Stellar magnetic activity and how it can limit astrometry

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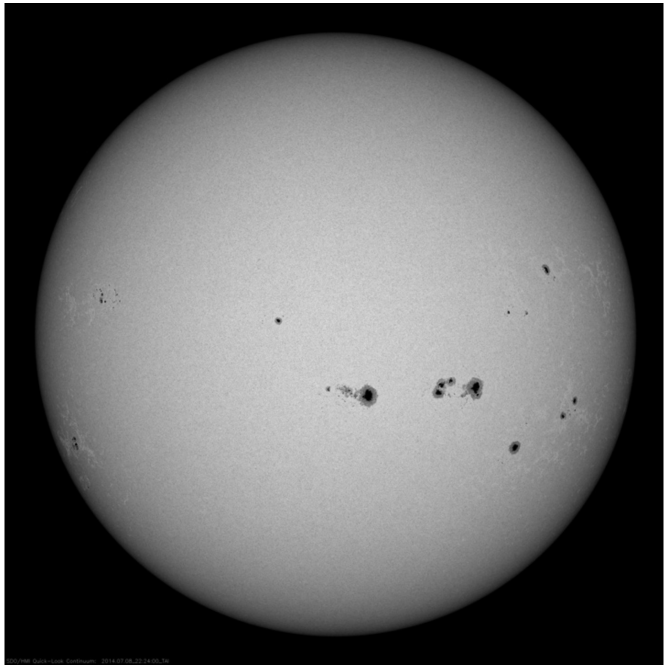
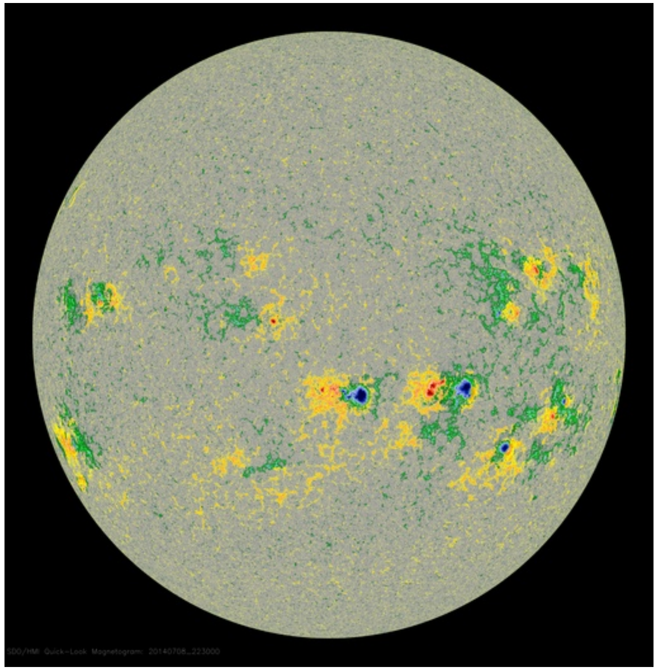
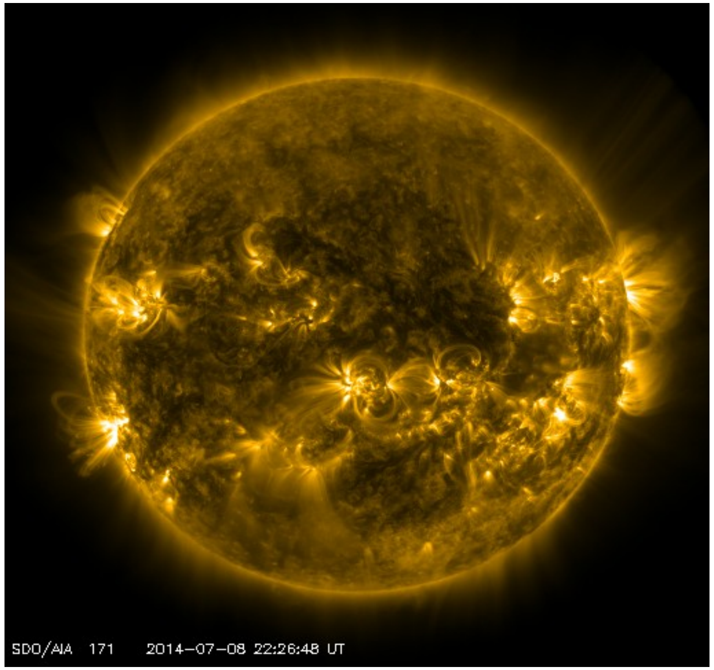
Finding Earth Twins within 10 pc – ASI Headquarters 19-20 Nov 2018

Solar magnetic activity



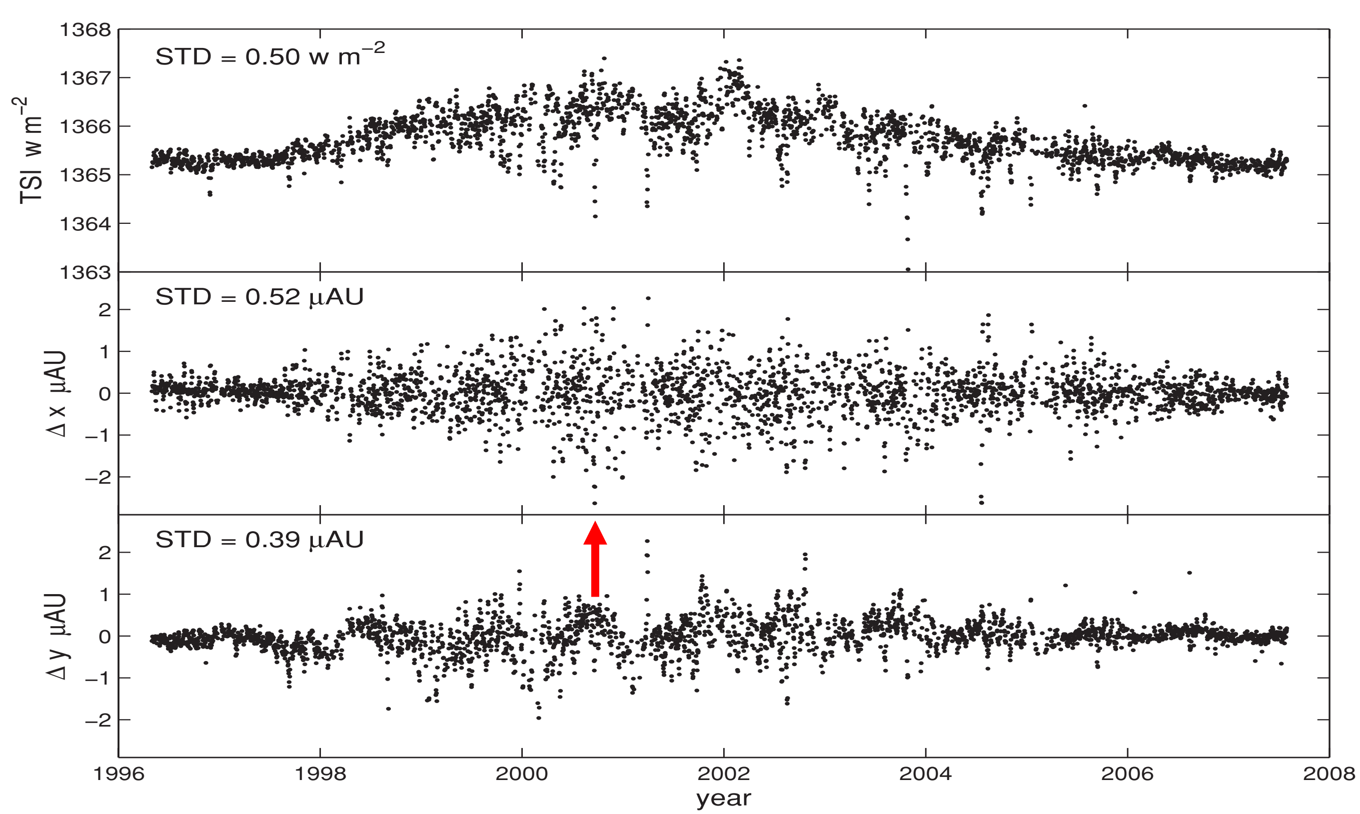


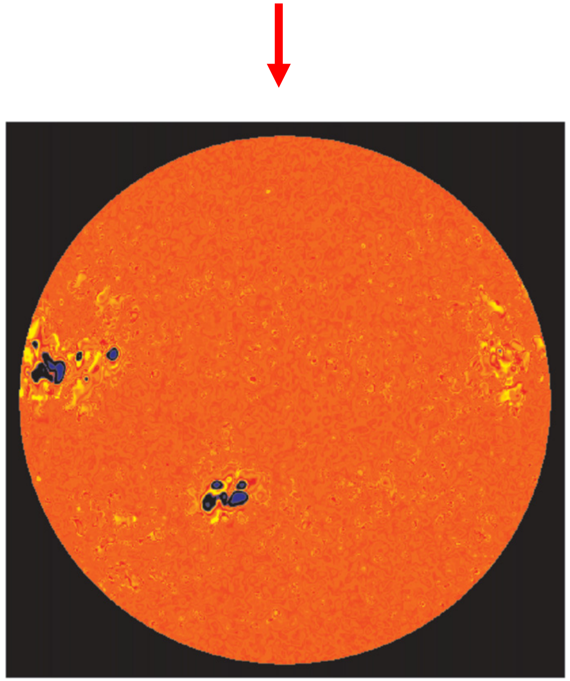


Magnetic activity and astrometry

- The brightness inhomogeneities produced by surface magnetic fields affect the position of the photocentre of the stellar disc;
- The changing pattern of active regions and stellar rotation modulate the coordinate of the photocentre on the plane of the sky;
- In addition to the position of the photocentre, the optical flux and the radial velocity of the star are affected by magnetic activity.

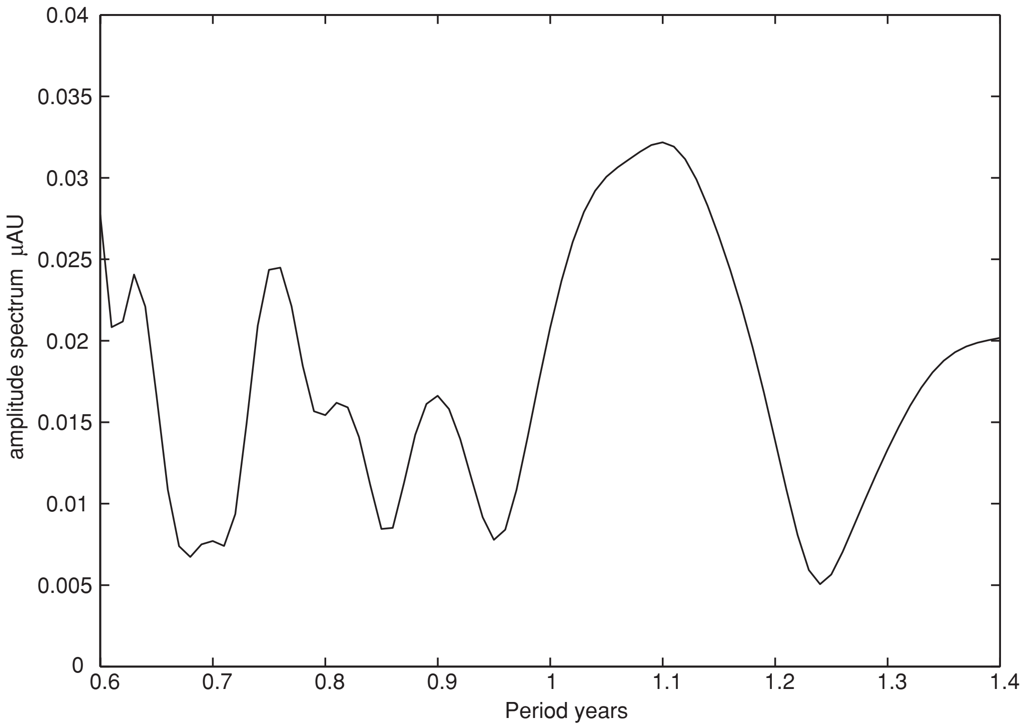
Photometric and astrometric jitter due to solar activity





Makarov et al. (2010)

Power spectrum of the astrometric jitter



Makarov et al. (2010)

Most of the power of the solar astrometric jitter is concentrated between 1.0 and 1.2 years, thus close to the period of the wobble of the Sun produced by the Earth.

Searching for the astrometric signal of an Earth-like planet around α Cen A or B

- The modulation of the photocentre of the Sun produced by the Earth has a semi-amplitude of 3.0 μAU with most of the power at the frequency of 1 yr^{-1} because of the small orbital eccentricity $e = 0.01671$;

- The activity-induced astrometric jitter has a standard deviation of ~ 0.65 μAU representing a significant source of noise in the determination of the Sun's astrometric orbit;

- The solar activity index log R'_{HK}, based on the chromospheric lines Ca II H&K, ranges between -5.0 and -4.75 (Dumusque et al. 2011), while it is -5.0 and -4.92 for α Cen A and B, respectively (from the stellar parameter compilation in Zhao et al. 2018);

- Therefore, we may expect an astrometric jitter at the level of the minimum of the solar 11-yr cycle for those two stars, that is at the level of ~ 0.17 μAU.

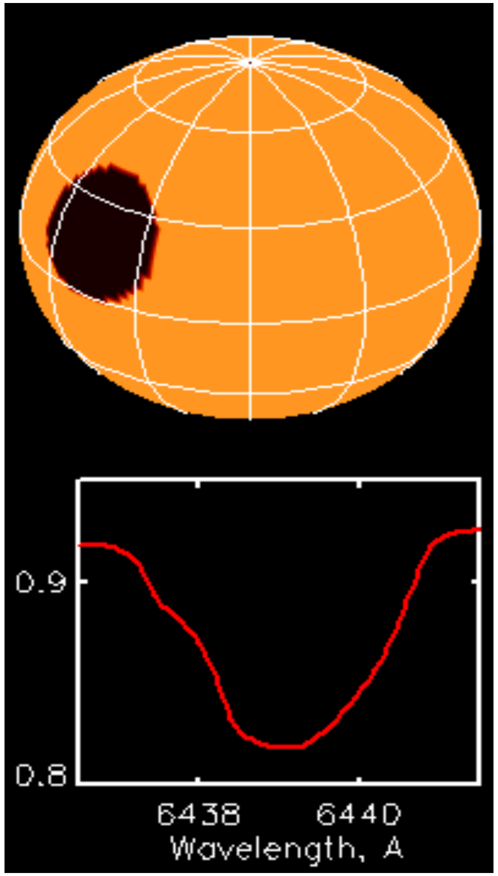
Can we correct for the activity-induced jitter ?

- Even if the expected jitter is at the level of the goal astrometric accuracy of TOLIMAN, it is not a white Gaussian noise, but it is correlated in time with most of the power at the period of an Earth-like planet;

- More active targets may show a greater jitter that needs to be corrected as much as possible;

- In principle, a correction could be based on a map of the surface brightness inhomogeneities.

Mapping brightness inhomogeneities



(animated image by S. Berdyugina)

- Doppler Imaging (e.g., Strassmeier & Rice 1998), based on high-resolution spectroscopy, is the most powerful technique to map solar-like stars;

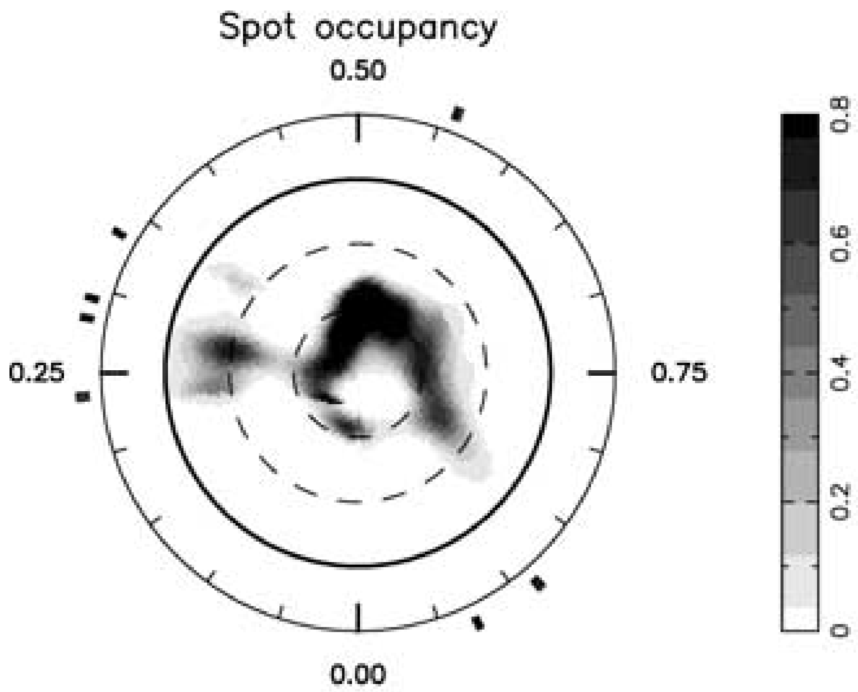
- It requires a sufficiently high projected stellar rotation, that is, $v\sin i \geq f\,\Delta\lambda$, where $\Delta\lambda$ is the local intrinsic line width resulting from thermal Doppler broadening, micro- and macro-turbulence, while f is a numerical factor;

- To derive a useful map, $f \gtrsim 3$-5, otherwise the stellar disc is not adequately resolved;

- In α Cen A and B, $v\sin i$ = 2.5, and 1.9 ± 0.5 km/s (Zhao et al 2018), respectively, comparable with $\Delta\lambda$; therefore, Doppler Imaging is not useful for these targets;

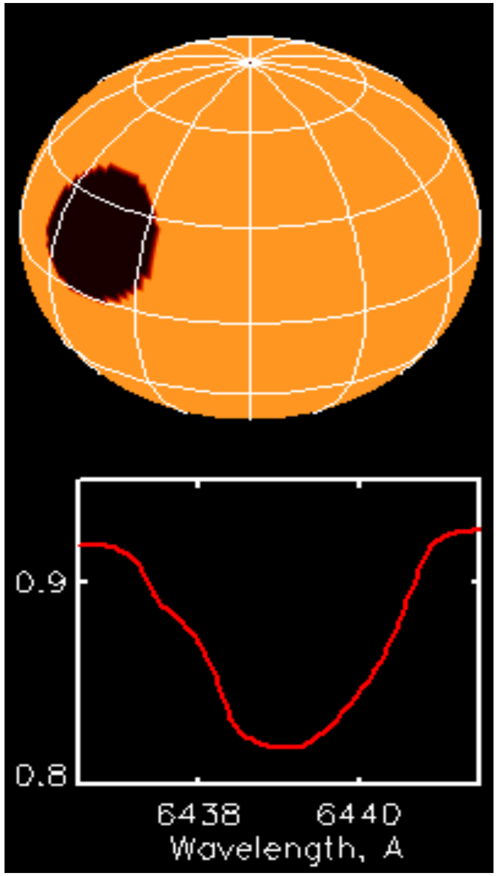
- Therefore, we must consider other proxies such as *photometry* or *radial velocity* (RV).

Astrometry vs. photometry



- For example, consider *a star viewed pole-on (i=0°)*; photometric measurements will show a constant flux;
- On the other hand, high-latitude spots, as in this image of HR 1099, produce a modulation of the position of the photocentre as the star rotates;
- Even if i ≠ 0°, photometry does not provide information on spot latitude making it impossible to reconstruct the photocentre position.

Stellar activity and RV variations

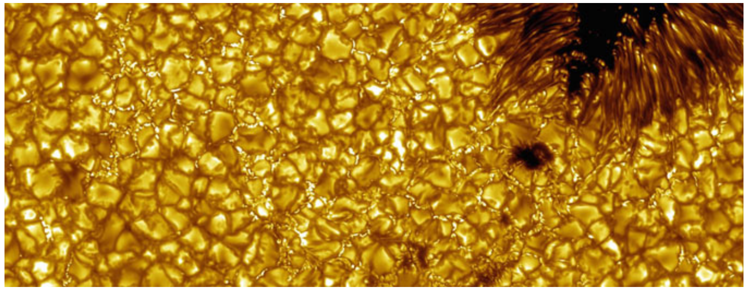


The *flux effect*: apparent radial velocity (RV) variations produced by distortions of spectral line profiles due to brightness inhomogeneities on a rotating star.

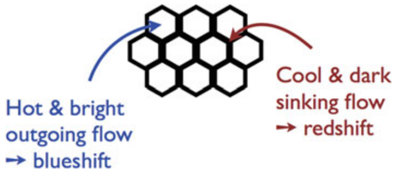
(animated image by S. Berdyugina)

Stellar activity and RV variations

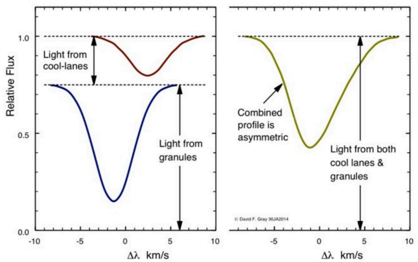
Quenching of convective line blueshifts in magnetic regions



(image credit: V. Henriques)



(Haywood 2016)



(credit David Gray http://astro.uwo.ca/~dfgray/Granulation.html)

In the Sun and in solar-like stars with low activity levels, the quenching of convective blueshifts is the *major source* of RV variations induced by activity (cf. Meunier et al. 2010; Haywood et al 2016; Lanza et al. 2016).

The rms solar RV variation is 4-5 m/s.

Convective quenching is mostly produced in solar faculae.

Information from the RV measurements

- In low-activity stars, such as the Sun, the RV jitter is dominated by the quenching of convective blueshifts occurring in faculae close to the centre of the disc;
- Therefore, it is poorly correlated with the brightness variations and the astrometric jitter because faculae have a very low contrast close to the disc centre (cf. Lagrange et al. 2011);
- In stars significantly more active than the Sun, dominated by dark spots, we expect the RV jitter to become more correlated with the astrometric jitter.

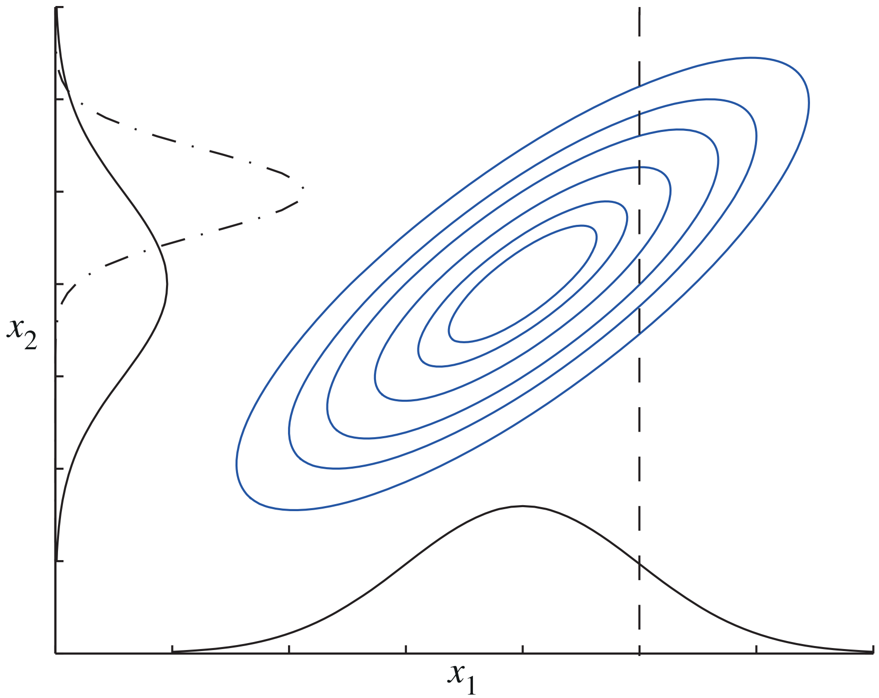
An approach based on Gaussian Processes

- In the case of astrometry, we face the same problem as in the analysis of stellar RV: a lack of information to reconstruct in a deterministic way the stellar jitter;

- From simultaneous photometry and/or RV measurements, we can estimate the evolution time scales of the active regions and the stellar rotation period that provide information to characterize the *time correlation* of the jitter;

- Gaussian Processes (GPs) can be used to reduce the impact of the jitter by exploiting such a knowledge.

Gaussian Processes: the principle

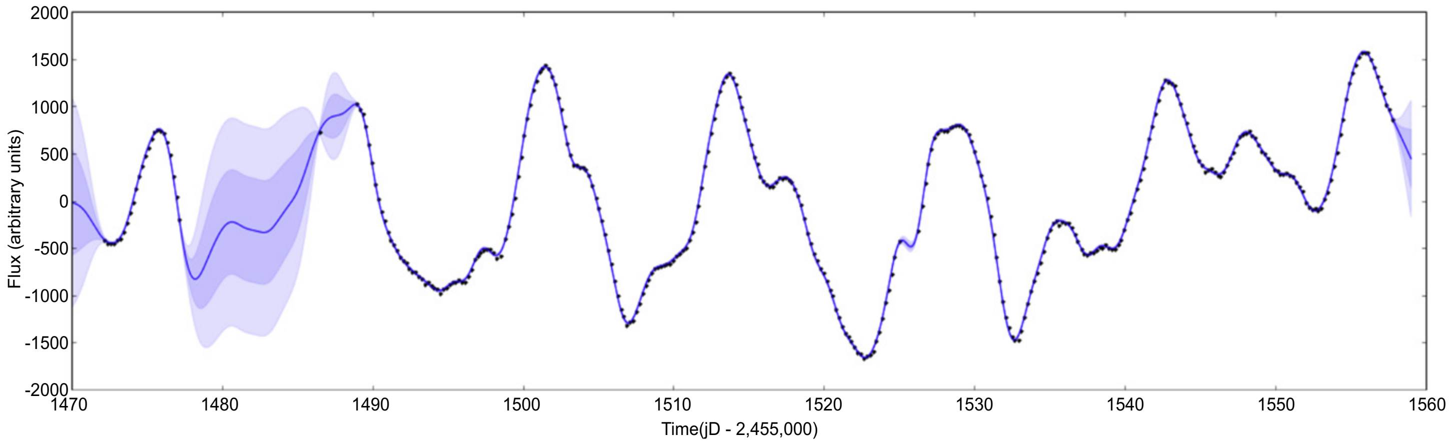


- A joint distribution (covariance ellipse) forms marginal distributions by projecting itself along the coordinate axes (solid lines);

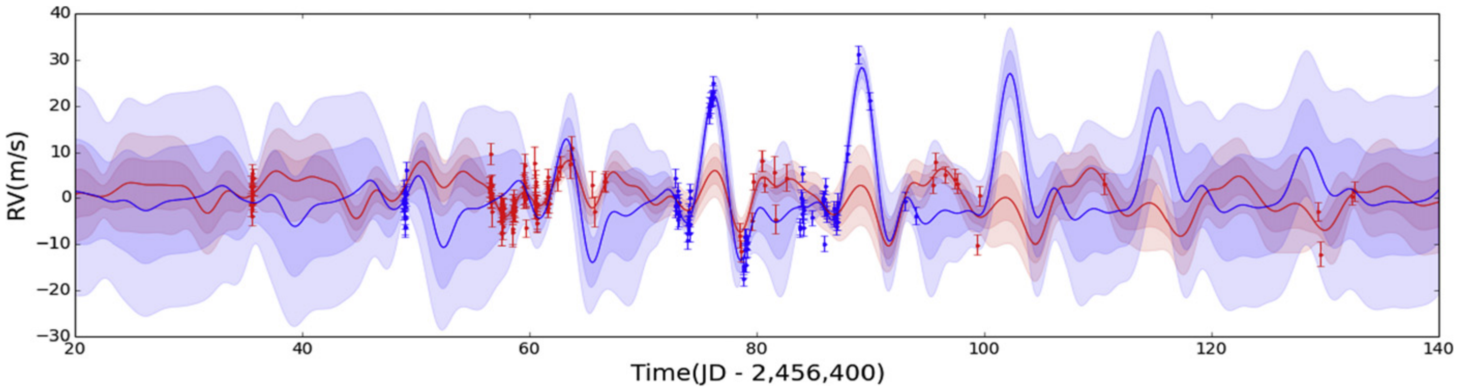
- Observing x_1 at a value indicated by the dashed vertical line changes our expectations about x_2 giving rise to a conditional distribution (dashed-dot line).

(Roberts et al. 2013; Haywood et al. 2014)

An example: GPs as applied to Kepler-78



Kepler-78 light curve with GP regression; the shaded regions correspond to 1σ and 2σ uncertainties.



GP regressions to the RV residuals (keplerian orbit of Kepler-78b subtracted) of the HIRES (blue) and HARPS-N (red) data. These GP regressions have been "trained" by using the GP hyperparameter distributions of the GP regression of the Kepler light curve.

(Grunblatt et al. 2015)

Conclusions

- We expect that the astrometric detection of an Earth twin around α Cen A and B should not be seriously hampered by the magnetic activity of the stars, but activity may preclude a fully exploitation of the measurement precision of TOLIMAN;

- A reduction of the impact of the astrometric jitter on modelling planetary orbits can be achieved by a proper treatment of activity, e.g., by means of Gaussian Processes;

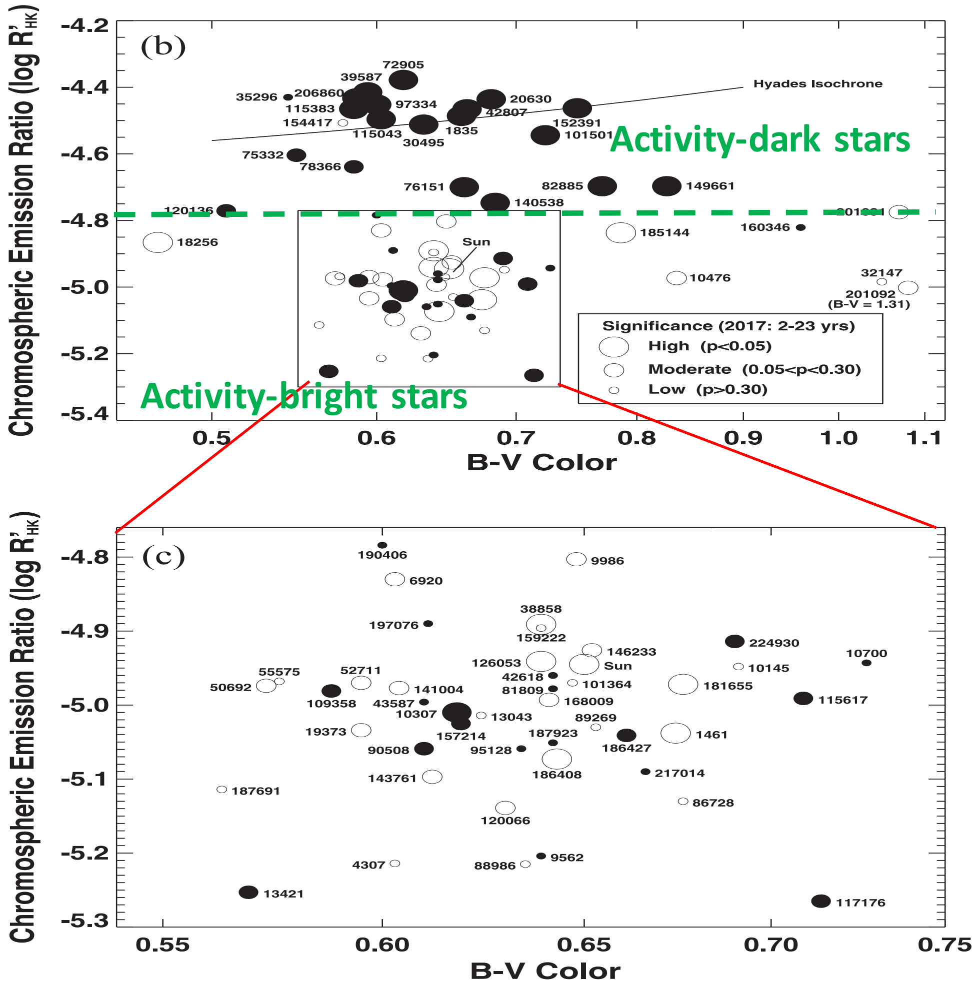
- By analogy with the case of RV in low-activity sun-like stars, we expect a reduction of the jitter amplitude by a factor of ~ 2, that is down to 0.1 μAU in our case;

- In stars with a low activity level such as α Cen A and B, a good proxy for measuring the timescales of active region evolution and time covariance could be the chromospheric index log R'_{HK}.

Thank you for your attention

Additional material

The role of faculae in solar-like stars



Open symbols: stars that become brighter when they are more chromospherically active, similar to the Sun; probably dominated by faculae;

Filled symbols: stars that become darker when more chromospherically active; probably dominated by dark spots.

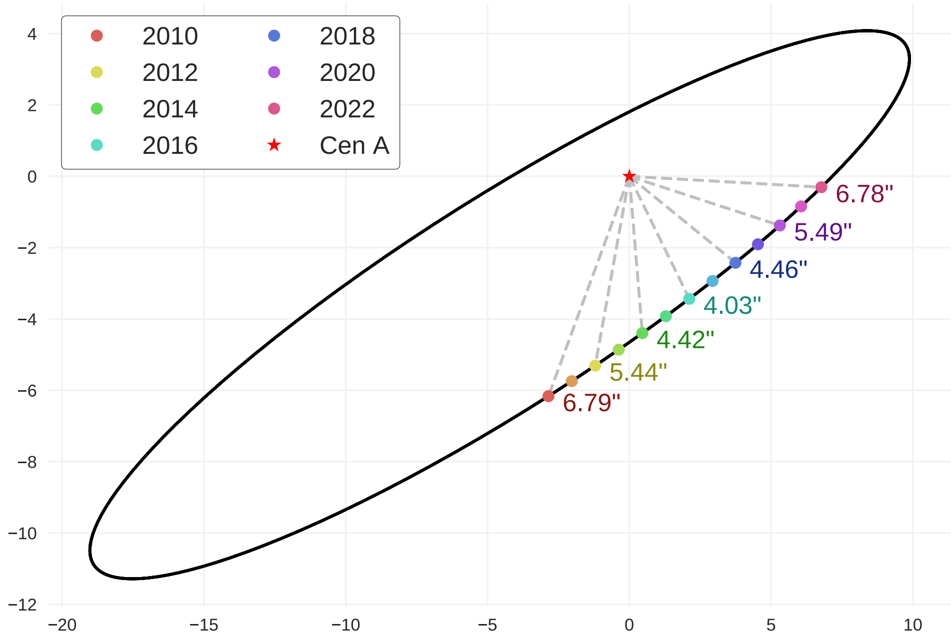
The lower panel is an enlargement of the inset in the upper panel.

The green dashed line marks the transition between activity-dark and activity-bright stars.

(Radick et al. 2018)

α Centauri A and B

$M_A = 1.133 \pm 0.005\ M_\odot$; $M_B = 0.972 \pm 0.005\ M_\odot$
P = 79.91 ± 0.013 yr; e = 0.524 ± 0.0011; i = 79.20 ± 0.041 deg



(Zhao et al. 2018; Pourbaix & Boffin 2016)

α Cen A:

- Spectral type: G2V;
- $P_{ROT} \approx 29$ d (Hallam et al. 1991; Pagano et al 2004)
- vsini = 2.51 ± 0.5 km/s (Zhao et al. 2018)
- Log R'_{HK} = -5.002 (Henry et al. 1996)
- Coronal activity cycle of ≈19 yr (Ayres 2015)

α Cen B:

- Spectral type: K0V;
- $P_{ROT} \approx 36.7 – 39.8$ d (Dumusque et al. 2012)
- vsini = 1.9 ± 0.5 km/s (Zhao et al. 2018)
- Log R'_{HK} = -4.923 (Henry et al. 1996)
- Coronal activity cycle of ~ 8 yr (Ayres 2015)
- Chromospheric activity cycle of ~ 8.4 yr with a FAP of 24% (Buccino & Mauas 2008)

Coronal activity cycles

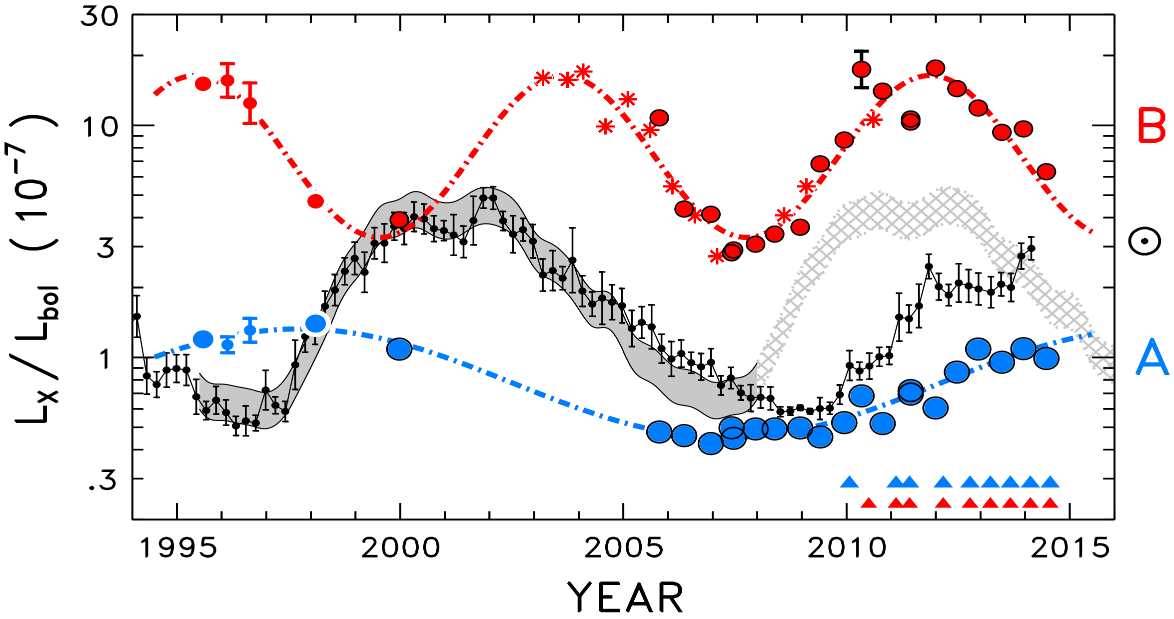


Figure 1. Coronal X-ray-to-bolometric luminosity ratios of the Sun (black dots and error bars), α Cen A (blue), and B (red). (Dividing by $L_{\rm bol}$ mitigates the bias introduced by the different stellar sizes.) Uncertainties of the AB values usually are smaller than the symbols. Pre-2000 values are from *ROSAT*; post-2000 values are from *Chandra* (dots) and *XMM-Newton* (asterisks: B only). The shaded background for the Sun is a schematic three-cycle average. Triangles mark epochs of post-SM4 STIS pointings.

(Ayres 2015)

Chromospheric S index vs. the time

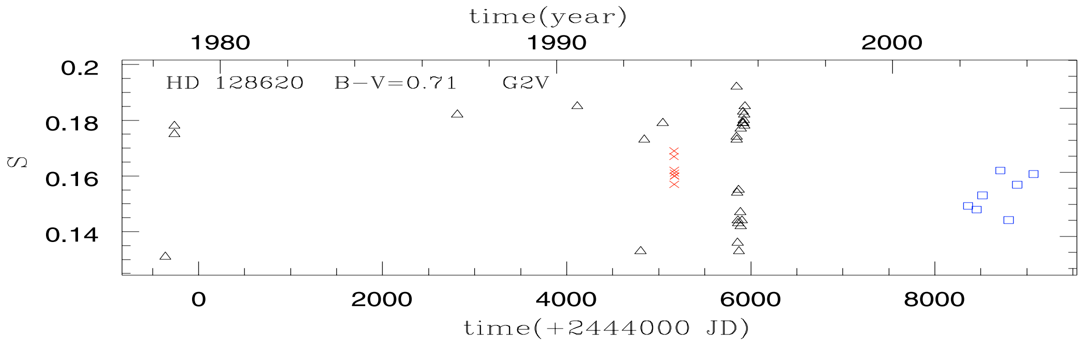


Fig. 13. Data for HD 128620. Symbols as in Fig. 7.

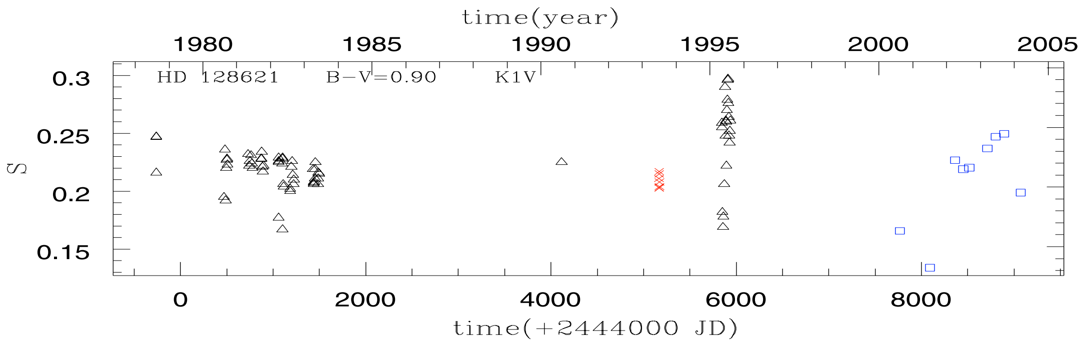


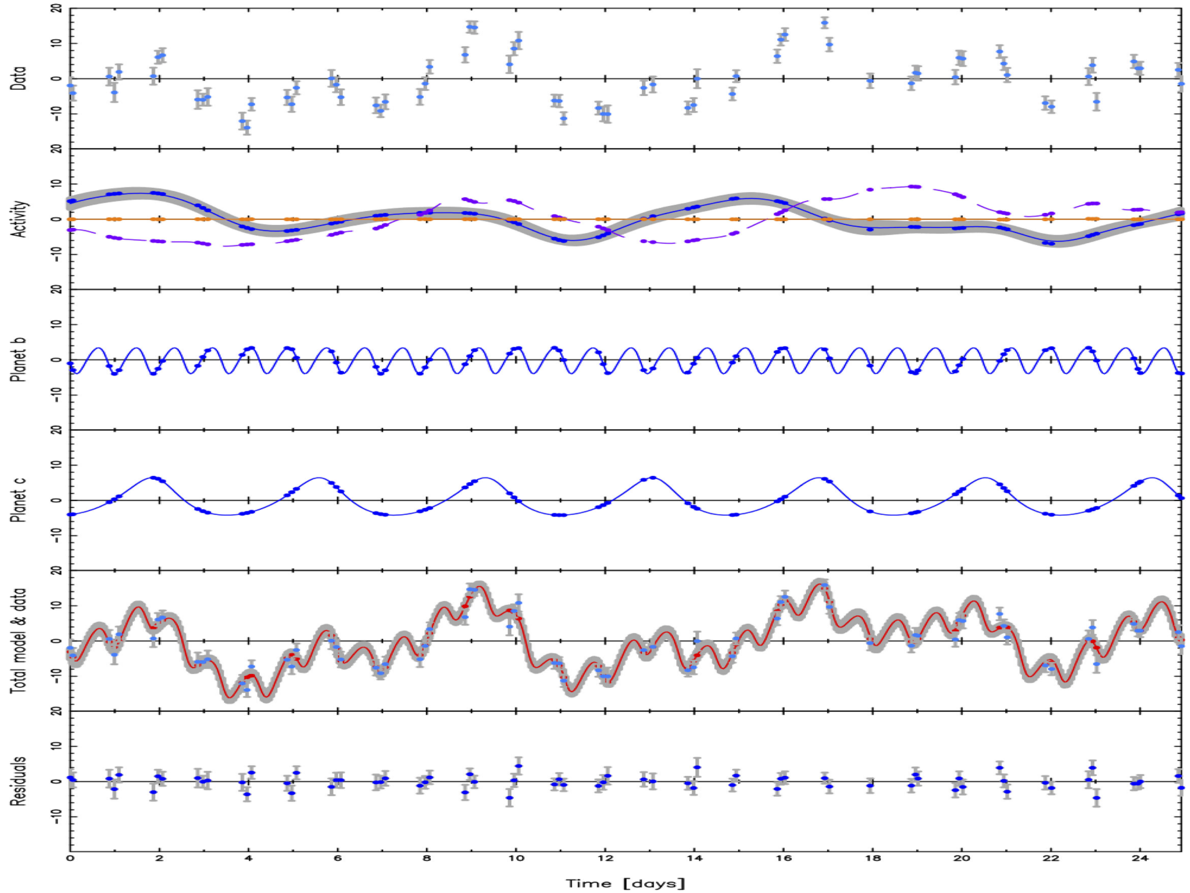
Fig. 14. Data for HD 128621. Symbols as in Fig. 7.

HD 128620 = α Cen A (no periodicity)

HD 128621 = α Cen B (possible cycle of 8.38 yr but with FAP = 0.24)

(Buccino & Mauas 2008)

GPs and planet detection in CoRoT-7



- A model including GPs to account for the RV jitter has been applied to CoRoT-7 by Haywood et al. (2014);
- The covariance matrix of the noise has been derived from the CoRoT light curve;
- This works very well in this active stars.

The role of faculae in solar-like stars

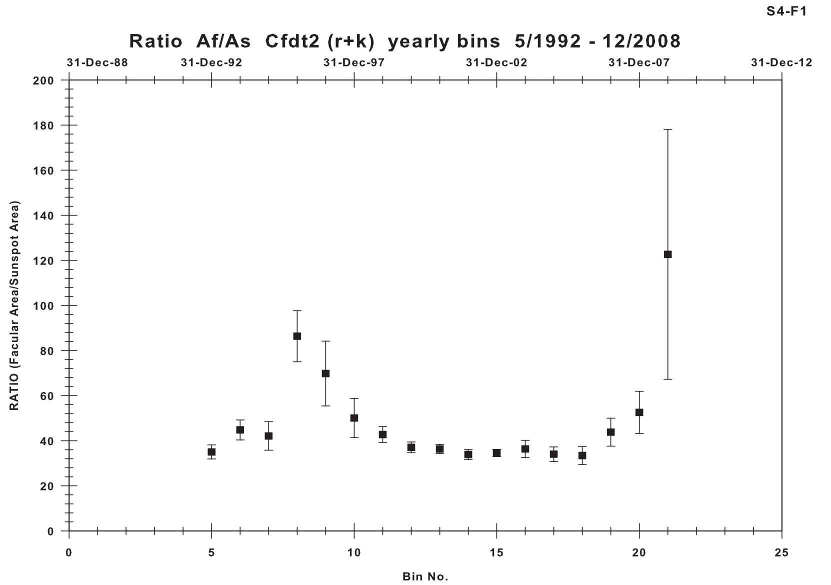
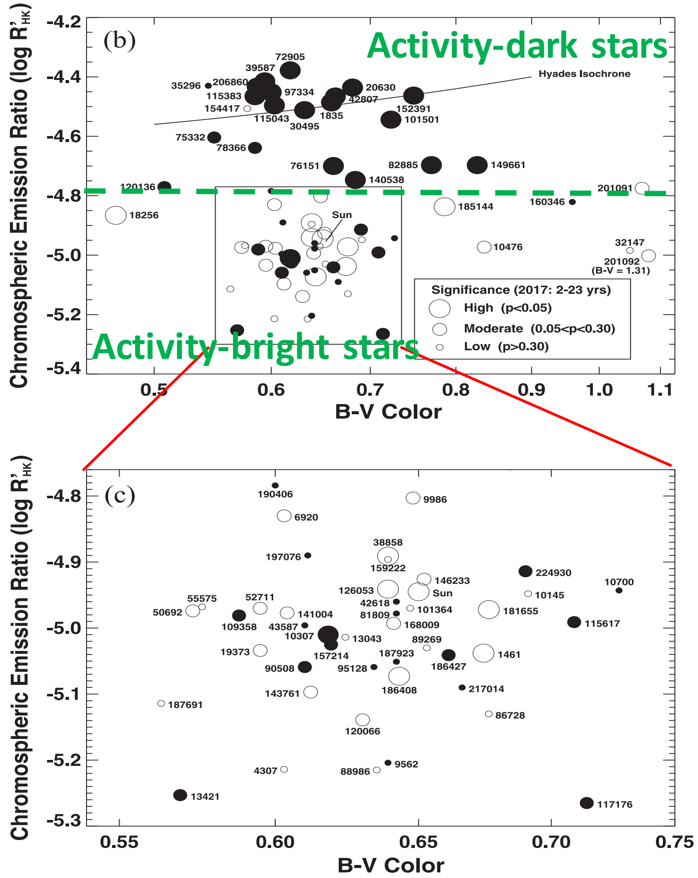


Figure 4. Ratio of facular to spot area from CFDT2. Points are annual means with error bars representing standard errors.

Solar A_{fac} / A_{spot} ratio vs. the time (Chapman et al. 2011)



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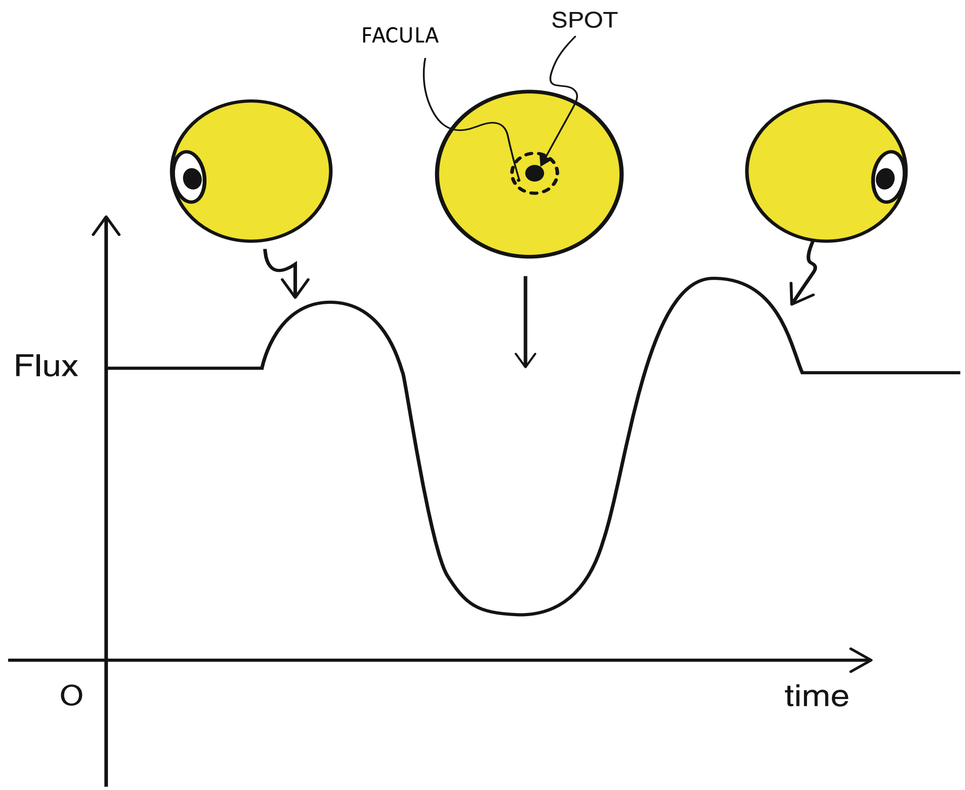
(Radick et al. 2018)

Light modulations due to spots and solar-like faculae



(Lanza 2016)

- Active regions consist of dark spots and faculae;
- The contrast of dark spots is independent of the position on the disc, while the contrast of faculae is zero at the disc centre and becomes maximum at the limb;
- The light modulation is only weakly dependent of the AR latitude, therefore, inverting a high-precision light curve does not constrain spot latitudes;
- Reconstructions based on light modulation are very poor in the case of stars with an inclination $i < 30^{o} – 40^{o}$