LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

Exoplanet characterization: dealing with stellar activity

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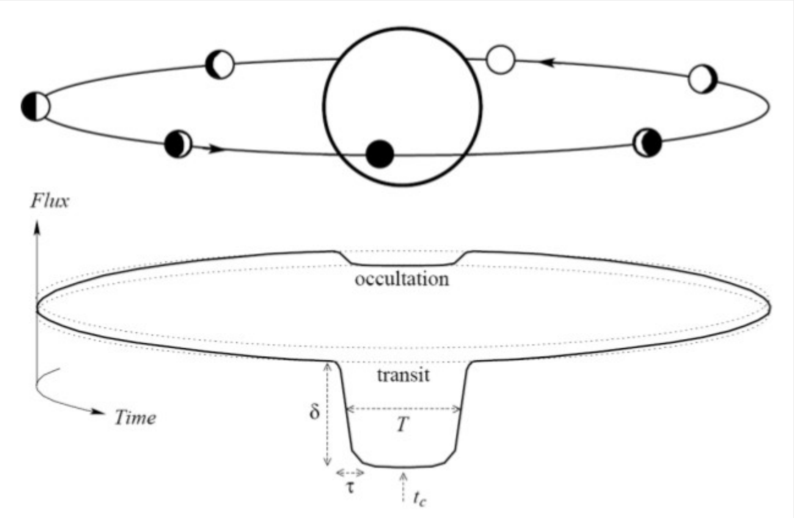
(Courtesy Stephen Kane)

Outline

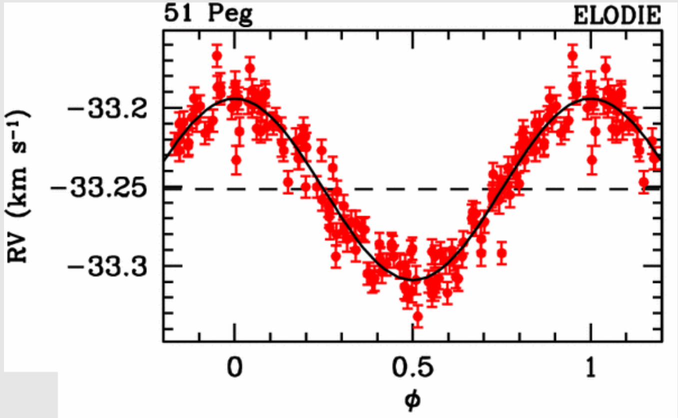
- Exoplanet detection methods
- Modeling the internal structure
- Stellar activty
- Our study on COROT-2
- Conclusions

DETECTION METHODS

Transits and radial velocities



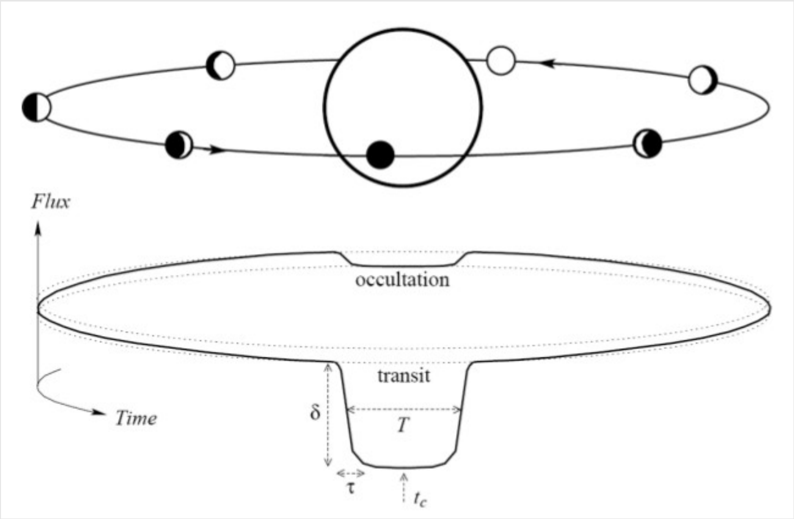
$$\frac{\Delta F}{F} = 8.41 \cdot 10^{-5} \left(\frac{r_p}{R_\oplus}\right)^2 \left(\frac{R_\star}{R_\odot}\right)^{-2}$$



$$K = \frac{8.95\,\mathrm{cm\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_\oplus} \left(\frac{M_\star + m_p}{M_\odot}\right)^{-2/3} \left(\frac{P}{\mathrm{yr}}\right)^{-1/3}$$

Mayor & Queloz (1995)

Transits and radial velocities



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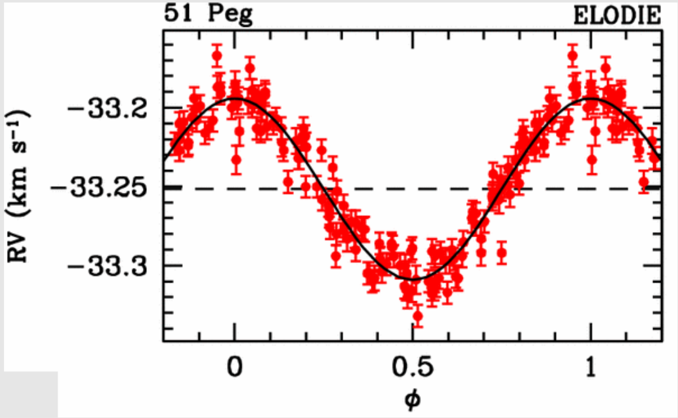

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Mayor & Queloz (1995)

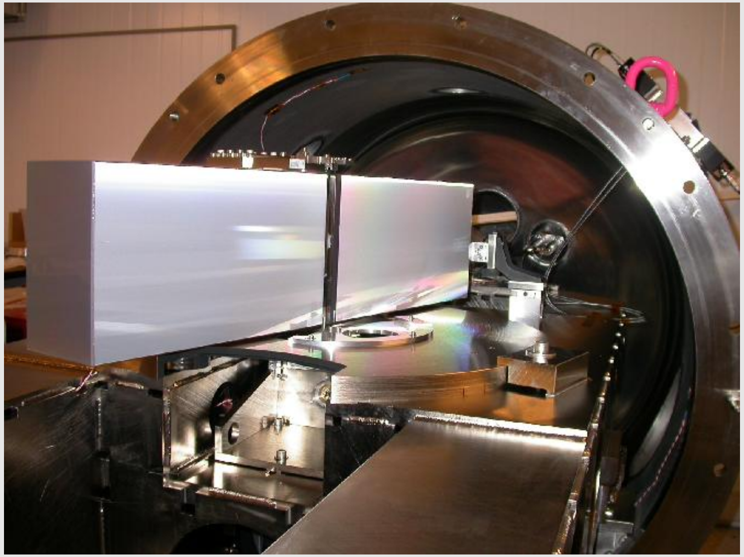
Transits

Ground: SuperWASP, HATNet
Space: CoRoT, Kepler, MOST
Future: TESS, CHEOPS, PLATO

- Architecture of planetary systems (mostly < 0.1 AU)
- Large eccentricities
- Multi-planetary systems and transit timing variations
- Planet occurrence (also in the habitable zone)
- Phase curves for planet atmospheres

Radial velocities

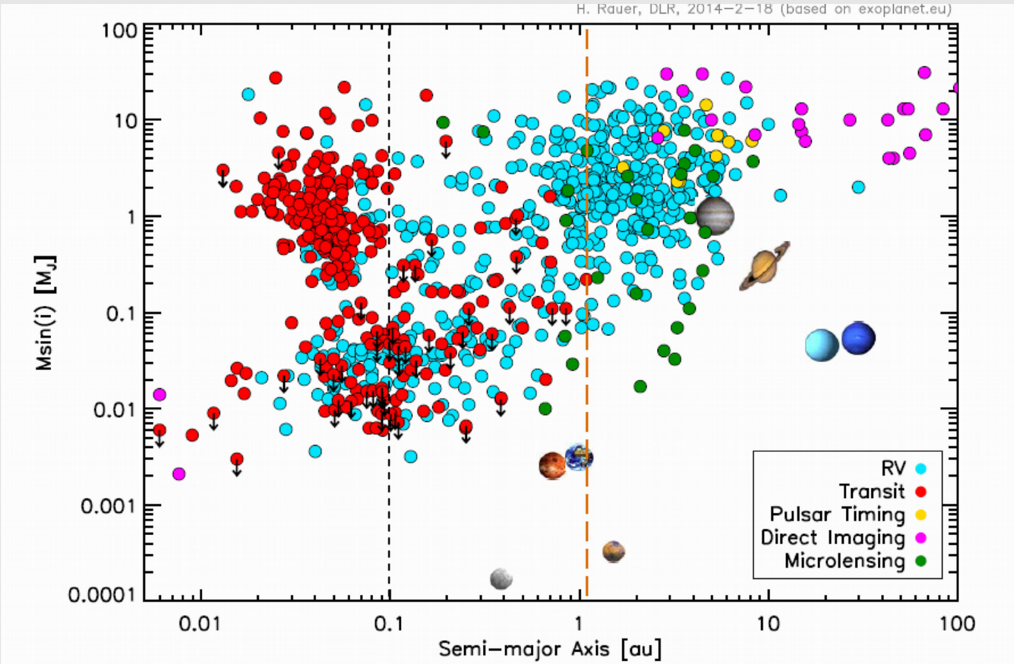
- First planet around a main-sequence star (Mayor and Queloz 1995)
- a > 0.1 AU as well
- Planets around M and giant stars
- Multi-planetary systems
- Coupling with transits:
    - Validation
    - Mass (solved for sini modulation)
    - Spin-orbit geometry
- Yields stellar spectrum



Future:

- Improving precision
- NIR spectroscopy (M dwarfs)

Exploring the "exoplanet zoo"



Rowe et al. (2014)

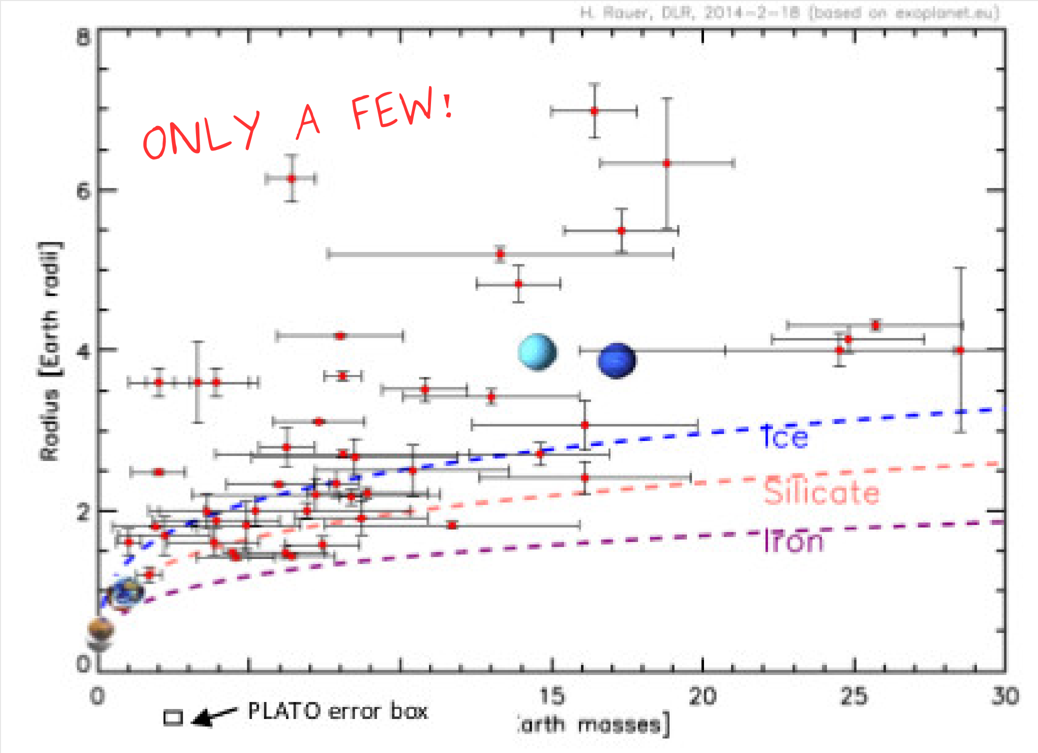
About 2000 planets confirmed

- Jupiter-sized
- Mini-Neptunes
- Super-Earths
- Terrestrial planets

Main hosts: FGKM stars

Different techniques, different parts of the pars. space

Internal structure

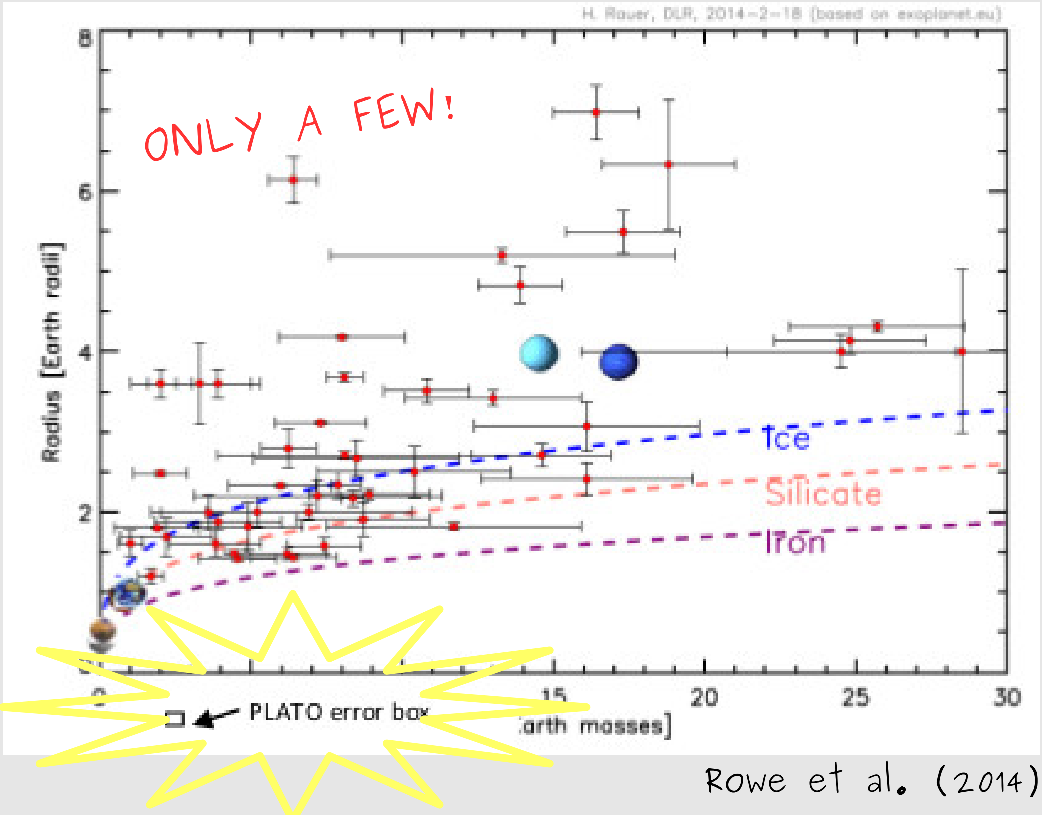


Rowe et al. (2014)

Needed ~ 1% precision on planet radius for bulk modeling (Wagner et al. 2011)

- Current precision: $\sigma_M \sim 20\%$, $\sigma_R \sim 6\%$ → $\sigma_\rho \sim 30-50\%$
- Expected for future: $\sigma_M \sim 10\%$, $\sigma_R \sim 2\%$ (PLATO)

Internal structure



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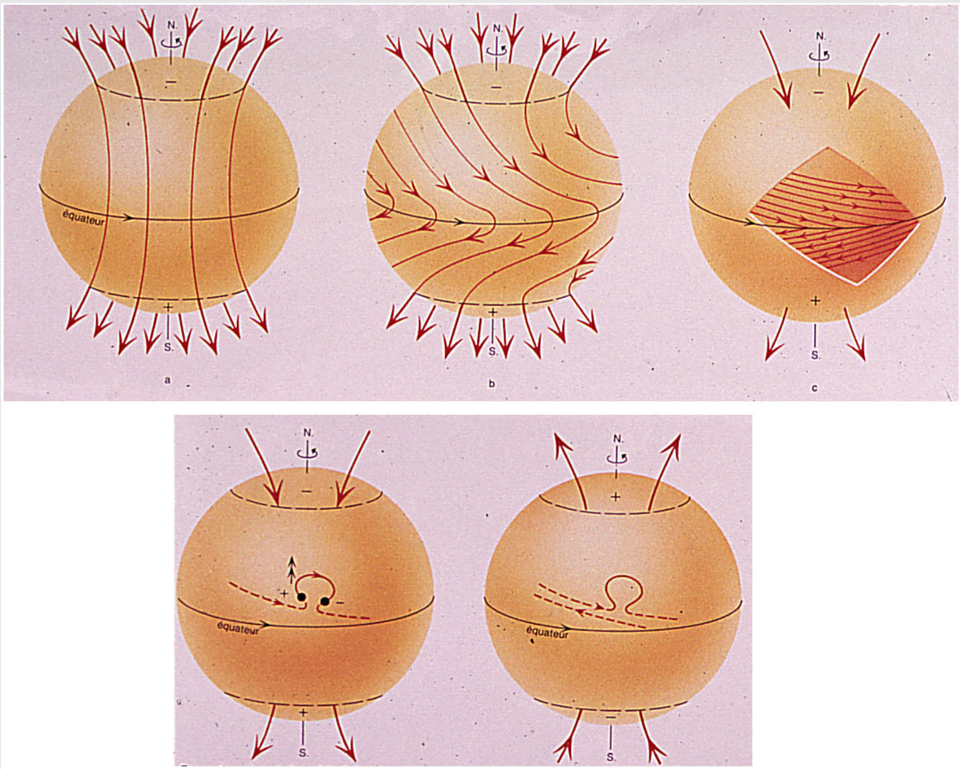
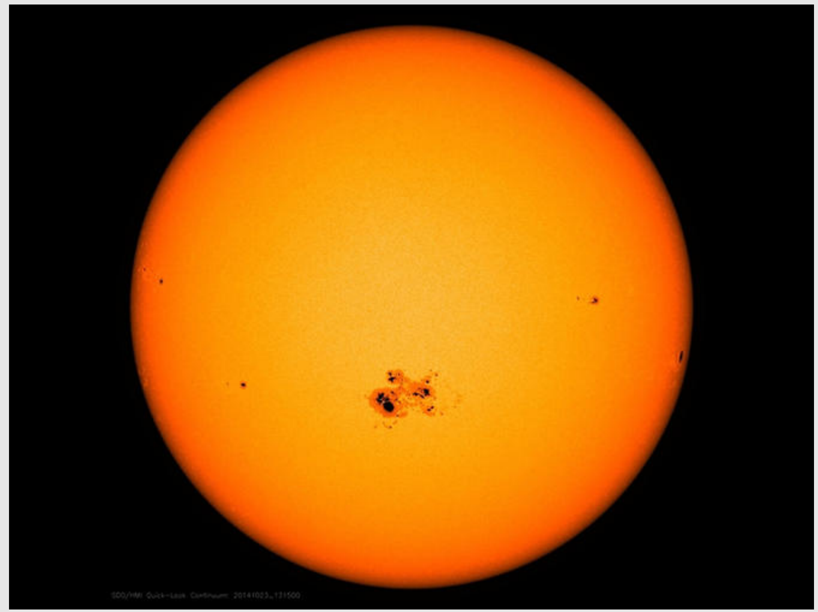
STELLAR ACTIVITY

Stellar magnetic activity

Stellar dynamo



Starspots & faculae

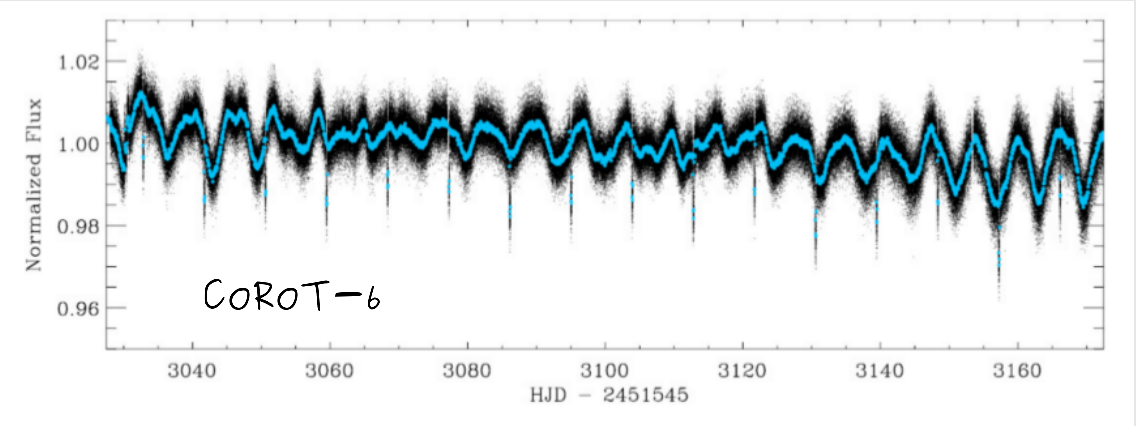


Out-of-transit starspots

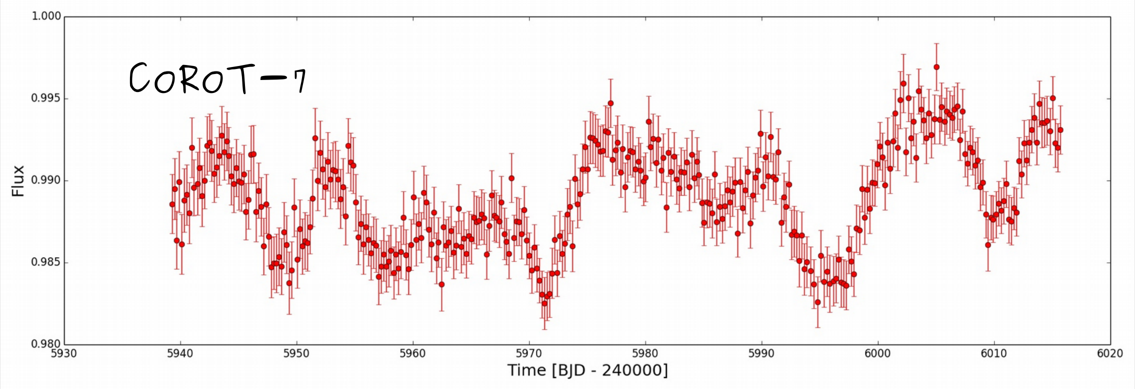
OK

- Some % brightness variations
- Allow to measure stellar period and differential rotation

→ Age indicator



Fridund et al. (2010)



Out-of-transit starspots

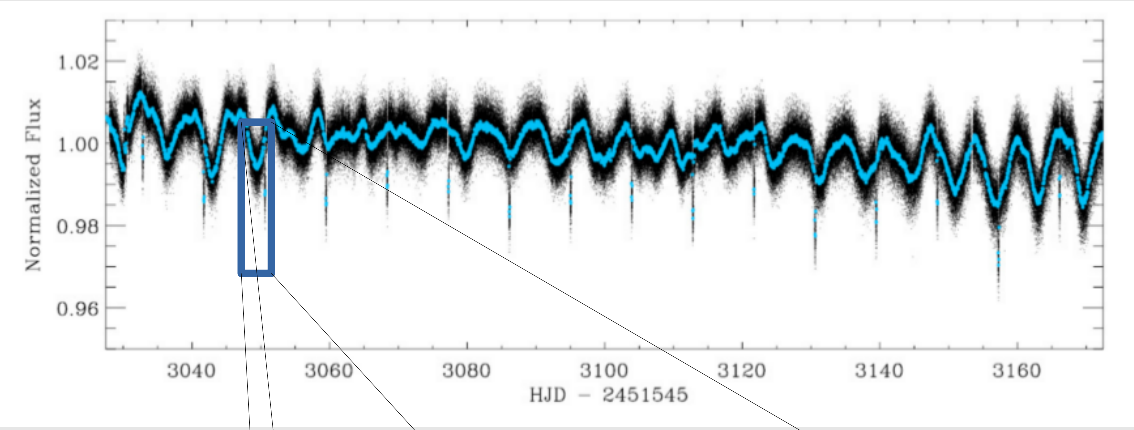
OK

- Some % brightness variations
- Allow to measure stellar period and differential rotation

→ Age indicator

KO

- Induce overestimates of the transit depth (Czesla et al. 2009)



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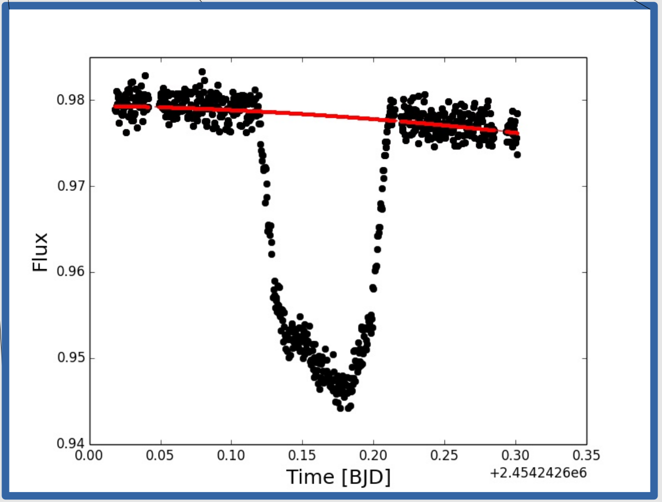
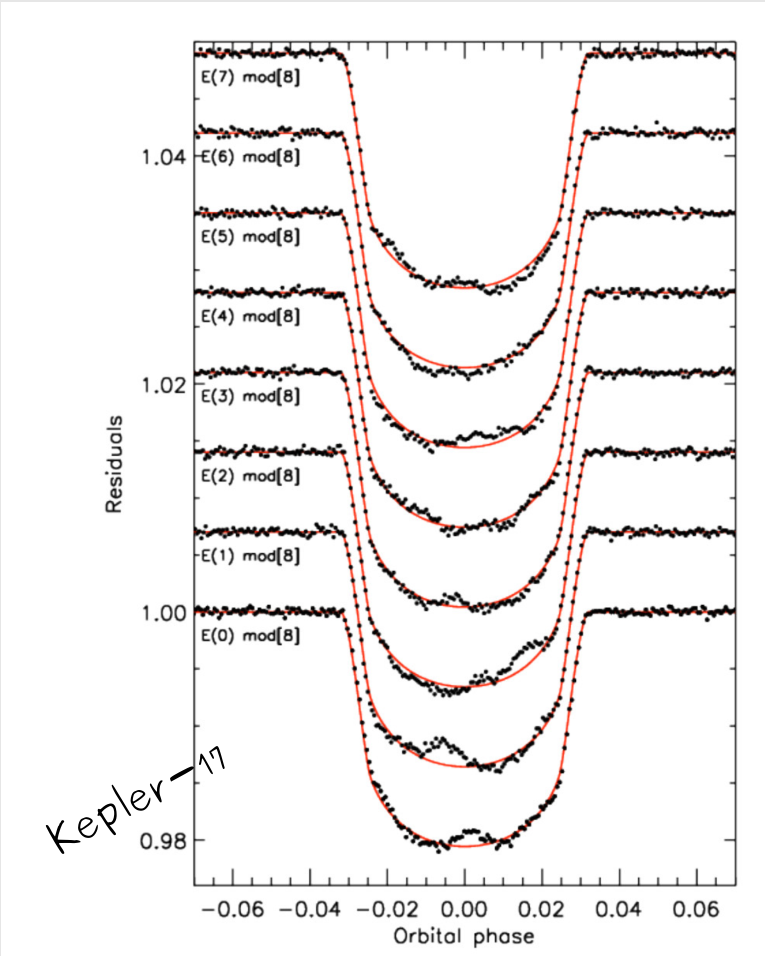


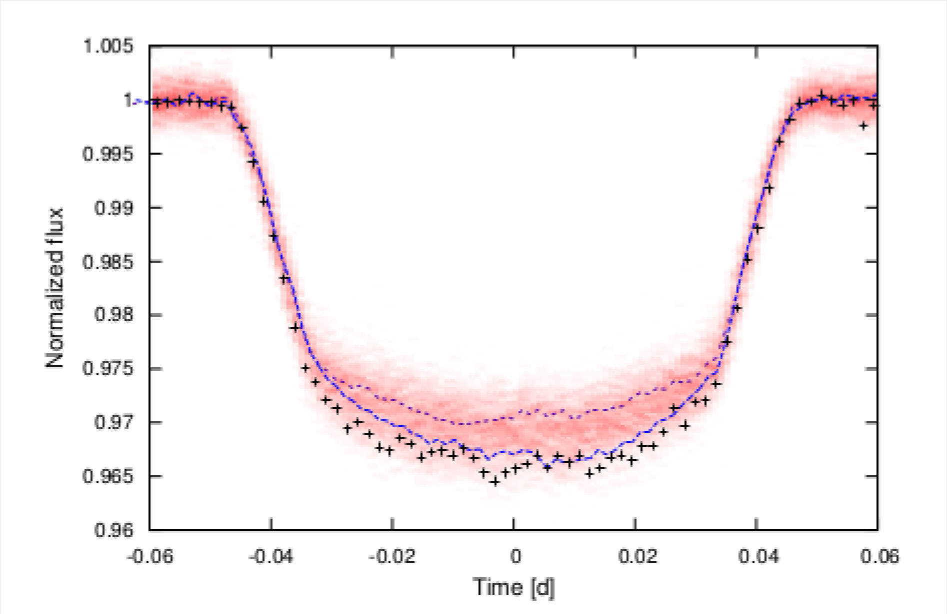
In-transit starspots



Desert et al. (2011)

- Distort the transit profile (e.g. Desert et al. 2011), affect the measure of:
  - Transit depth (Czesla et al. 2009)
  - Stellar density (Léger et al. 2008)
  - Limb darkening coefficients (Csizmadia et al 2013)
  - Orbital period (Barros et al. 2013)

In-transit starspots



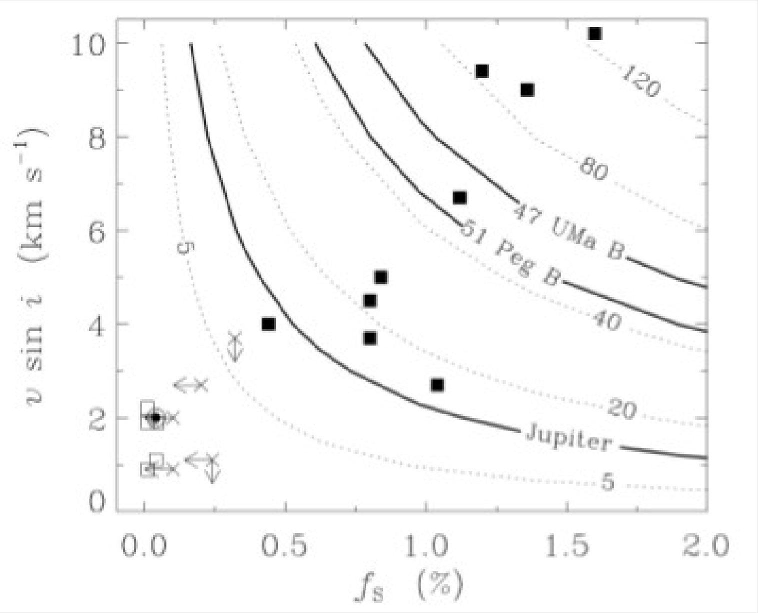
Czesla et al. (2009)

- Distort the transit profile (e.g. Desert et al. 2011), affect the measure of:
  Transit depth (Czesla et al. 2009)

- Lowest envelope: least affected one?

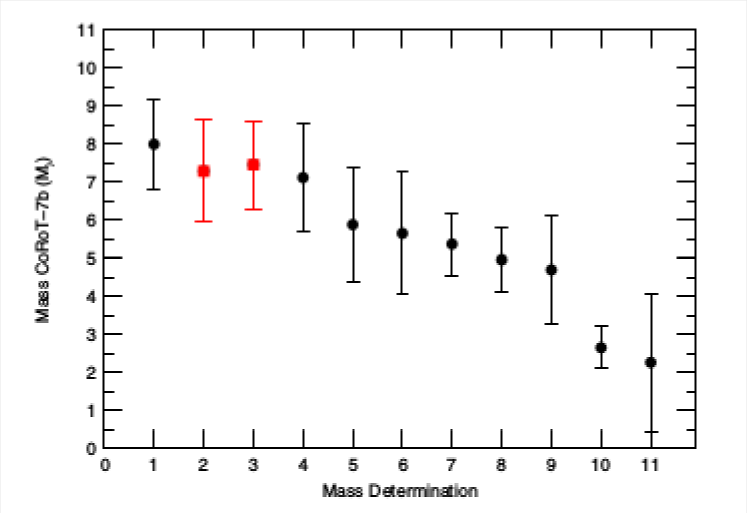
Starspots in RVs

- Produce time-varying jitter
- Measured orbital parameters affected
- Planet features can be mimicked (Desort et al. 2007)



Saar & Donahue (1997)

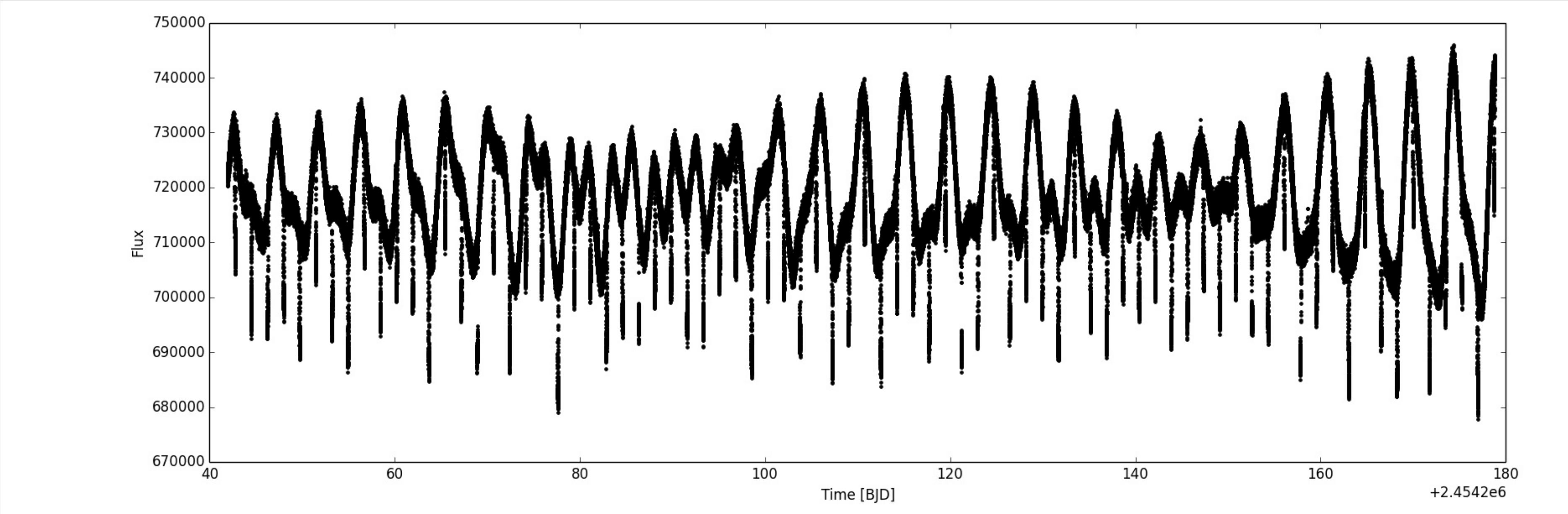
- Diagnostics can reveal false positives (e.g. Queloz et al. 2001)
- Need to observe RV stars for transit follow-up



Hatzes et al. (2010)

OUR STUDY ON CoRoT-2

CoRoT-2



- Active, young (Alonso et al. 2008)
- Long-duration light curve
- Spots both outside and inside transits
- Hosts a Hot Jupiter (1.47 R_J, $P_* \sim 3\ P_{orb}$)

Our study

What?

Simultaneous spot-transit fitting in the light curve

Why?

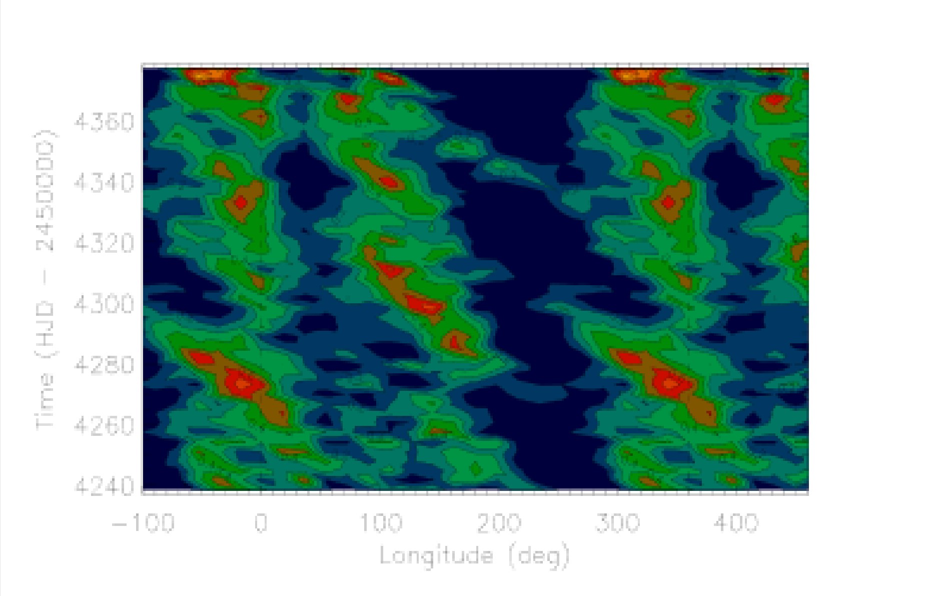
Correction for activity, more consistent transit parameters

Why AGAIN?

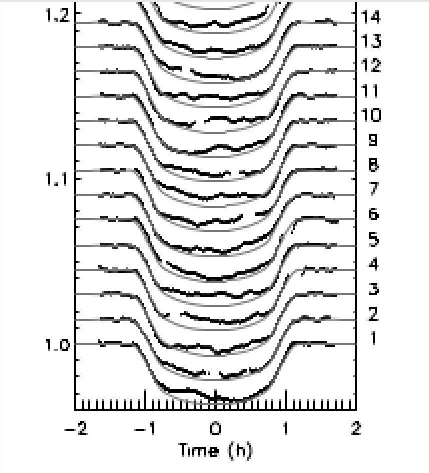
No current approach is complete

Previous attempts

Lanza et al. (2009): out-of-transit brightness distribution



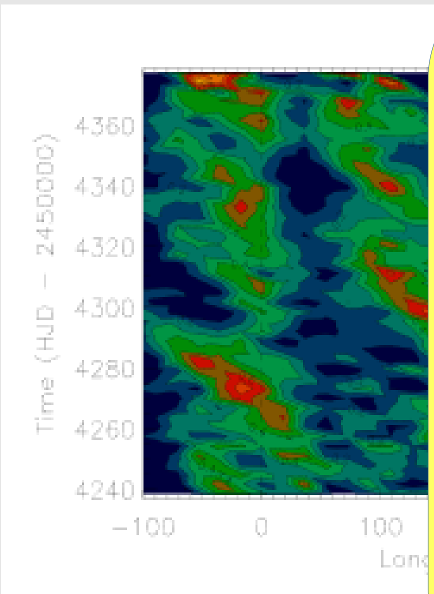
Silva-Valio et al. (2010): spots inside all transits



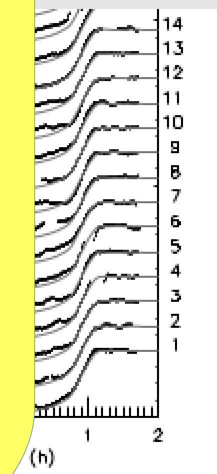
- Huber et al. (2010): surface model of ~30 strips: also transits, no evolution

Previous attempts

Lanza et al. (2009): out-of-transit brightness distributio



. (2010): spots



What we add:

- Simultaneous spot-transit fit
- Spot evolution
- Fit of longer segments of light curve

- Huber et

model of ~30 strips: also transits, no evolution

Method

Starspot models

- Numerical (computation of a grid and numerical integration)
- Analytical (much faster to execute, but need assumptions)

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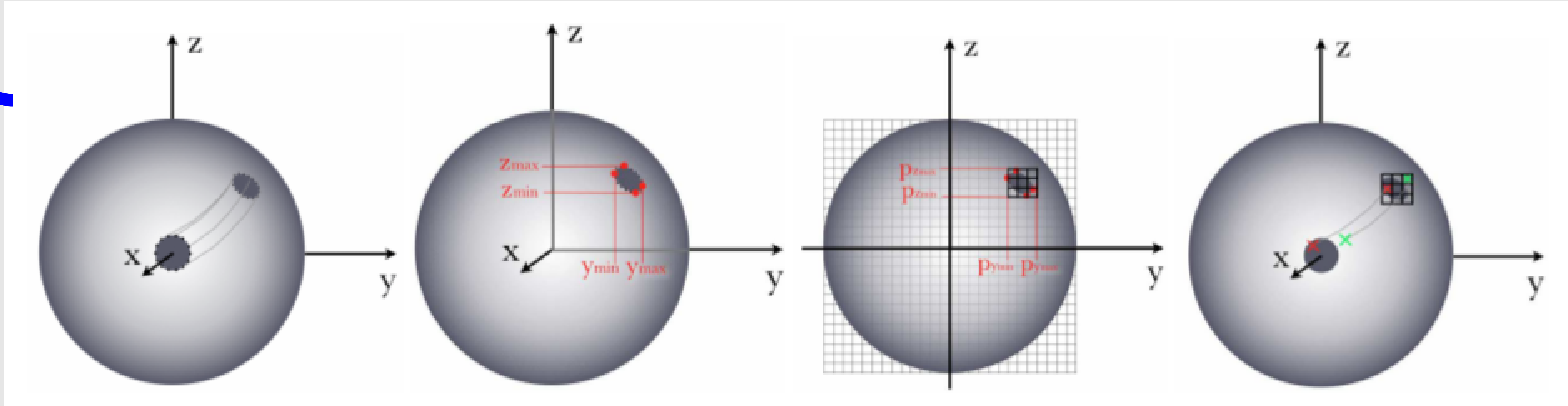

Boisse et al. (2012)

Method

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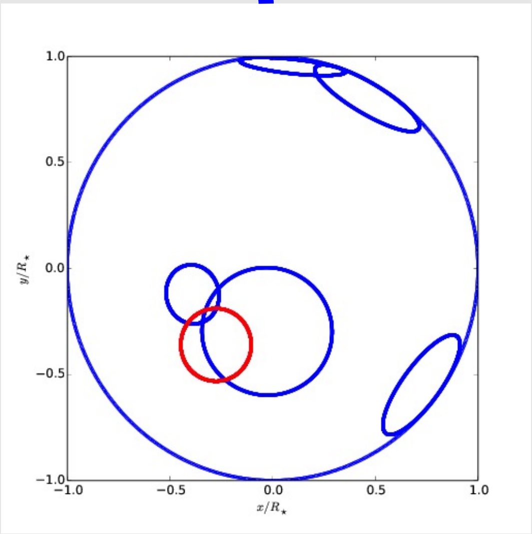

Montalto et al. (2014)

Transits modeling

+

Longitude, latitude, size, constrast for each spot

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Method

Starspot models
- ~~Numerical (computation of a grid and numerical integration)~~
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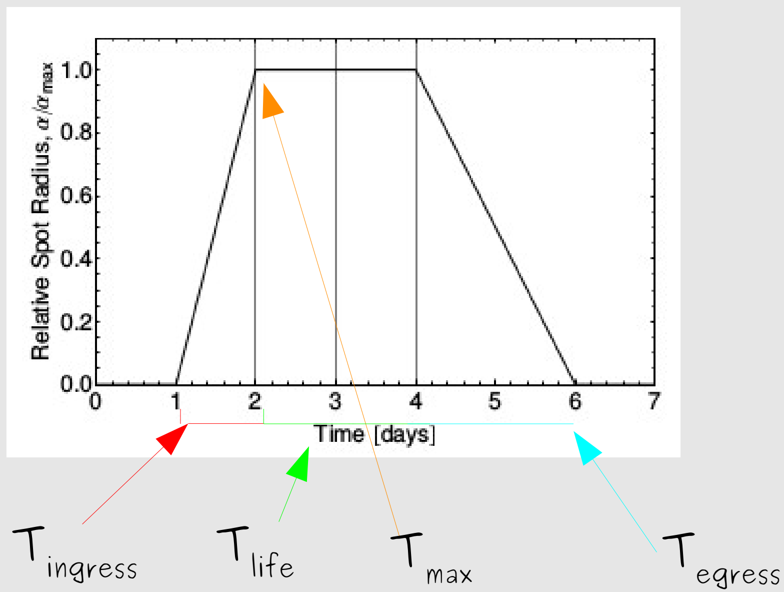
Added linear spot evolution (Kipping 2012)



Method

Starspot models

- Numerical (computation of a grid and numerical integration)
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Fitting method

- χ^2 minimization
- maximum entropy regularization
- MCMC

Ill-posed problem

Method

Starspot models

- ~~Numerical (computation of a grid and numerical integration)~~
- Analytical (much faster to execute, but need assumptions)

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Fitting method

- χ^2 minimization
- maximum entropy regularization
- MCMC

Ill-posed problem

Strategy

With spot modeling

Fit in two steps

1) **Fit spots**

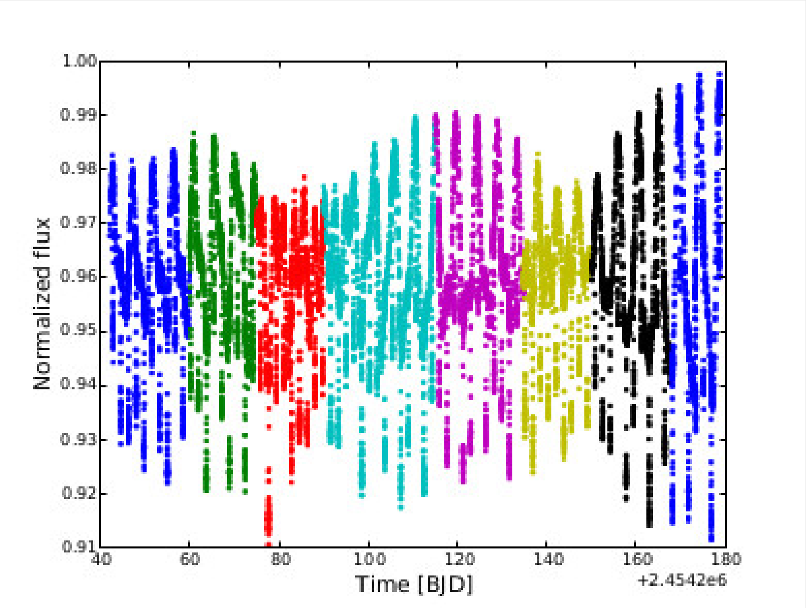
Fixed transit pars.

2) **Fit transits, adjust spots**

Adjust λ, α for spots,

fit transit pars.

+ Standard transit fit using model 1



About the activity cycle

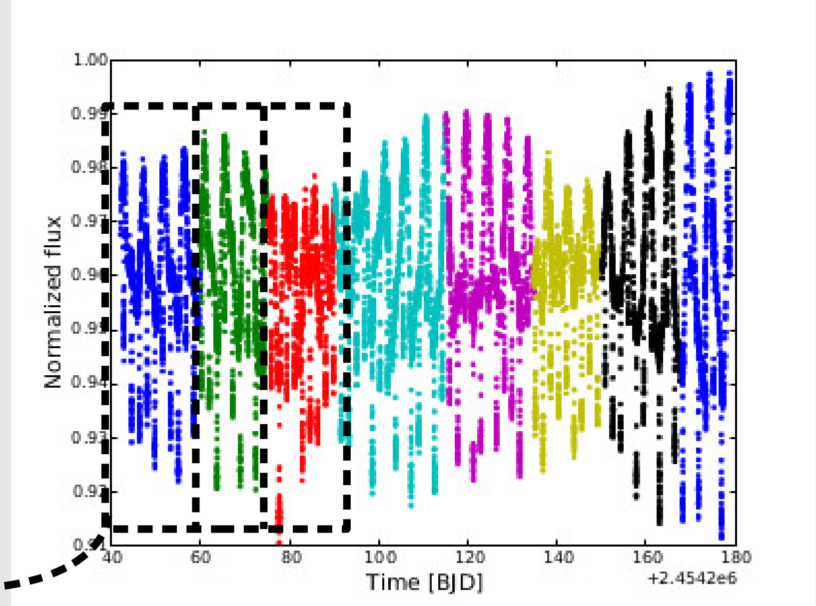
Classic transit fit

All transits folded and fitted at once

With spot modeling

Too many spots needed: light curve cut in segments

15–25 days-length, ~ lifetime of active regions, Lanza et al. (2009)

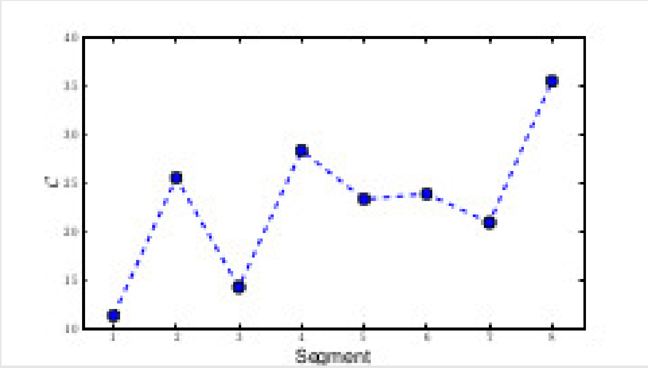


Results: spot parameters

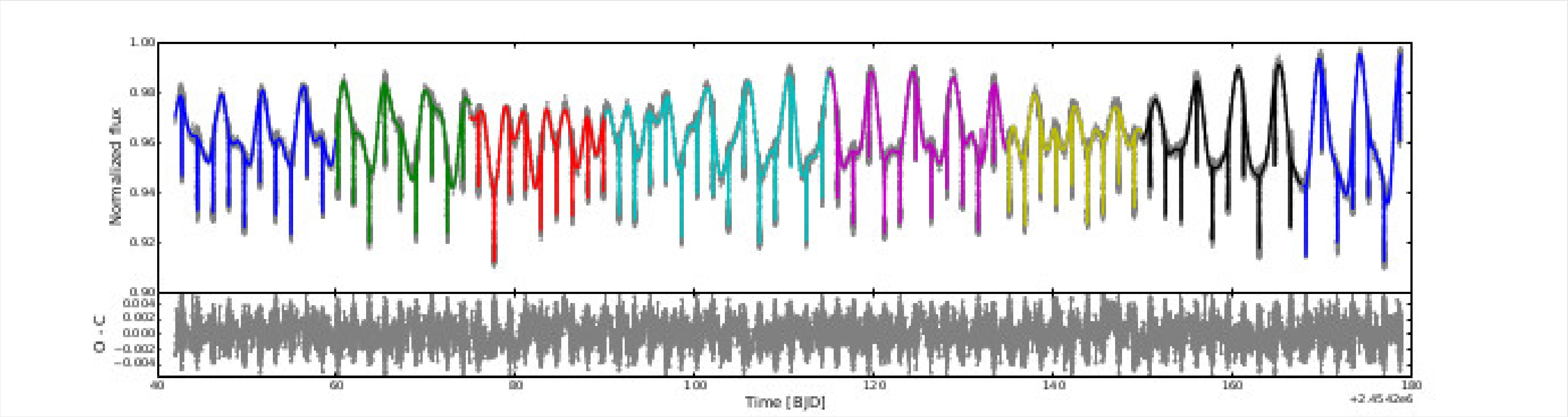
6 to 9 spots/segment required
5–30 deg. size

Hints of longitudinal migration

Average 1–2 faculae per segment
1–2 features constantly in the transited belt



$$\mathcal{C} = \sum_i \alpha_{\max,i}(1 - c_i)$$

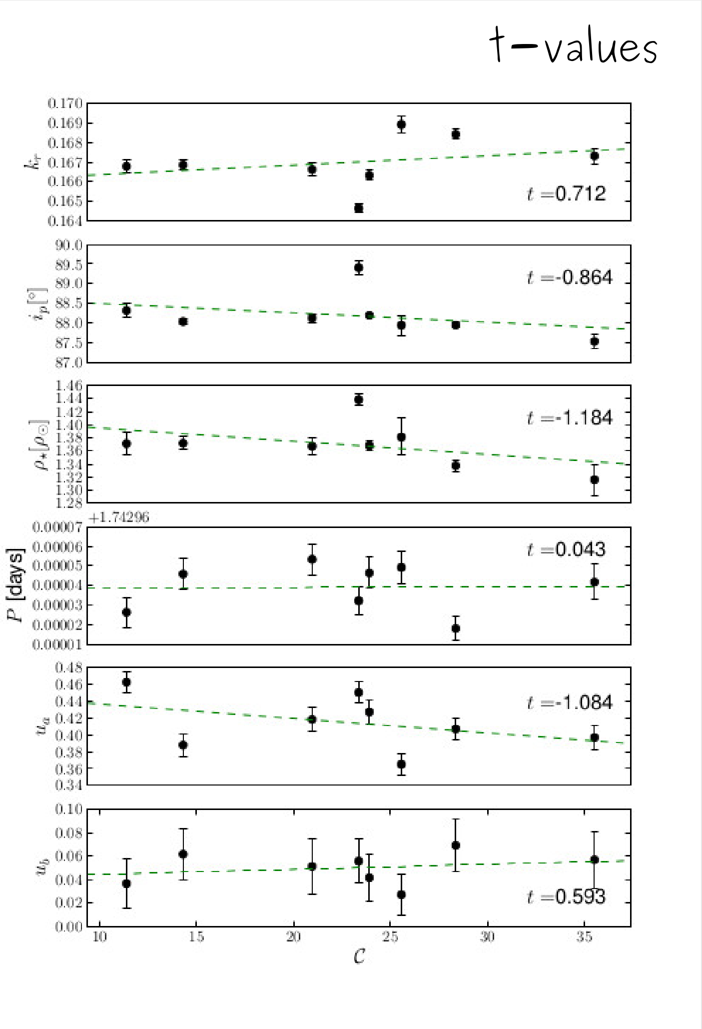


Results: transit parameters

- Transit depth, incl.: Non-significant correlations
- Stellar density, LD: needed improvements
- Period: not affected by spots

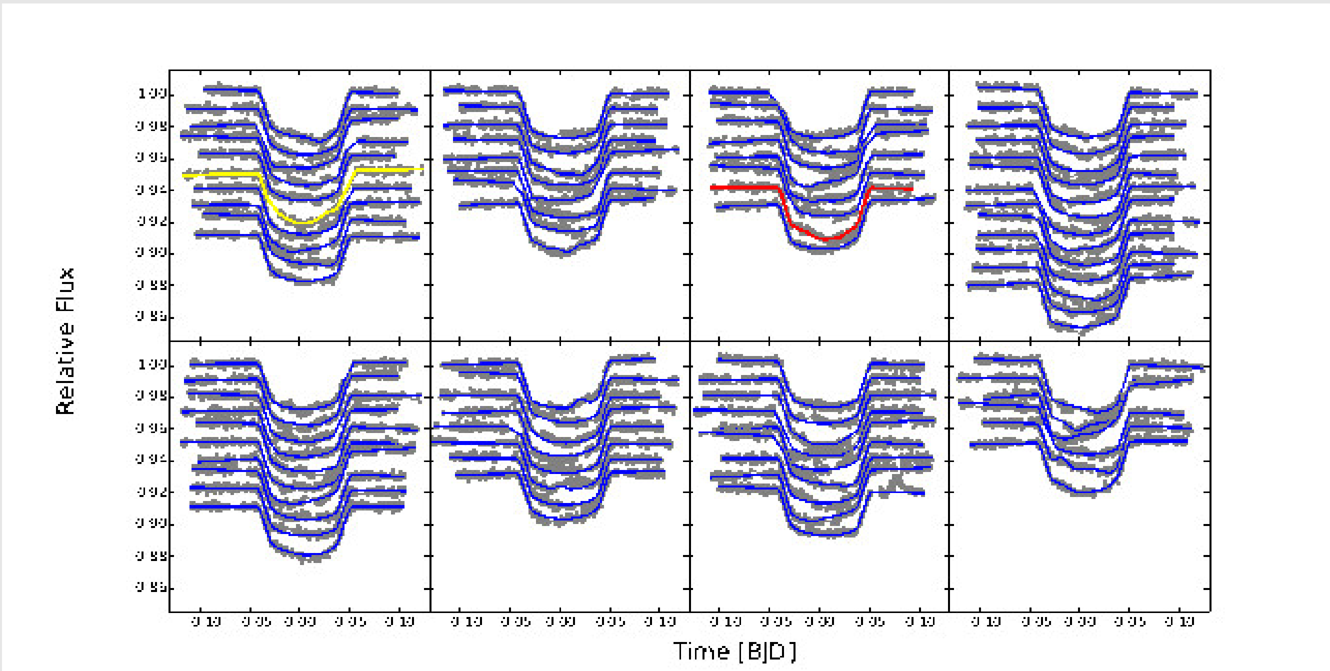
Possible improvement

- Automatic fit no. of spots



Least distorted transit

- Czesla et al. (2009): <u>average</u> of deepest transits less affected. Transit depth >3% than Alonso et al. (2009)
- On <u>single</u> deepest transit, result in agreement

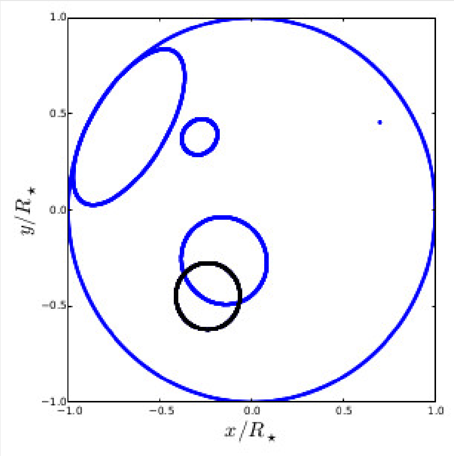


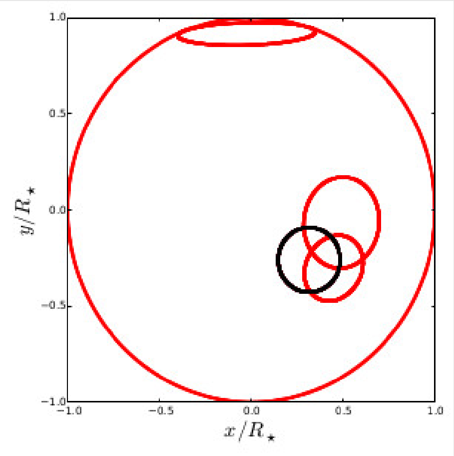
Least distorted transit

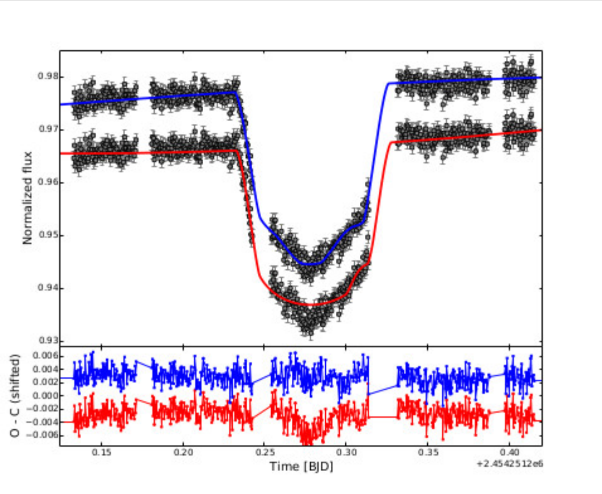
- Czesla et al. (2009): average of deepest transits less affected. Transit depth >3% than Alonso et al. (2009)

From our fit:

1) On single deepest transit, result in agreement
2) Deepest with only dark spots? Worse fit (Bayes factor 2%)







CONCLUSIONS

Conclusions

- Analytic evolving spot modeling + transit features + MCMC fit
- More consistent transit parameters,
  explored correlations spots–transit parameters
- Required presence of faculae

Future developments

- Refine spot modeling
- Explore more efficient MCMC algorithms
- Test on synthetic data and other real cases