Stellar-Planet interaction (SPI) at radio wavelengths

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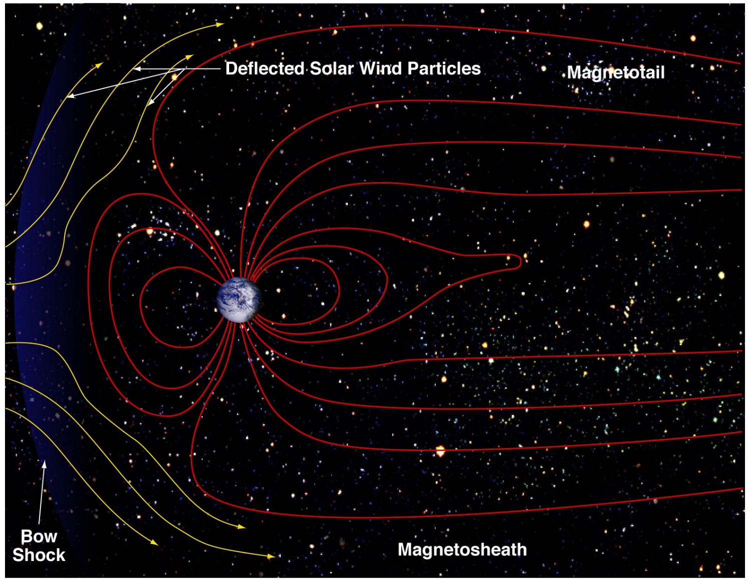
Why study ARE and SPI in Exo-Systems?

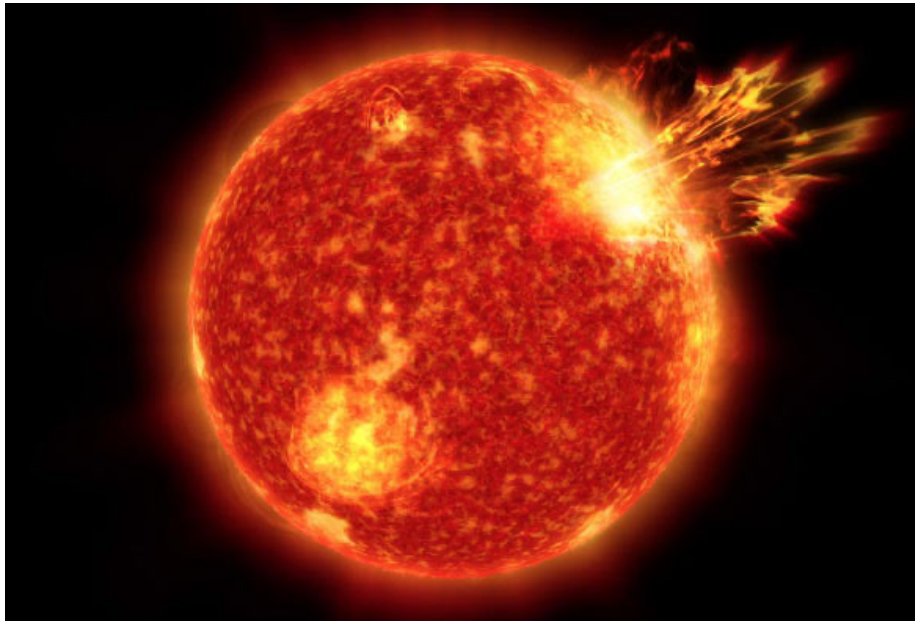
- Presence of **magnetospheres** in stars and planets
- **Magnetospheres acts as a shield** that prevents the arrival of ionized and potentially dangerous particles at the surface
- Important condition for life, as it **protects against the activity** of the parent star



Why study ARE and SPI in Exo-Systems?

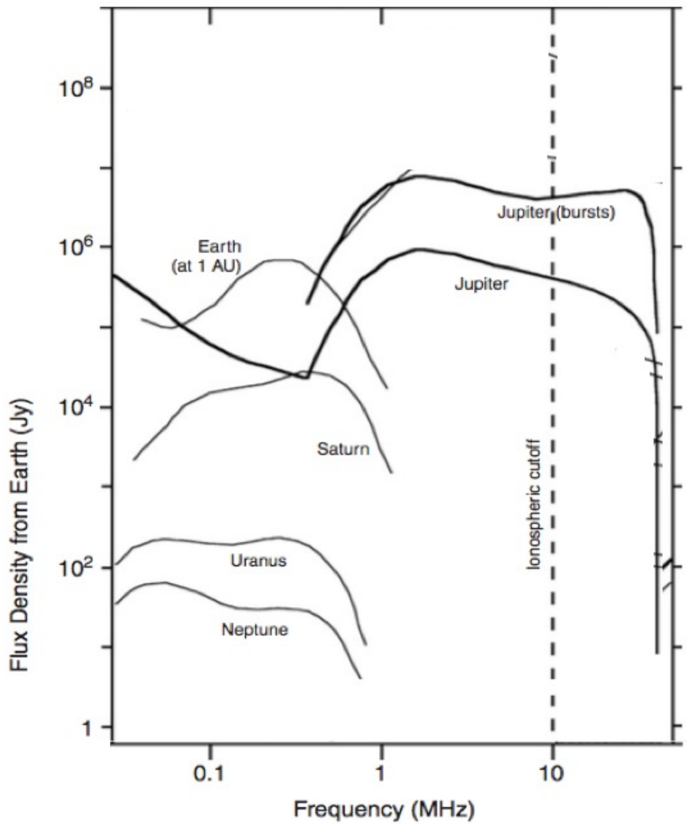
- Strong **magnetic activity** in the **early phases** of evolution
- Flares, Superflares, CME may have played a role in the evolution of the Earth's atmosphere

  (e.g. fixation of N and other molecules)



Strong activity in early phases and magnetic field as a shield in a second phase are both important for study of the conditions for life development in exoplanets

Radio Emission From Planets of Solar System



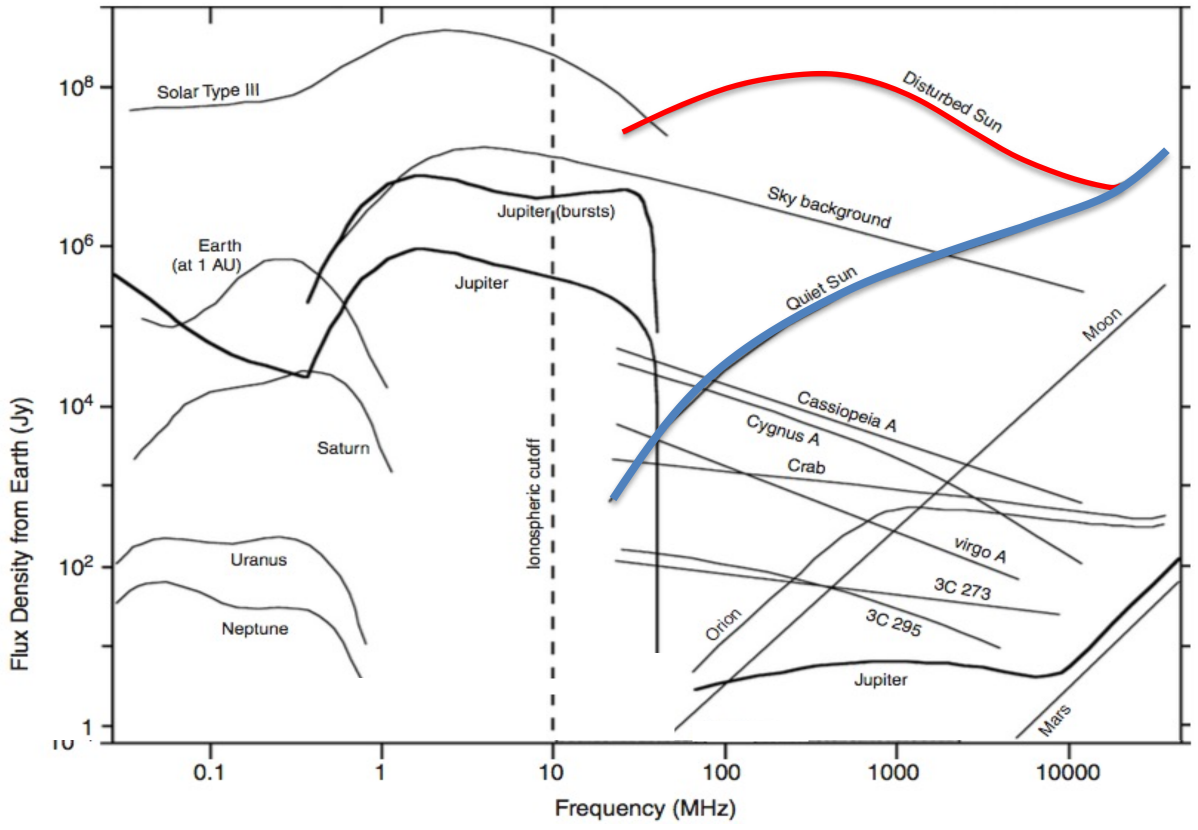
Adapted from Zarka 2007

All Planets
with magnetosphere
Earth, Jupiter, Saturn, Uranus, Neptune

Auroral Radio Emission
Pulses, bursts
Low frequency ($\leq \nu_{ionosph}$ cutoff)
(Ulysses, Voyager, Cassini…)

Cyclotron MASER

Radio Emission From Planets of Solar System



Adapted from Zarka 2007

Characteristics:

Intensity

Emission **more intense than active Sun**

If at 1 AU:

Jupiter x 20

Saturn x 100

Uranus x 400

Neptune x 900

Frequency

kHz- few MHz

ν_B = s 2.8 B (MHz)

Depends on B planet

Spectra

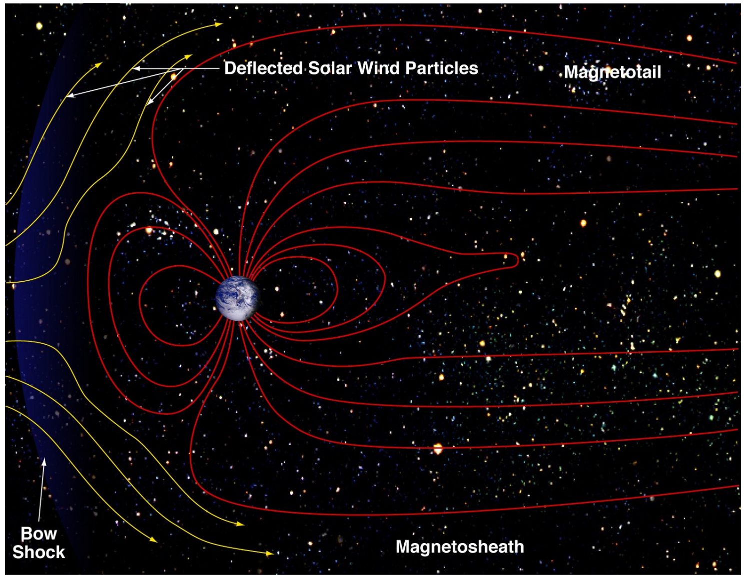
Broad $\Delta\nu/\nu \approx 1$

Polarisation

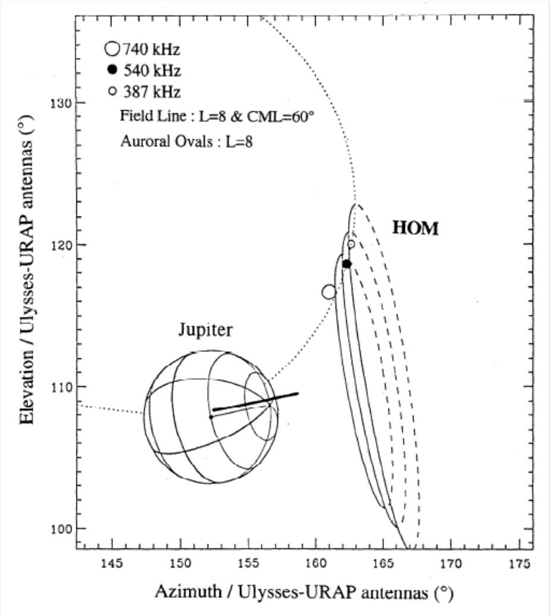
Circular 100%

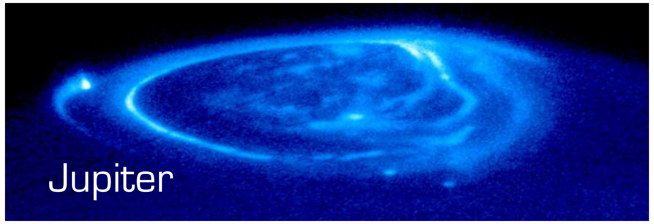
Type 1 – Stellar Wind – Planet magnetosphere or kinetic

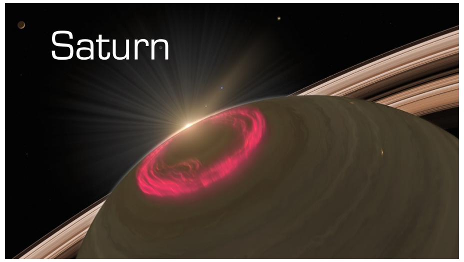
Formation of magneto-tail → current sheets → particle acceleration
Back to planet→ converge over magnetic poles → aurorae



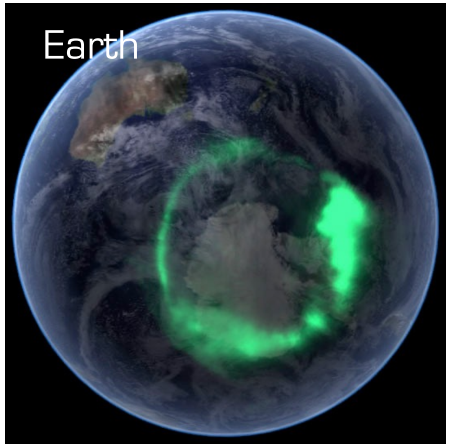
Polarization: circular (x-mode) RCP/north LCP/south
Brightness Temperature > 10^{15} K





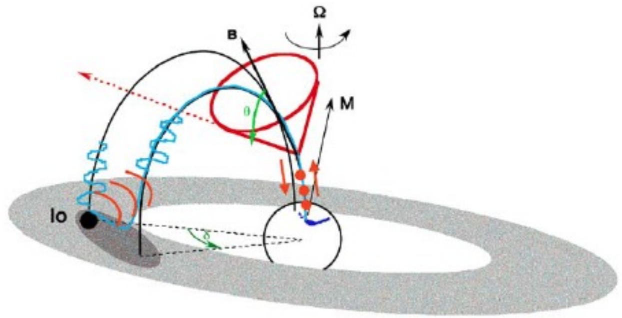


ECM Frequency:
$\nu_B \approx s \cdot 2.8 \cdot B_G (MHz)$
with B_G of the planet



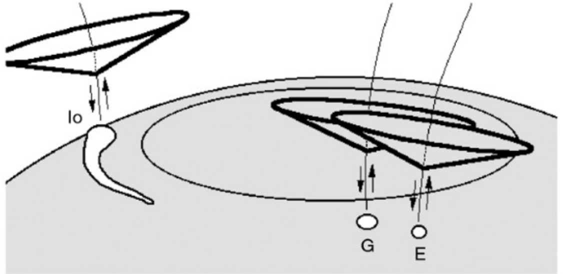
Cyclotron MASER Instability

Type 2 – Planet crossing stellar magnetosphere or magnetospheric

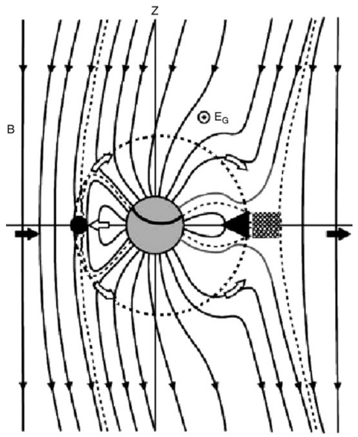


Instability due to the transit of the moons (Io, Europa, Ganymede) across the Jovian magnetosphere

Satellite without magnetic field:
Ionospheric plasma – magnetosphere
Currents - Acceleration



Emission pattern
hollow cone



Satellite with magnetic field:
Magnetospheric plasma – magnetosphere
Magnetic reconnection

Prangé+ 2004

ECM Frequency:
$\nu_B \approx s \cdot 2.8 \cdot B_G (MHz)$
with B_G of the central star (Jupiter)

Cyclotron MASER Instability

Searching for SPI at radio

Searching in two directions:

1. detection of ARE above the planet (kinetic, type 1) due to the impact of stellar wind on the planetary magnetosphere

2. detection of ARE above the star (magnetospheric, type 2) induced by Stellar-Planet Interaction

Frequency of ARE is proportional to B:

of the **planet** (few G). Low frequency. Tens of MHz.

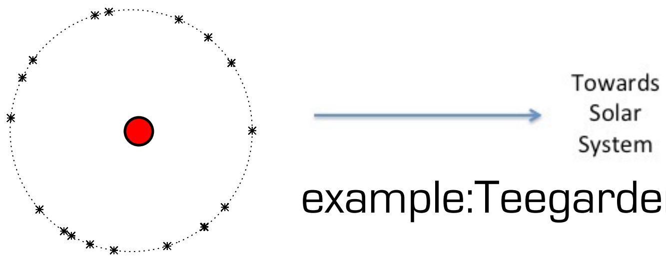
of the **star** (up to thousand of G). High frequency. GHz.

Our campaign:
Search for ARE at "high" Frequency

Since 2015

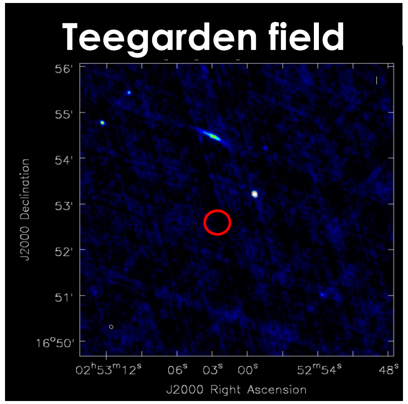
- Sp type later than M0 (Teff < 4000 K)
- d < 15 pc
- P_{orb} < 4 days
- ATCA, GMRT, MeerKAT, VLA
- Frequency range: 400-3000 MHz

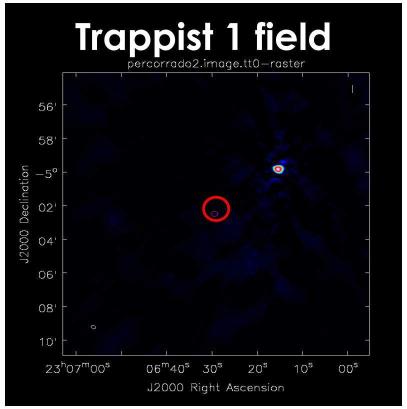
ECME highly directive
It is important to sample the orbit



example:Teegarden star with JVLA

Often in crowdy fields





several system monitored:
α **Cen B b** with **ATCA** (Trigilio+2018)
Trappist-1 with **ATCA and GMRT**.
Teegarden star with **JVLA**
... others...

YZ Cet: first confirmed SPI at radio

The Star

M4.5V type
Mass 0.14 $M_\odot$
Radius 0.157 $R_\odot$
Distance 3.71 pc

P_{rot} = 68 days
age ~ 3.8 Gyr
eruptive variable (flares at visual, X-ray)
Axisymmetric **dipolar magnetic field** (kG)?

The Planetary System

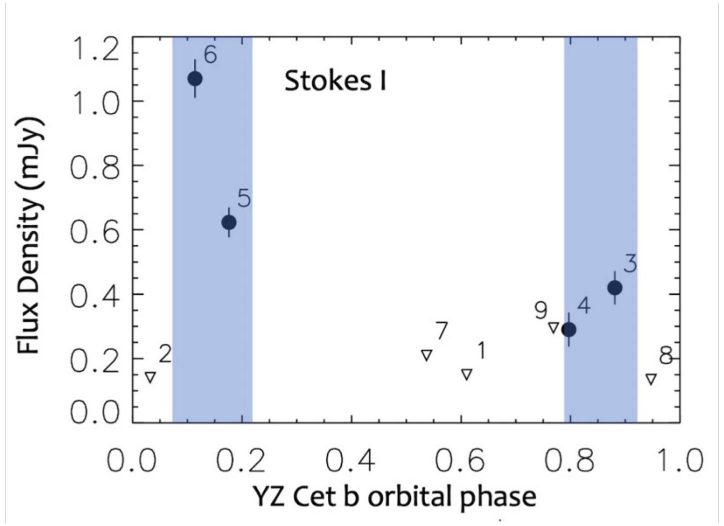
3 known Earth-mass planets with RV method (Stoke+2000):

- YZ Cet b P_{orb}= 2.02d, R_{orb}= 0.016 au, R ~ 0.93 $R_\oplus$
- YZ Cet c P_{orb}= 3.06d, R_{orb}= 0.022 au, R ~ 1.05 $R_\oplus$
- YZ Cet d P_{orb}= 4.66d, R_{orb}= 0.028 au, R ~ 1.05 $R_\oplus$

YZ Cet: Never detected in radio till 2020
First detection of coherent bursts (Pineda & Villadsen 2023) at 2 GHz with VLA, probably due to SPI - stellar activity not excluded

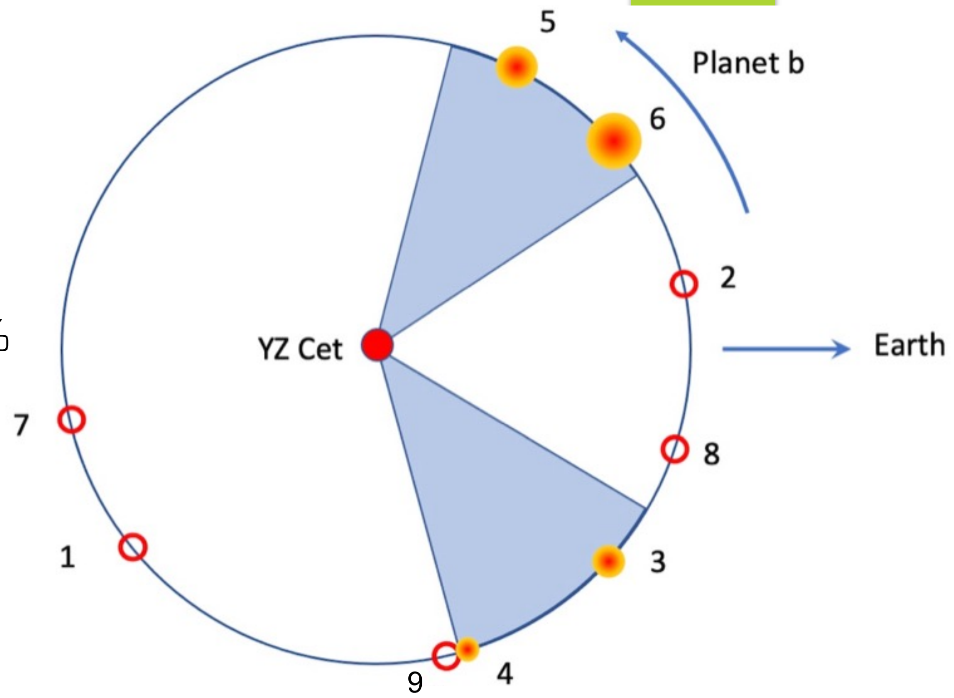
Our Radio Observations

9 observations with GMRT at 550—900 MHz
May – Sep 2022



4 Detections, 5 non detections
2 / 4 Detections with $\pi_V \sim$ 80-90%

(Trigilio+2023)



Good orbital coverage: never achieved so far

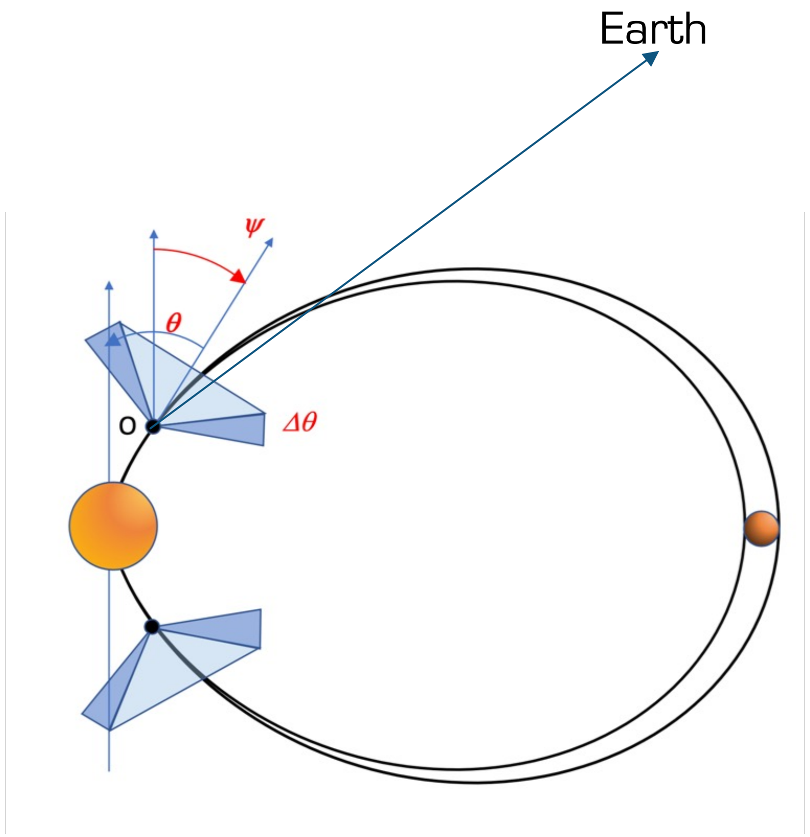
Emission behaviour vell correlated with the orbital phase of planet b
Detections in two sectors of the orbit.
The two sectors are symmetric with respect to the line of sight
High degree of circular polarization

Auroral Radio Emission due to
Stellar-Planet Interaction

From statistical consideration
Degree of confidence higher than 4.37 σ

Emission pattern is a **hollow cone**

During the revolution of YZ Cet b:
the **radiation intercepts the line of sight two times**, defining **two sectors**

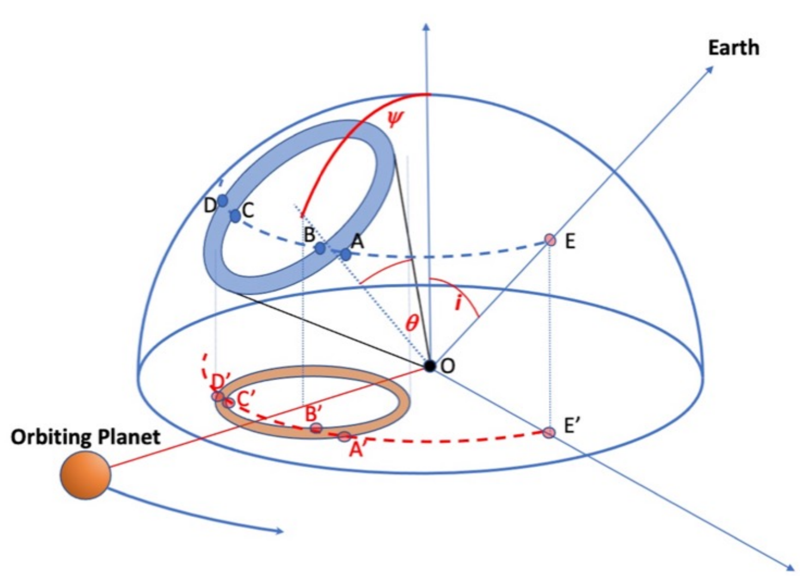


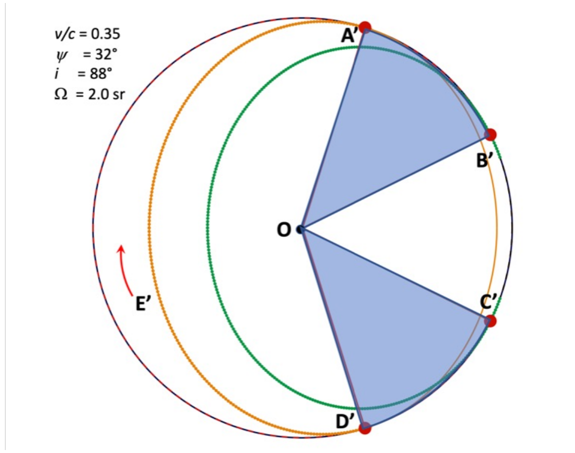
Modelling the hollow cone

$$\cos\theta \approx \Delta\theta \approx \frac{v}{c}$$

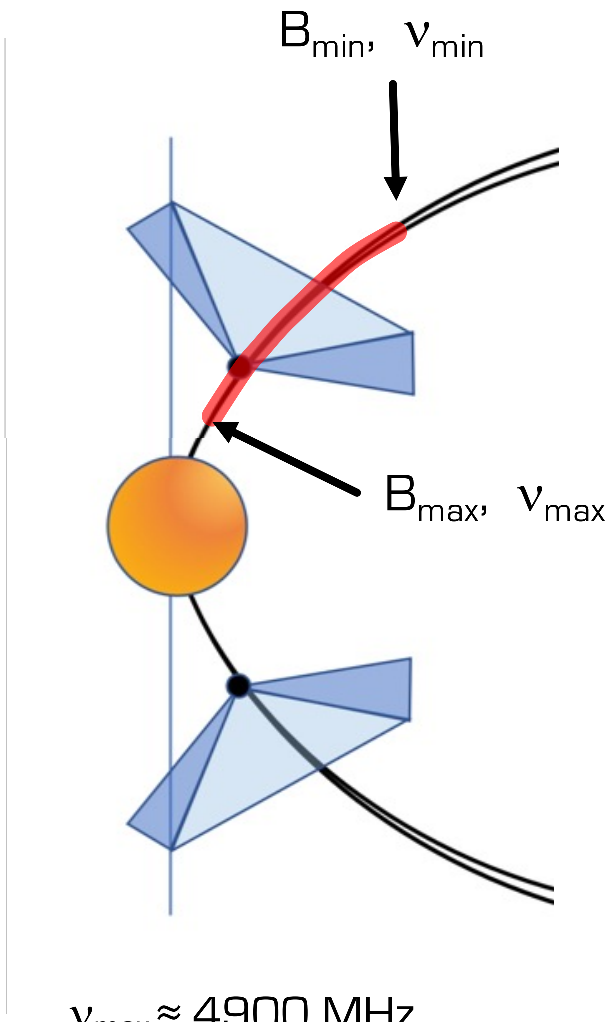
parameters of the ECME:

$\Omega \sim 2$ sr
v/c emitting electrons ~ 0.35
i inclination of the line of sight $\sim 88°$





Stellar Magnetic Field



Defined by the limits of the **spectrum** of the radiation.
The ECME occurs at height ranging from 1.4 to 3 R_* (red line).

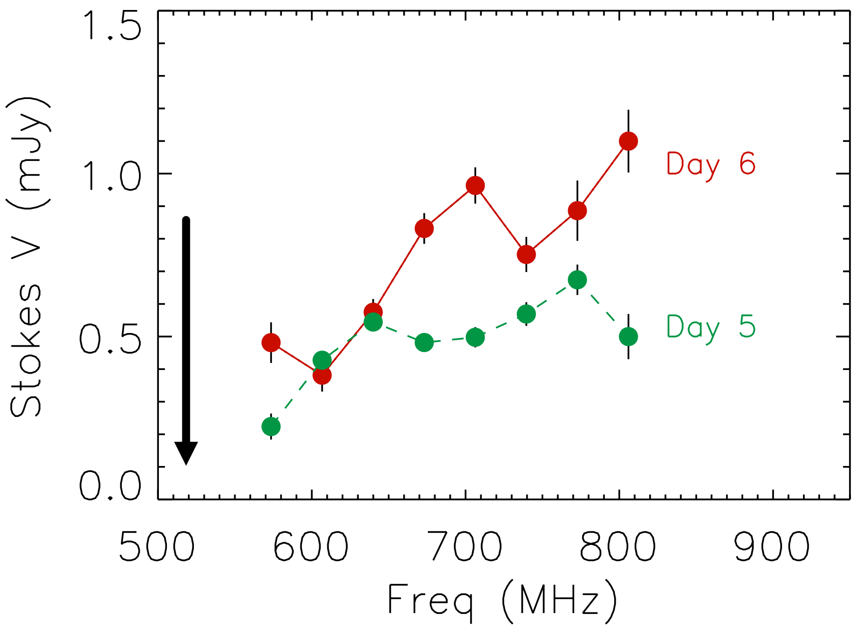
Dipole: $B = B_* \, (R_*/r)^3$

$\nu_B = s\, 2.8\, B$ (MHz) (with s=2)

Frequency cutoff
$\nu_{min} \approx$ 500 MHz
at $R_{max} \approx 3\, R_*$

$\nu_{max} \approx$ 4900 MHz
$\nu_{min} \approx$ 500 MHz

$B_* \approx$ 2400 G
$\Delta\nu \approx$ 4400 MHz

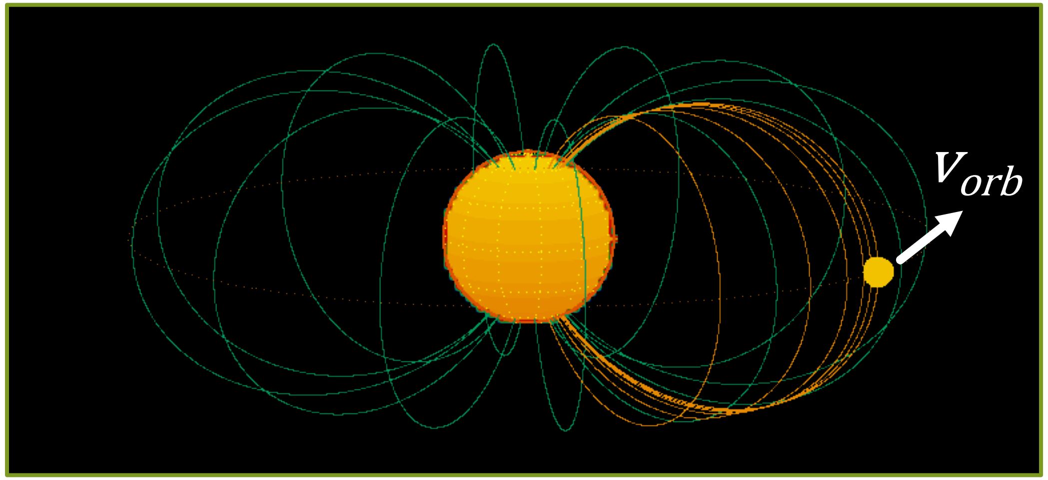


Planetary Magnetic Field

The magnetic field of the planet comes from energetic considerations

In SPI

$$P_{mag} = \frac{B^2}{8\pi} A\, v_{orb}$$



Cross section:
A = area of: planet or magnetopause

From radio measurements:

$$P_{radio} = F_\nu \, \Delta\nu \, 2\Omega \, d^2$$

if A = area planet

$$P_{radio} > P_{mag}$$

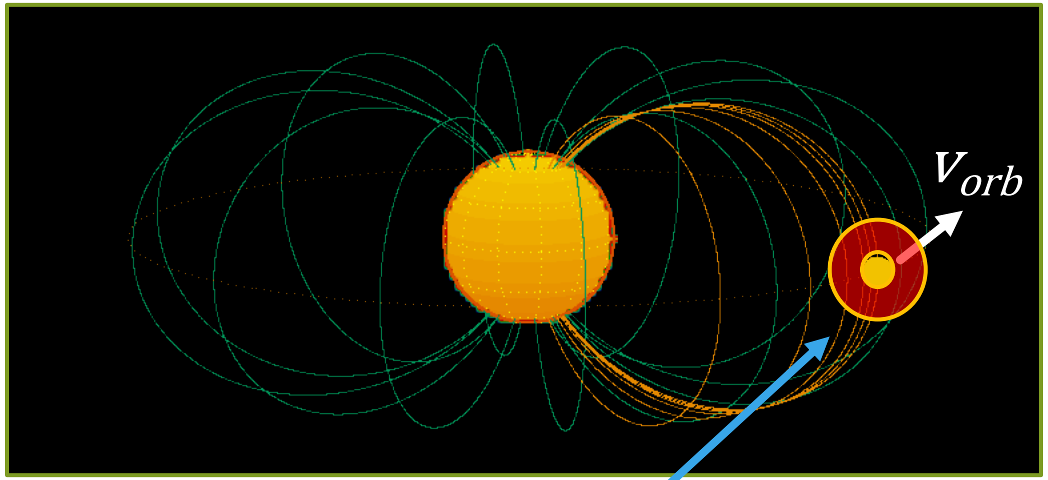
MUST BE $P_{radio} \leq P_{mag}$ **!!!**

Planetary Magnetic Field

The magnetic field of the planet comes from energetic considerations

In SPI

$$P_{mag} = \frac{B^2}{8\pi} A \, v_{orb} \Rightarrow$$



The only parameter we can change is A
we need a magnetopause

R_{MP}

distance from centre of planet where planetary and stellar field are equal (0.1 G)

Minimum $B_{\mathrm{planet}} = 0.4\ \mathrm{G}$

Conclusions

High risk, high return

very promising technique for:

- direct measurement of stellar B
- indirect measurement of planetary B
- stellar activity and impact to live development

Next generation Radio Interferometers

- MeerKAT, ASKAP, SKA