Recent advances in spot modelling

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Outline

- Objective of spot modelling
- Challenges
- Main approaches & general properties
- Recent advances
- How to lift degeneracies?
- Conclusion

- Focus on out-of-transit modelling

Objective of spot modelling (ideally)

- Spot properties
  - Rotation rates
  - $\Delta\Omega$
  - Activity cycle
  - Longitude, latitude
  - Lifetimes
  - Size, contrast

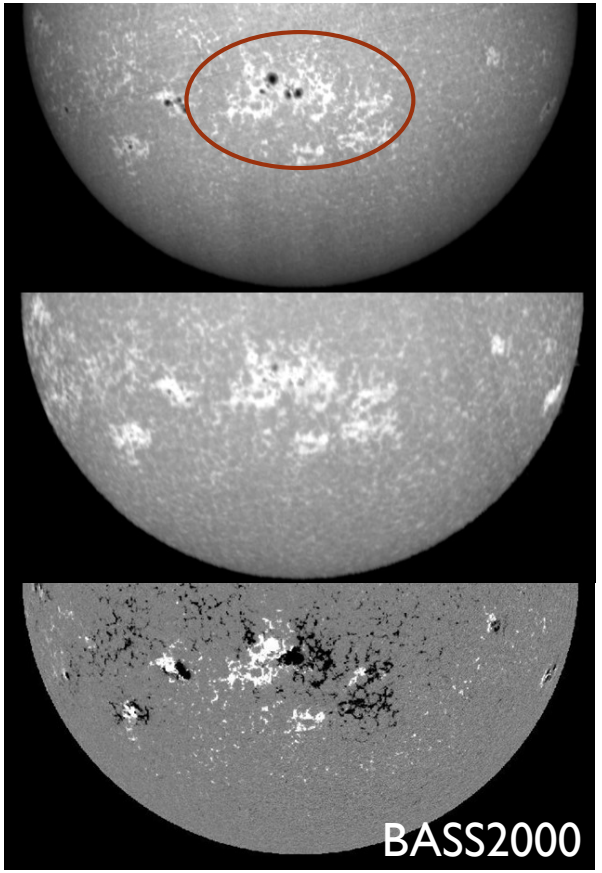
With pdf functions

Do this for different spectral types / ages

- Plages
  - Degeneracies -> Plage/spot ratio
  - Informations on plages properties

Challenges

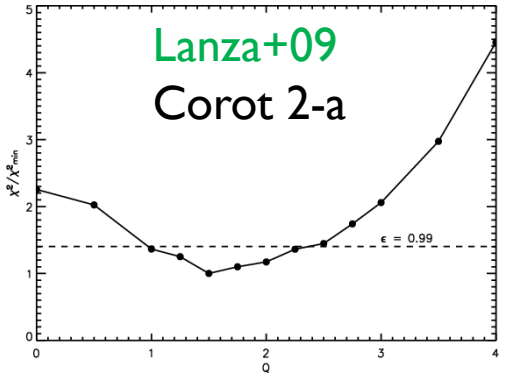
- Residual between spots and plages
  - True for other observables (polarimetry, RV)
- Main degeneracies
  - Spot - plage coverage
  - Size - contrast (spot & plage)
  - Small/large spots
  - Latitude - stellar inclination
  - Unspotted level / activity coverage
- Other issues
  - Structure evolution / finite lifetime
  - Instrumental long-term trends / offsets / normalizations (spot-plage regime)

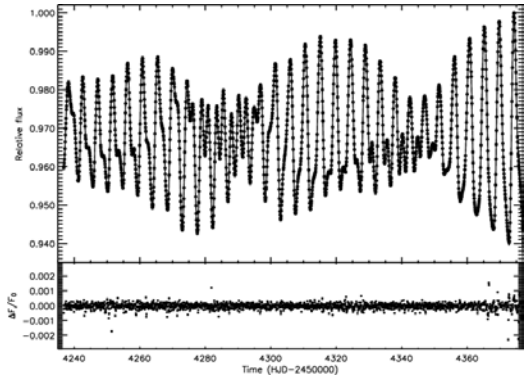


1/ Spot models

Direct information on spots (plages)

- Fit N spots
  - Different N Values
    - Large N, ex Mosser+09 = many short-lifetime spots
    - Small N, ex. Walkowicz+13
  - Tools including spot (linear) evolution (Kipping12, Wilson12)
  - Usually analytic
  - Impact of morphology on parameters determination Walkowicz+13
- 3-spot model + plages
  - Lanza+03 (used in Lanza+07,09,09b,10,11,12…)
  - Useful to determine Q=plage/spot ratio
  - Numerical approach
  - Multi-λ possibilities (Lanza+04)

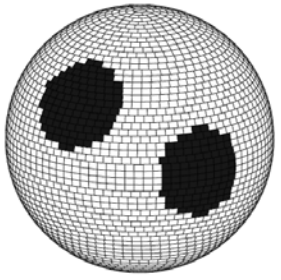


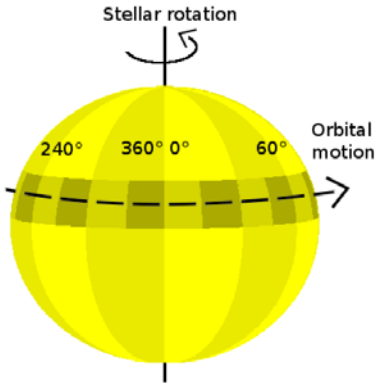


2/ Maps

Indirect - filling factors

- Pixel maps → spot & plage coverage
  - Need regularization (100s parameters)
    - Bias towards a certain size distribution
  - Lanza+98,02
    - Used in many papers (Lanza+06,07,09,09b,10,11,12,19)
    - Q fixed from 3-spot modelling
    - More efficient than 3-spot model in the solar case
  - Harmon&Crews00 (LI)
    - Roettenbacher+11
- Longitudinal strips
  - Huber+09,10
    - No regularization (less parameters)
    - N chosen to get minimum χ2, reconstruction with different starting points





General properties

- Strong assumptions needed
  - Contrast are fixed (dependent on μ for plages)
  - Center to limb darkening fixed (sensitive: Kipping12)
  - Reference level S0 (no activity) unknown: assumption necessary
  - Degeneracy / inclination: helps if input
  - Fixed parameters → impact a posteriori pdf

- Computationnal issues
  - Need to search for Q
  - Manual adjustment of subset size to each target
  - Stability problems, iterations on fits
  - Time consuming
  - Different minimisation schemes (including Bayesian minimisation: Croll+06, Froehlich+12, Lanza+14)
  - Bayesian criterion to determine N: too much information in LC (Froehlich+12)

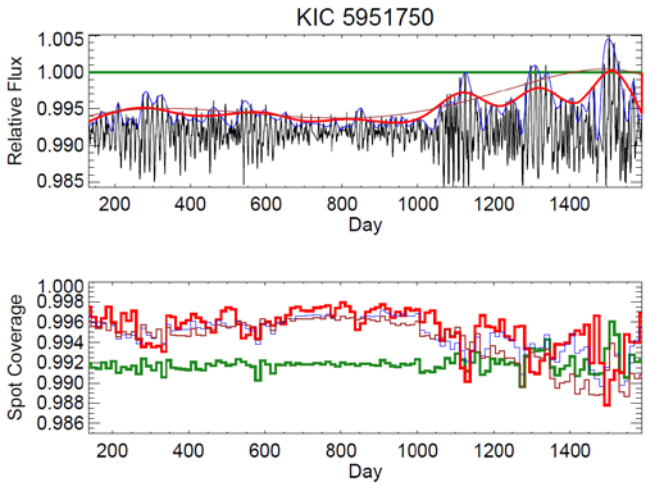
- Use of wavelength dependence: noisy
- **Claimed robust outputs: longitudinal pattern, total spotted area (but S0 effect!!!)**

Recent advances

- Not many spot modelling publications on Kepler data!
- Use of previously published methods (Lanza+19, Huber+18)
- Attempt combined modelling with other observables: simultaneous and well sampled
  - Spot modelling of RV+LC Giguere+16
  - RV included in LC fit Herrero+16 [Starsim, *public*]
  - Haywood+14 Rajpul+15, Diaz+18 RV+LC with GPs
- Main advances
    - Minimization techniques / more developments bayesian approaches
    - Attempts to fit evolution + contrasts take
  - Few publications
    - Zhan+19 based on Gunther&Daylan 8 spots, contrast AND size are fitted, nested sampling [allesfitter, *public*]
    - Luo+19, bipartite regularization on LI / contrast
    - Bruno+16 (out and in transit), structure evolution / longer subsets (MCMC / Ksint Montalto+14 [*public*])
    - Prvak, used in Reindl+19, genetic algorithm, spot only

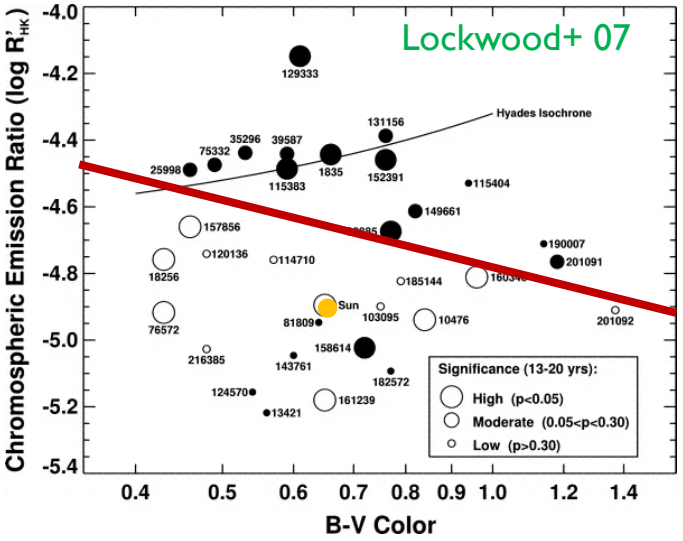
Unspotted reference level: Basri+18

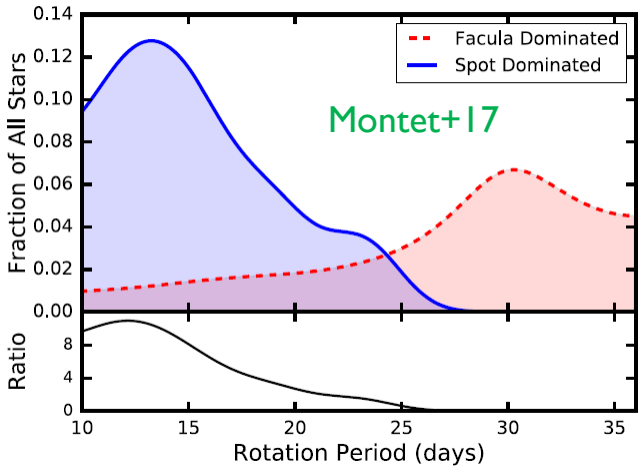
- Change in amplitude: spot coverage & evolution, spot distribution (ΔΩ)
  - + Impact plages
  - + Impact inclination (persistent spottedness, ampl.)
- If all quarters are normalized to same median: removal of variability at these scale (faculae)
- No good solution to estimate the unspotted reference level
  - Flat: better if dominated ΔΩ
  - Midfit: often better, worse in certain conditions
- Solar case: not bad, perhaps because of median normalization? (but seems completely wrong for quiet Sun)
- Absolute photometry: does not help because noisy (Kepler)



Long-term variability / cycle, spot/plage regime

- Spot / plage dominated regimes
  - From photometry+LogR'HK: Radick+98, Lockwood+07, Radick+18
  - From Kepler: Montet+17
    - Correlation absolute flux and rms LC
- Simulations → interpretation
  - Shapiro+14, Meunier+19
  - Strong impact of inclination (on variability, spot/plage regime)
  - Regime not always intrinsic to the star
  - + probably other factors (Witzke+18)





Need for long-term stability (trends/normalization , stitching)

Are alternative approaches useful?

- Power spectrum fits
  - Harvey+85; Karoff+12,13
  - **Information on times scales**
- Autocorrelation functions
  - On LC: Giles+17
  - On FT peaks amplitude: Arkhypov+15,16,18
  - **Information on lifetimes + stability of time series**
  - ***Different weight spot / plage?***
- Aspot from signal amplitude
  - E.g. Shibayama+13, Notsu+13, Maehara+17, Savanov+14, Howard+19
  - Need contrasts (Tspot)
  - ***Strong impact of S0, plage degeneracy, inclination, different sources of variability***
- Morphology metrics
  - Successive local minima in light curves Namekata+18 → **decay/emergence rates, lifetime**
  - Double dipping Basri&Nguyen18
  - Ingress/egress shape, visibility Walkowicz+13
  - Degree of periodocity He+15, 17, used in Mehrabi+17
  - Neglect inclination, plage effects

As a preliminary step?
Input guesses/parameters
Subset size
Selection purposes
Classification

How to lift degeneracies

Need for more theoretical/independant observations to better constrain the fits

- Constraints on spot contrasts for similar stars (obs Berdyugina 05, models Panga+19)
- Constraints on plage contrast for similar stars (models, e.g. Norris+18)
- Chromospheric emission for plages (useless if not simultaneous?)
  - Could constrain range of brightness variations due to plages?
- Other TBD

Inputs from other WPs

- Prot ($\Delta\Omega$) (guess) / WP123500
- Constraints from in-transit spot modelling (guess) / WP123600
  - Spot size, contrast distribution from a subsample
- Alternative analysis (preliminary step)
- Stellar parameters (fixed) WP122300
- Limb darkening (fixed) / WP122400
- Inclination (range of parameters)
  - Asteroseismology Gizon&Solanki 04
  - Derived from R_*, (v sin i) & Prot
- Other seismic inference?
  - Activity latitude from mode cycle dependence (e.g. Gizon&Solanki 03, Thomas+19)

Conclusion

- Assumptions and star selection necessary
- Future work will need to
  - Simulate realistic LC
  - Compare performance: model + assumptions + minimisation schemes
    - Determine stellar type, SNR regime where acceptable / selection
    - Determine which trend can be reliable (trends in biases?)
    - Determine which inputs need to be fixed & necessary precision / effect on final uncertainties
  - Improve computing time?

Need
Simulating tools (several exists + work done on input parameters)
Spot modelling tools from the community to test/compare
People willing to be involved in these tests