Star-Planet Interactions
Activity proxies

Rim Fares
United Arab Emirates University

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Outline

- Star-Planet Interactions – An overview
- Main ingredient for Star-Planet Interactions – Magnetic Field
- SPI and Activity proxies: a love/hate story

Star-Planet Interactions (SPIs)

SPIs refer to *several* types of interactions between a planet and its hosting star

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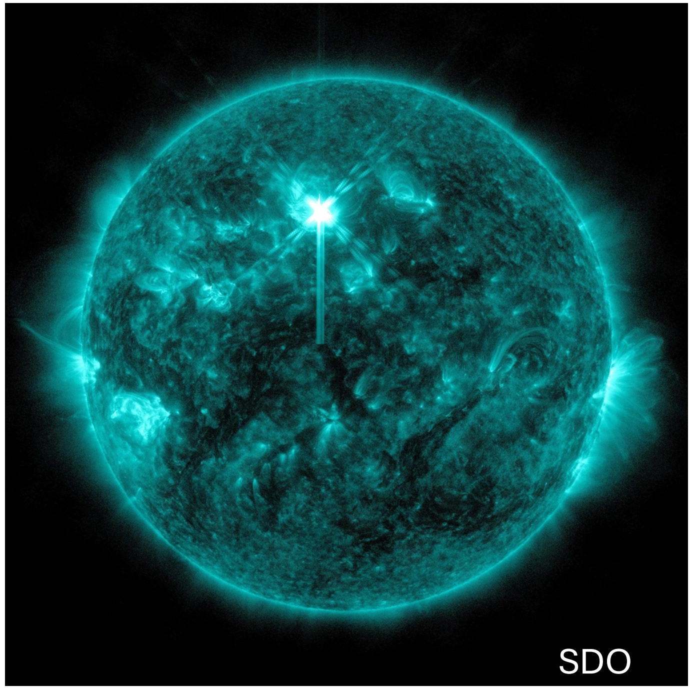
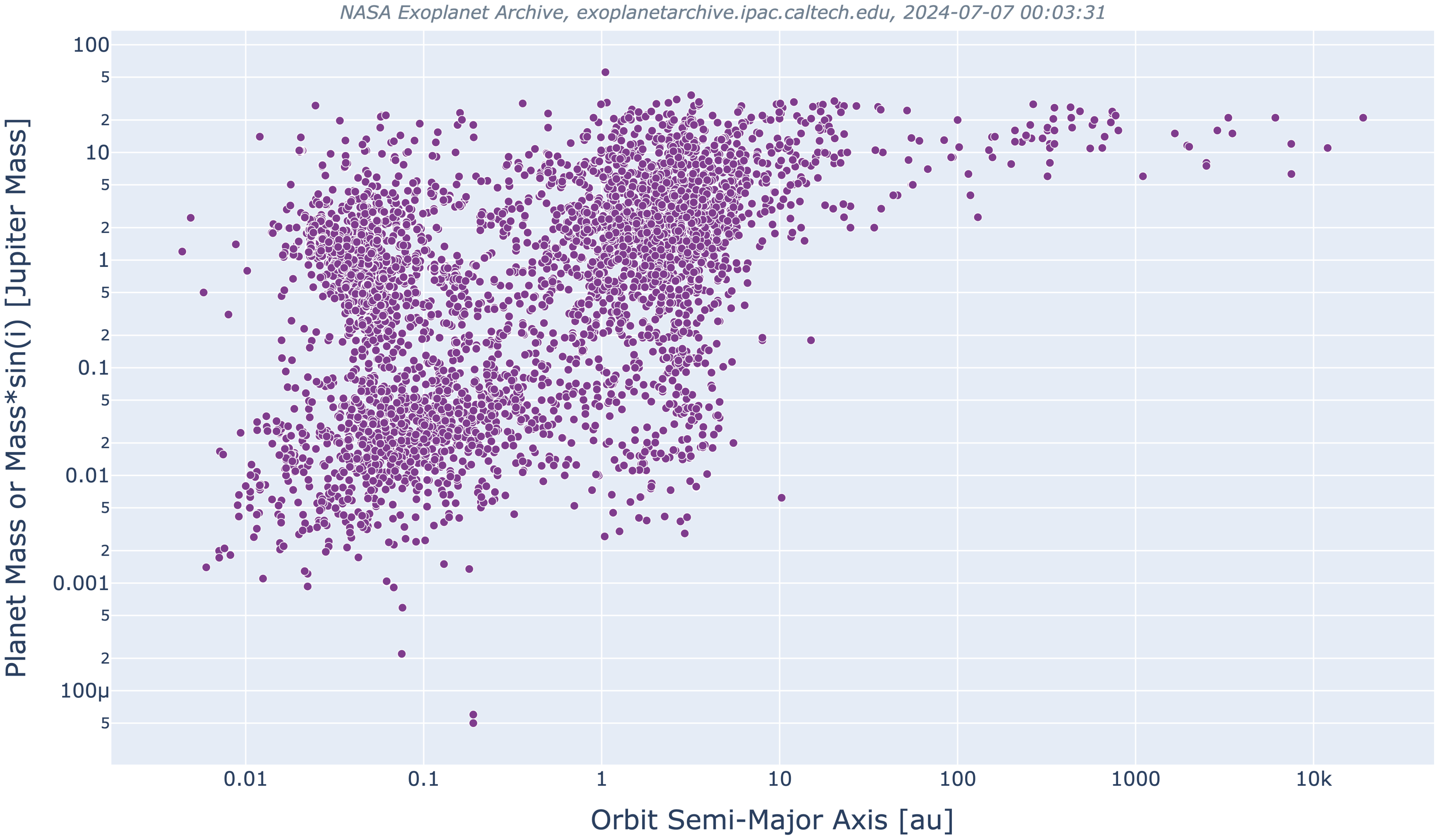
Solar strom – May 2024



Northen light over Berga, Spain, May 2024

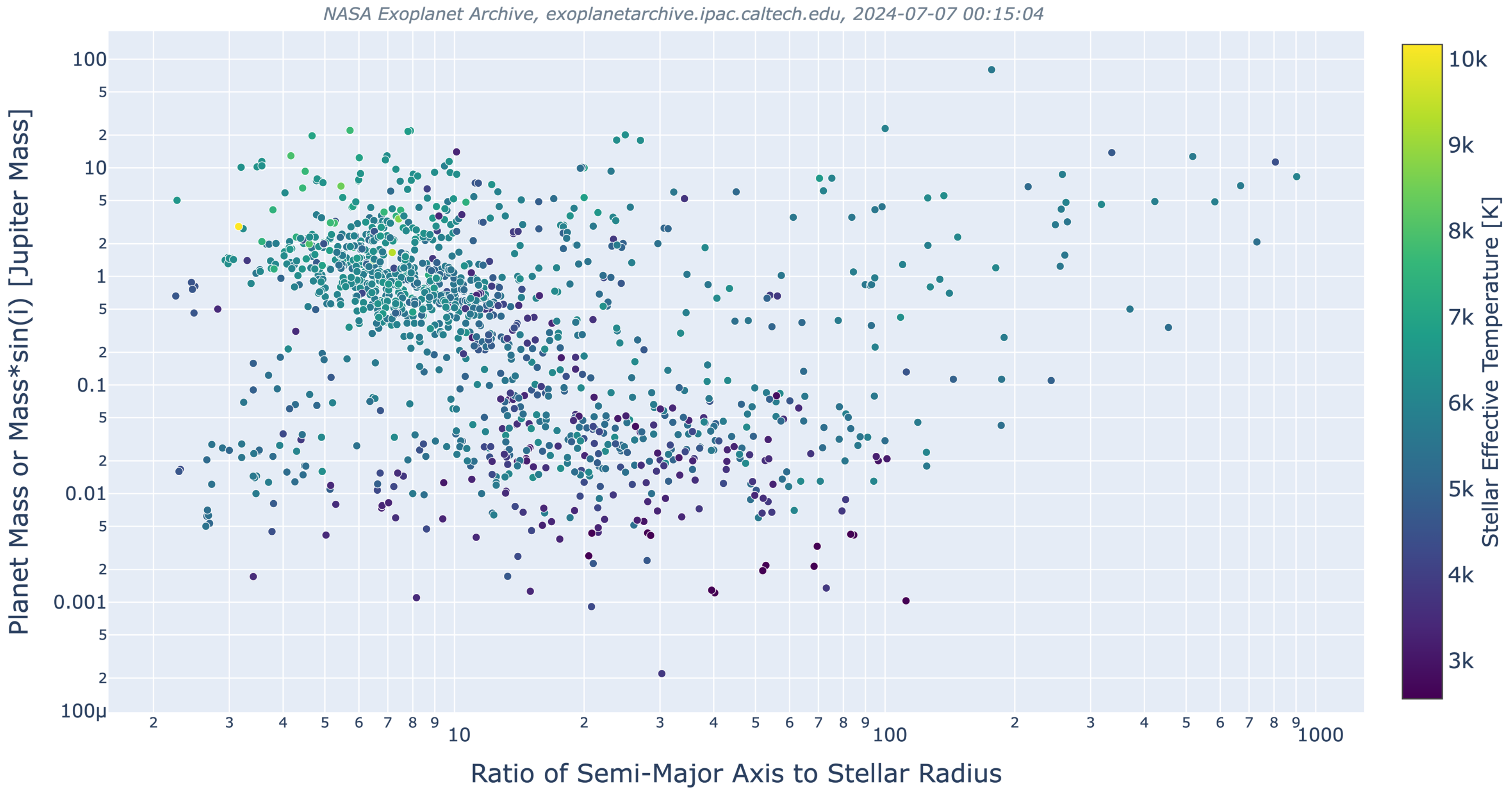
Sun – Earth distance: ~ 215 $R_\odot$

Exoplanets



NASA Exoplanet Archive, exoplanetarchive.ipac.caltech.edu, 2024-07-07 00:03:31
Planet Mass or Mass*sin(i) [Jupiter Mass]
100
5
2
10
5
2
1
5
2
0.1
5
2
0.01
5
2
0.001
5
2
100μ
5
0.01
0.1
1
10
100
1000
10k
Orbit Semi-Major Axis [au]

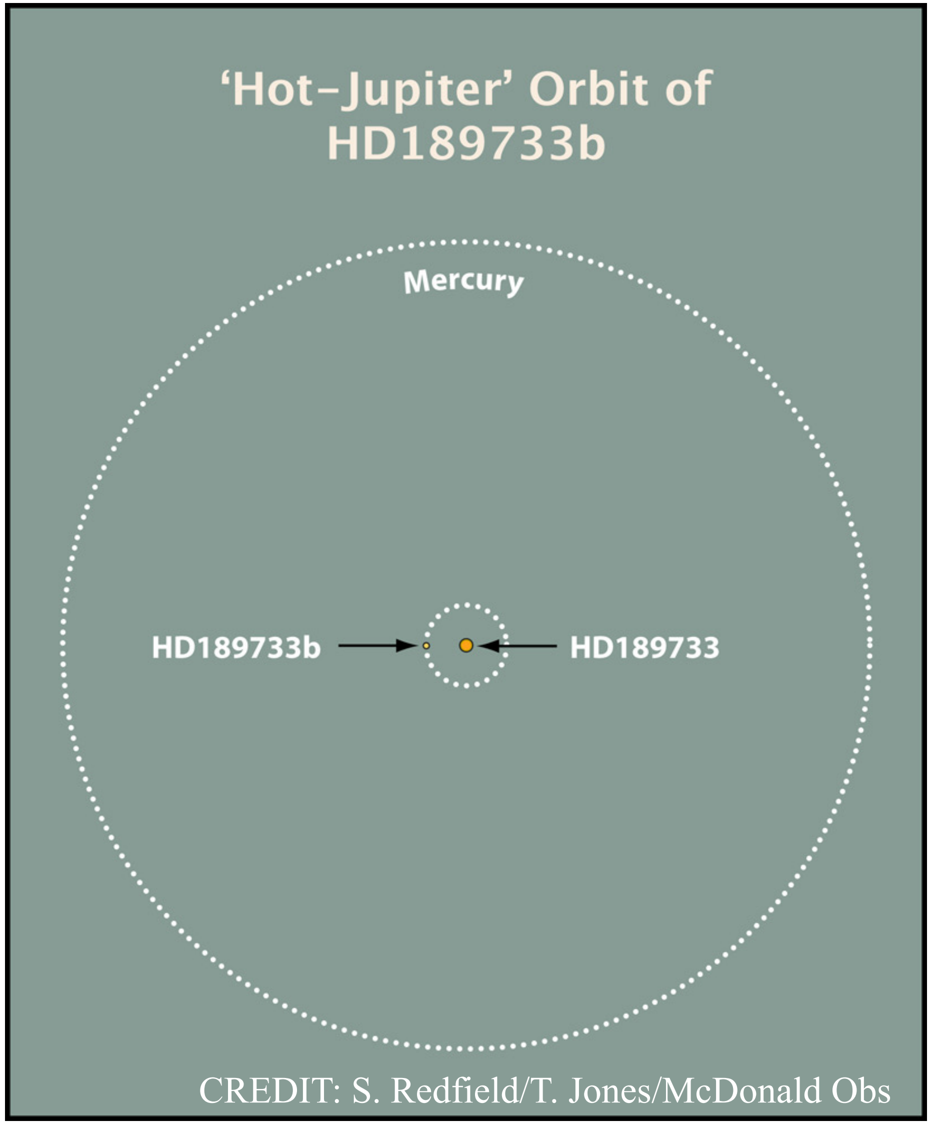
How far are they from their stars?



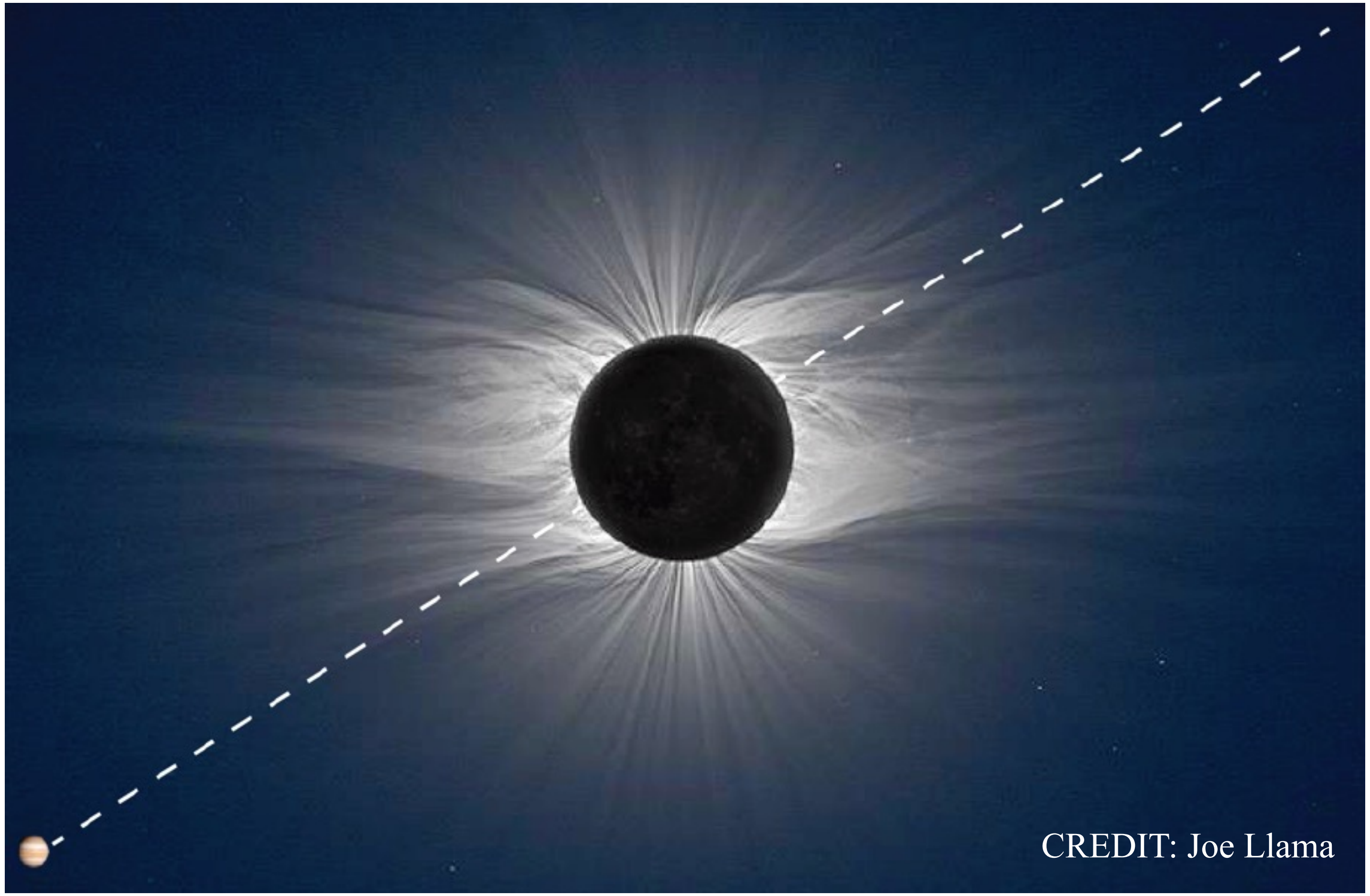
Planets are relatively close to their stars
(in terms of stellar radius)

The ratio of planet mass to stellar mass is an important factor

How far are they from their stars?



They could be as close as few stellar radii
(Mercury is at about 83 $R_\odot$)

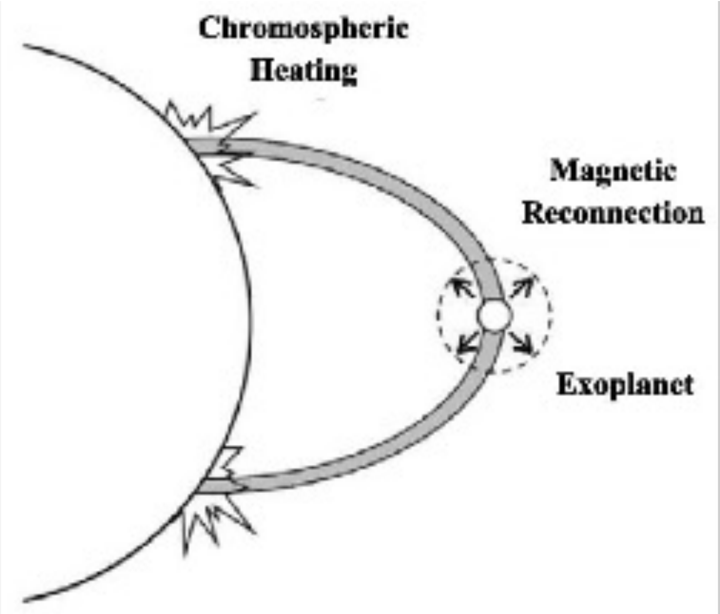


Star-Planet Interactions (SPIs)

SPIs refer to *several* types of interactions between a planet and its hosting star

Magnetic Interaction/Stellar Wind Interaction

(e.g. Cuntz et al 2000, Shkolnik et al 2003,2005,2008, Kashyap et al 2008, Zarka et al 2007, Smith et al 2009, Lanza 2013, Llama et al 2013, Vidotto et al 2015, Strugarek 2021, Fischer &Saur 2022, Alvarado-Gómez et al 2022, Lloyd et al 2023, Chebly et al 2023, Vidotto et al 2023, Ilin et al 2024)



Ip et al 2004

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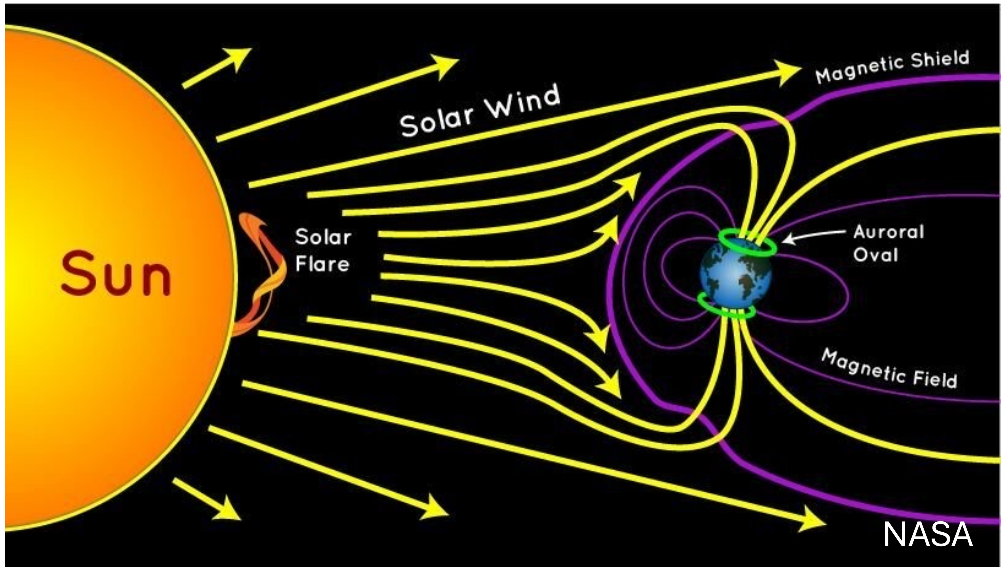
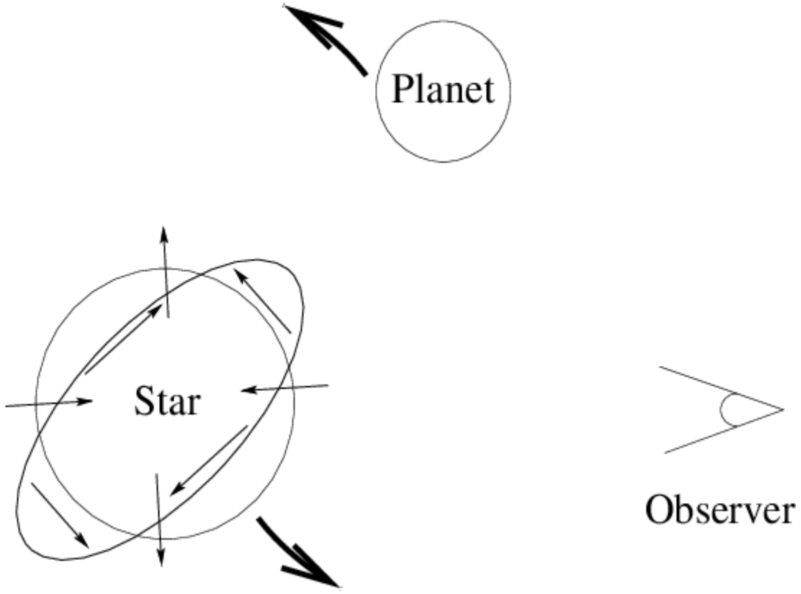


Star-Planet Interactions (SPIs)

SPIs refer to *several* types of interactions between a planet and its hosting star

Tidal Interactions

(e.g. Cuntz et al 2000, Brown et al 2008, Pont 2009, Ibigui et al 2010, Winn et al 2010, Cebron et al 2010, Damiani 2015, Lin & Ogilvie 2017, Gallet et al 2018, Ogilvie 2020)



Arras et al 2012

Star-Planet Interactions (SPIs)

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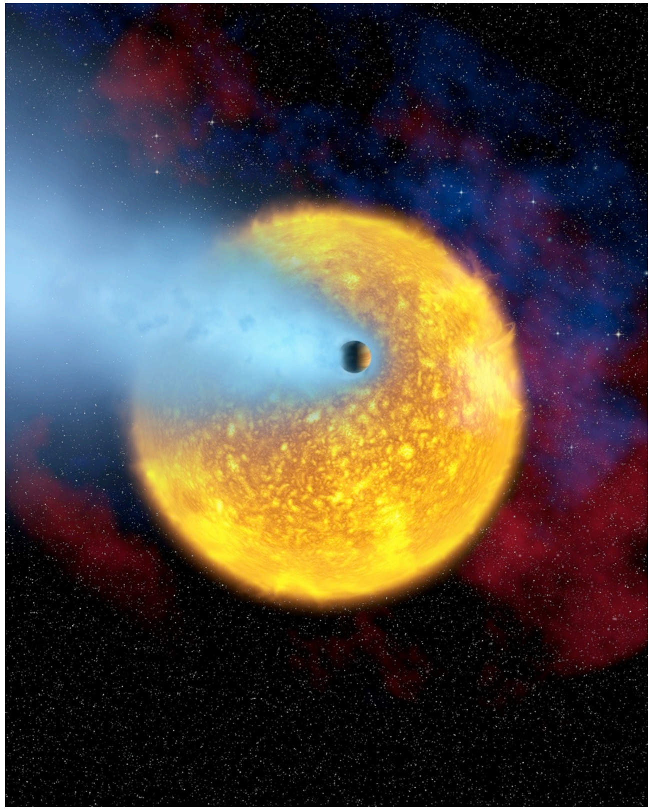
Radiative Interactions

(e.g. Vidal-Madjar et al 2008, Lecavalier Des Etangs et al 2010, Haswell et al 2010, Fossati et al 2013, Bourrier et al 2013, Mordasini 2020, Modirrousta-Galian Korenaga 2023)



CREDIT: ESA, A.Vidal-Madjar (Institut d'Astrophysique de Paris, CNRS, France) & NASA

Manifestation of SPIs

SPIs: Tidal (T) , Magnetic (M) and Stellar Wind (W), Radiative (R)

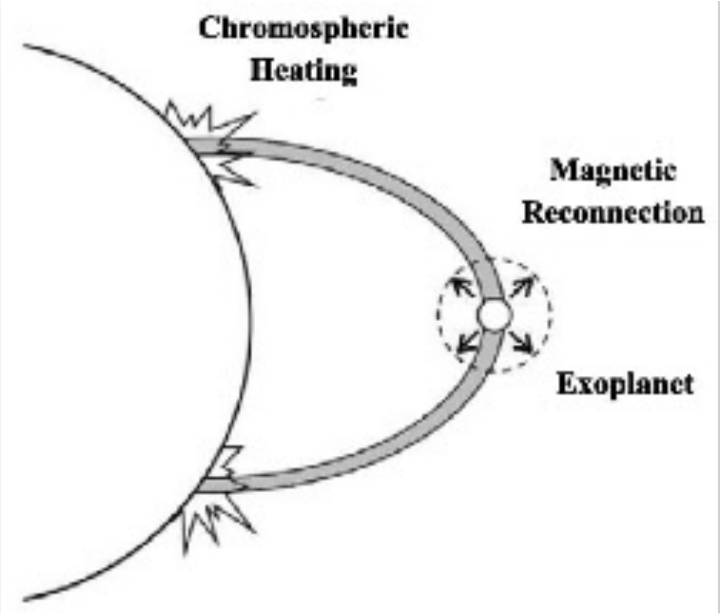
Star

Rotation spin-up (T)

Stellar inclination (T)

Stellar activity (Spots, Flares, ...) (M + T)

Stellar magnetic field (M + T)



Ip et al 2004

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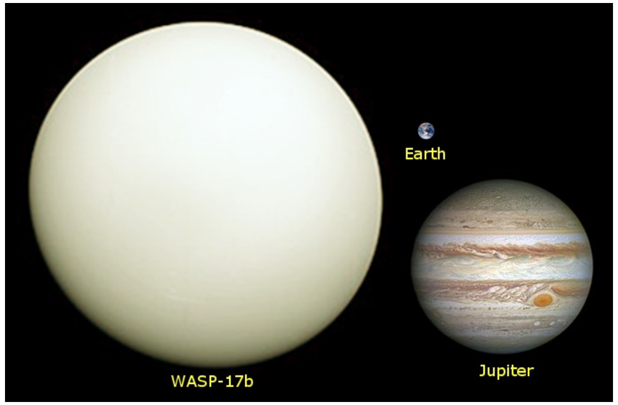
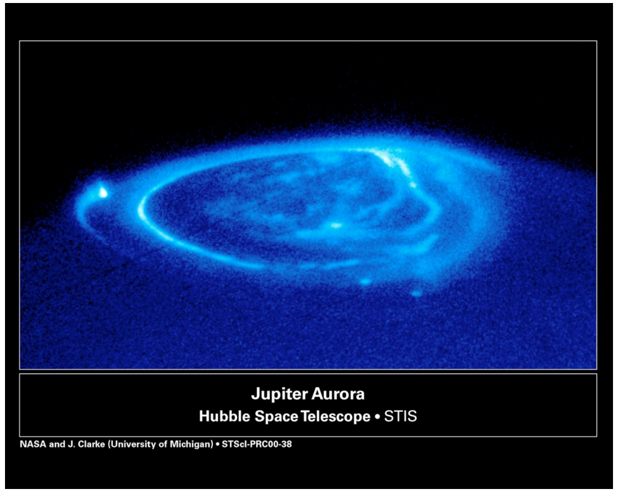




Planet

Tidal heating? (T)

Orbital evolution (T + W?)

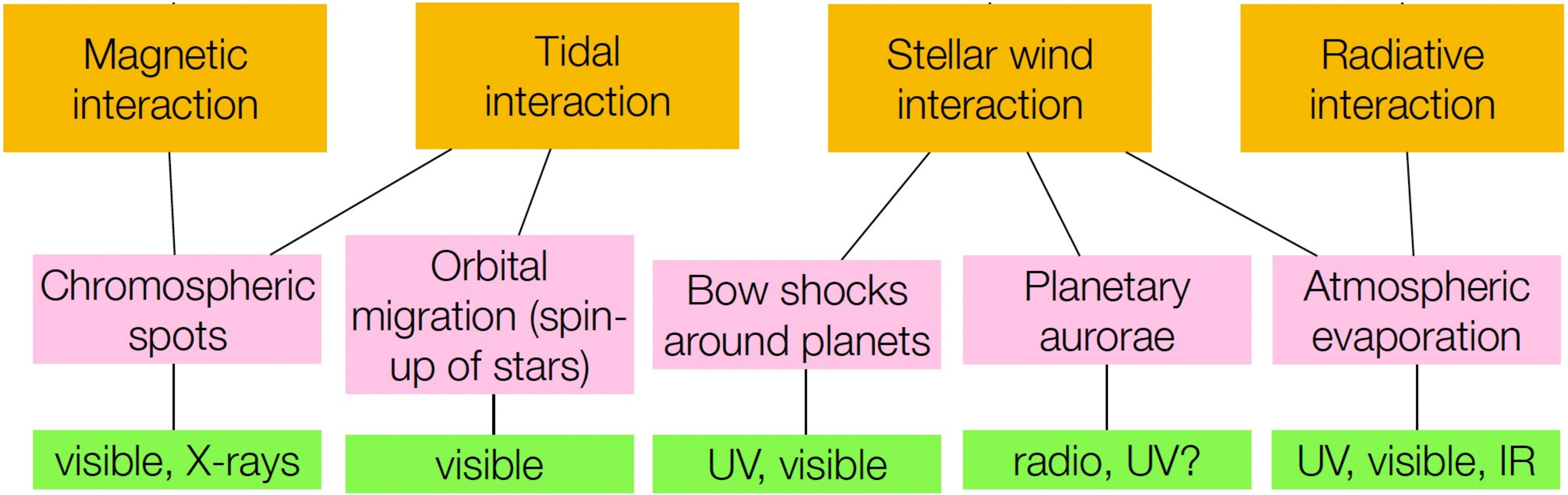
Atmospheric evaporation (W + R)

Aurora / Radio emission (W)

Bow shock formation (W)

Llama et al 2013

Manifestation of SPIs – wavelength approach



Vidotto 2019

Techniques: Spectroscopy, Photometry, Spectro-Polarimetry

How to study SPIs?

➢ Statistical approach

- Observe a sample of planet hosting stars
- Study the effect you want to explore (magnetic field cacaretristics, activity, flares, X-ray luminosity, ...)
- Compare to a sample of stars not hosting planet

➢ Multi-wavelength observations of particular systems

Stellar magnetic field & stellar activity, model the stellar wind, predict and radio emission/ bow shock formation, study effect of activity of the planetary atmosphere

(e.g. MOVES programme -Multiwavelength Observations of an eVaporating Exoplanet and its Star, Fares et al 2017, Kavanagh et al 2019, Bourrier et al 2020, Barth et al 2021, Strugarek et al 2022)

Key element in SPI – Magnetic Field

Star

Rotation spin-up

Stellar inclination

Stellar activity (Spots, Flares, ...)

Stellar magnetic field

Planet

Tidal heating

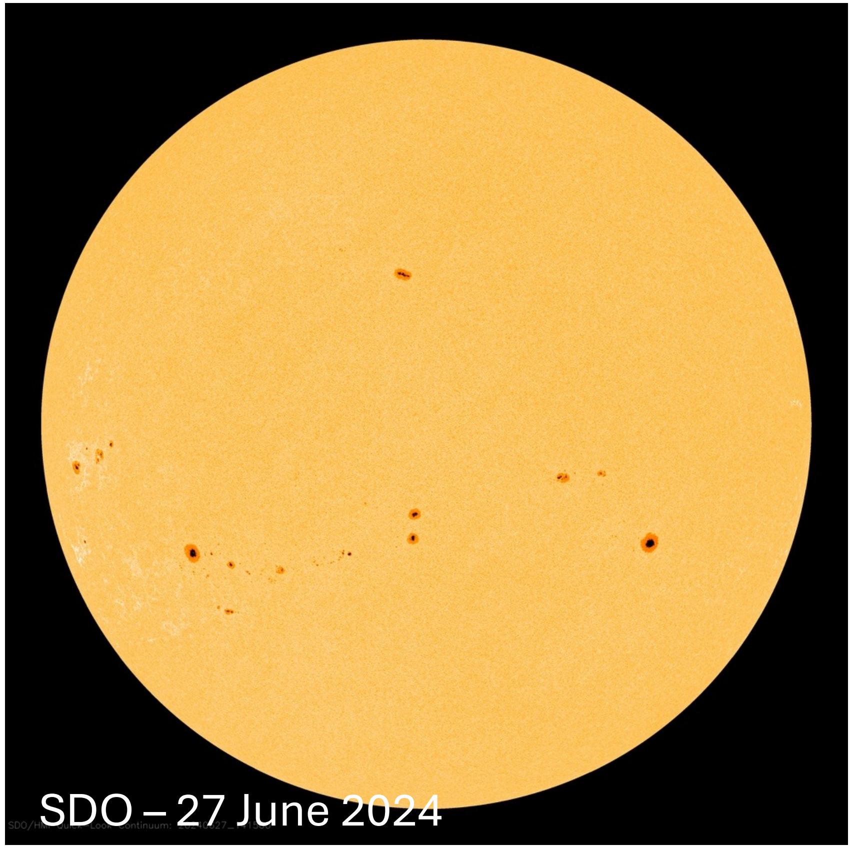
Orbital evolution (partially)

Atmospheric evaporation

Aurora / Radio emission

Bow shock formation

Solar magnetism



✓ Spots
✓ Faculae

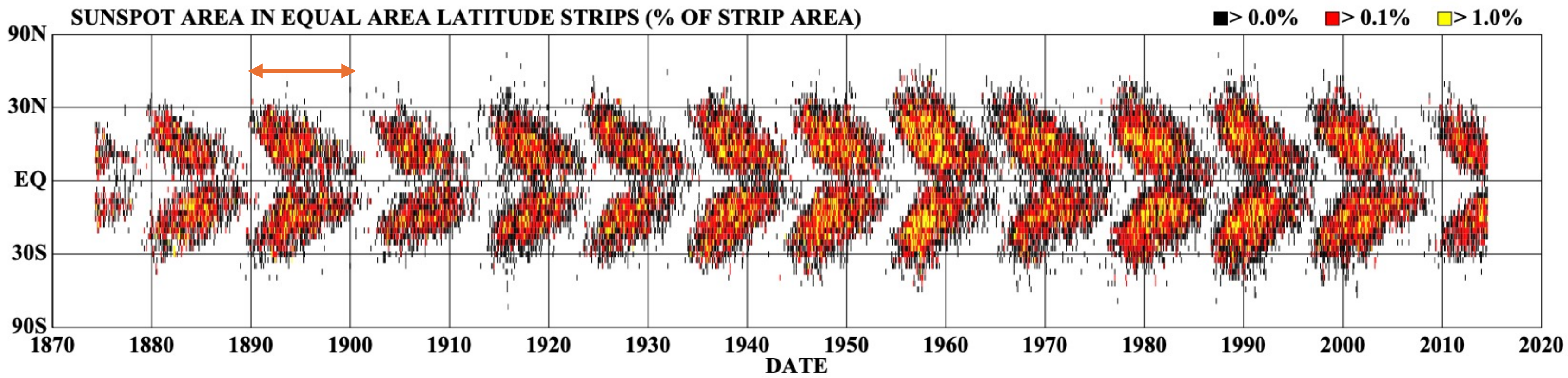
↓

➢ Small Scale Magnetic Field

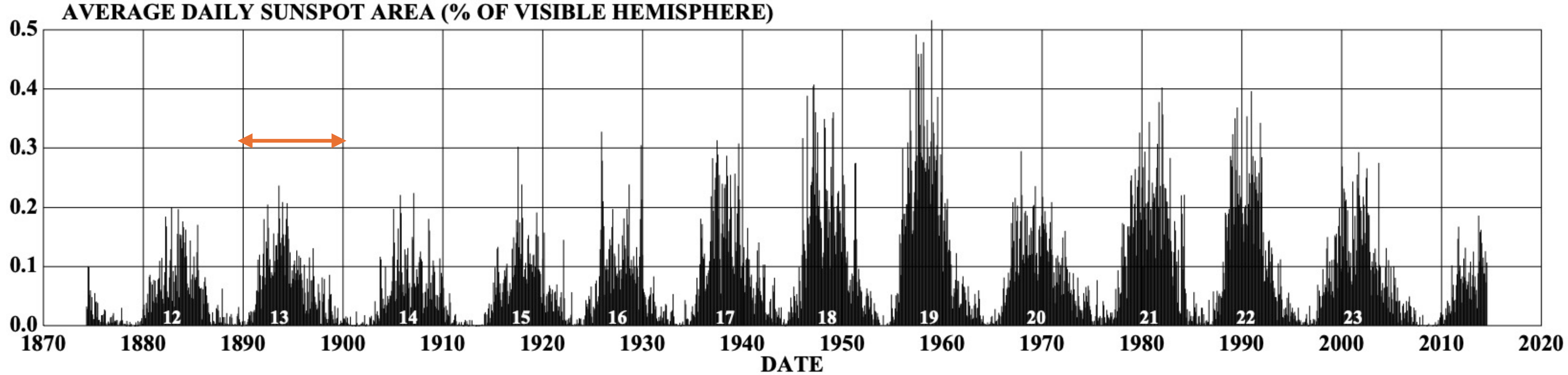
➢ Solar Activity

Solar cycle

Sunspot Cycle ~ 11 years



Butterfly Diagram

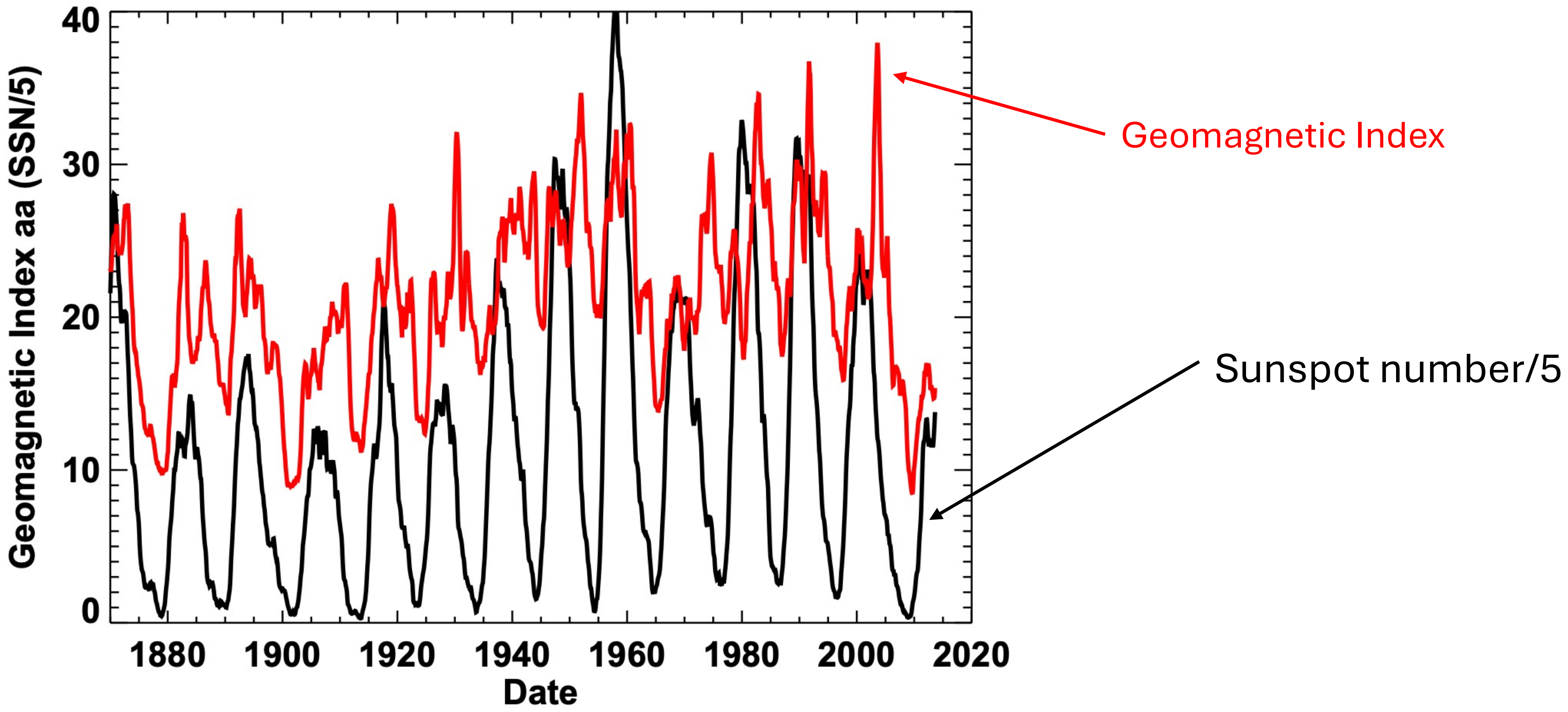


Sunspot Area

Hathaway 2015

Solar cycle

Geomagnetic perturbation follow the solar cycle



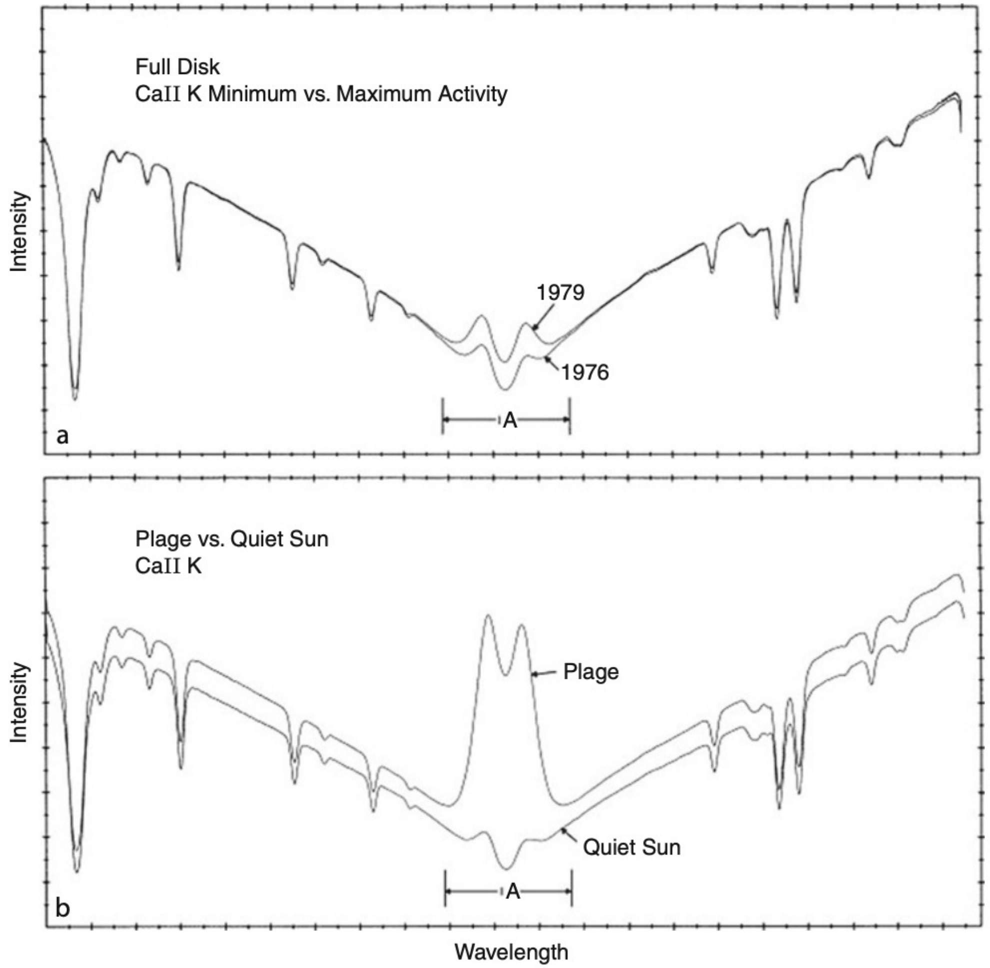
Activity tracers

Some spectral lines are activity tracers

CaII H (396.8 nm)
CaII K (393.4 nm)
Halpha (656.3 nm)
…

In CaII H&K lines:

Emission in the line core can be present (in case of activity)
due to (magnetic) heating
Chromospheric emission



Ca II K line

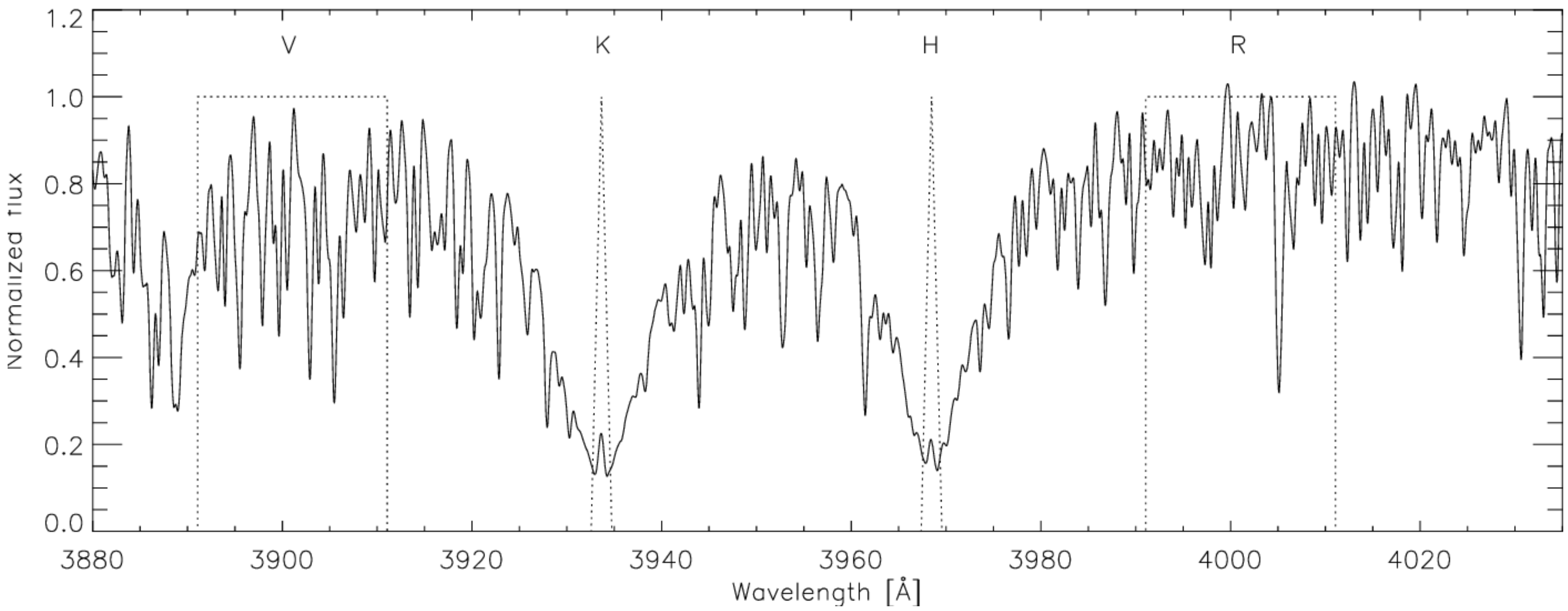
Activity tracers

Ca II H&K

S-index

$$S = \frac{F(H) + F(K)}{F(R) + F(V)}$$

(See, Mount Wilson HK project, Baliunas et al 1995)



Activity tracers

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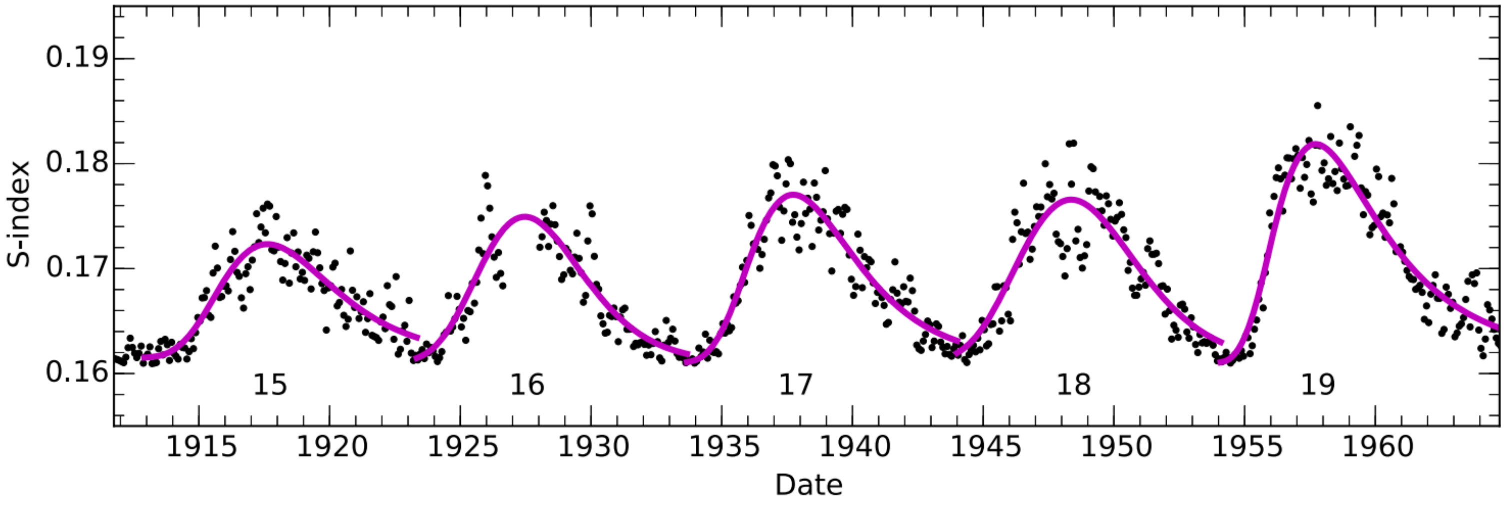
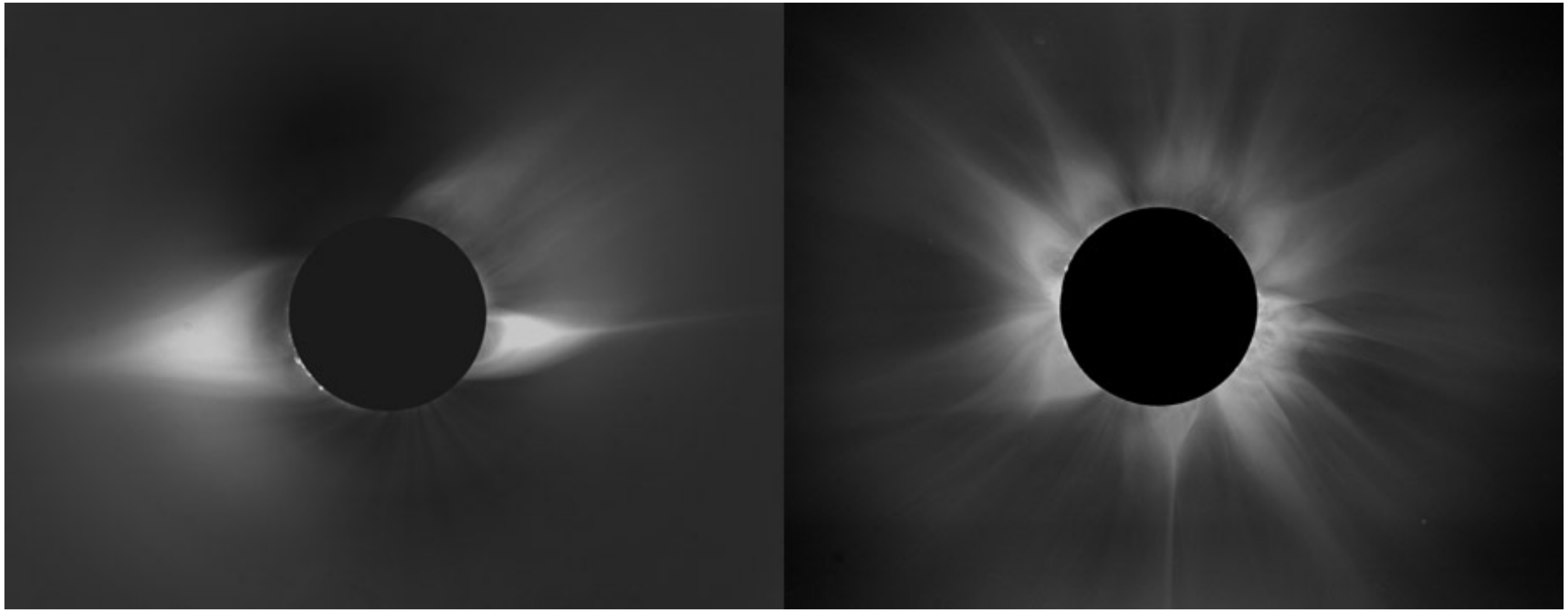


Egeland et al 2017

Solar cycle

Large-Scale Magnetic Field

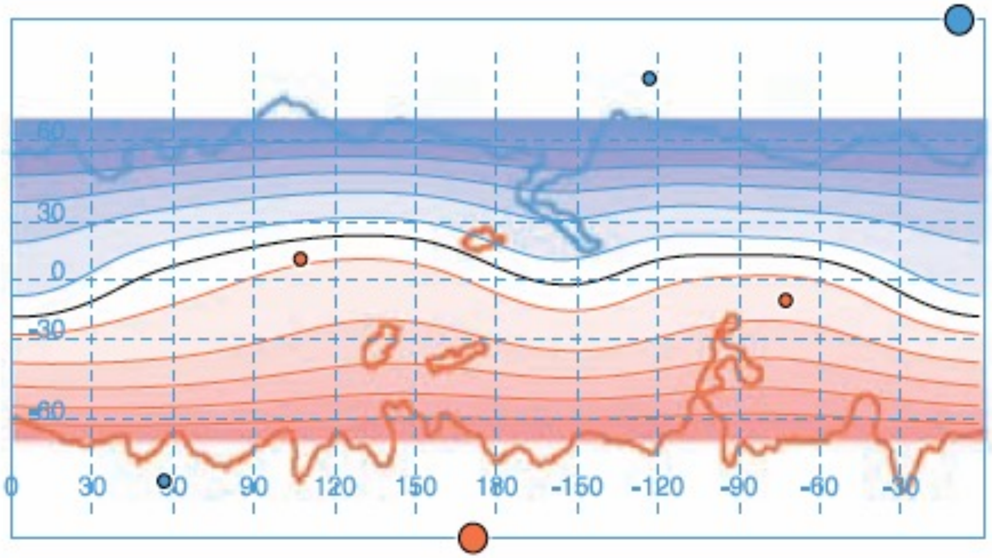


Solar Minimum

Solar Maximum

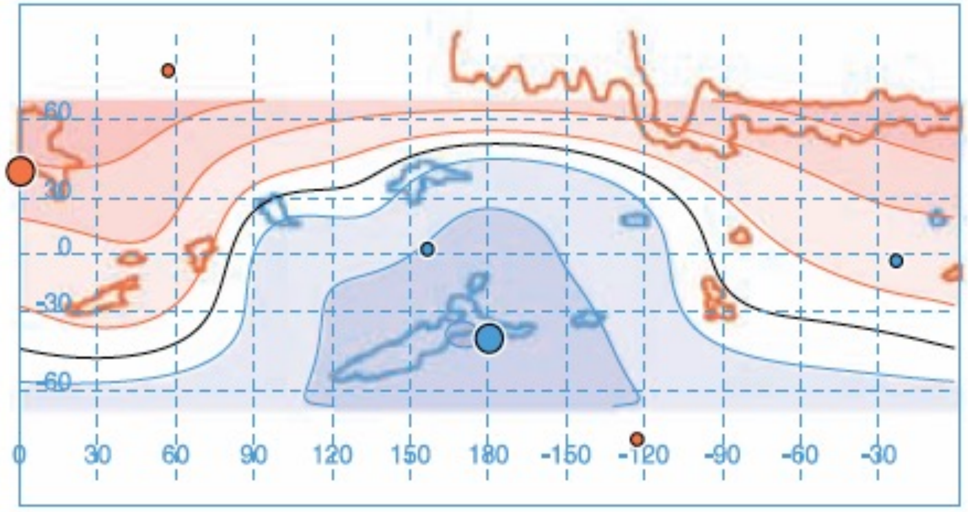
Different Configurations at different epochs

Solar cycle – polarity reversal every 11 years



1997

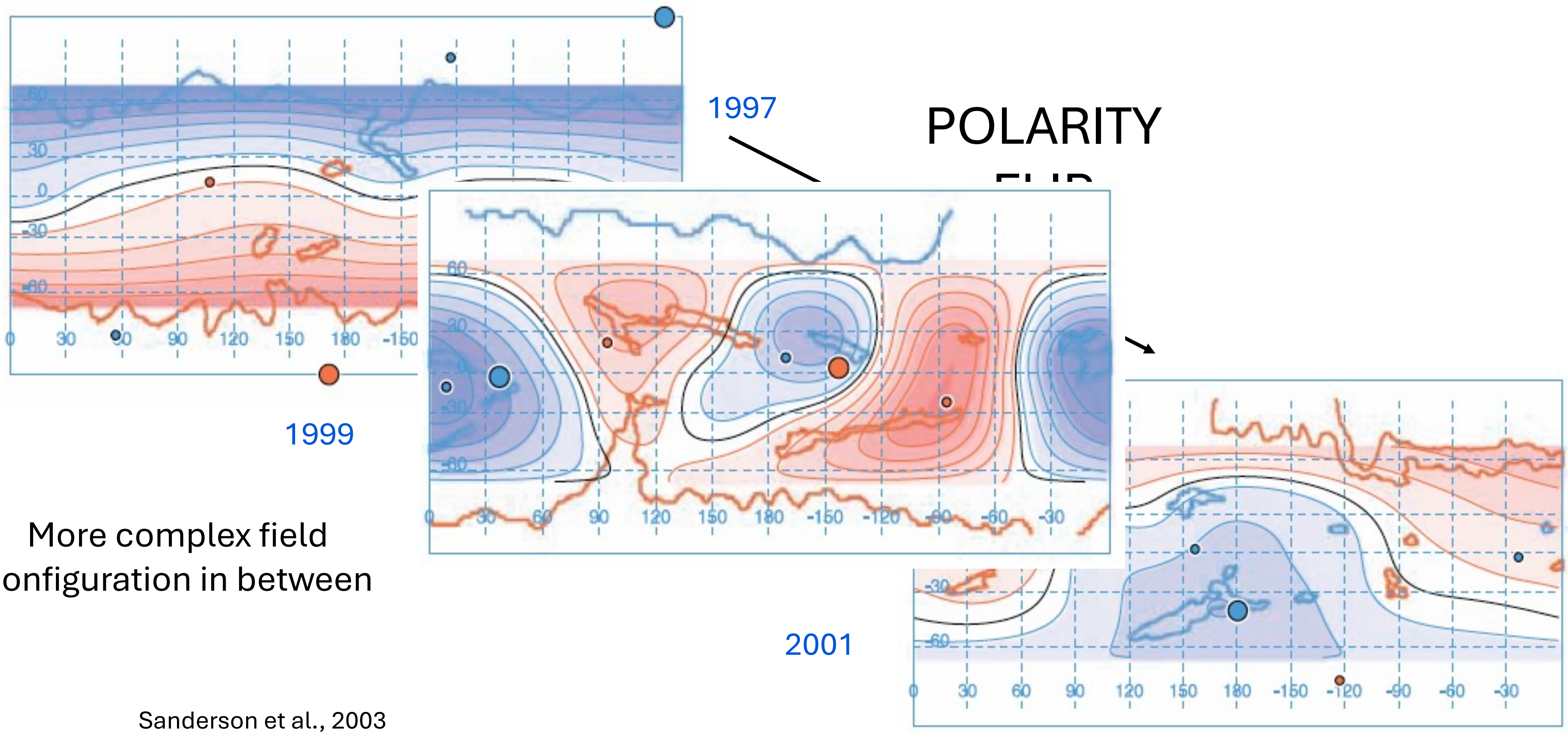
POLARITY FLIP



2001

Sanderson et al., 2003

Solar cycle – polarity reversal every 11 years

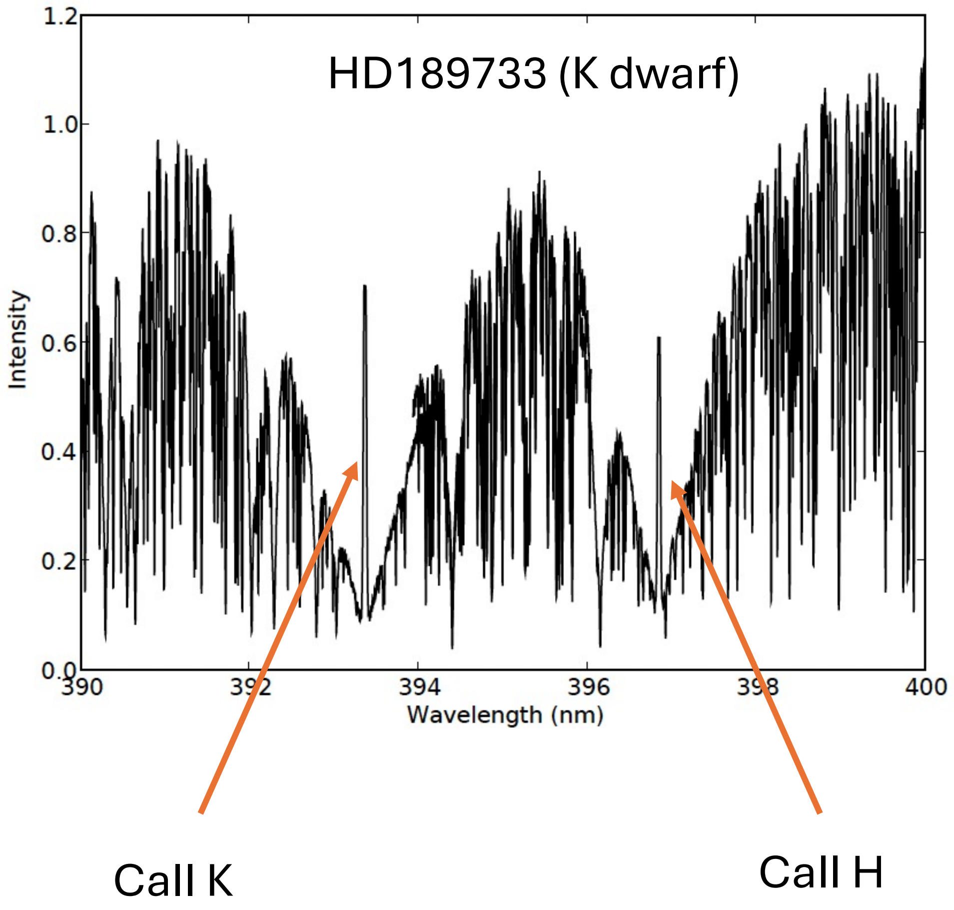


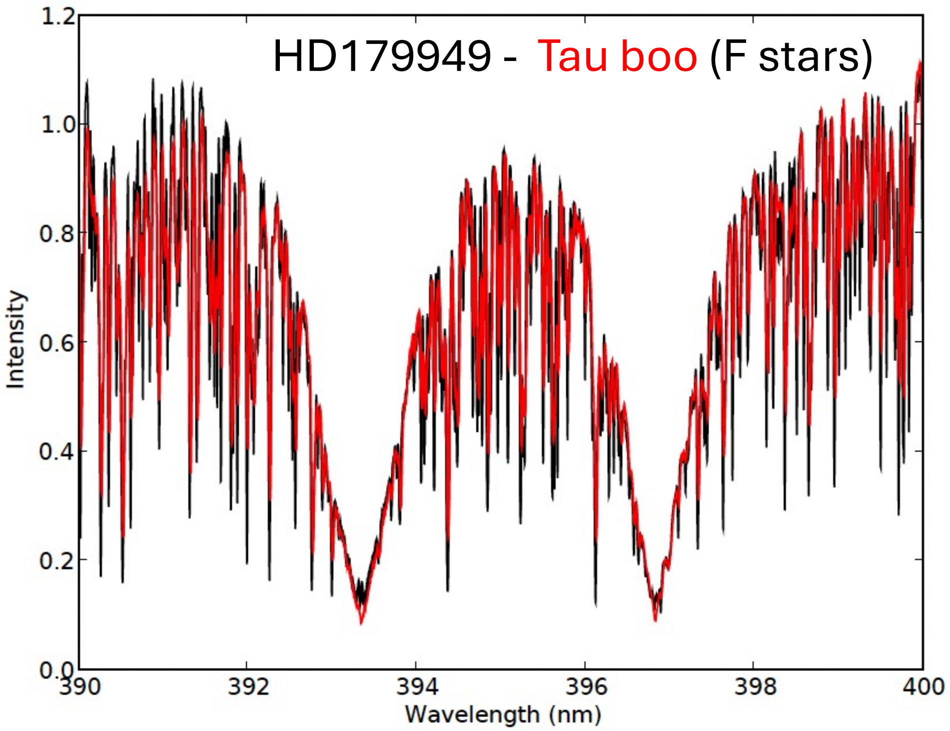
More complex field configuration in between

Sanderson et al., 2003

How about stars?

CaII H&K lines for cool stars of different activity levels

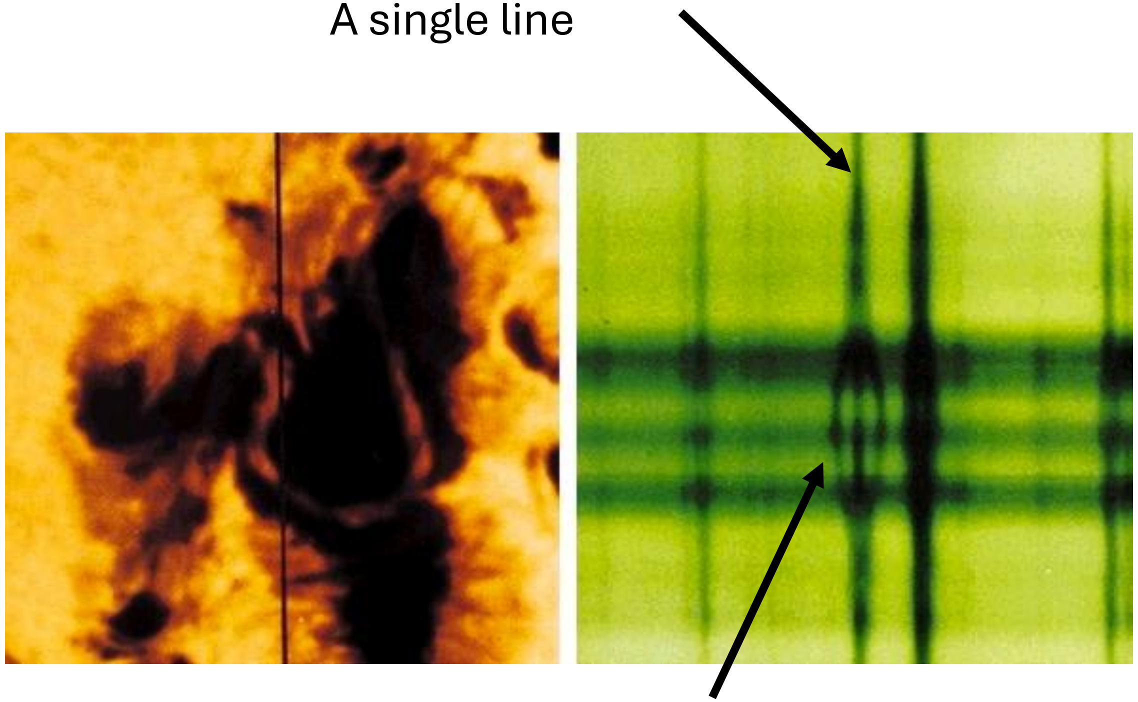




Stellar magnetism

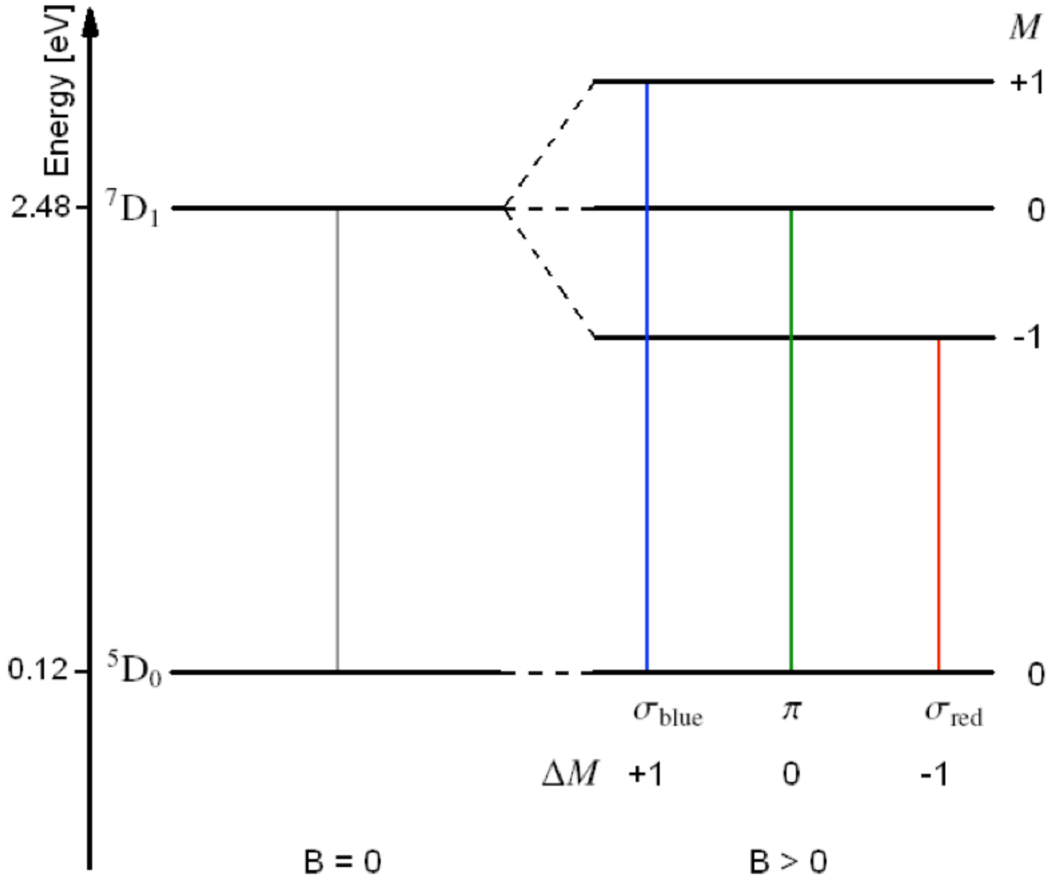
Sunspot

Outside the sunspot:
A single line



Inside the sunspot:
Line splitting due to Zeeman Effect

Zeeman Effect

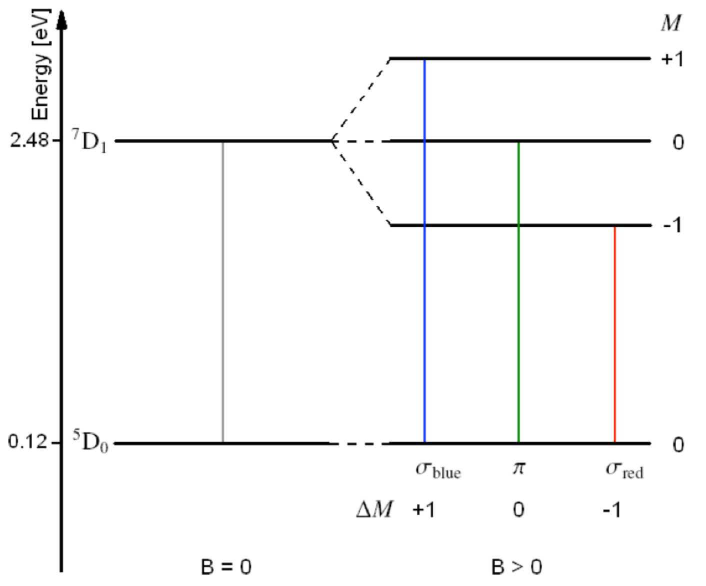


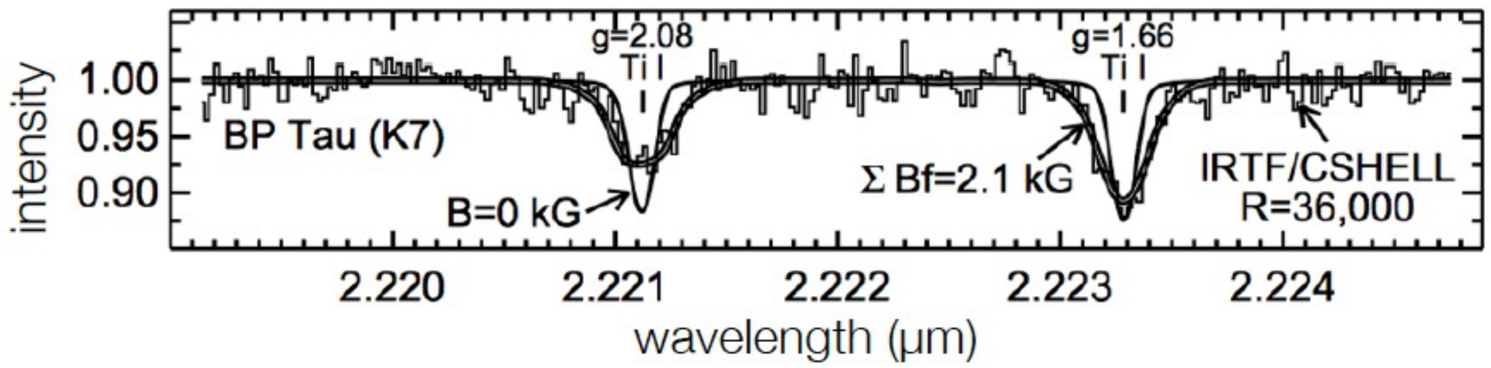
Stellar magnetism

1. Zeeman broadening is prop. to magnetic field

$$\Delta\lambda[\text{nm}] = 4.67 \times 10^{-12} \lambda^2[\text{nm}]\, g_{\text{lande}}\, B[\text{G}]$$

2. It depends on wavelength of the line and lande factor

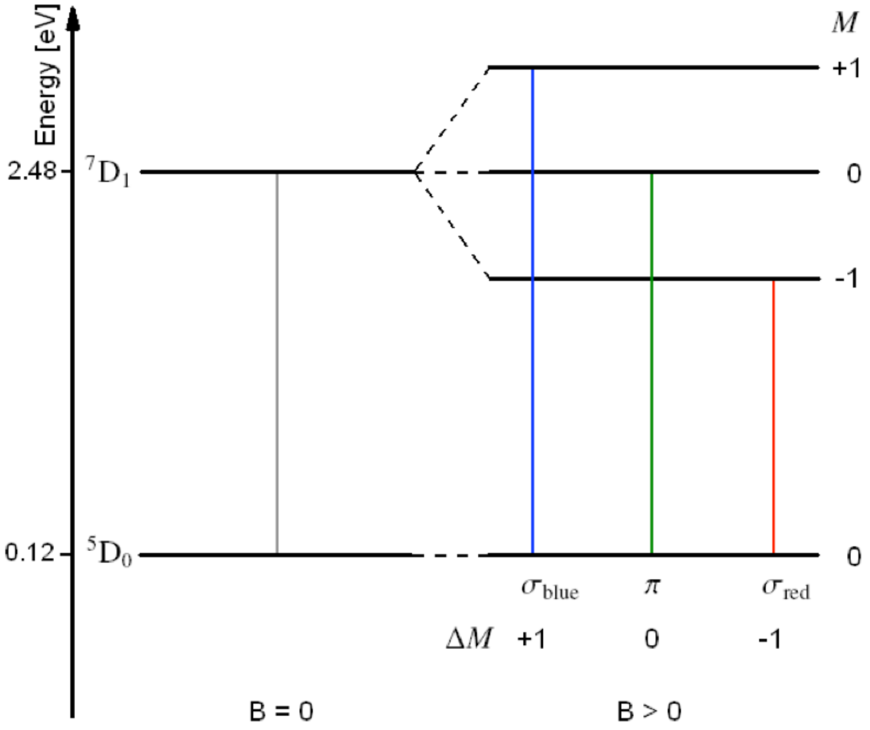




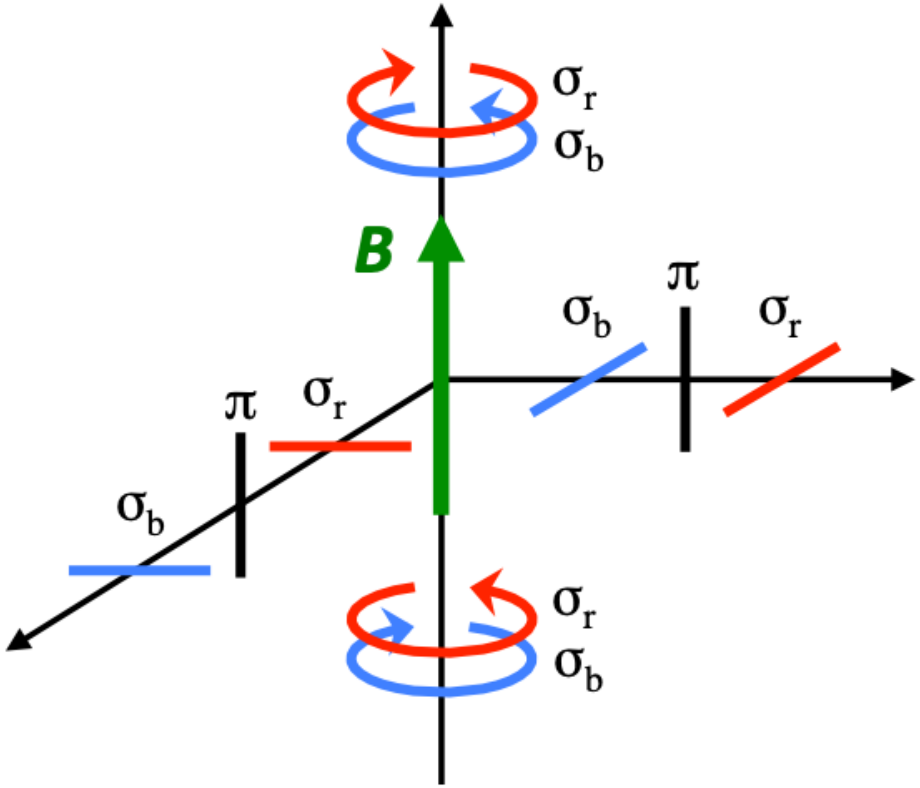
Johns-Krull 2009

Stellar magnetism

Zeeman Effect



The new spectral lines are polarised



The polarisation depends on the magnetic field orientation relative to the observer

Stellar magnetism

Zeeman effect

Magnetic field on the surface

Polarization in spectral lines

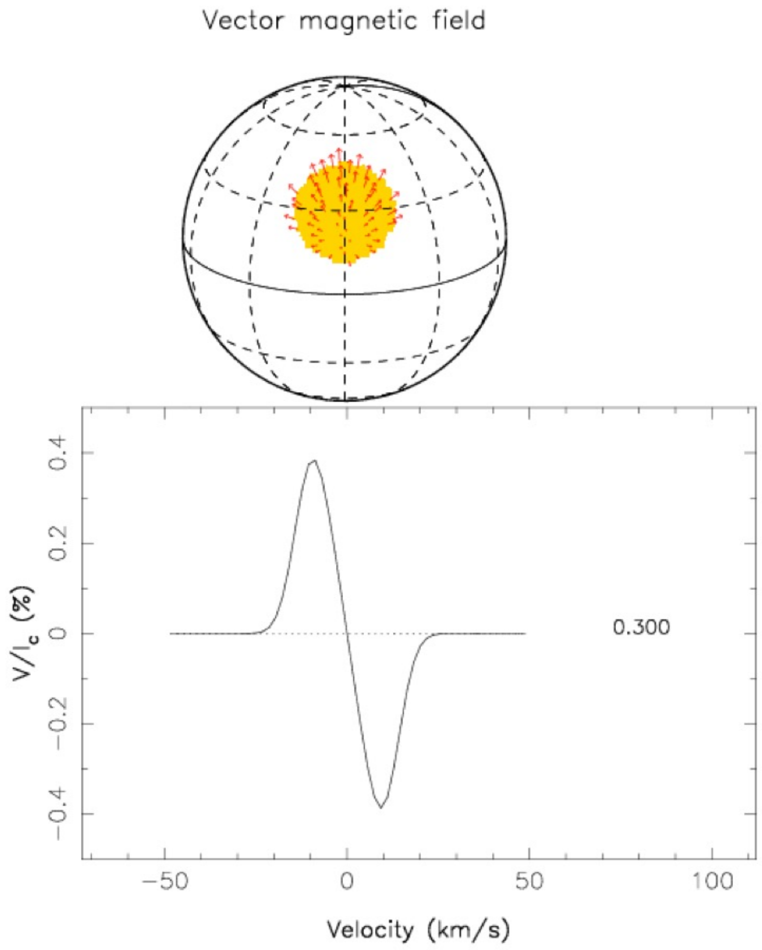
depends on

- ✓ Field Orientation
- ✓ Rotational phase

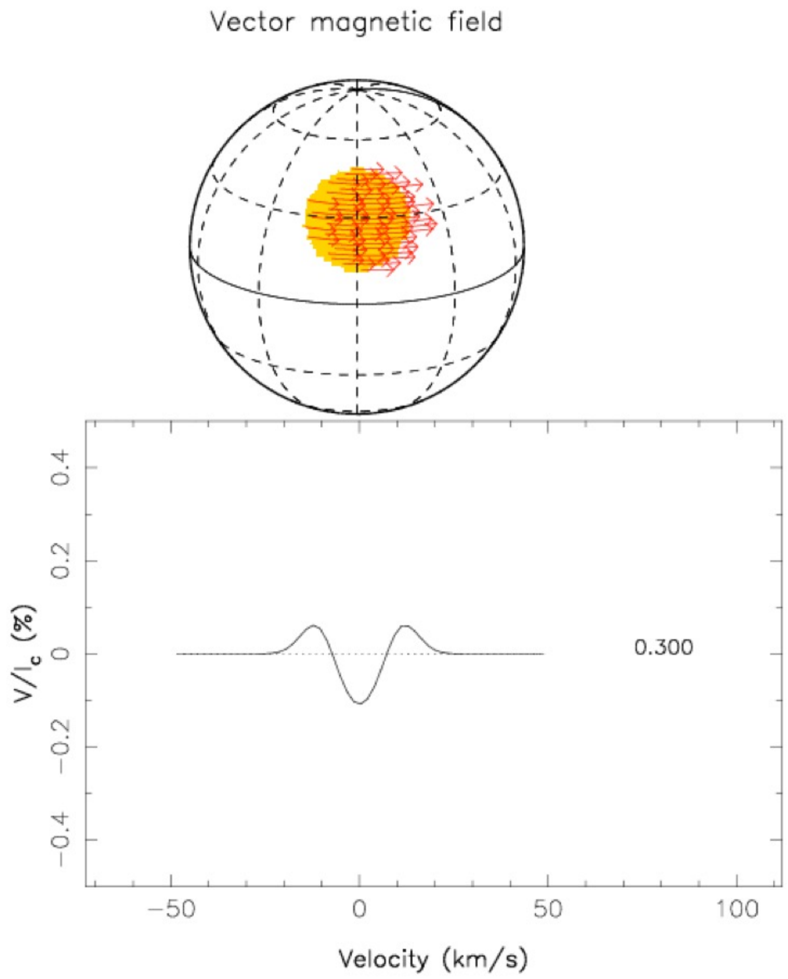
Stokes V, Circular polarisation

Stellar magnetic fields

Radial



Azimuthal



Credit: J.-F. Donati

Zeeman-Doppler Imaging ZDI

Tomographic Imaging - ZDI

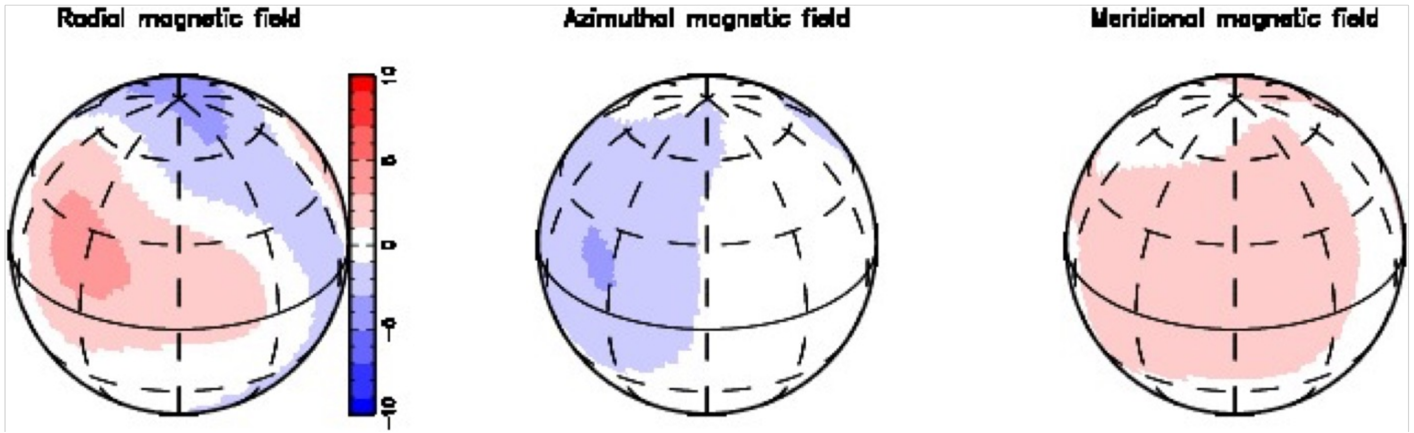
(Donati et al 1997, Donati et al 2006)

We collect

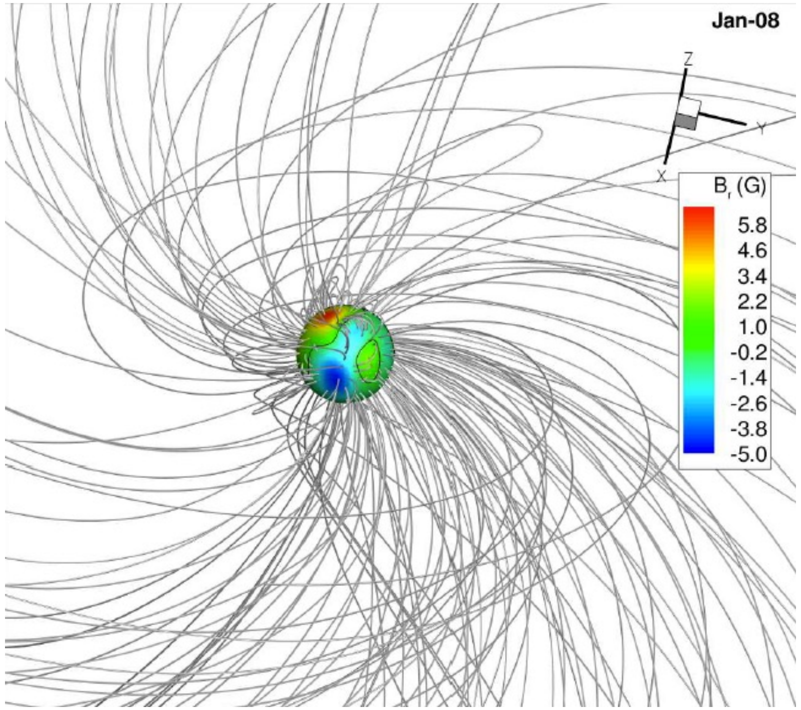
Time series of
polarized spectra

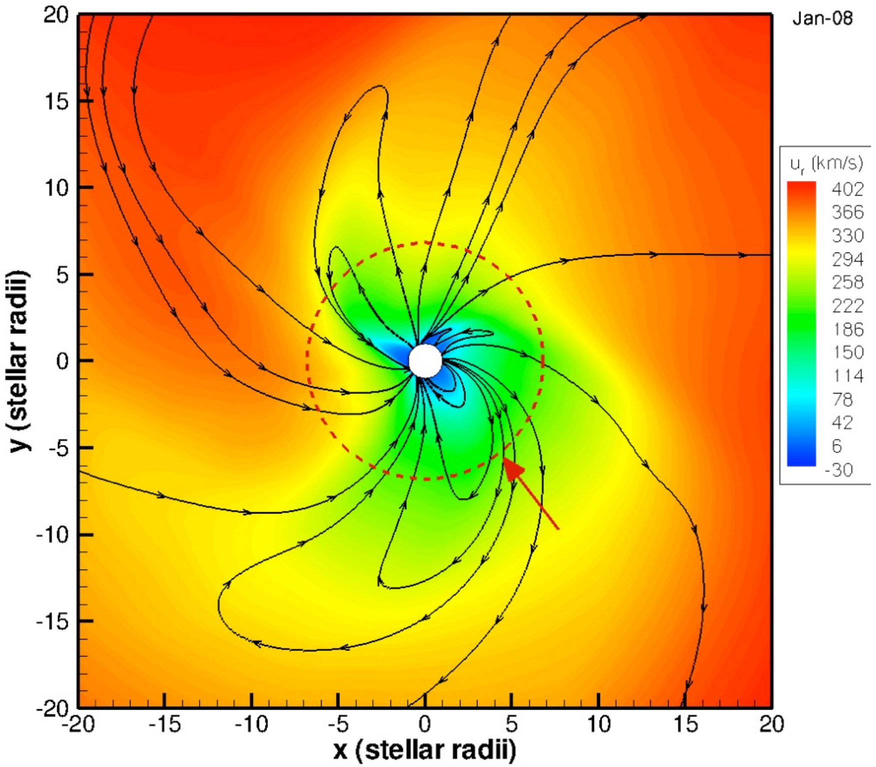
We reconstruct

Magnetic region localisation
Field orientation
Field strength



ZDI maps and SPI

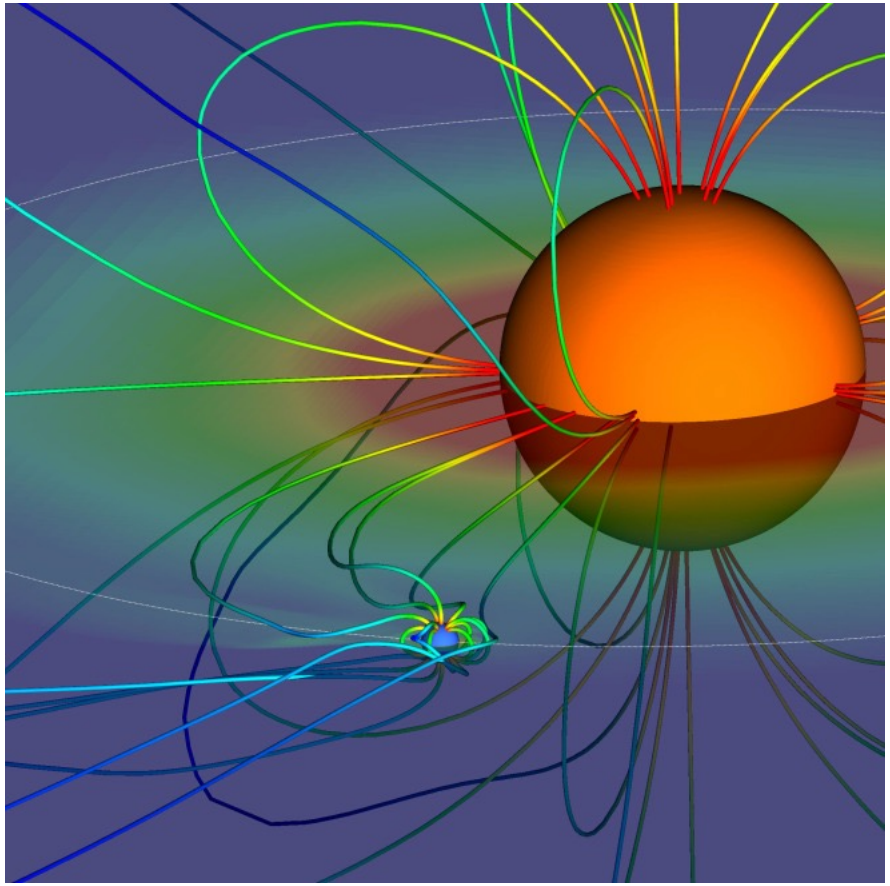




Vidotto et al, 2012

- Model the corona and stellar wind - See Julian’s talk
- Model exoplanet radio emission – See J.-M.’ s talk
- Study effect on planetary atmosphere – See Ekatrina and Sudeshna’s talks

ZDI maps and SPI



Credit: A. Strugarek

- Stars have a complicated magnetic field (usually not a simple dipole)
- The magnetic fields of cool stars evolve over short period e.g. Tau Boo (F, planet hosting) has a magnetic cycle of 8 months!
- Planetary environment is thus:
  - Variable on the orbit
  - Variable over time

And so are SPIs ...

ZDI Challenges

- Telescope time, ZDI is very demanding

Id	Telescope	Mode	Instrument	Total duration
A	TBL	Service	Neo-Narval	18h 03m 00s (18.05h)
B	OHP	Service	Sophie	2h 00m 00s (2.00h)

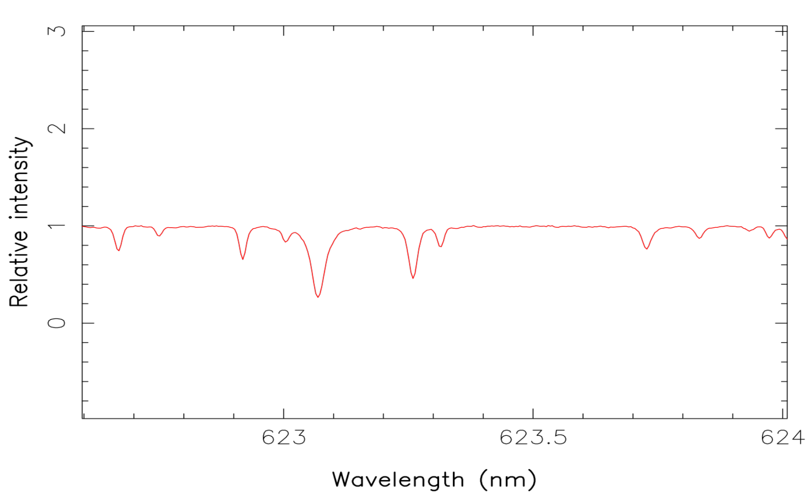
Spectropolarimetry

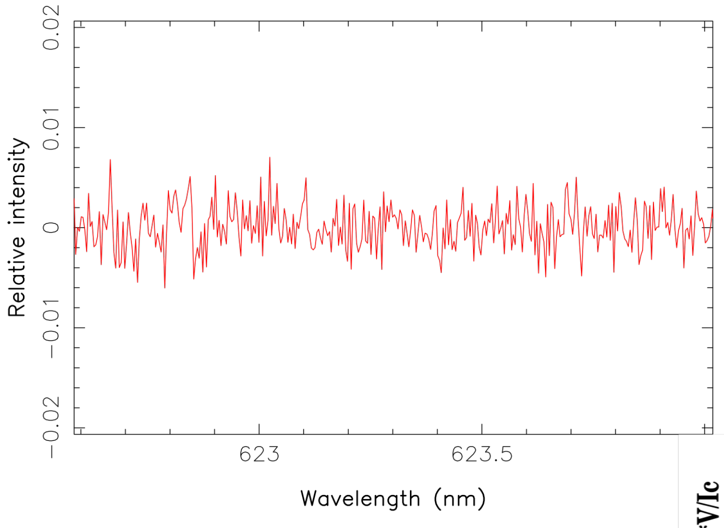
Spectroscopy
(to collect more spectra than in polar)

- ZDI recovers large-scale polarity, small-scale field can cancel out in some field geometries

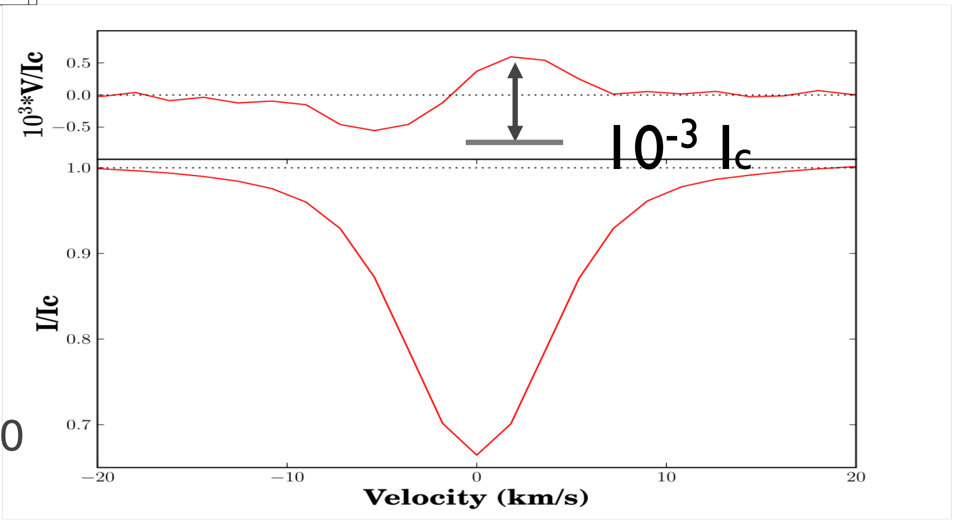
Spectropol signatures

➢ Polarised signatures within the noise level





➢ Extract the signal from many lines, e.g. LSD

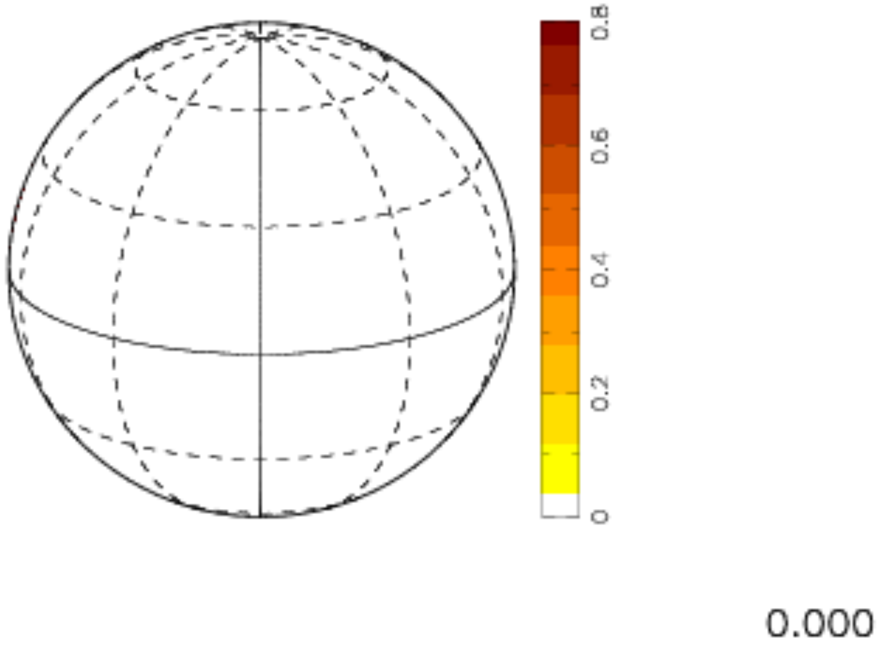


HD189733, Fares et al 2010

Stellar activity as tracer of SPI?

Spot on the stellar surface → It has the same rotation as the star (at its latitude)

Activity index → Modulated by the Stellar Rotation



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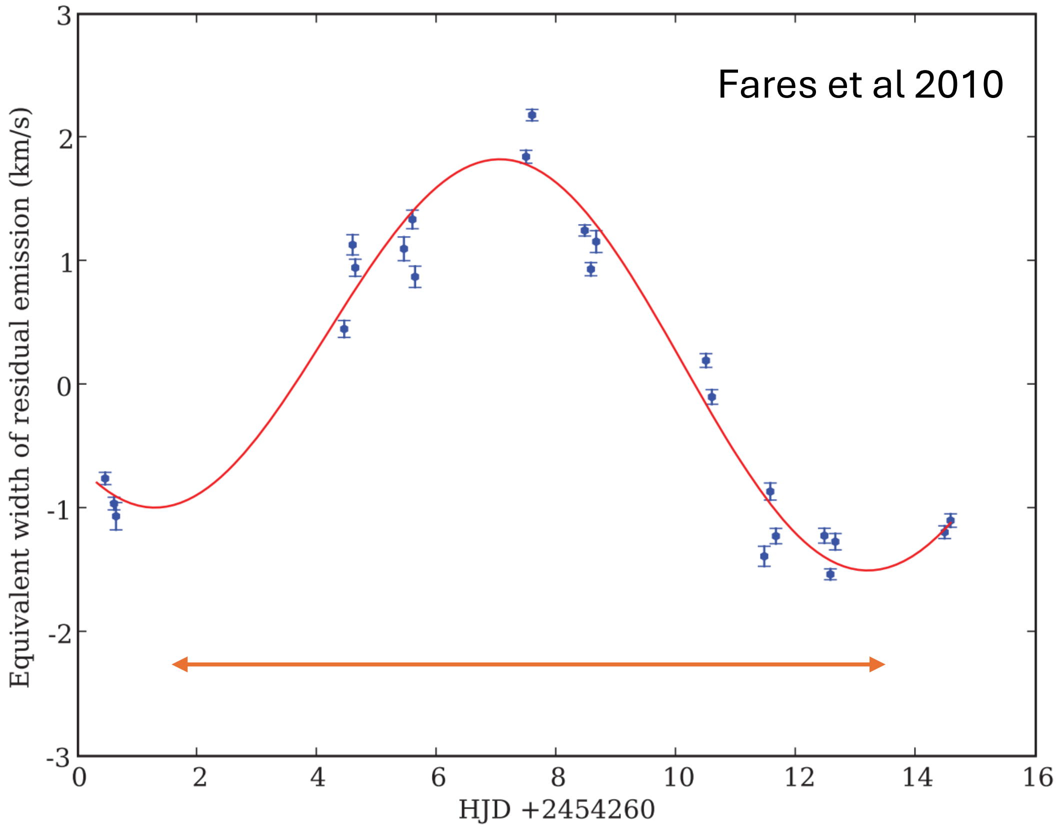
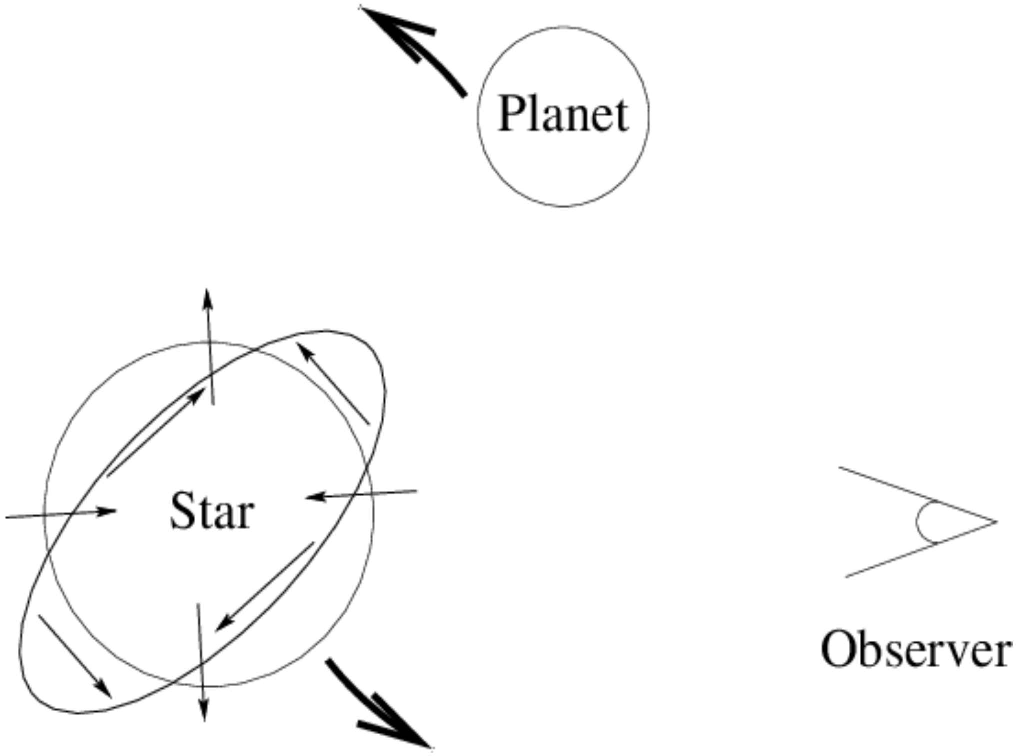
HD189733

Prot ~ 12 days



Stellar activity as tracer of SPI?

Tidal Interactions



Arras et al 2012

Two tidal bulges

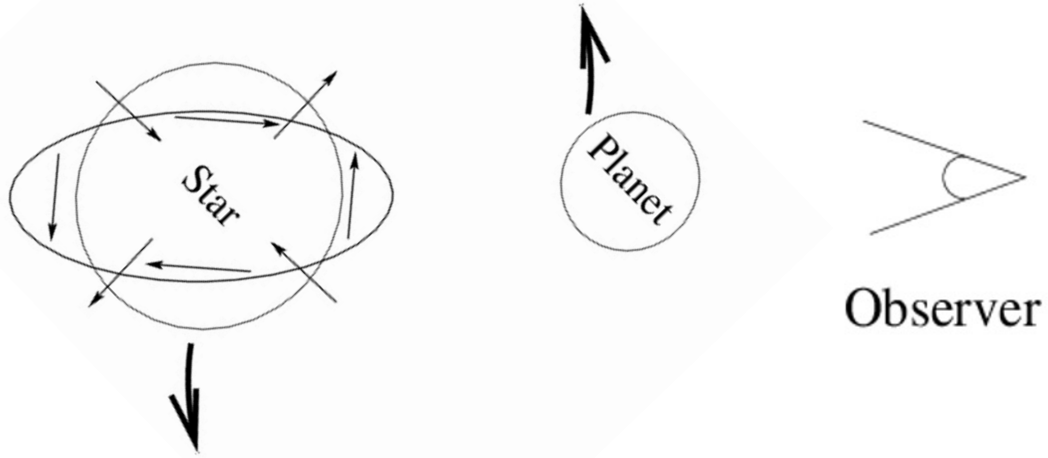
Scale height depends on relative masses of the planet and the star

Expansion & contraction of tidal bulges → waves → non-radiative energy

Enhanced heating → Stellar Activity

Stellar activity as tracer of SPI?

Tidal Interactions



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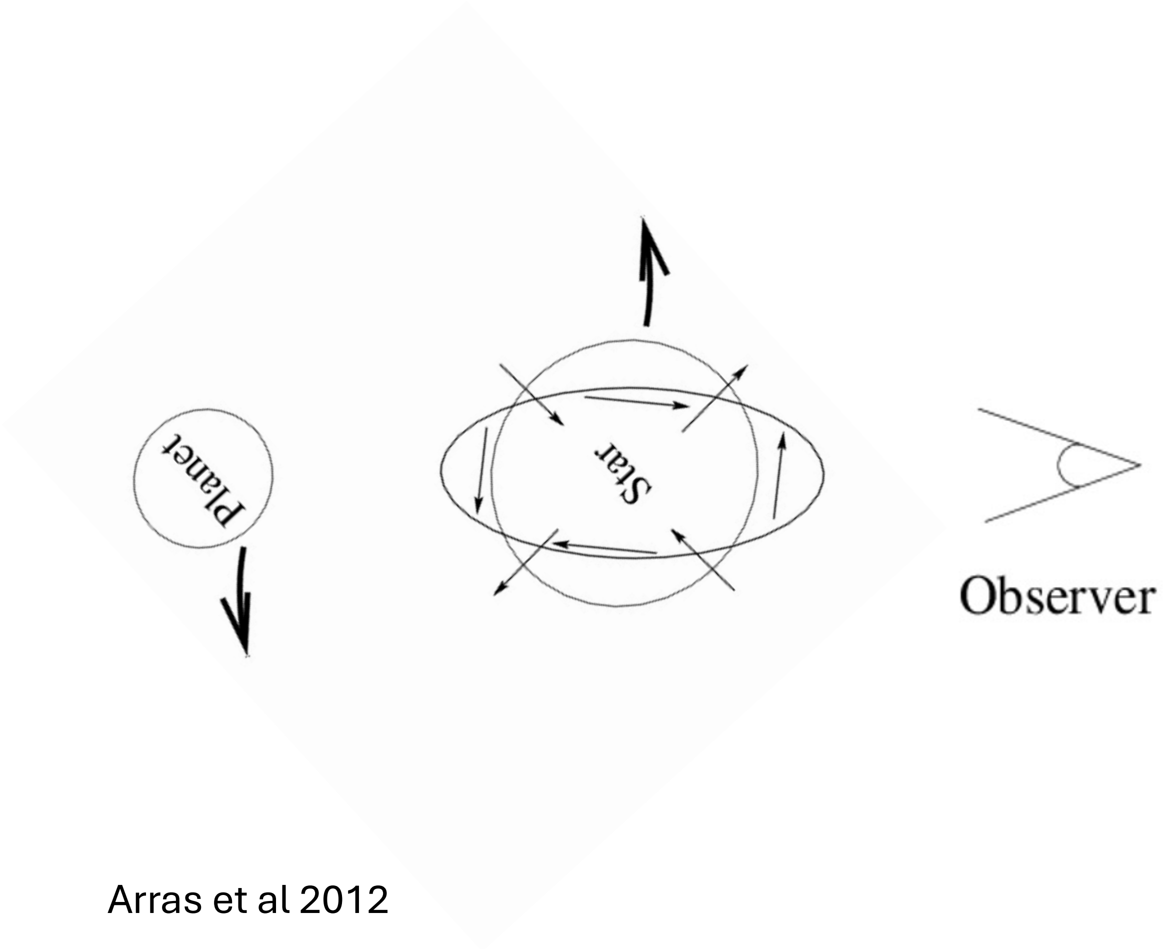

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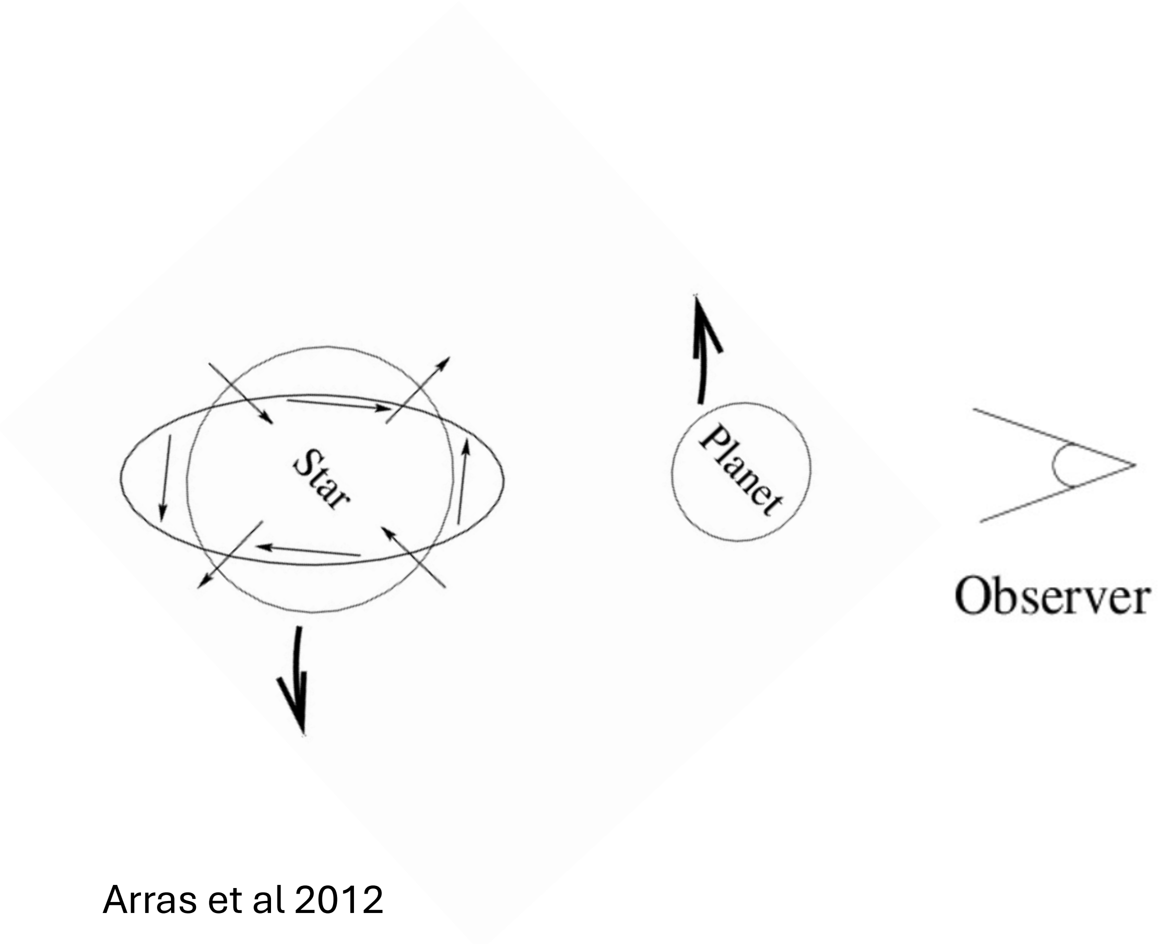


Arras et al 2012

Two tidal bulges

Scale height depends on relative masses of the planet and the star

Expansion & contraction of tidal bulges → waves → non-radiative energy

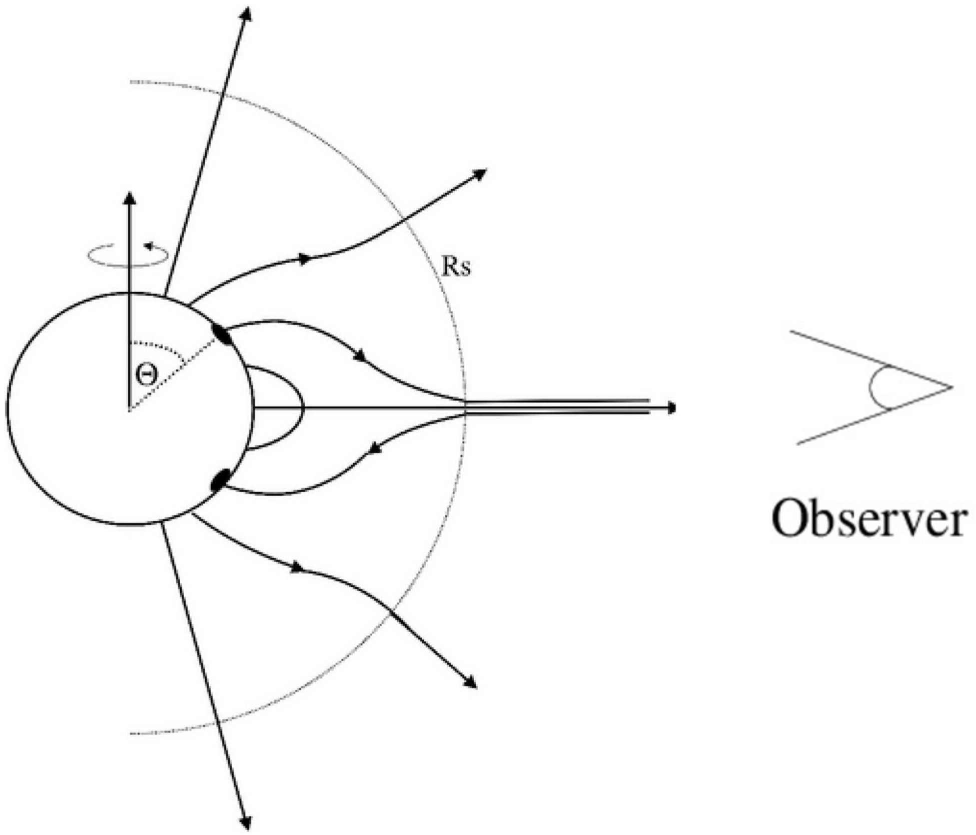
Enhanced heating → Stellar Activity

Observed twice in every planetary orbit

Activity modulated by Porb/2

Stellar activity as tracer of SPI?

Magnetic Interactions



McIvor et al 2006

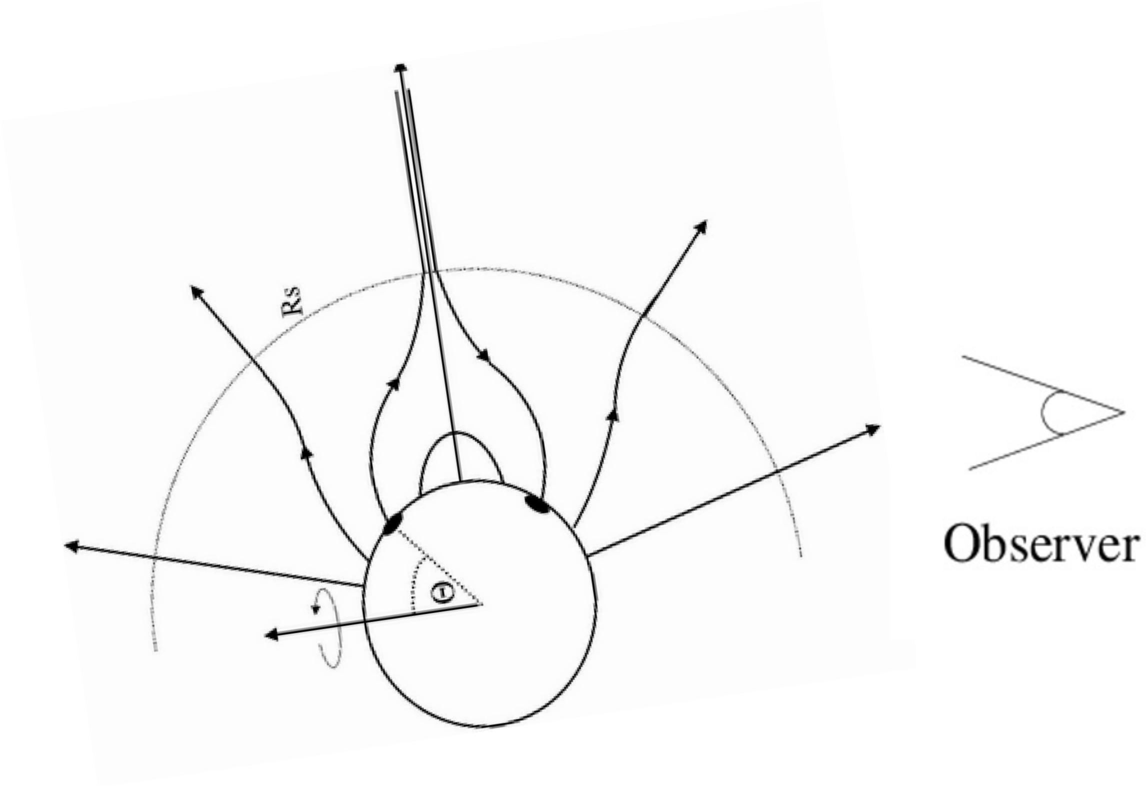
Magnetic Reconnection
(other models to be detailed in E. Ilin talk)

Particle impact the star

Enhanced heating → Stellar Activity

Stellar activity as tracer of SPI?

Magnetic Interactions



McIvor et al 2006

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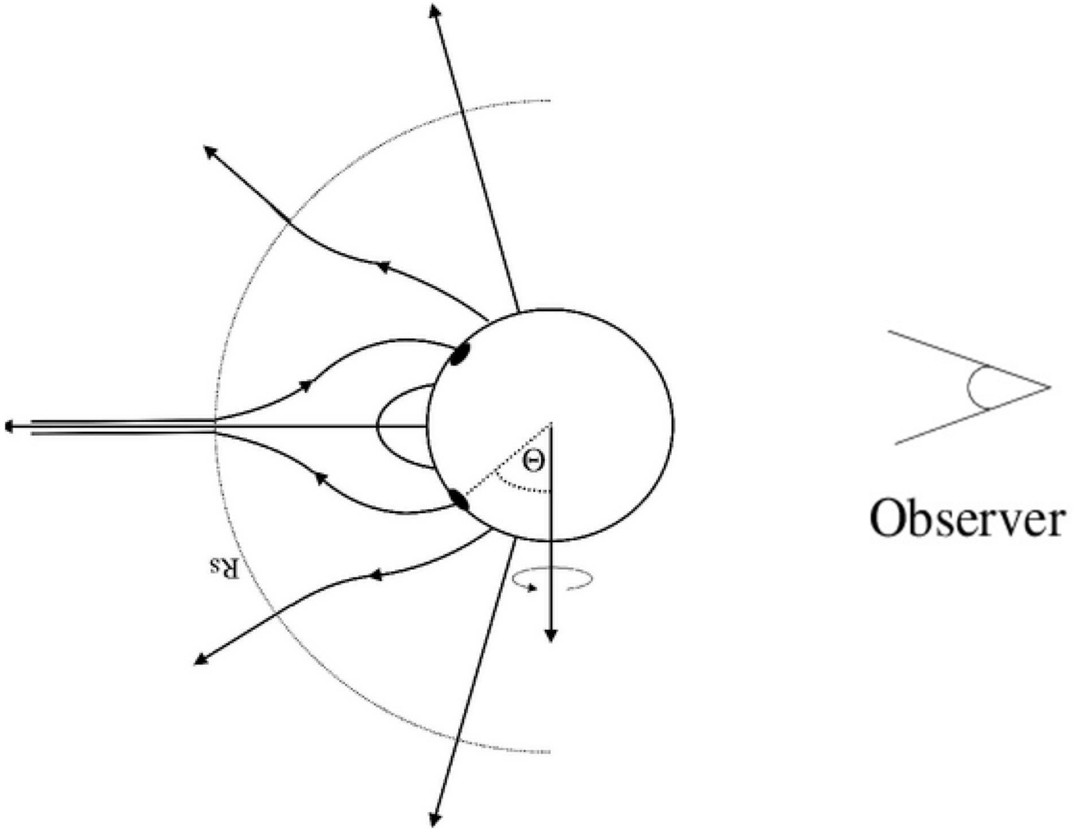
Stellar activity as tracer of SPI?

Magnetic Interactions



McIvor et al 2006

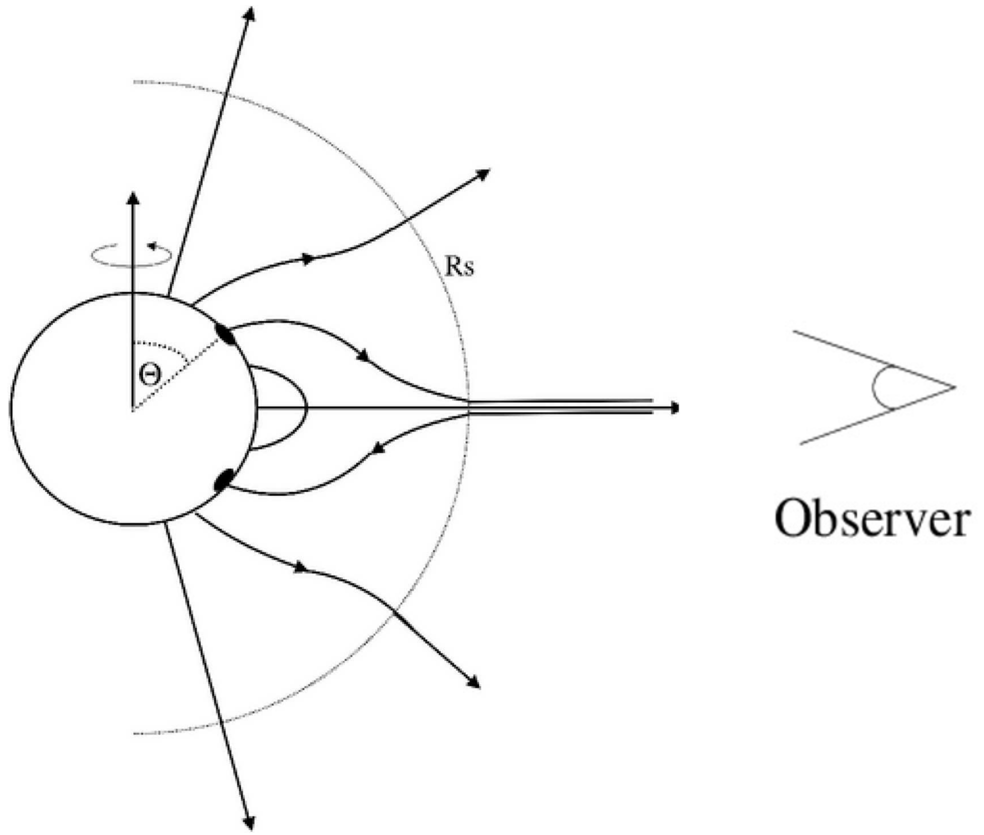
Magnetic Reconnection
(other models to be detailed in E. Ilin talk)

Particle impact the star

Enhanced heating → Stellar Activity

Stellar activity as tracer of SPI?

Magnetic Interactions



McIvor et al 2006

Magnetic Reconnection
(other models to be detailed in E. Ilin talk)

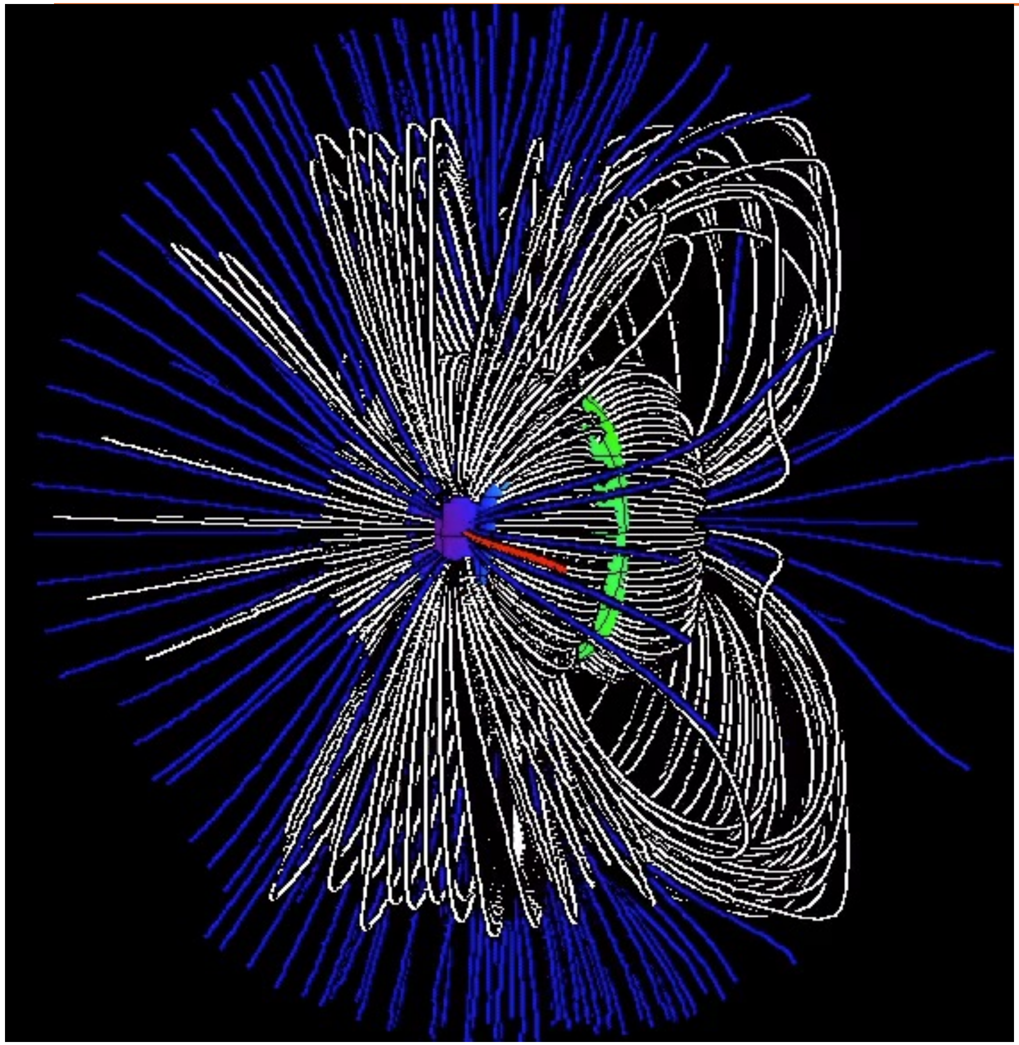
Particle impact the star

Enhanced heating → Stellar Activity

Observed once every planetary orbit

Activity modulated by Porb

Stellar activity as tracer of SPI?



Fares et al, 2009

Magnetic Reconnection
(other models to be detailed in E. Ilin talk)

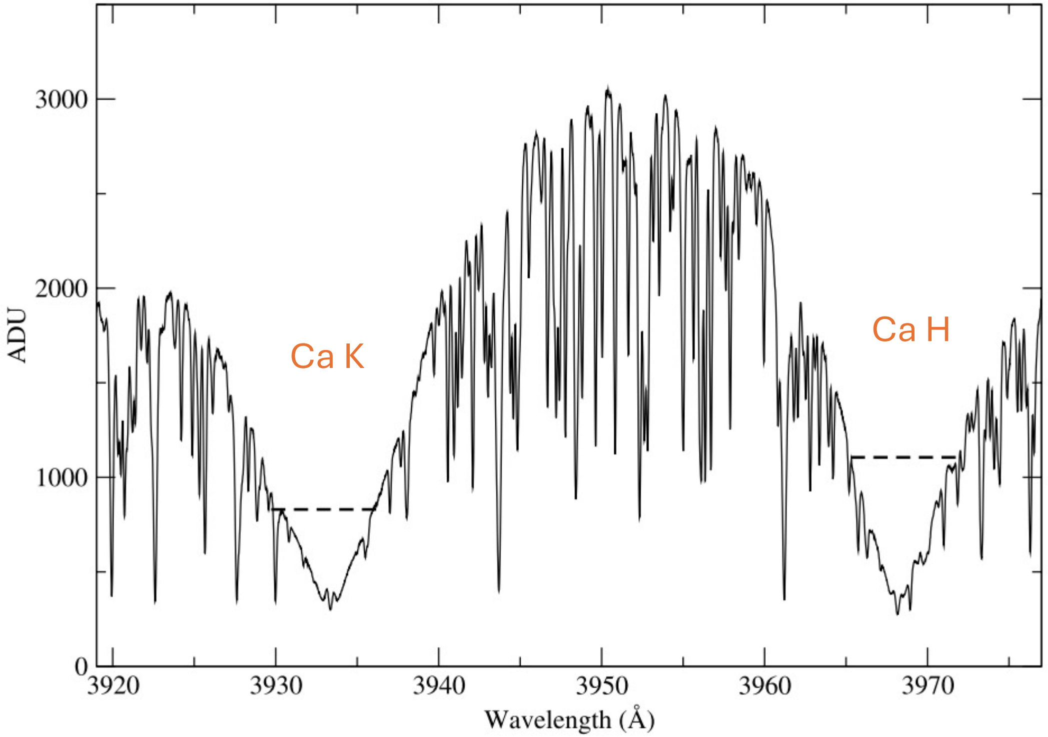
Particle impact the star

Enhanced heating → Stellar Activity

Observed once for every beat period (the period after which the star and the planet have the same configuration relative to the observer)

Activity modulated by
Beat Period $|Porb^{-1} - Prot^{-1}|^{-1}$

Hurray! Magnetic SPI detection on HD179949



Normalise the lines

Calculate the mean profile for all observations

Calculate nightly variations by subtracting the mean from each observation

System:

F8 star

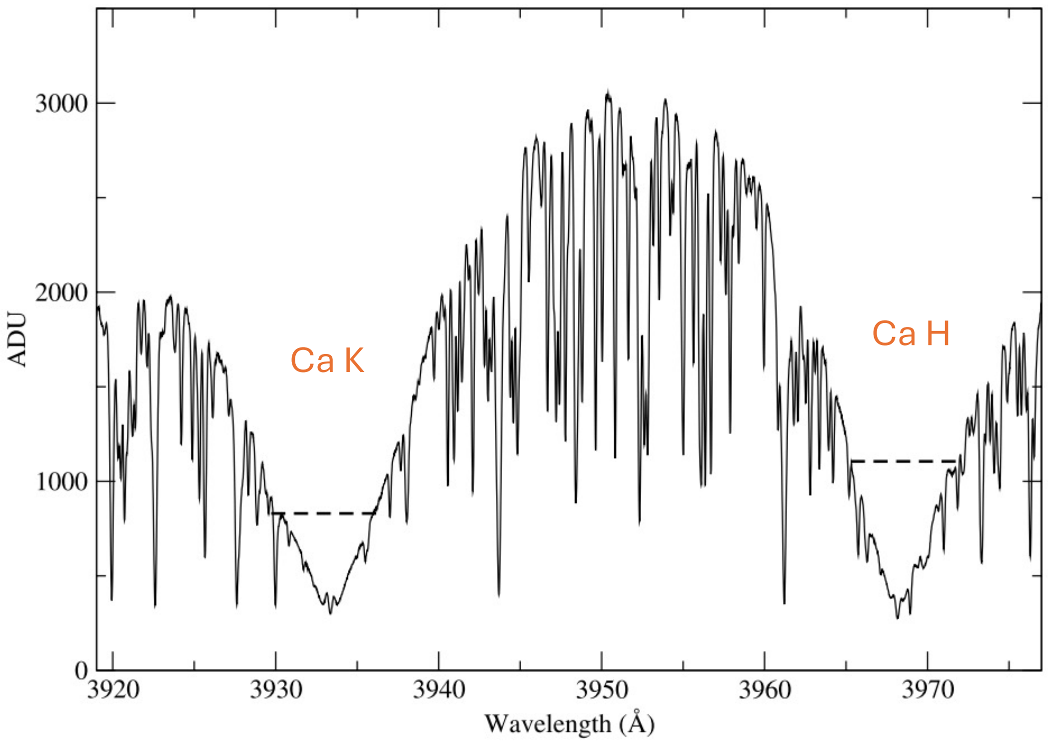
P_{rot} ~ 9 d

Planet: 0.92 M_{Jup}, orbits at 8.8 R_{star}

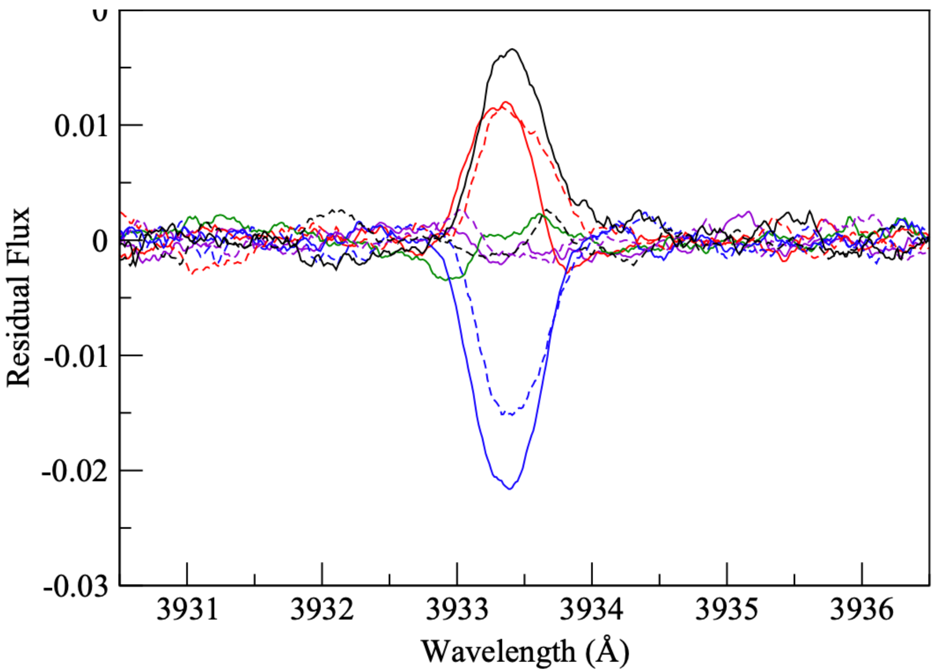
Porb = 3.09 d

Shkolnik et al 2003

Hurray! Magnetic SPI detection on HD179949



Nightly variations in Ca II K line



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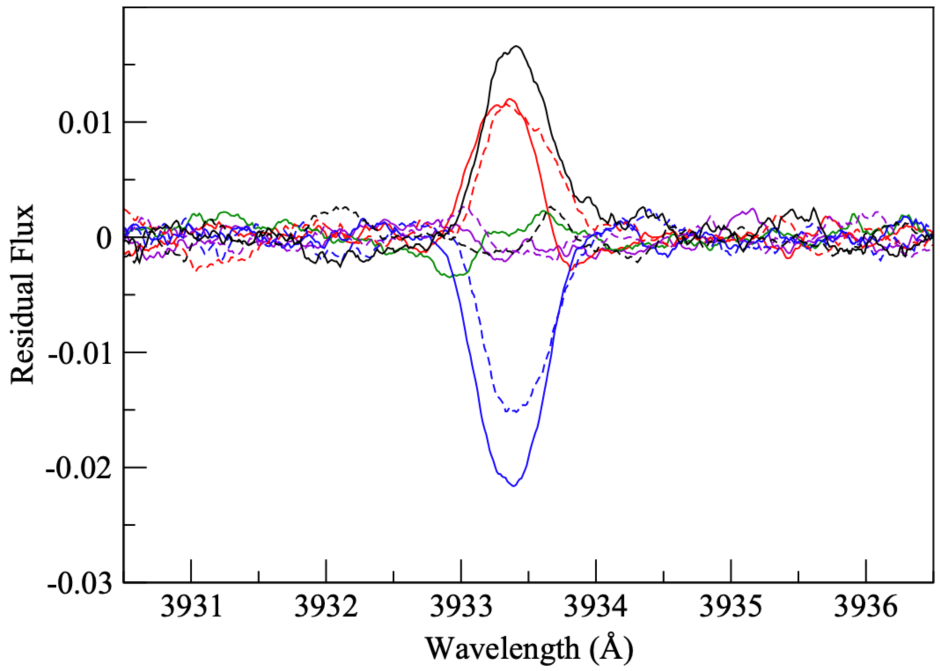
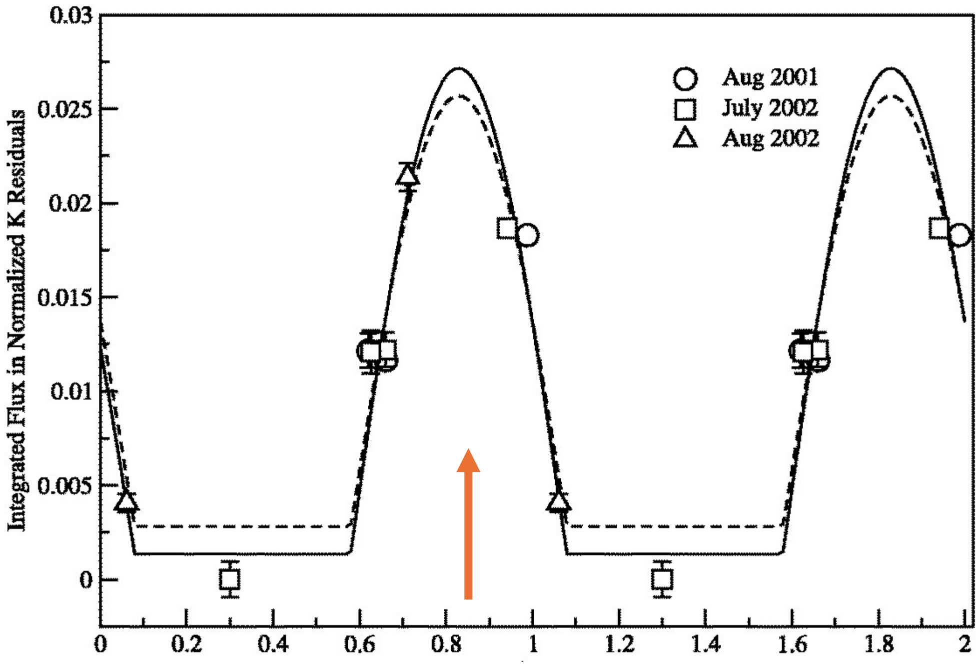


Modulated by Orbital phase



Orbital Phase

System:

F8 star

$P_{rot} \sim 7.6$ d

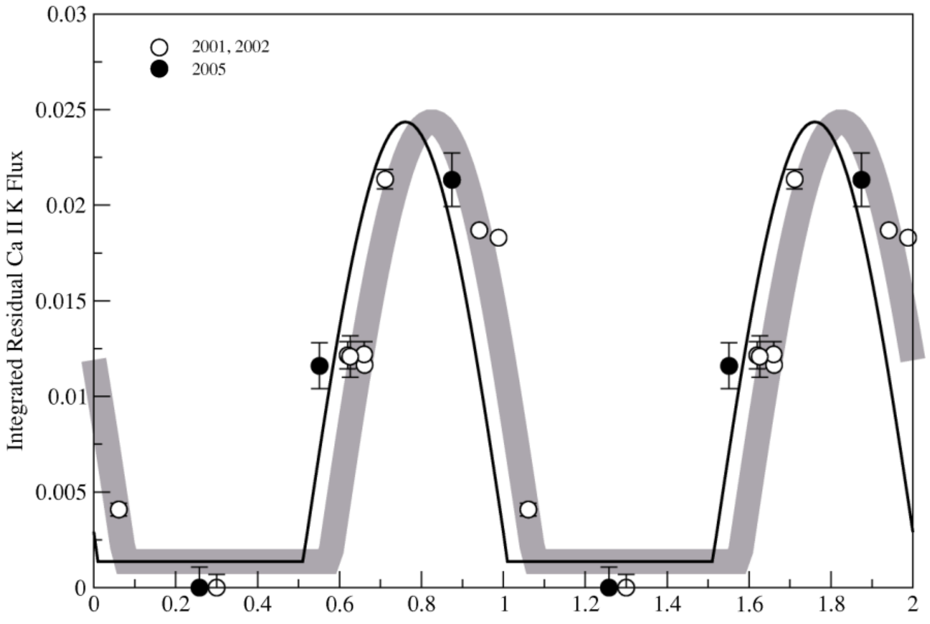
Planet: 0.92 M_{Jup}, orbits at 8.8 R_{star}

Porb = 3.09 d

Shkolnik et al 2003

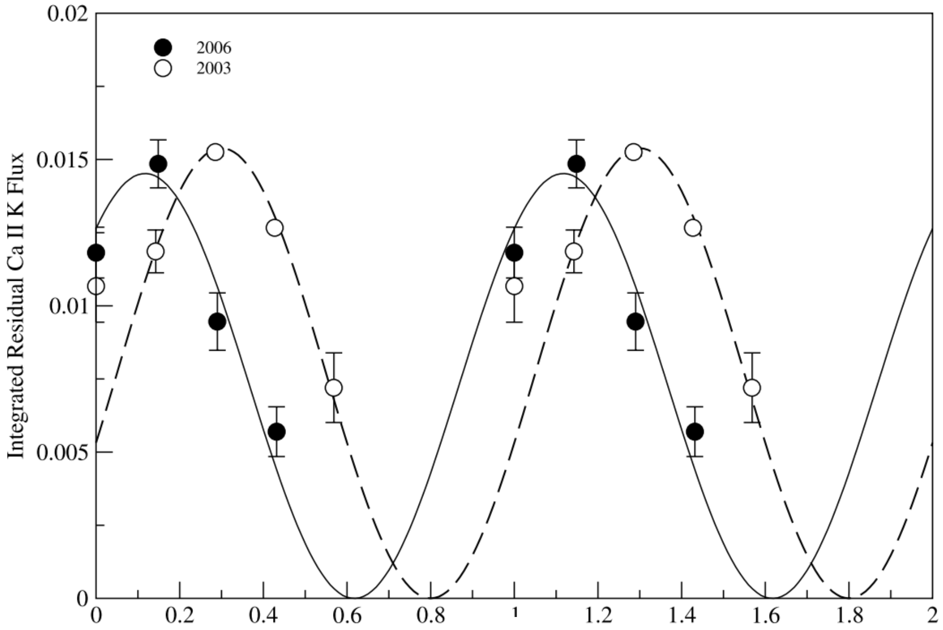
SPI detection is not reccurent for every obs

HD 179949 observed at different epochs



Orbital Phase

Modulated by Orbital phase



Rotational Phase

Modulated by Rotational phase

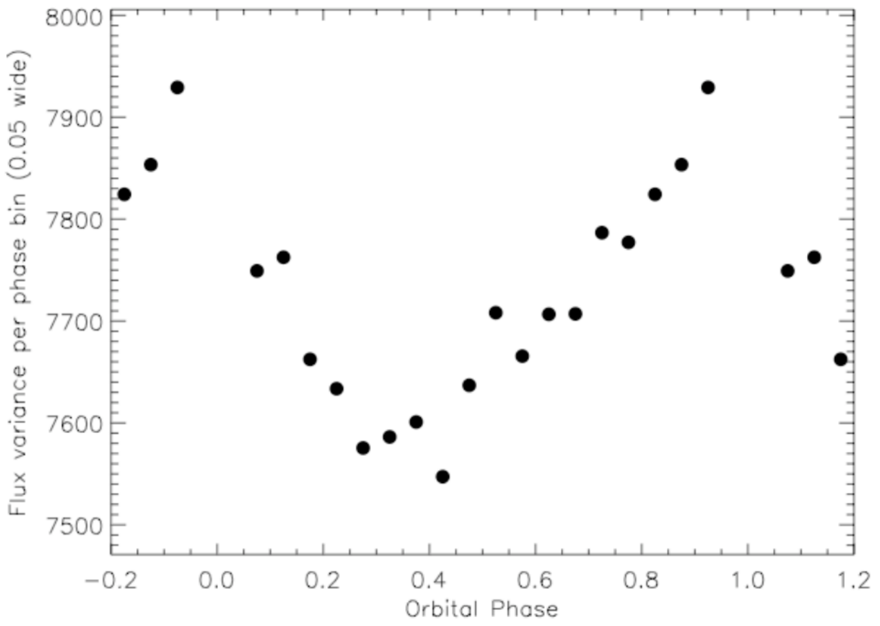
SPI has an ON/OFF Nature

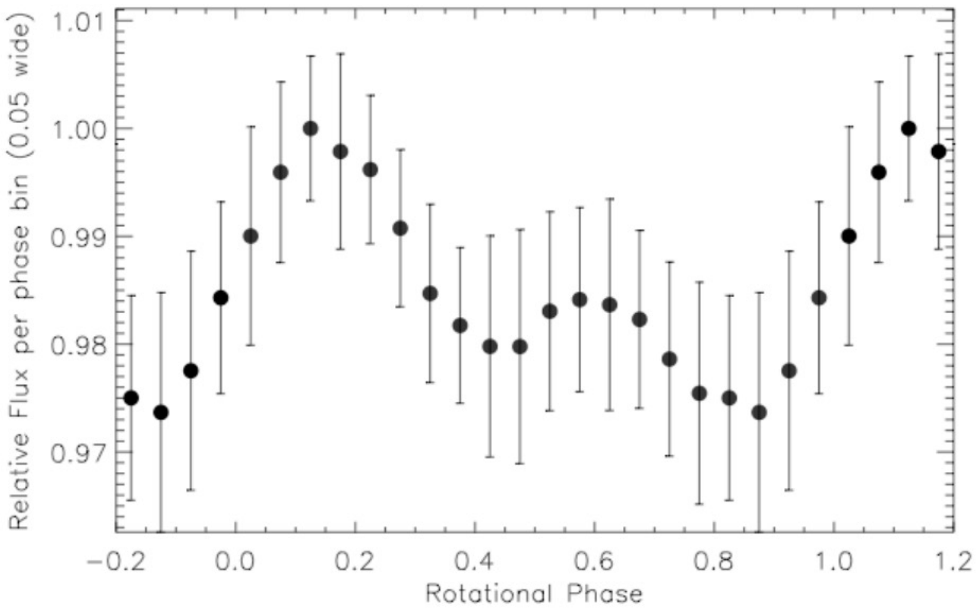
Shkolnik et al 2003, 2005, 2008

SPI detection generated a lot of interest

Photometry

Corot-2 spot modelling (Pagano et al 2009)





Modulated by Orbital phase

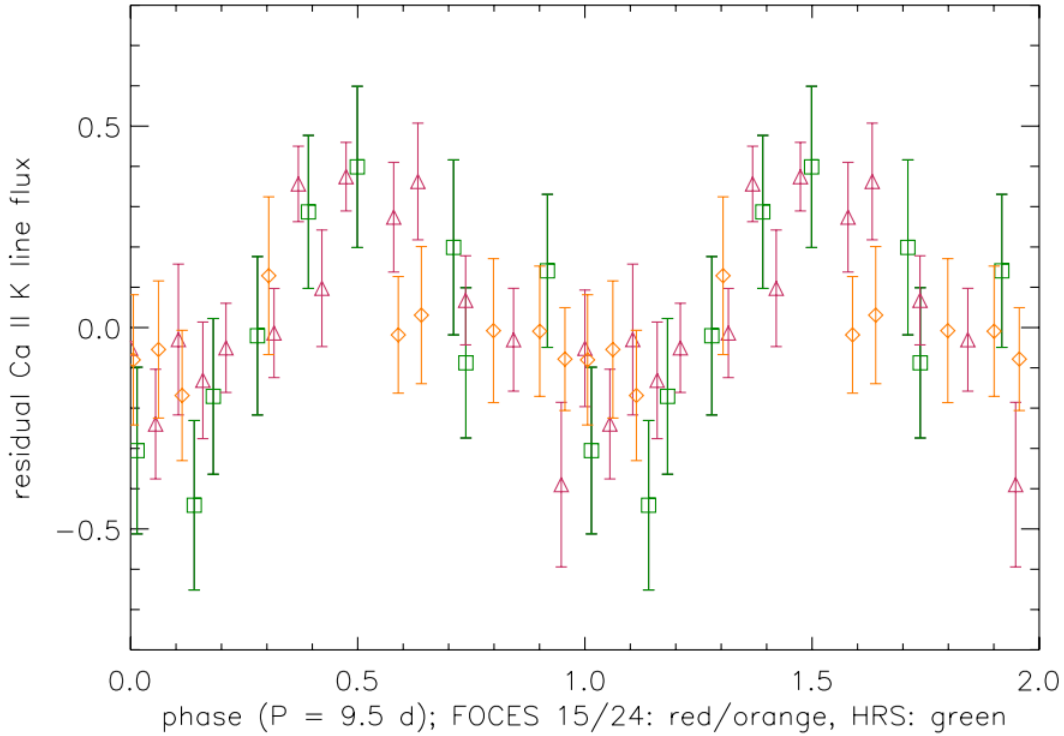
Modulated by Rotational phase

Hints of SPI?

SPI detection generated a lot of interest

X-Ray

υ And in CaII and X-Ray (Poppenhaeger et al 2011)



Ca II K line modulated by Rotational phase

No activity variations in the X-Ray that could hint to SPI

SPI detection on HD189733

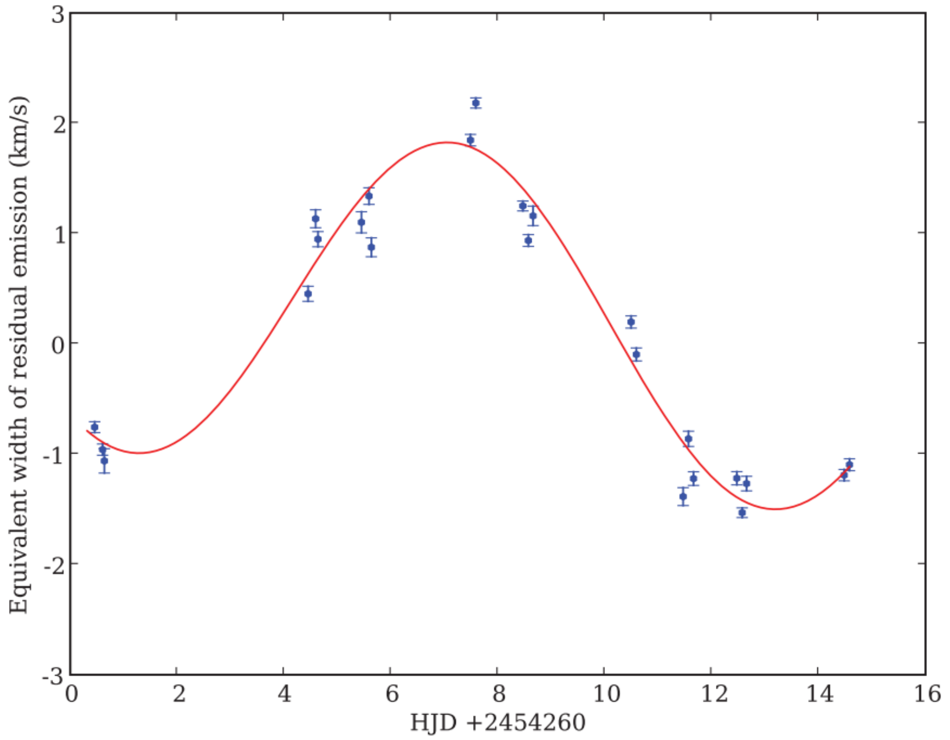
System:

K dwarf (active)

P_{rot} ~ 12 days

Planet: 1.13 M_{Jup}, orbits at 8 R_{star}

P_{orb} = 2.2 days



Fares et al 2009

July 2008

Modulated by Rotational phase

Subtract the rotational modulation and look for SPI modulation in the residuals

SPI detection on HD189733

System:

K dwarf (active)

P_{rot} ~ 12 days

Planet: 1.13 M_{Jup}, orbits at 8 R_{star}

P_{orb} = 2.2 days

Star's magnetic field (ZDI) was studied over 9 epochs (Moutou et al 2007, Fares et al 2010, 2013,2017)

Observation epoch	UT start	UT end	N_{nights}	Instrument	Telescope	$\lambda/\Delta\lambda$	References
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2006 Jun[a]	2006 Jun 10	2006 Jun 13	4	ESPaDOns	CFHT	65,000	Moutou et al. (2007)
	2006 Jun 16	2006 Jun 19	4	ESPaDOns	CFHT	80,000	Shkolnik et al. (2008)
2007 Jun[b]	2007 Jun 23	2007 Jul 4	8	ESPaDOns	CFHT	65,000	Fares et al. (2010)
2008 Jul	2008 Jul 15	2008 Jul 24	8	NARVAL	TBL	65,000	Fares et al. (2013)
2013 Aug	2013 Aug 4	2013 Aug 22	11	NARVAL	TBL	65,000	Fares et al. (2017)
2013 Sep	2013 Sep 2	2013 Sep 24	13	NARVAL	TBL	65,000	Fares et al. (2017)
2015 Jul	2015 Jul 6	2015 Jul 16	10	NARVAL	TBL	65,000	Fares et al. (2017)

Cauley et al 2018: Looking for SPI signals after removing the rotational modulation

SPI detection on HD189733

System:

K dwarf (active) — Planet: 1.13 M_{Jup}, orbits at 8 R_{star}

P_{rot} ~ 12 days — P_{orb} = 2.2 days

Star's magnetic field (ZDI) was studied over 9 epochs (Moutou et al 2007, Fares et al 2010, 2013,2017)

Observation epoch (1)	UT start (2)	UT end (3)	N_{nights} (4)	Instrument (5)	Telescope (6)	$\lambda/\Delta\lambda$ (7)	References (8)	ZDI
2006 Jun[a]	2006 Jun 10	2006 Jun 13	4	ESPaDOns	CFHT	65,000	Moutou et al. (2007)	Yes
	2006 Jun 16	2006 Jun 19	4	ESPaDOns	CFHT	80,000	Shkolnik et al. (2008)	No
2007 Jun[b]	2007 Jun 23	2007 Jul 4	8	ESPaDOns	CFHT	65,000	Fares et al. (2010)	Yes
2008 Jul	2008 Jul 15	2008 Jul 24	8	NARVAL	TBL	65,000	Fares et al. (2013)	Yes
2013 Aug	2013 Aug 4	2013 Aug 22	11	NARVAL	TBL	65,000	Fares et al. (2017)	Yes
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								Yes

Cauley et al 2018: Looking for SPI signals after removing the rotational modulation

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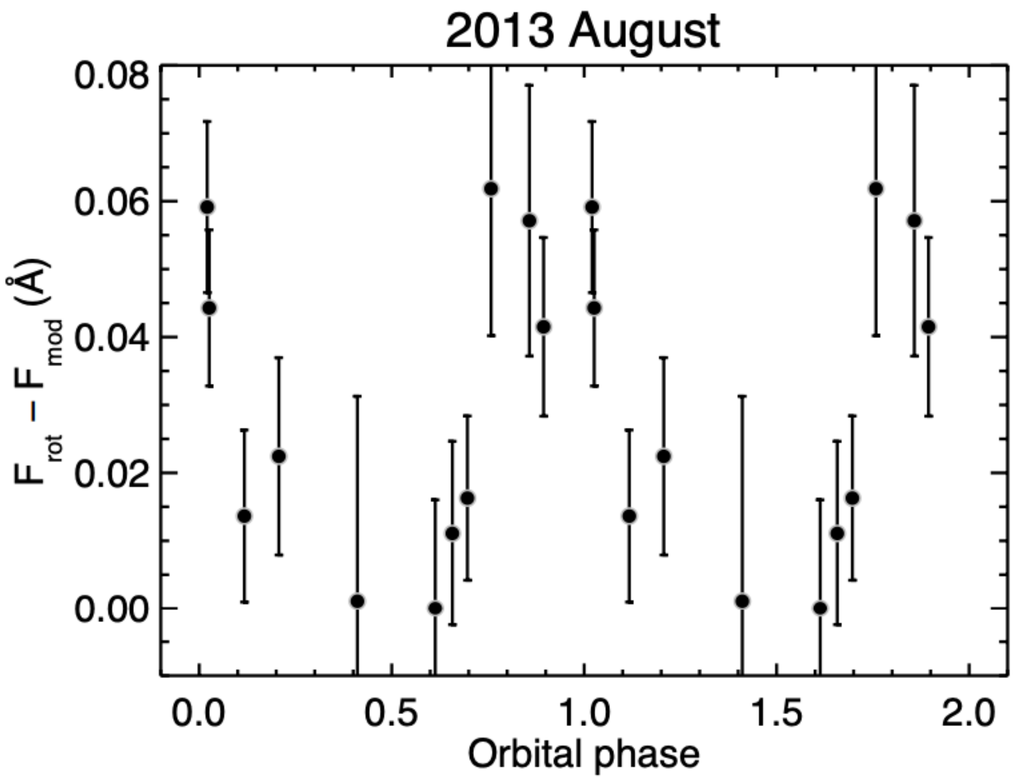


Cauley et al 2018

1 out of 6 epochs showed SPI (August 2013)

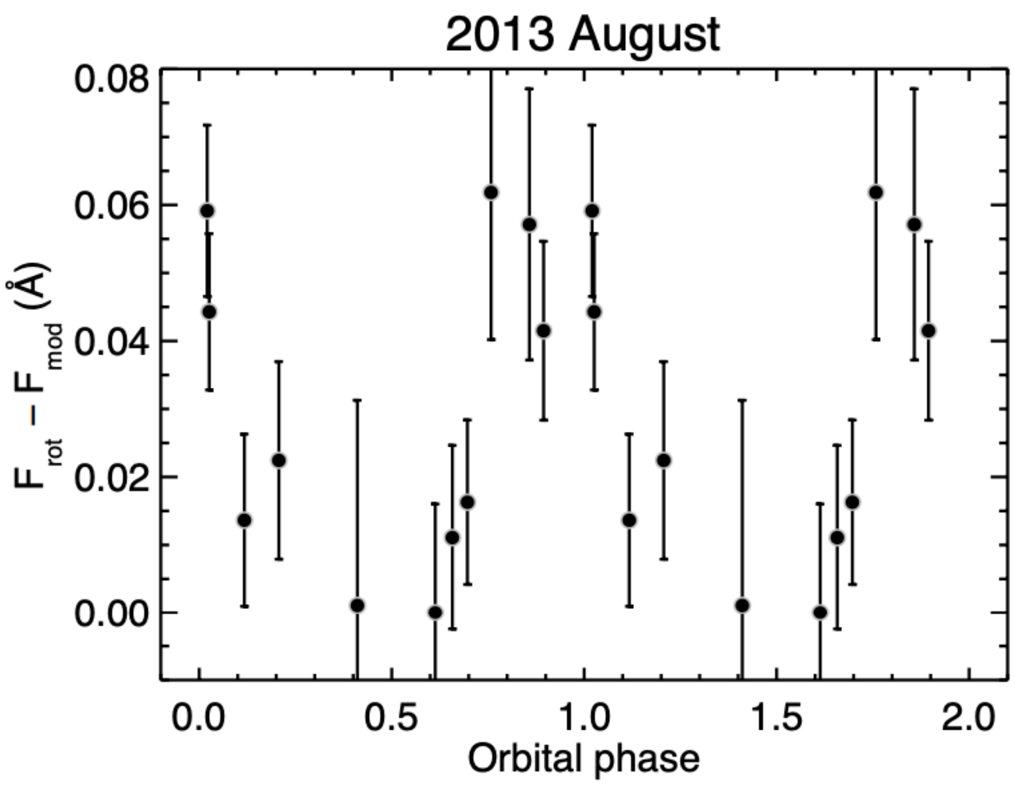
SPI detection on HD189733

August 2013

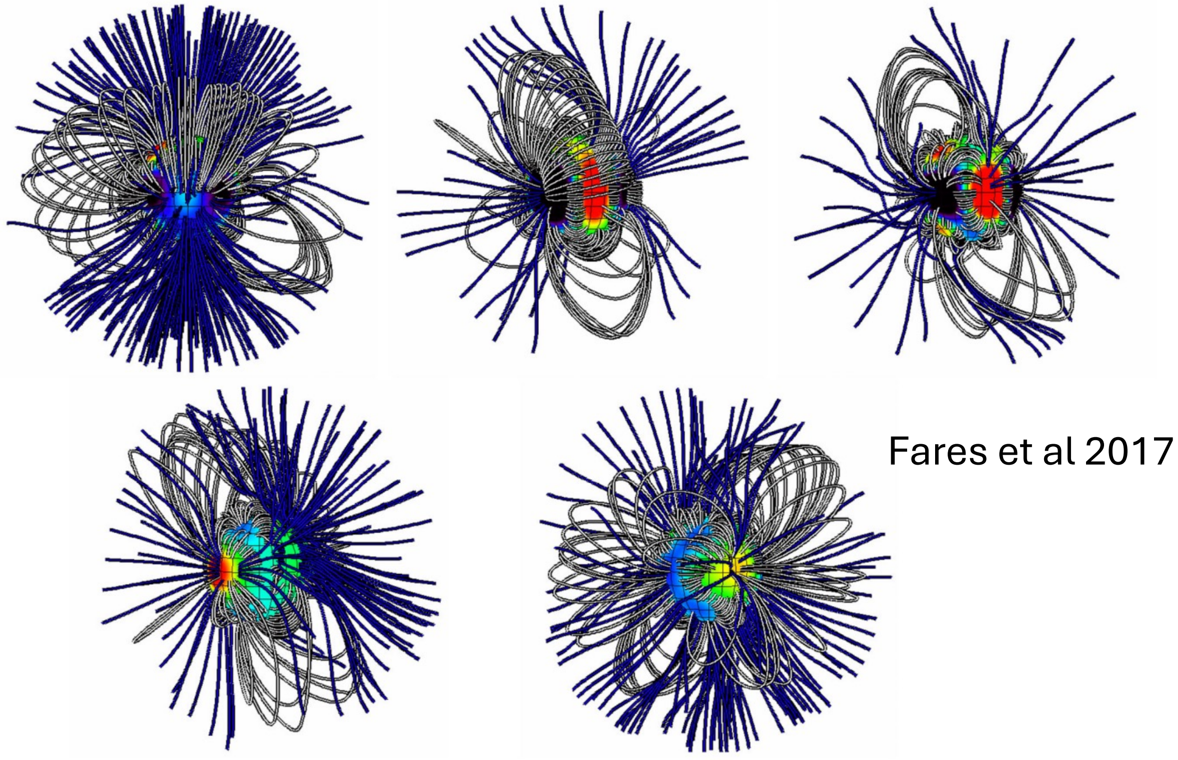
System:

K dwarf (active)

Planet: 1.13 M_{Jup}, orbits at 8 R_{star}



Cauley et al 2018



Fares et al 2017

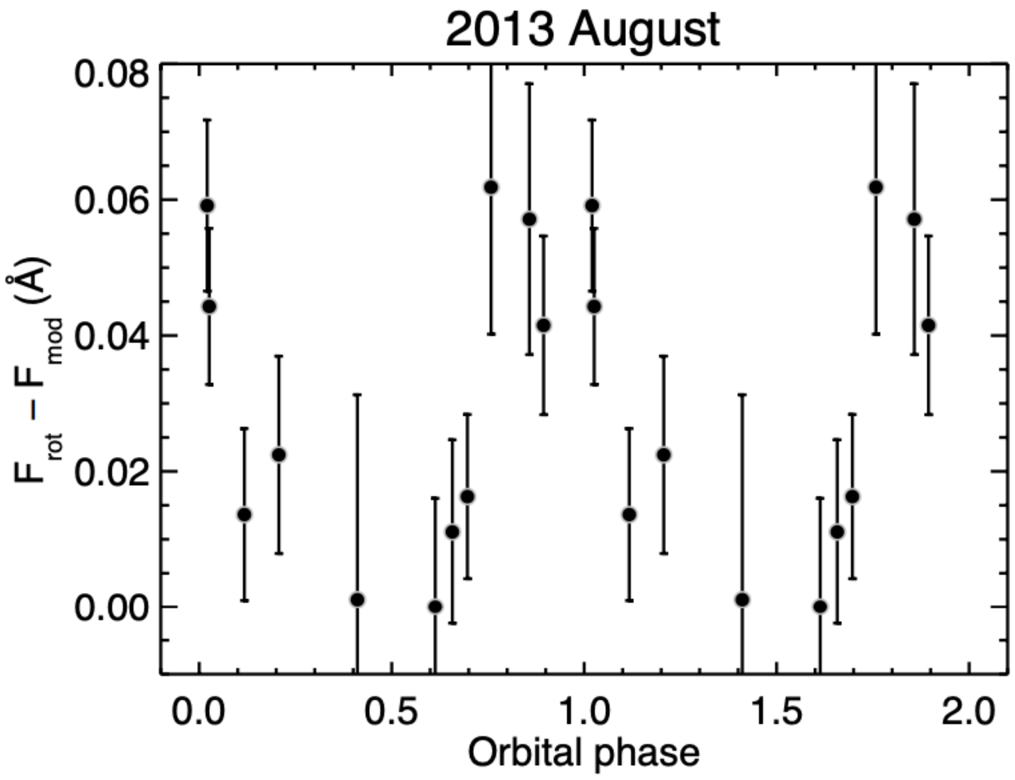
ZDI maps of the stellar field show:
It varies in strength and characteristics

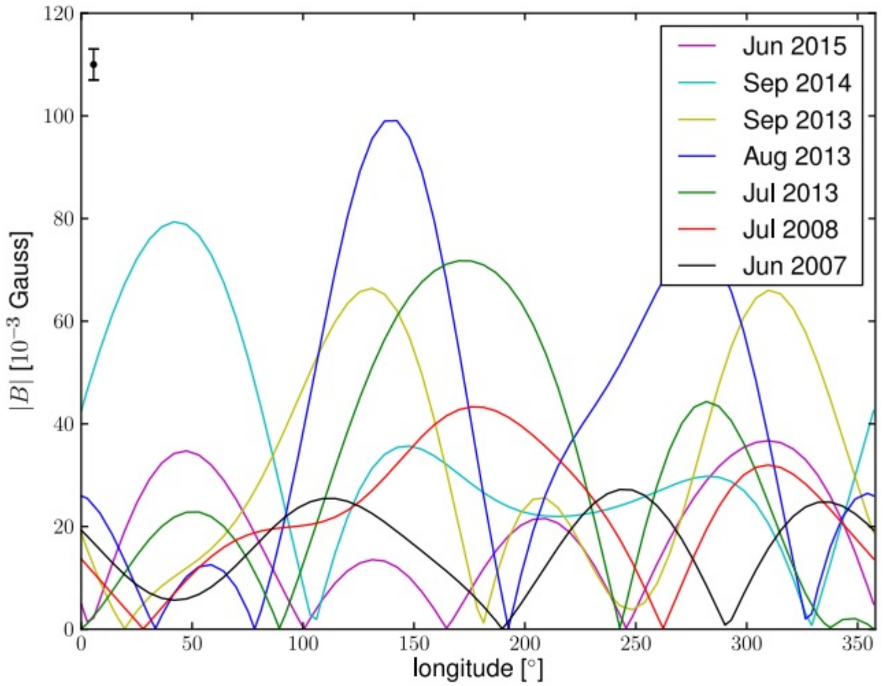
SPI detection on HD189733

System:

K dwarf (active)

Planet: 1.13 M_{Jup}, orbits at 8 R_{star}

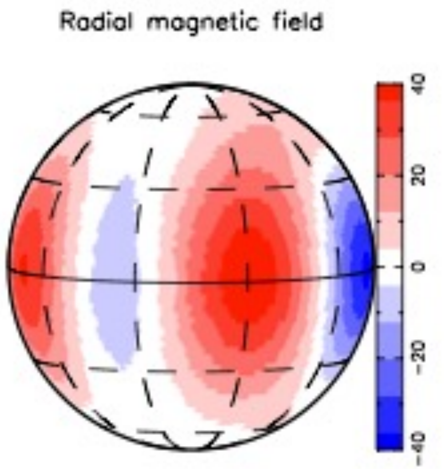


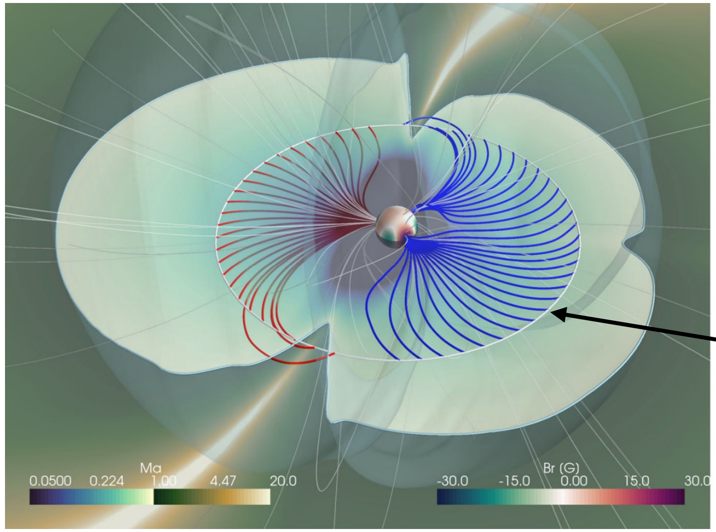


Orbital phase modulation Aug 2013 corresponds to the Largest stellar magnetic field

Modelling SPI detection

ZDI Magnetic Maps





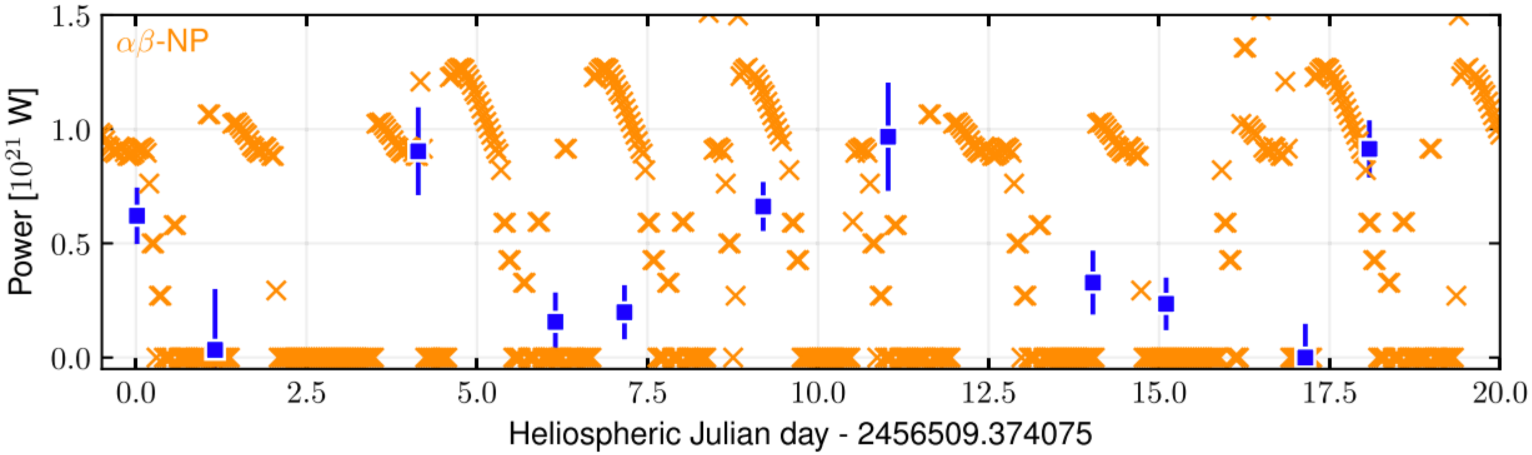
Stellar wind model

Planet Orbit

Strugarek et al 2019

With the scarcity of data, SPI detection rate is estimated to 12-23%

Cauley et al 2018 found SPI in 1 out of 6 epochs (i.e. 17%)



Need: Dense observation campaigns, with several observations per night

SPI detection

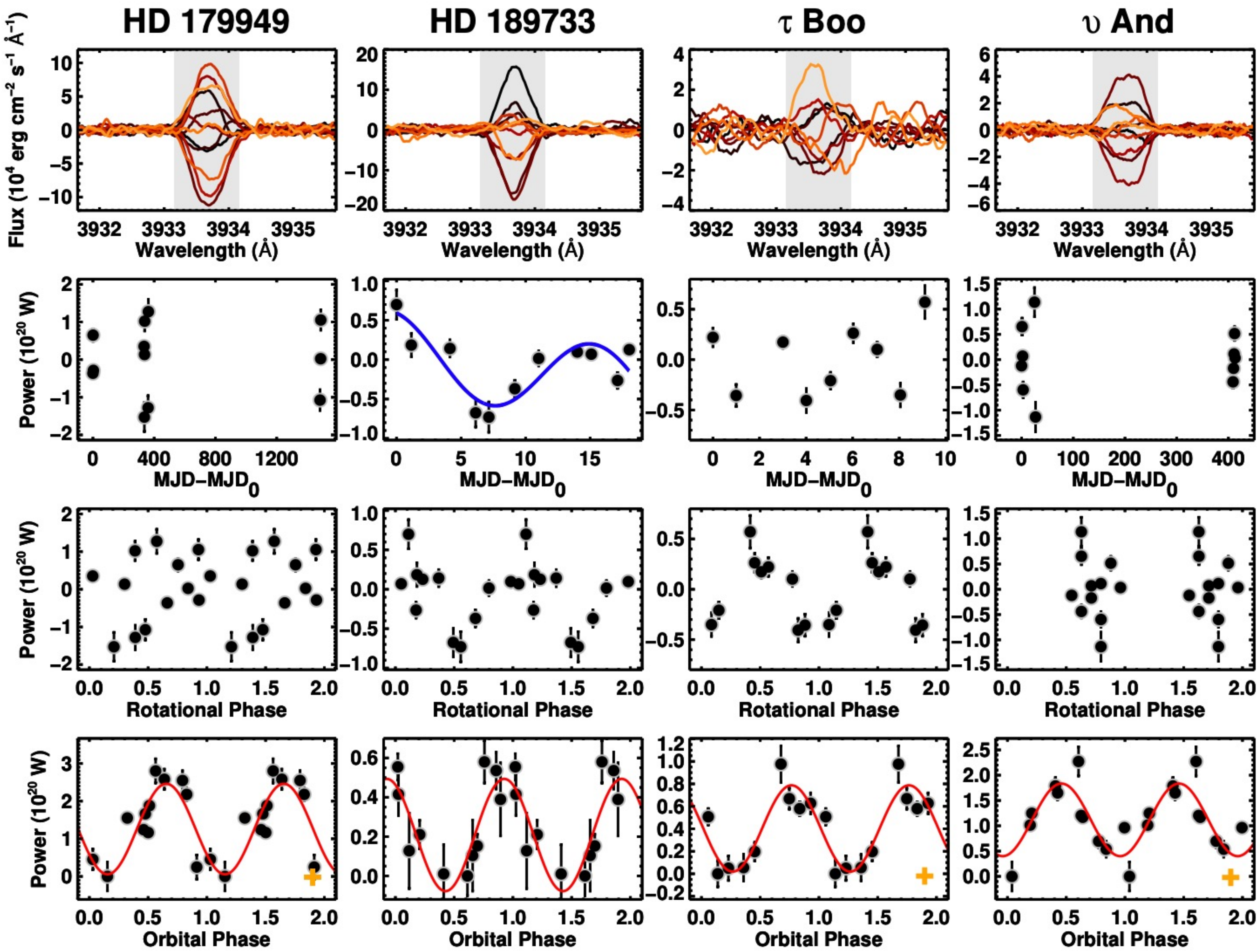
Call K Flux

Power as a function of

Date

Rotational Phase

Orbital Phase



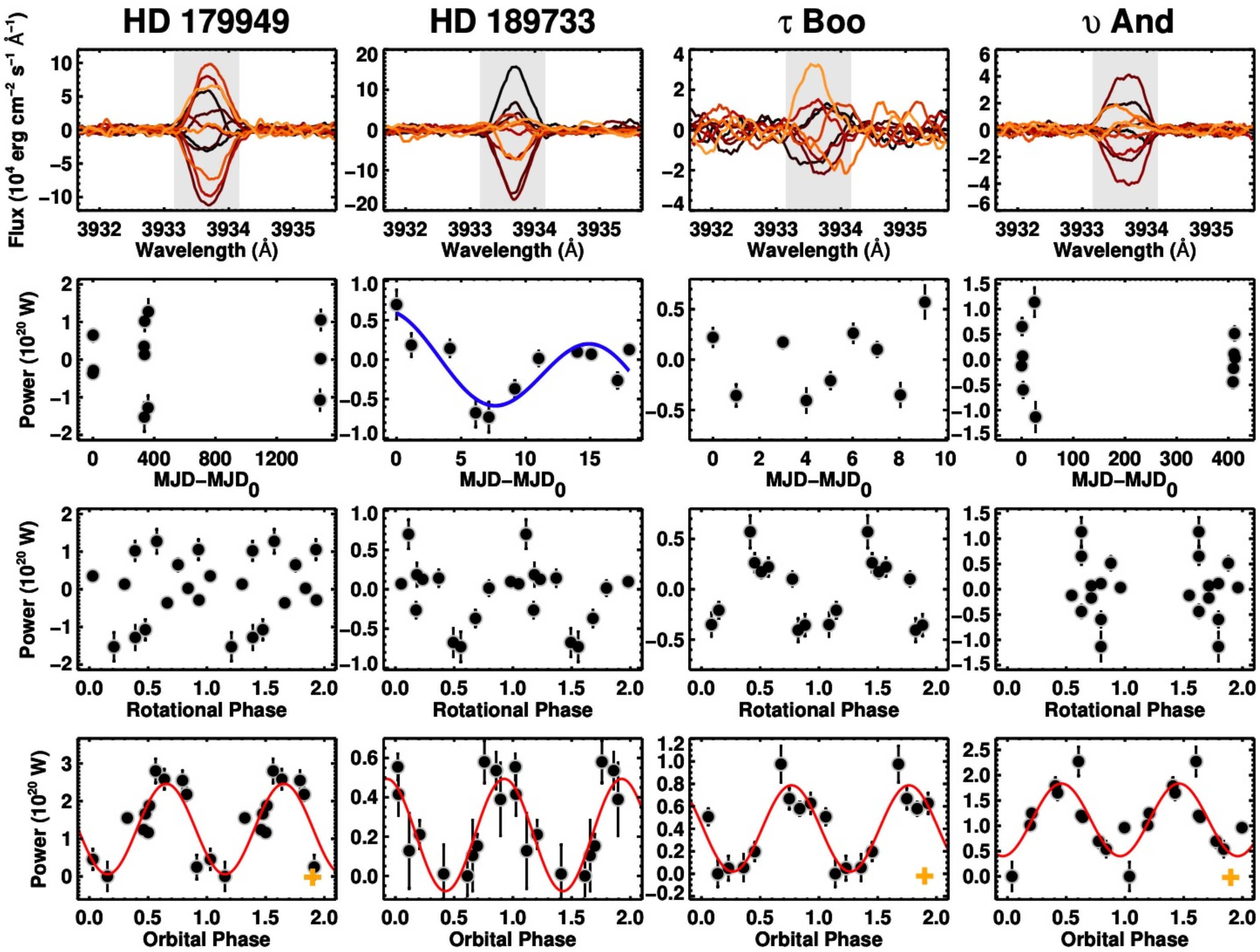
Cauley et al 2019

SPI detection

Assuming some models of interactions

↓

B(Planet) varies between 20 to 120 G



Cauley et al 2019

To conlcude

- SPI has an ON/OFF nature

- SPI activity enhencement is still controversial

- Well sampled observational campaigns are needed

- If well designed, a campaingn could:

    - Favour one model of interactions (see Ekatrina’s talk)
    - Measure the planetary magnetic field
    - Interpret planetary emissions
    - Predict best observing times for SPI