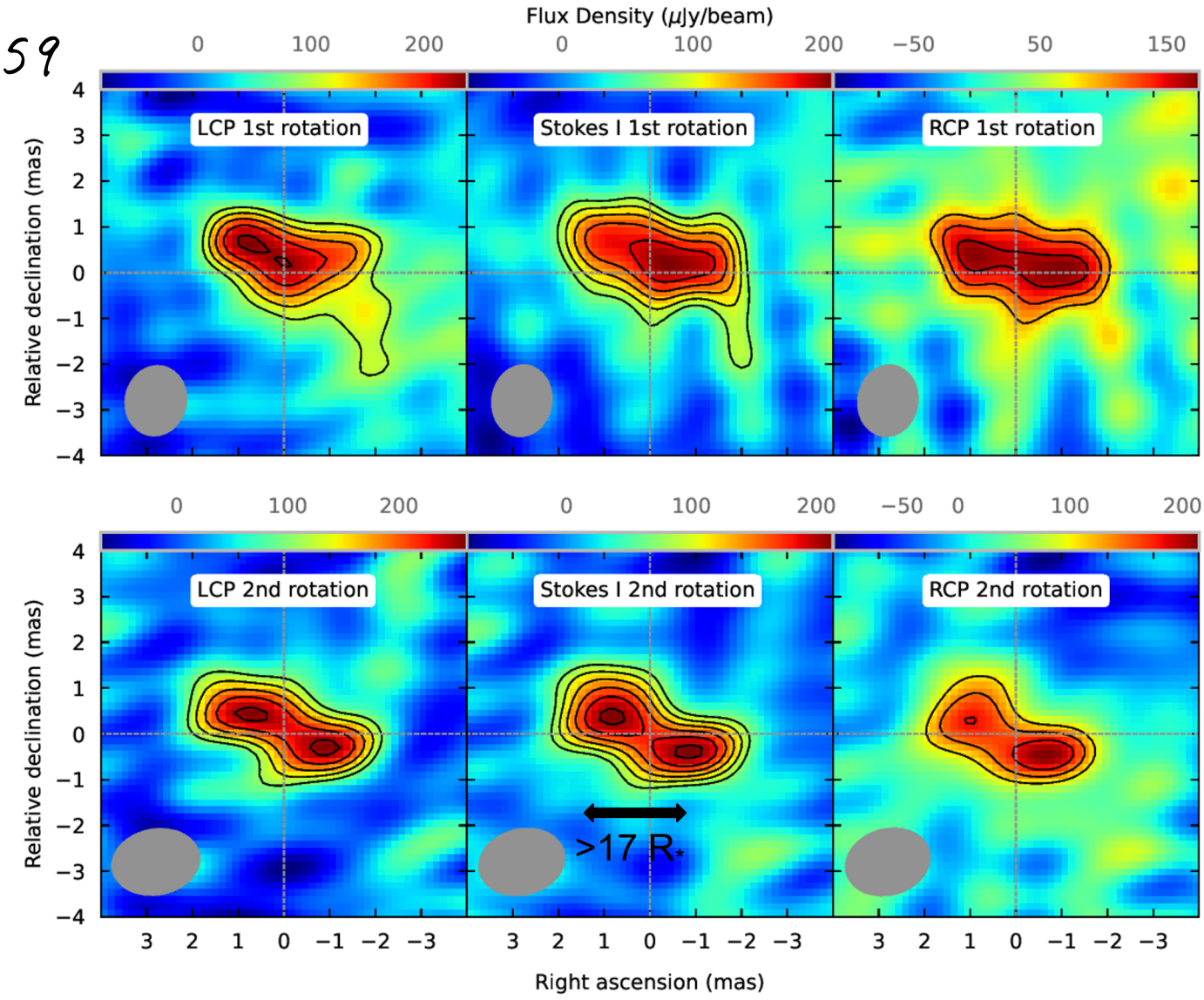
LSR J1835+3259. Fact Sheet.

- ★ **Extended structure (>17 R_*) during two consecutive rotations.**

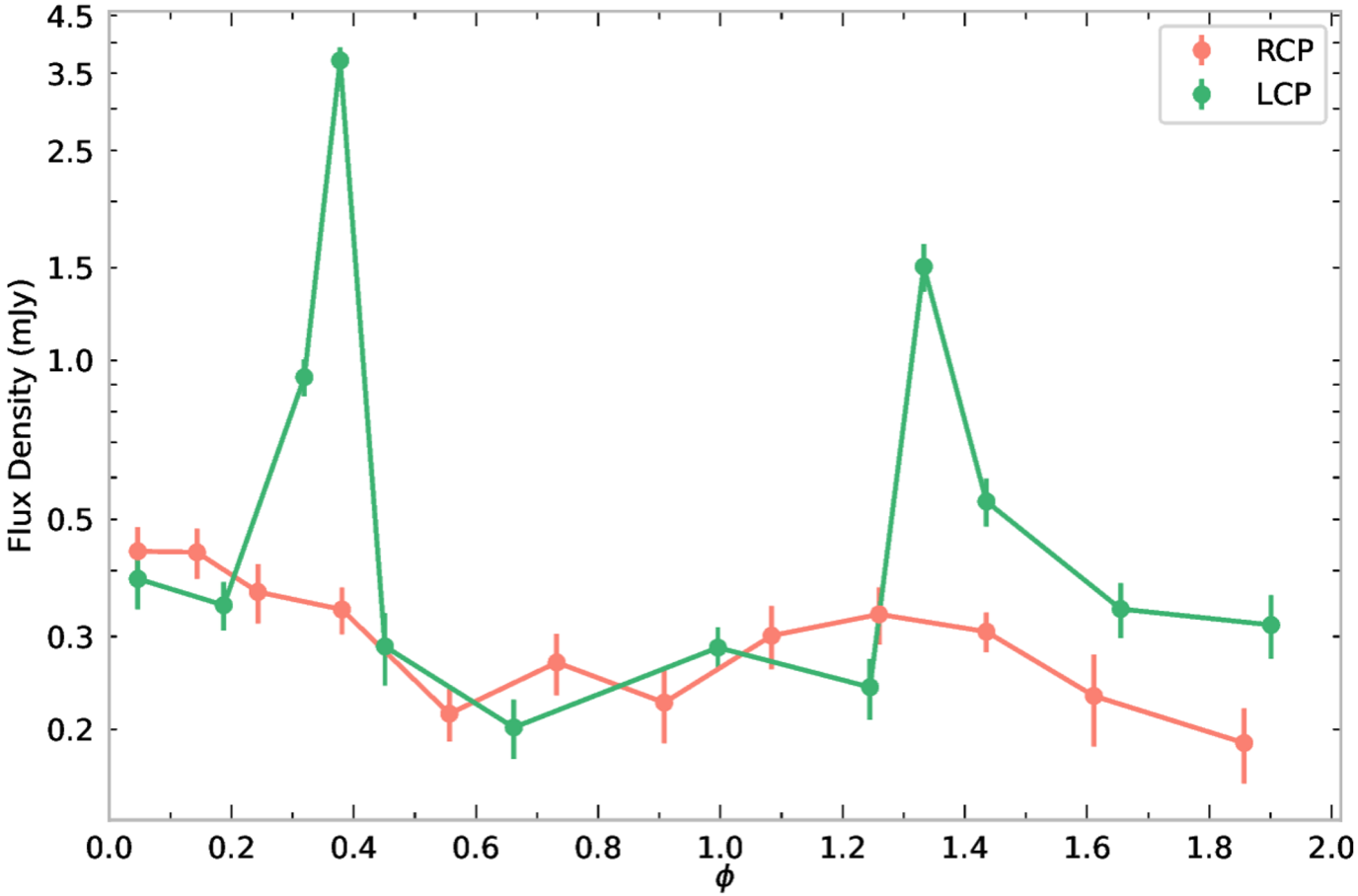
LSR J1835+3259

6-hour observation in 2021 → two complete rotations!

Rotation average LCP and RCP are different. But they are averaged!



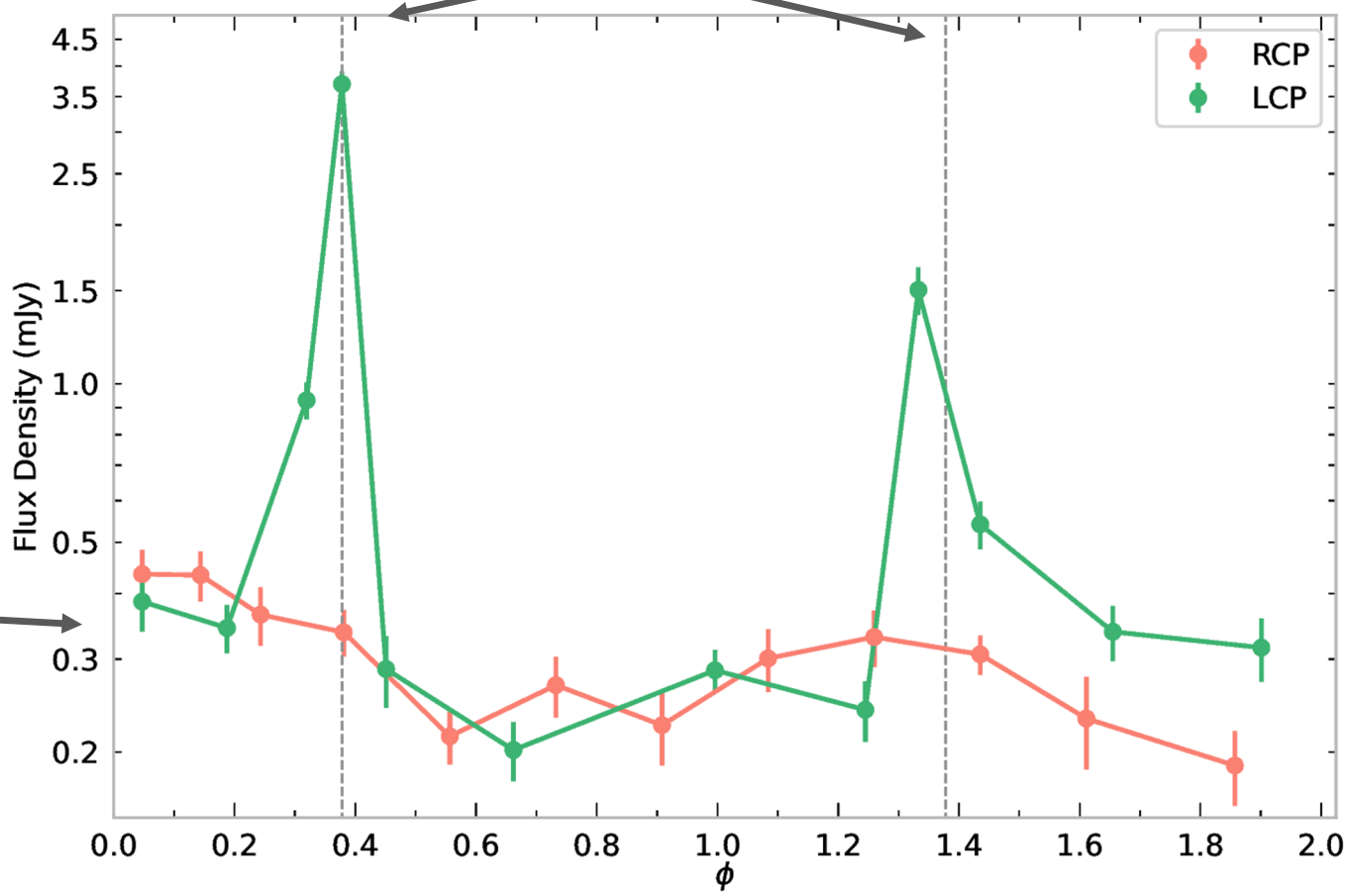
LSR J1835+3259



LSR J1835+3259

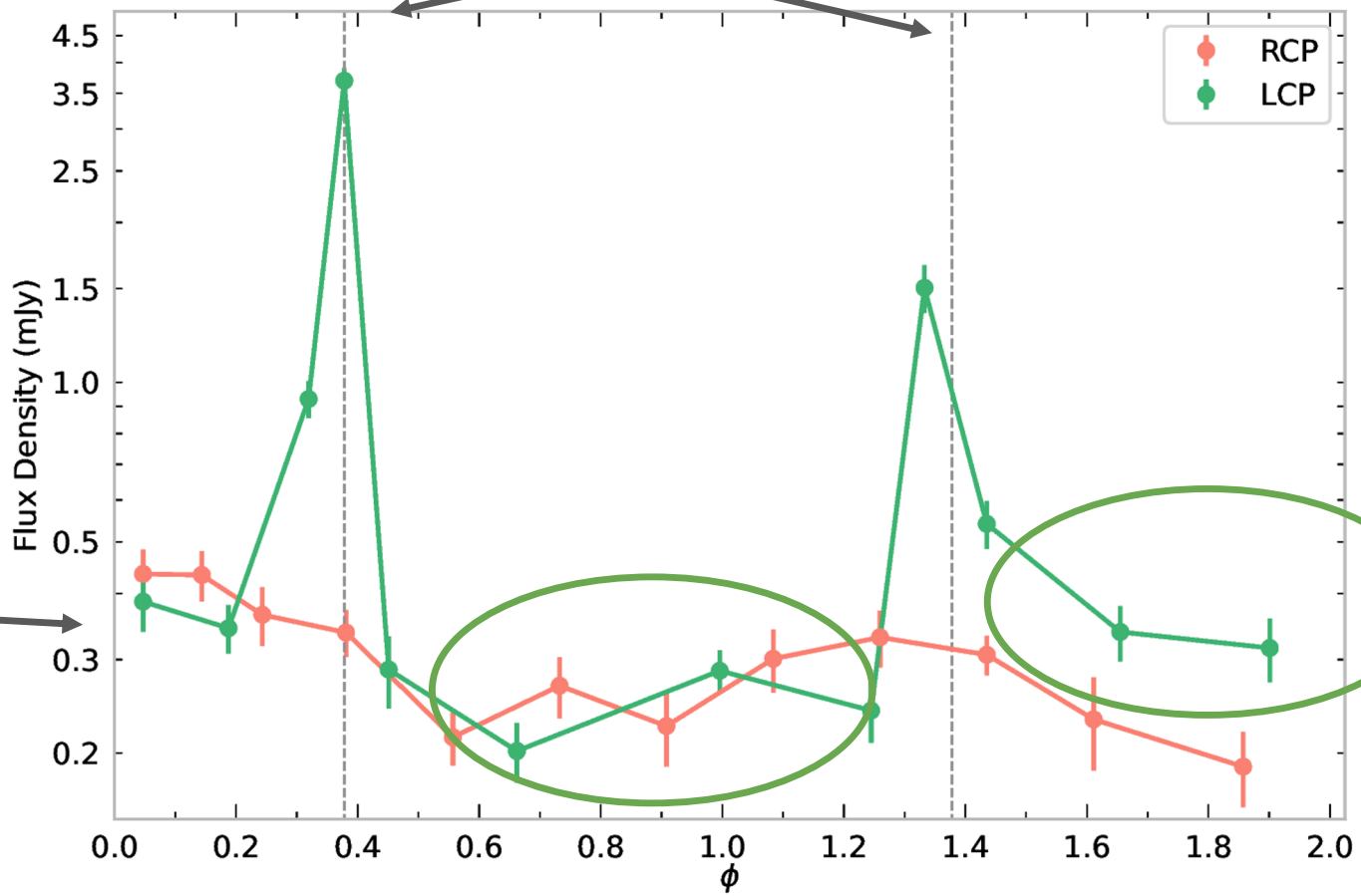
Bursts: modulated in total flux and in time

Quiescent: slowly varying and low polarization → gyrosynchrotron



LSR J1835+3259

Bursts: modulated in total flux and in time



Quiescent: slowly varying and low polarization → gyrosynchrotron

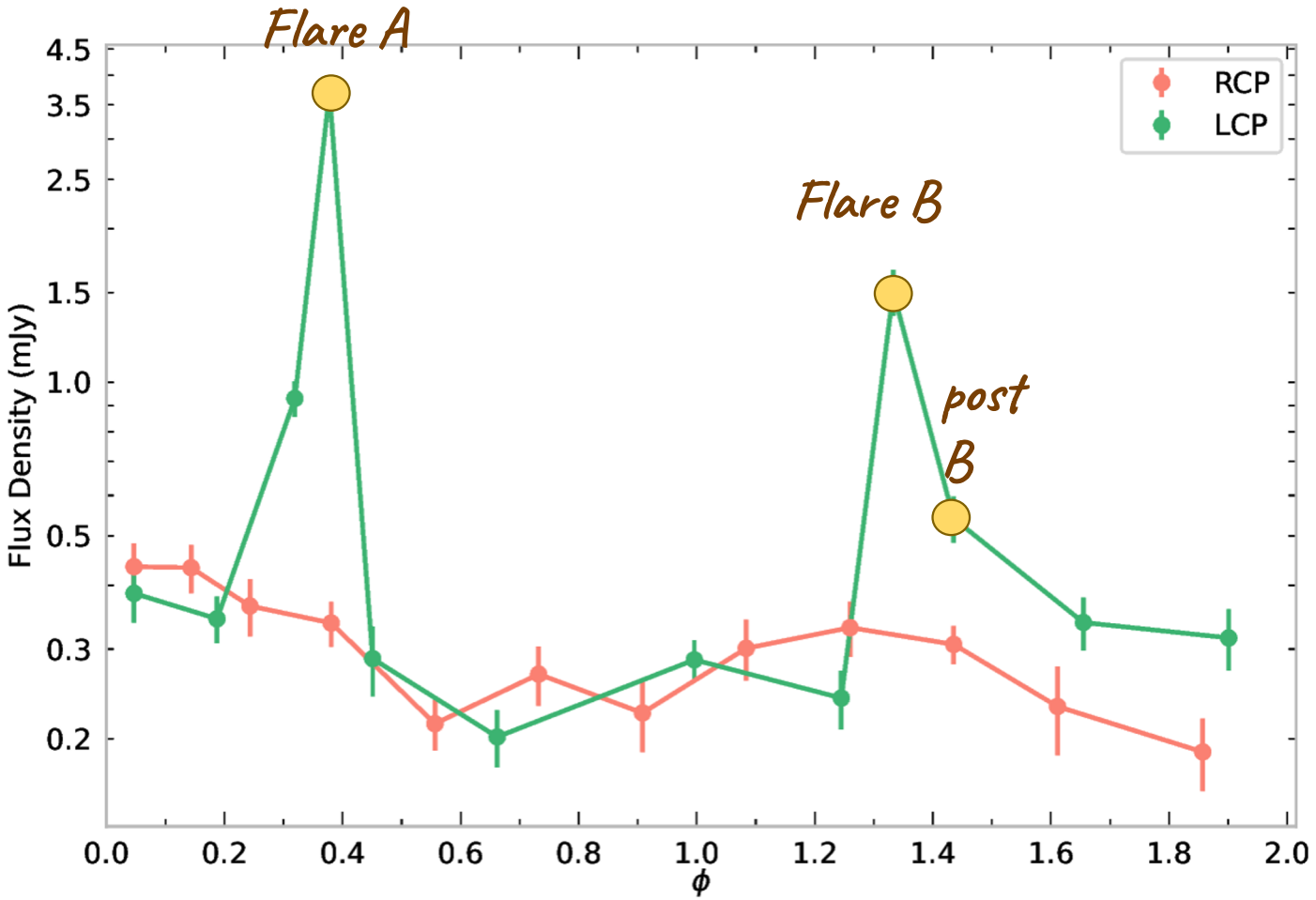
Different post-flares

LSR J1835+3259. Fact Sheet.

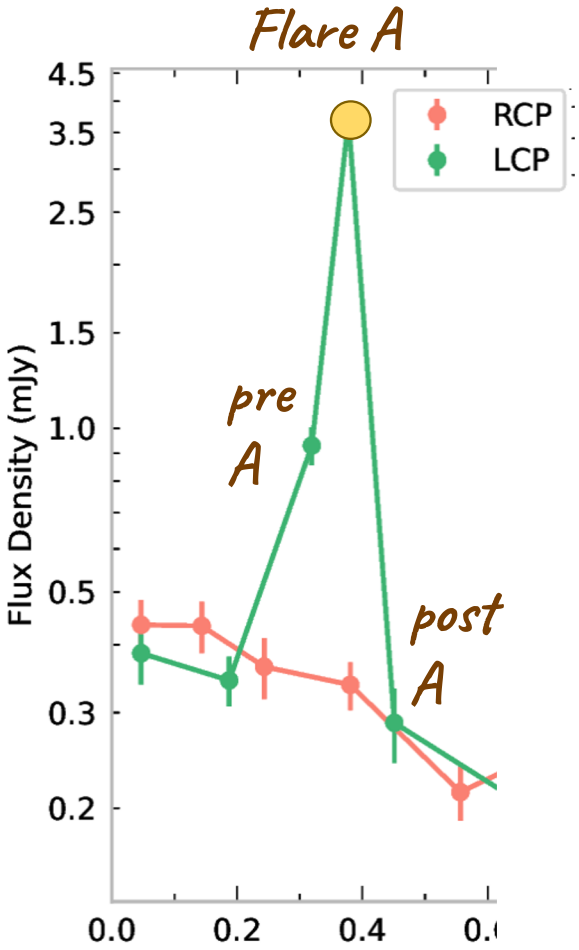
- ★ Extended structure (>17 R_*) during two consecutive rotations.
- ★ **Lightcurve shows quiescent and bursting emission.**
- ★ **The bursts or pulses:**
  - ○ **Occur at slightly different rotation phases.**
  - ○ **Are different in total LCP flux**
  - ○ **Have different LCP post-flare behaviour**

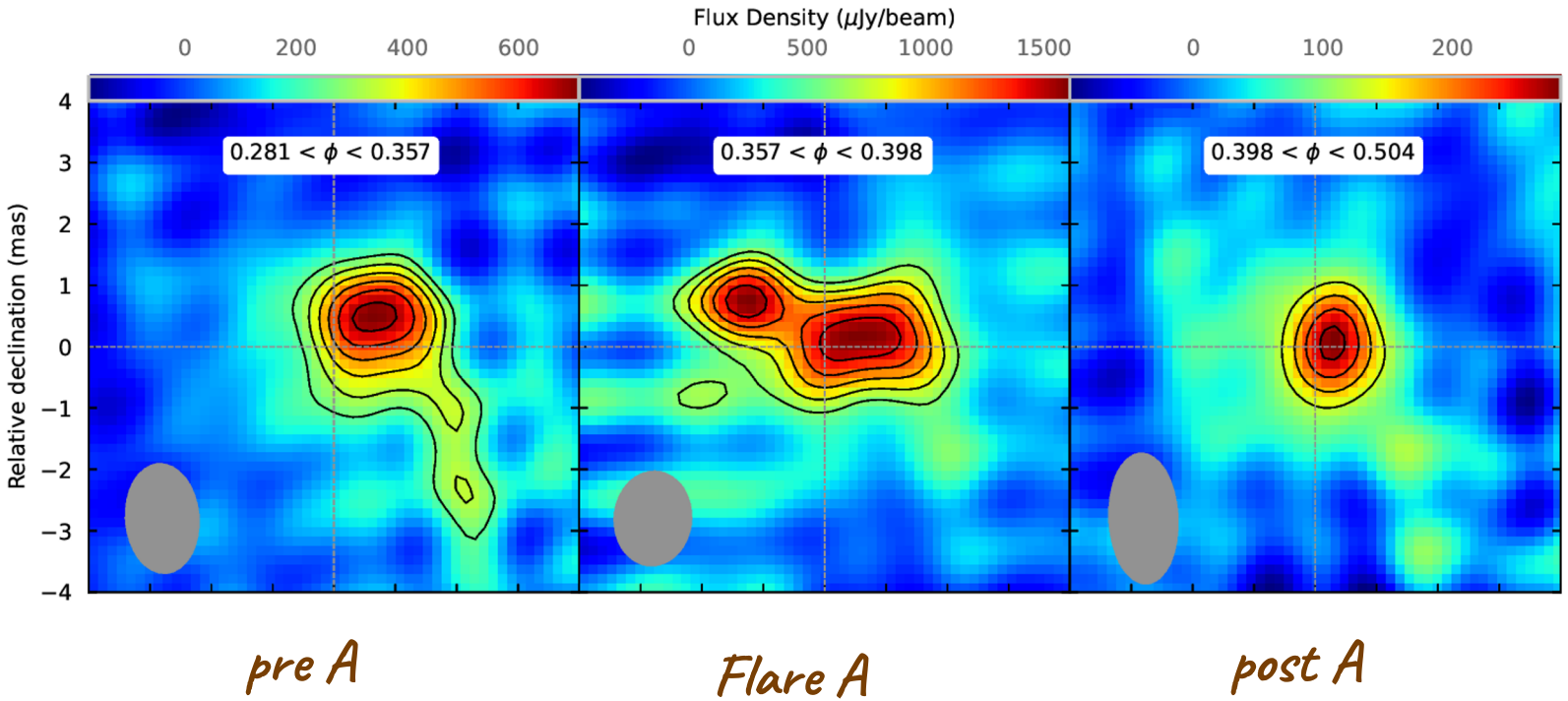
LSR J1835+3259

Important: LCP and RCP do not coincide spatially

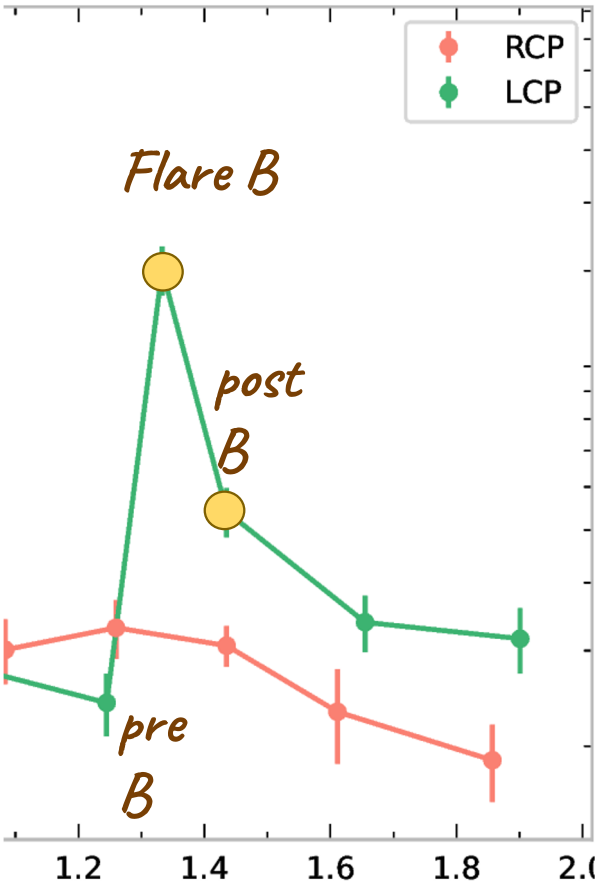


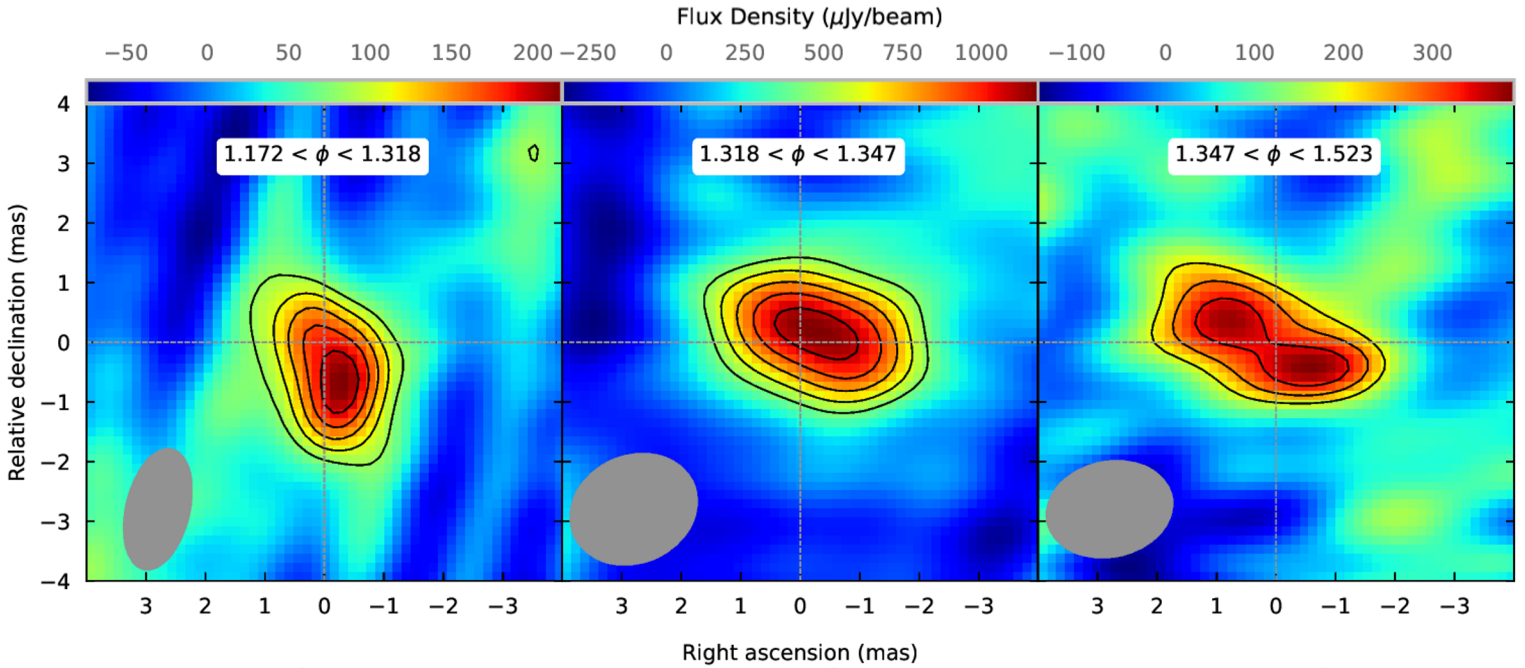
LSR J1835+3259





LSR J1835+3259





pre B

Flare B

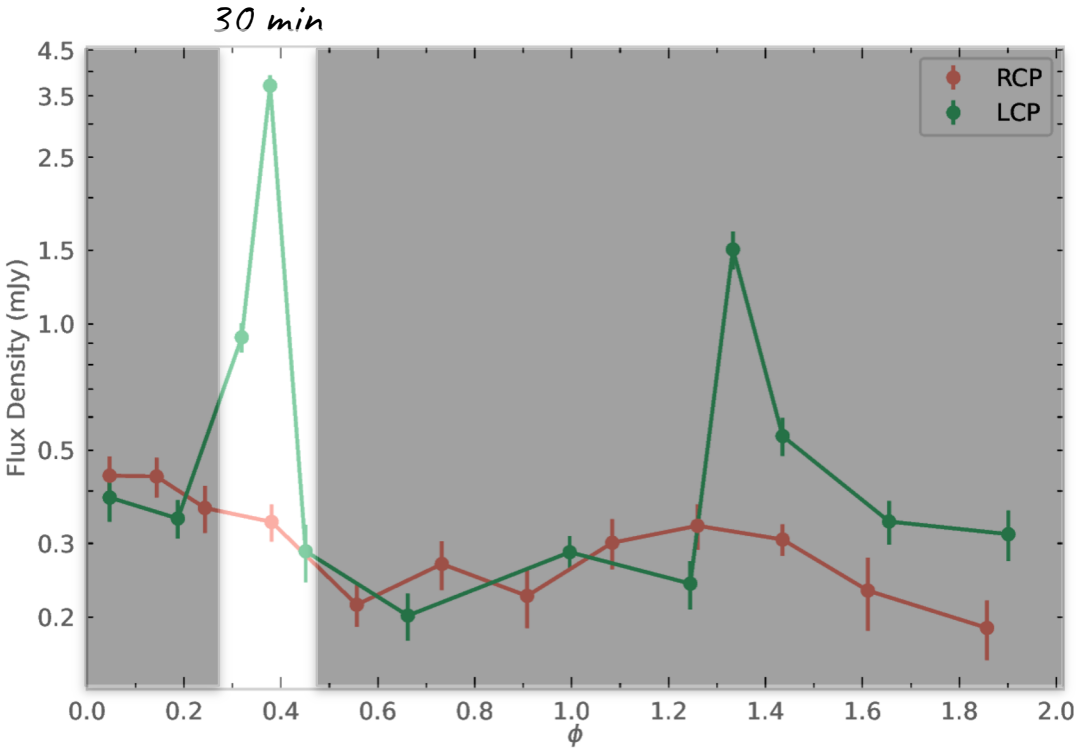
post B

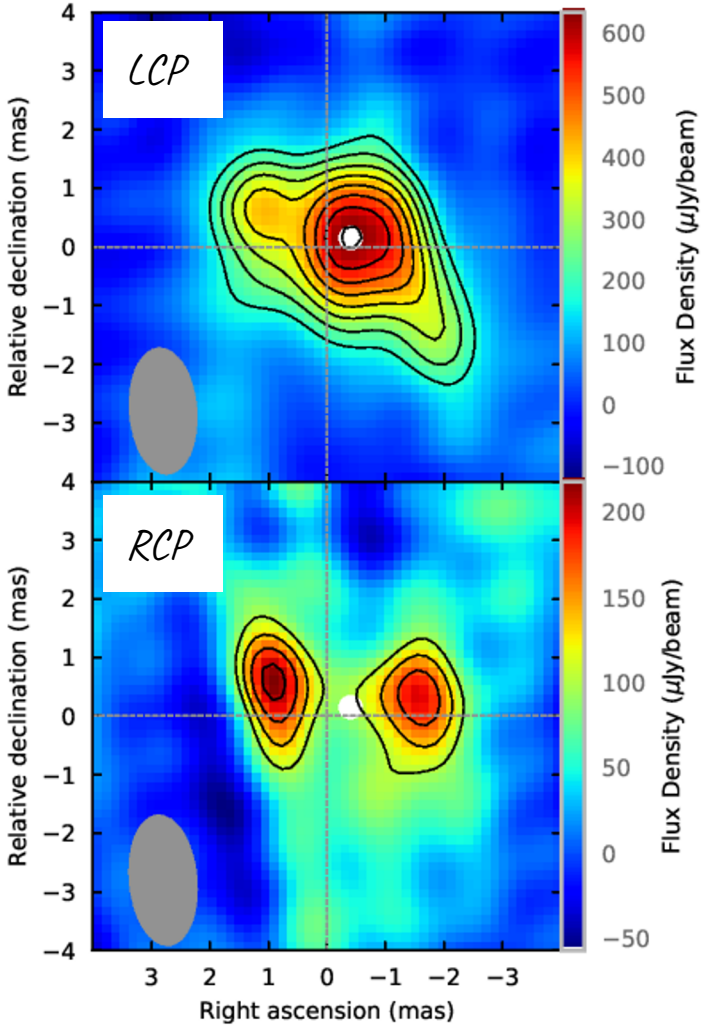
Different post-flares

LSR J1835+3259. Fact Sheet.

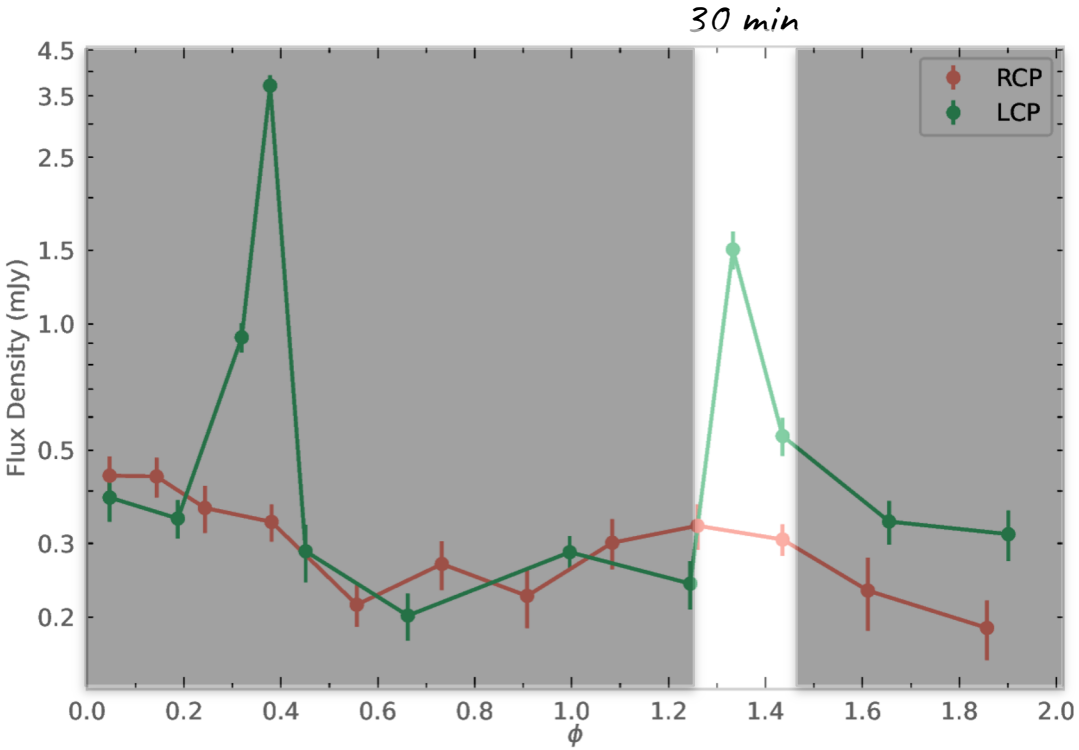
- ★ Extended structure (>17 R_*) during two consecutive rotations.
- ★ Lightcurve shows quiescent and bursting emission.
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux
  - Have different LCP post-flare behaviour. **LCP post-flare maps are different between rotation periods.**
- ★ **The time intervals when LCP fluxes peak show extended structures.**

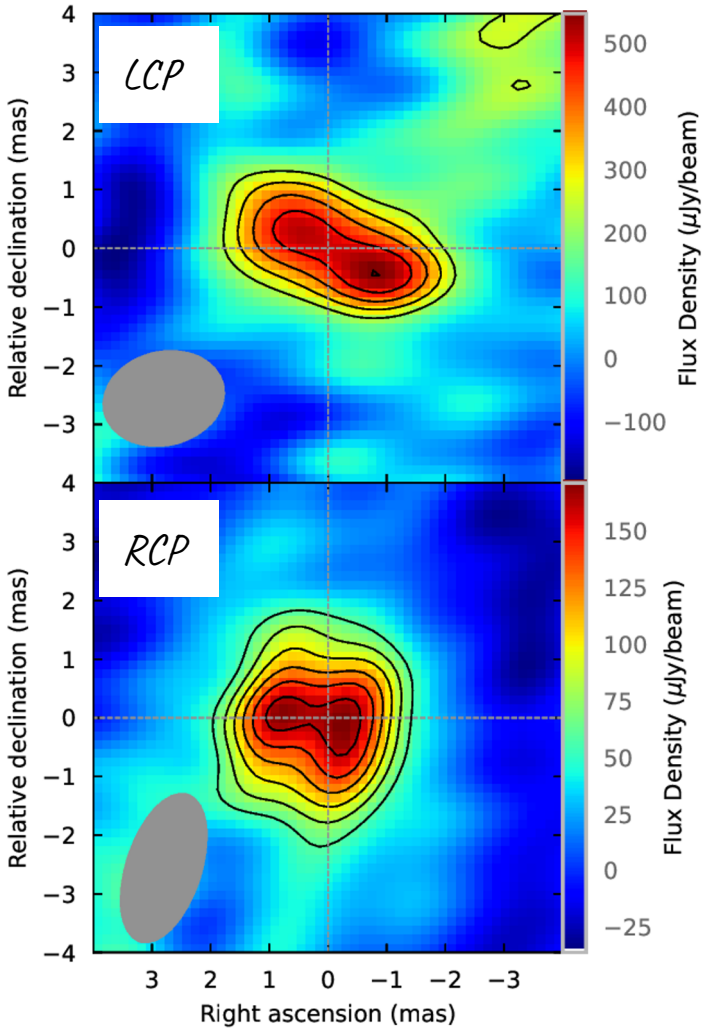
LSR J1835+3259





LSR J1835+3259

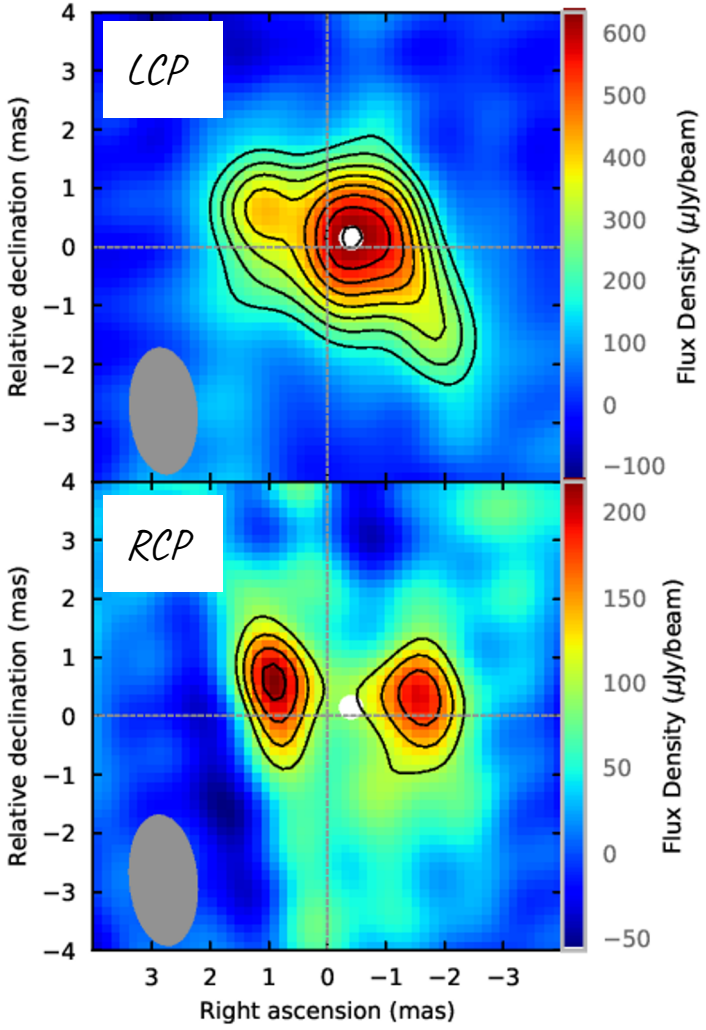


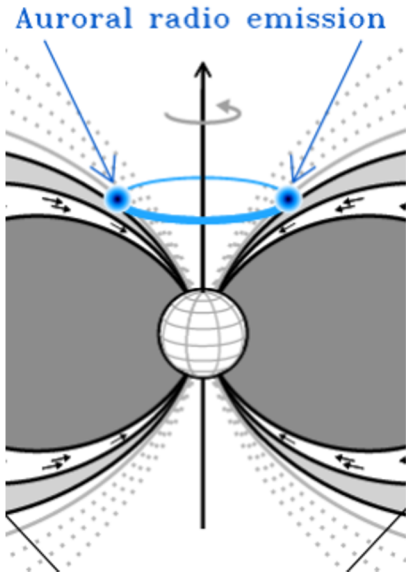


LSR J1835+3259. Fact Sheet.

- ★ Extended structure (>17 R_*) during two consecutive rotations.
- ★ Lightcurve shows quiescent and bursting emission.
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux
  - Have different LCP post-flare behaviour. LCP post-flare maps are different between rotation periods.
- ★ The time intervals when LCP fluxes peak show extended structures.
- ★ **30-minutes maps during the bursts show:**
  - **The morphology varies from one rotation to another.**
  - **Both LCP and RCP maps present extended structures**
  - **During the first rotation, bursting emission (LCP) and quiescent emission (RCP) do not coincide spatially!**

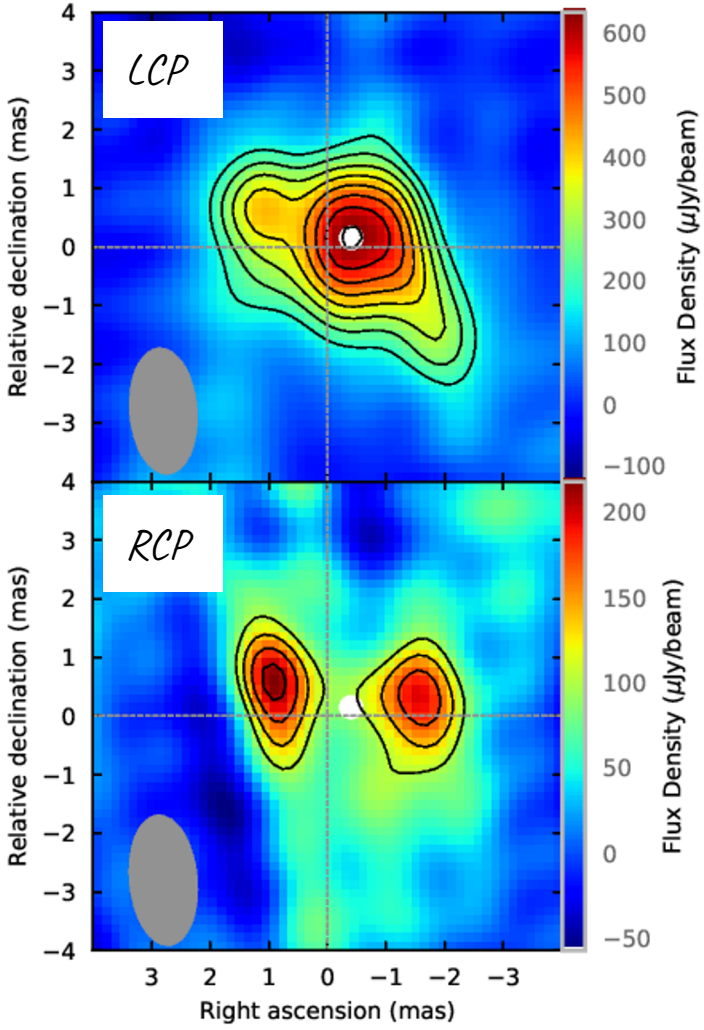
How do we explain this *Fact Sheet?*

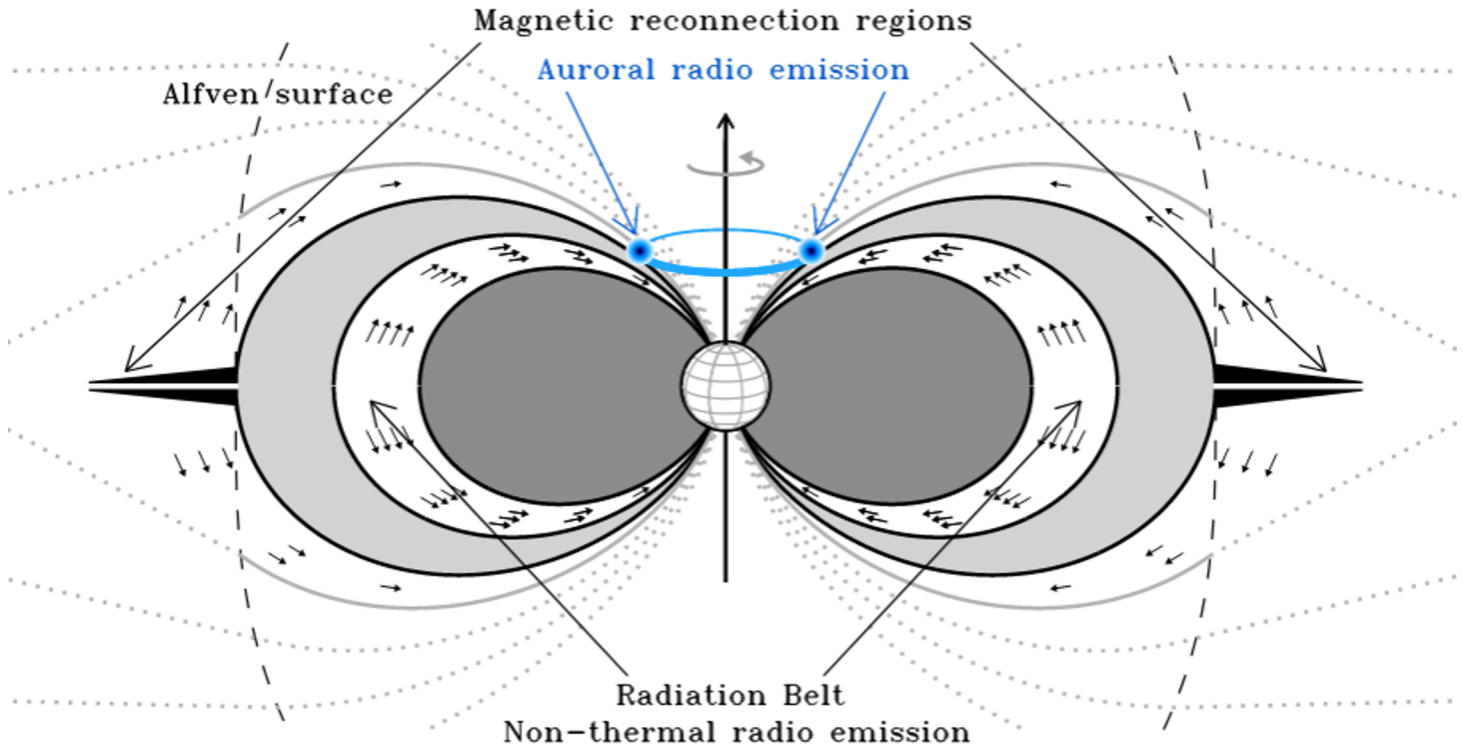




Remember: Maps are registered. We are using phase-referencing

How do we explain this *Fact Sheet?*





LSR J1835+3259. Fact Sheet.

- ★ Extended structure (>17 R_*) during two consecutive rotations. 👌
- ★ Lightcurve shows quiescent and bursting emission. 👌
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux
  - Have different LCP post-flare behaviour. LCP post-flare maps are different between rotation periods.
- ★ The time intervals when LCP fluxes peak show extended structures.
- ★ 30-minutes maps during the bursts show:
  - The morphology varies from one rotation to another.
  - Both LCP and RCP maps present extended structures 👌
  - During the first rotation, bursting emission (LCP) and quiescent emission (RCP) do not coincide spatially! 👌

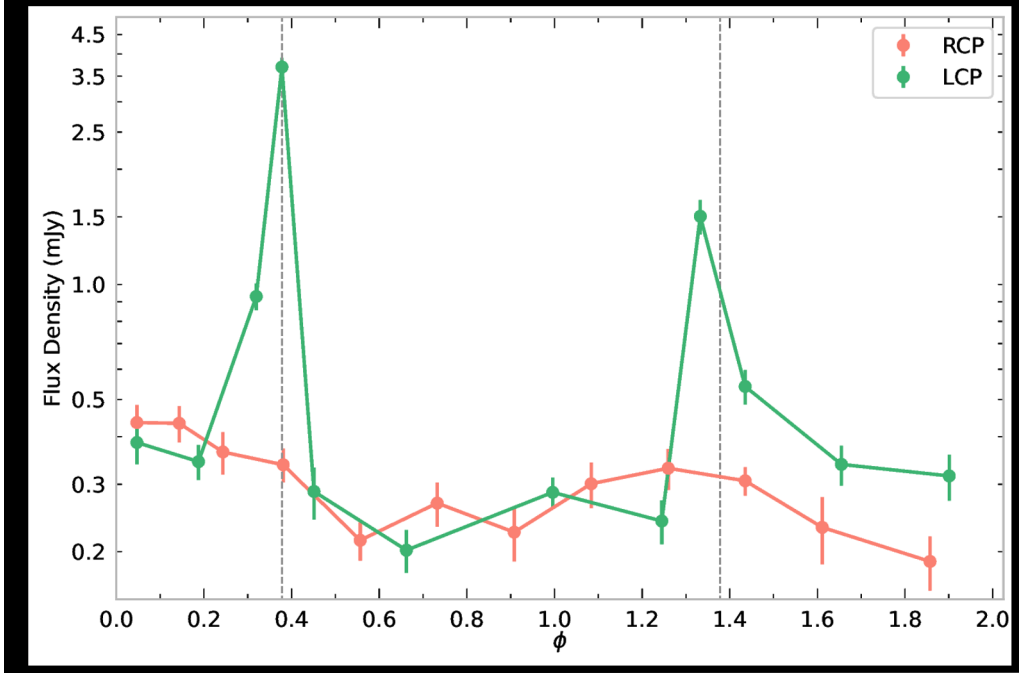
LSR J1835+3259. Fact Sheet.

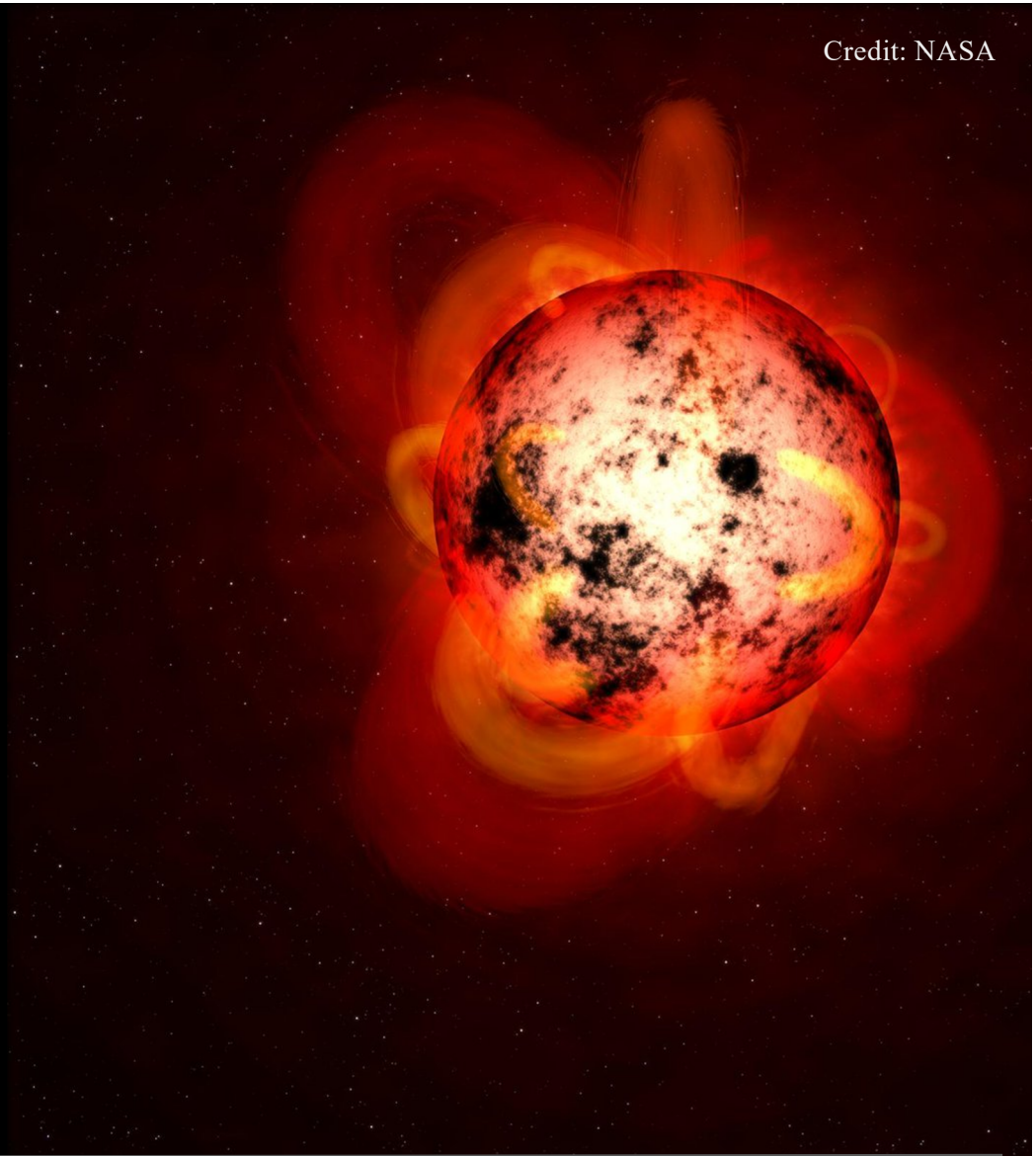
- ★ Extended structure (>17 R_*) during two consecutive rotations.
- ★ Lightcurve shows quiescent and bursting emission.
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux
  - Have different LCP post-flare behaviour. LCP post-flare maps are different between rotation periods.
- ★ The time intervals when LCP fluxes peak show extended structures.
- ★ 30-minutes maps during the bursts show:
  - The morphology varies from one rotation to another.
  - Both LCP and RCP maps present extended structures
  - During the first rotation, bursting emission (LCP) and quiescent emission (RCP) do not coincide spatially!

We haven't discussed the origin of the pulses yet!

LSR J1835+3259

★ Saur et al. (2018) proposed that these pulses are driven by internal processes.





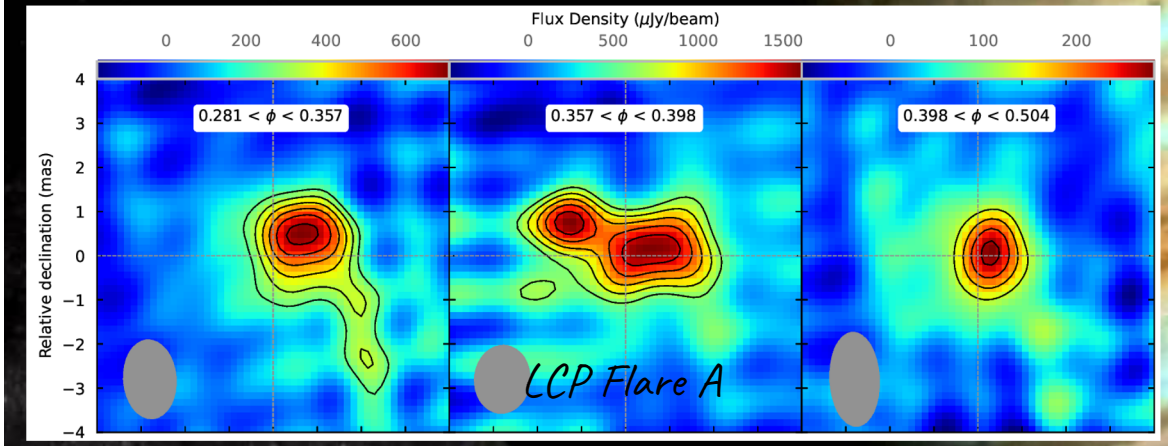
LSR J1835+3259. Fact Sheet. Loop hypothesis.

- ★ Extended structure (>17 R_*) during two consecutive rotations.
- ★ Lightcurve shows quiescent and bursting emission.
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux
  - **Have different LCP post-flare behaviour. LCP post-flare maps are different between rotation periods.**
- ★ The time intervals when LCP fluxes peak show extended structures.
- ★ 30-minutes maps during the bursts show:
  - **The morphology varies from one rotation to another.**
  - Both LCP and RCP maps present extended structures
  - During the first rotation, bursting emission (LCP) and quiescent emission (RCP) do not coincide spatially!

LSR J1835+3259

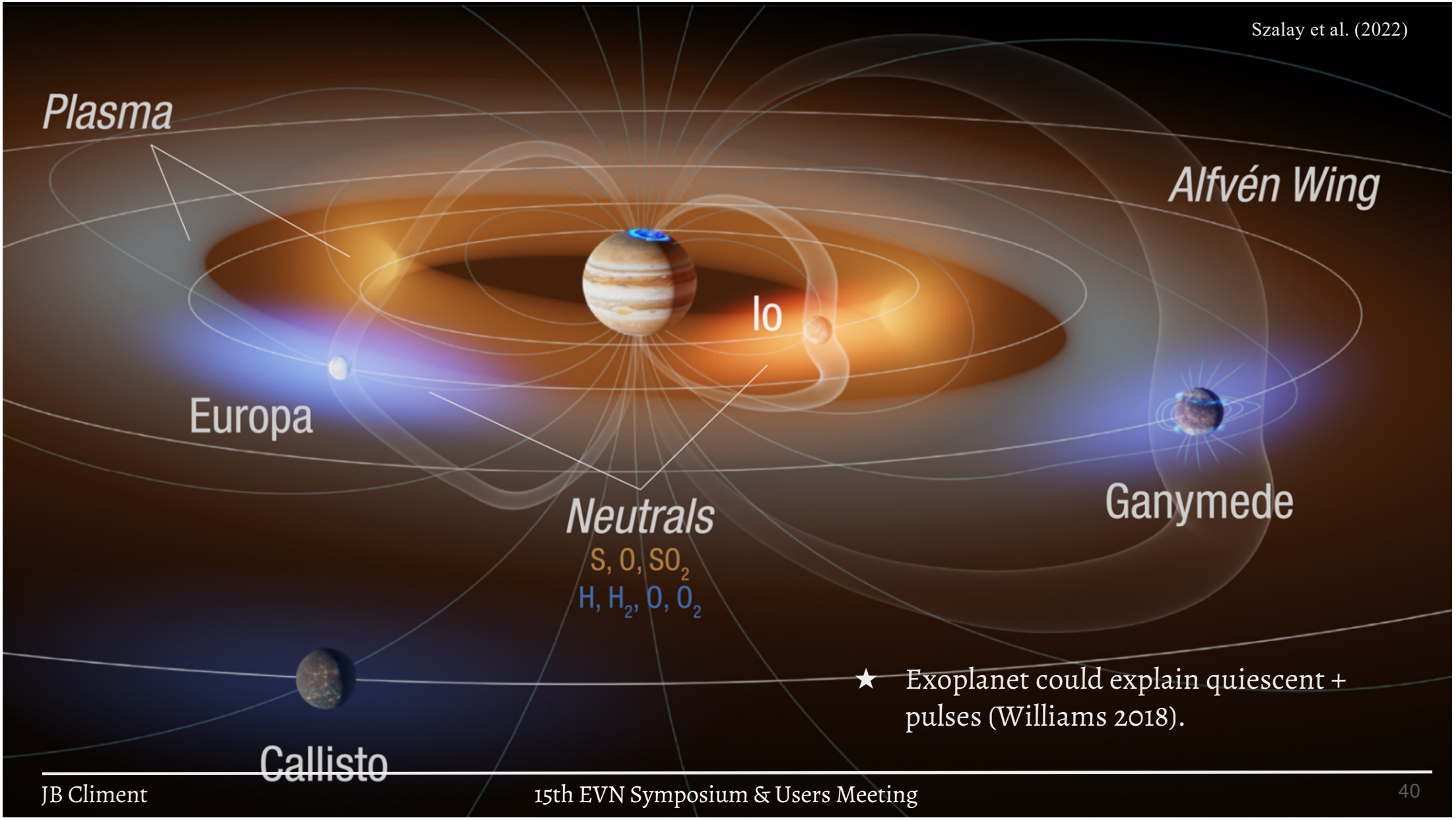
Credit: NASA

★ Hallinan et al (2015) raised the possibility of an external origin: star-planet interaction.



LSR J1835+3259. Fact Sheet. Exoplanet hypothesis.

- ★ Extended structure (>17 R_*) during two consecutive rotations. 👌
- ★ Lightcurve shows quiescent and bursting emission. 👌
- ★ The bursts or pulses:
  - Occur at slightly different rotation phases.
  - Are different in total flux 👌
  - Have different LCP post-flare behaviour. LCP post-flare maps are different between rotation periods.
- ★ The time intervals when LCP fluxes peak show extended structures. 👌
- ★ 30-minutes maps during the bursts show:
  - The morphology varies from one rotation to another. 👌
  - Both LCP 👌 and RCP maps present extended structures 👌
  - During the first rotation, bursting emission (LCP) and quiescent emission (RCP) do not coincide spatially! 👌



★ Exoplanet could explain quiescent + pulses (Williams 2018).

Conclusions

- ★ The field of radio emission from low-mass objects with VLBI at GHz is still in its infancy (specially UCD) but with promising results.

- ★ Thanks to great sensitivity and resolution achieved by the EVN we can:

    - Measure much-needed dynamical masses.
    - Provide accurate parallax and proper motion
    - Resolve the magnetosphere.
    - Investigate the presence of exoplanets by proper motion or star-planet interaction.

- ★ EVN observations of LSR J1835 point towards a unifying model for the radio emission of this UCD: radiation belts (quiescent component) + exoplanet induced aurorae (bursting emission).

THANK YOU

cliojuan@uv.es