Searching for Rieger-like activity cycles in late-type stars: from ground-based to CoRoT and Kepler times series

Antonino F. Lanza

INAF-Catania Astrophysical Observatory, Italy

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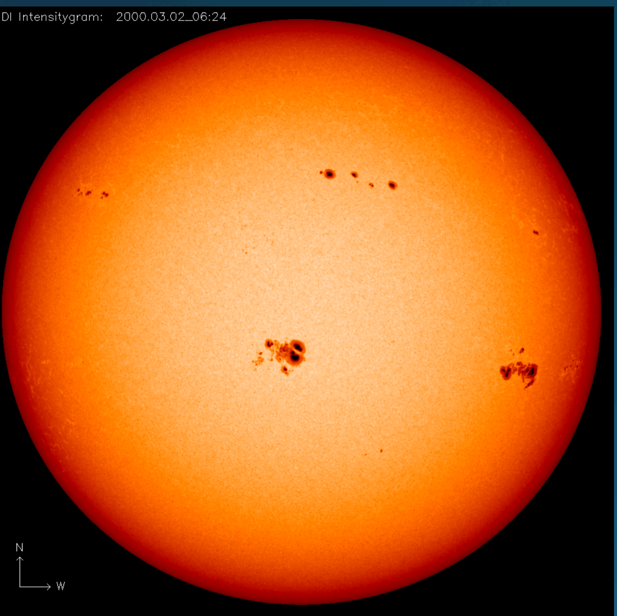
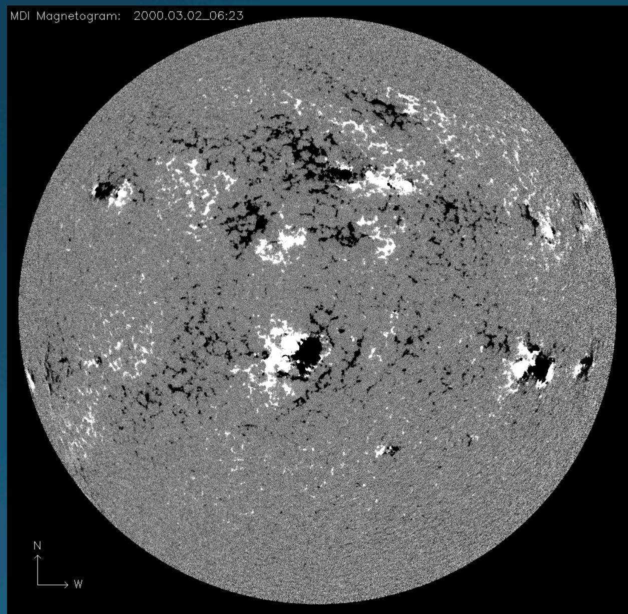
Characteristic of solar Rieger cycles

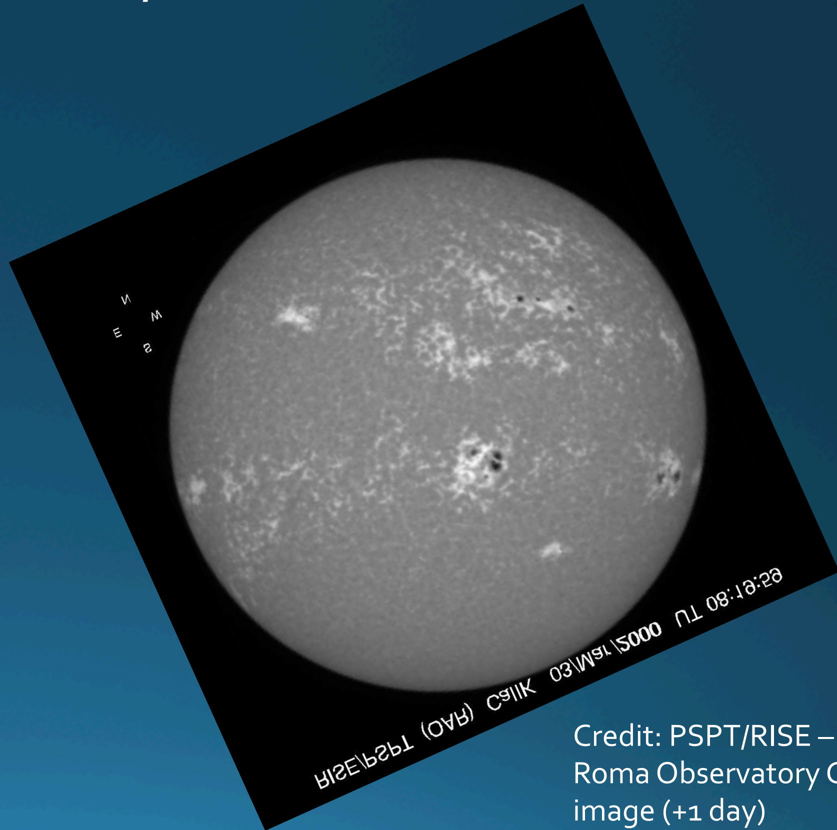
- Observed in several indicators: flare energy frequency; total sunspot area; modulation of the total solar irradiance (TSI);
- Typical period of 150-160 d, i.e. 5-6 solar mean rotation periods;
- Intermittent cycles around the maxima of the 11-yr cycles;
- No polarity reversal of the global magnetic field;
- No appreciable latitudinal migration of the activity belts;
- Possible connection with the quasi-biennial oscillations (Krivova & Solanki 2002) ?
- *Can we observe similar cycles in other late-type stars ?*

Solar activity

- In the Sun we can study stellar activity in detail, thanks to the spatial and time resolution (down to 50-100 km and a fraction of a second, respectively);
- In the photosphere, the features associated with magnetic fields are sunspots, faculae, and the network.
- In the chromosphere, they are chromospheric faculae, best visible in chromospheric lines.

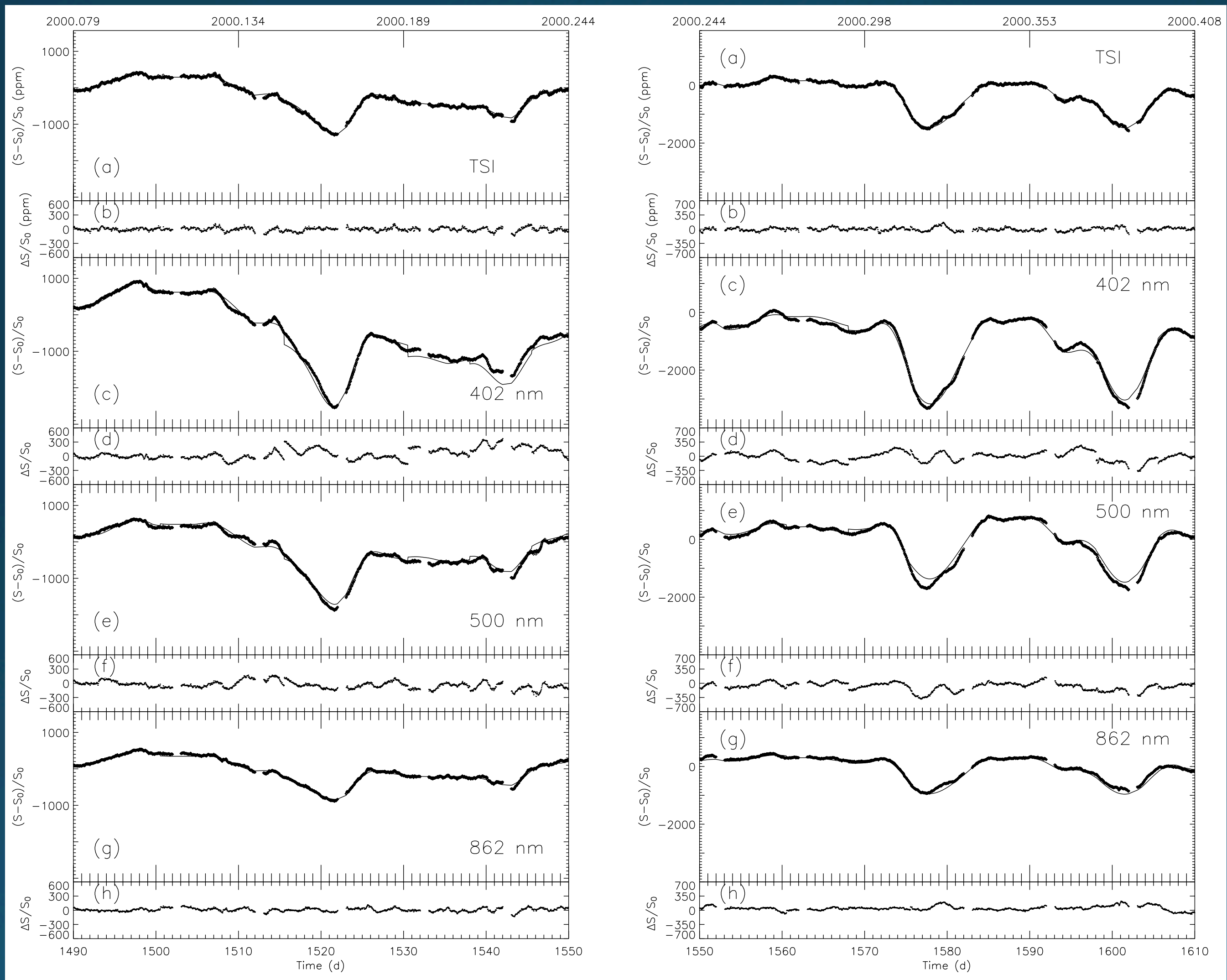






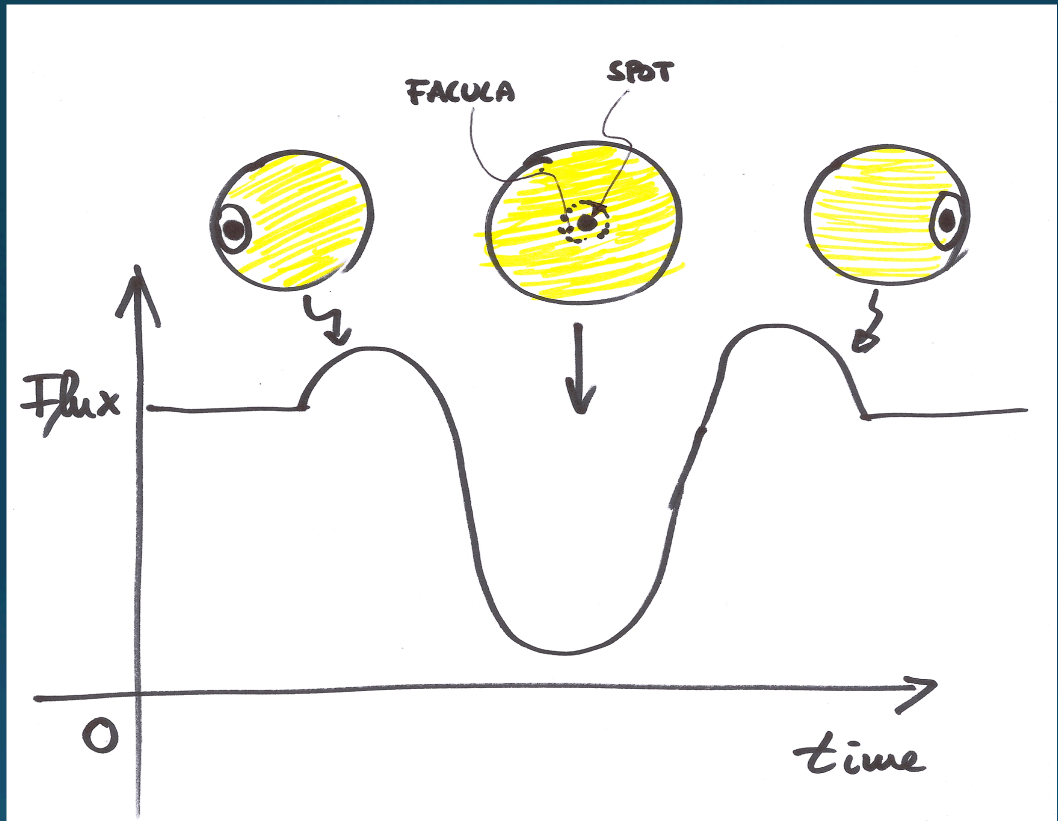
Credit: PSPT/RISE – IN
Roma Observatory Ca
image (+1 day)

The Sun as a star: Variation of Solar Irradiances



(Lanza et al. 2004)

otometric effects of an active region in the optical passba



Faculae are more contrasted close to the limb and produce an increase of the flux, while spots produce the maximum flux decrement when they are closer to disc centre because of projection effects. On the other hand, faculae have a small contrast at disc centre, so the effect of the spots is prevailing there.

Methods to study activity cycles from the ground

- Long-term (decadal) time series of chromospheric activity indicators (the most popular is R'_{HK} based on the Ca II H&K lines; Baliunas et al. 1995);
- Long-term RV monitoring for planet searches because they monitor stellar activity as a source of noise and false positives;
- Long-term wide-band optical photometry (e.g., Olah et al. 2009);
- Long-term radio patrol of very active stars, e.g., RS CVn and Algol binary systems (Massi et al. 2002; Richards et al. 2003).

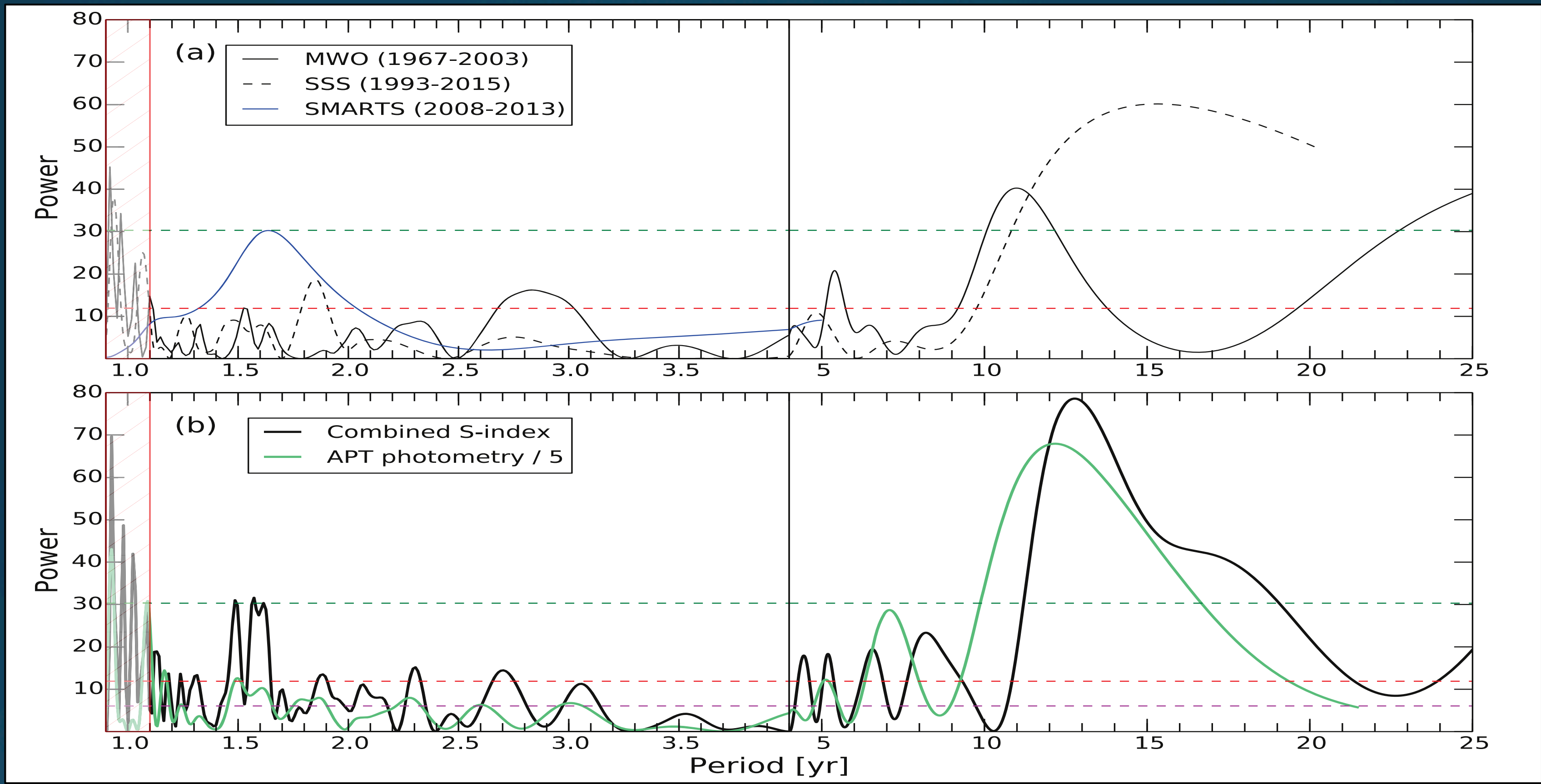
Caveats

Seasonal duty cycle of the observations: typical ground-based time seri have duration between 4 and 8 months depending on the targ coordinates;

Rotational modulation in solar-like stars with periods of 20-40 days and/ the intrinsic evolution of active regions with periods of the order of a fe months may combine with the (quasi-periodic) observation gaps produce spurious periodicities in the power spectrum;

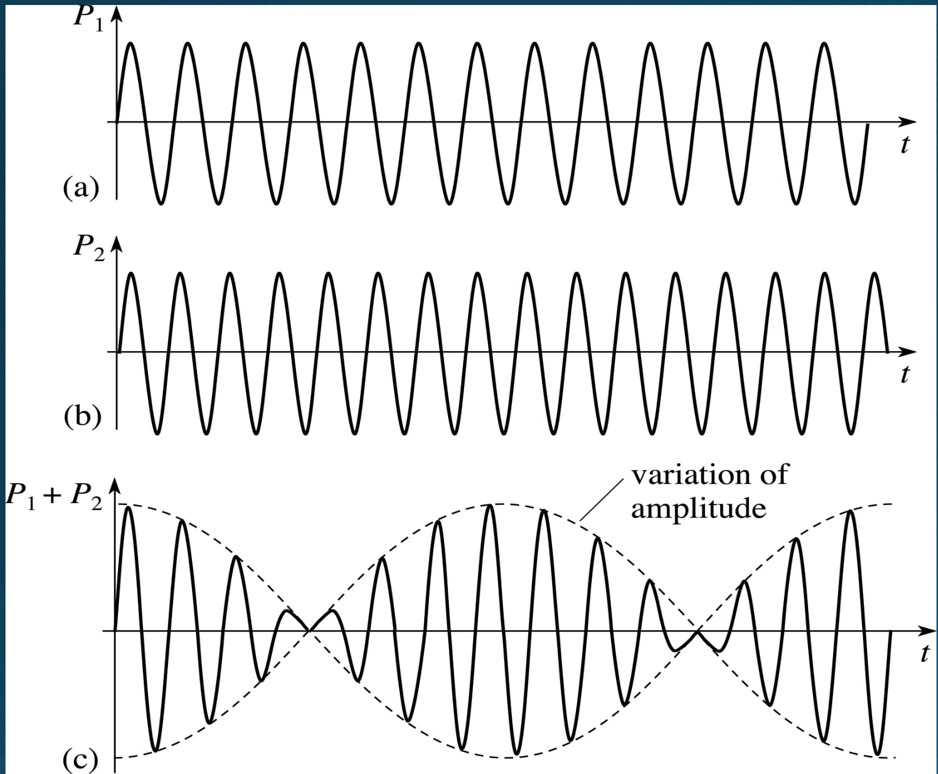
Stellar surface differential rotation combined with active regions living f several rotations leads to beating in the amplitude of the light curves th can be misinterpreted as Rieger-like cycles;

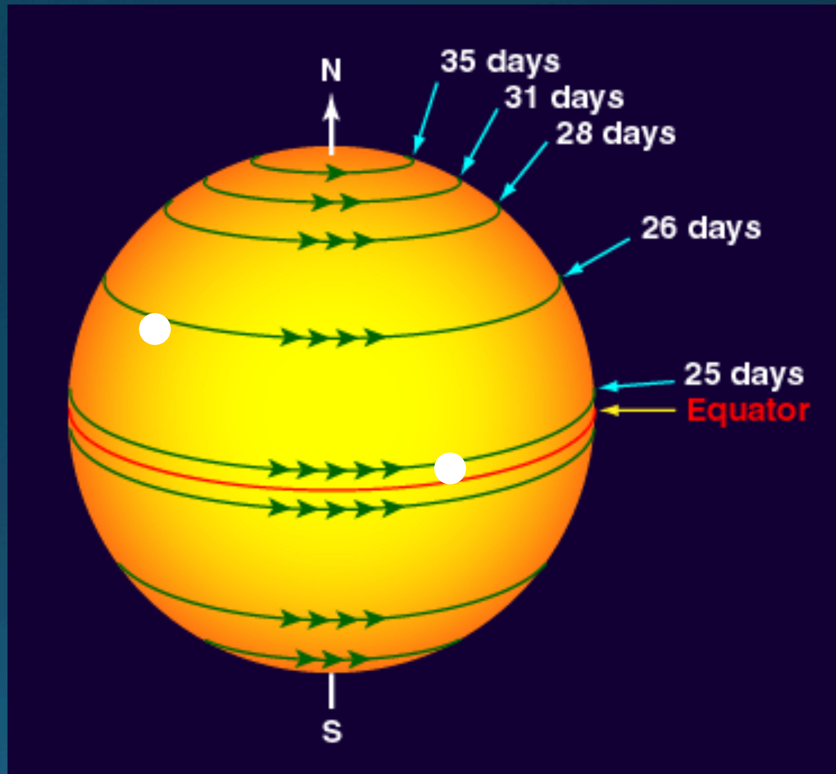
Effects of the time sampling on the periodogram



riodogram of the chromospheric index and optical photometry of HD 30495 (Egelan 2015). The hatched region below 1.1 yr indicate the part of the periodogram dominate efacts produced by the spectral window (i.e., the observation sampling).

The beating phenomenon





Close rotation frequencies can produce a remarkable variation of the amplitude of a light curve *without any variation of the total spotted area* (e.g., Mathur et al. 2014; Arkhypov et al. 2015)

How to cope with caveats

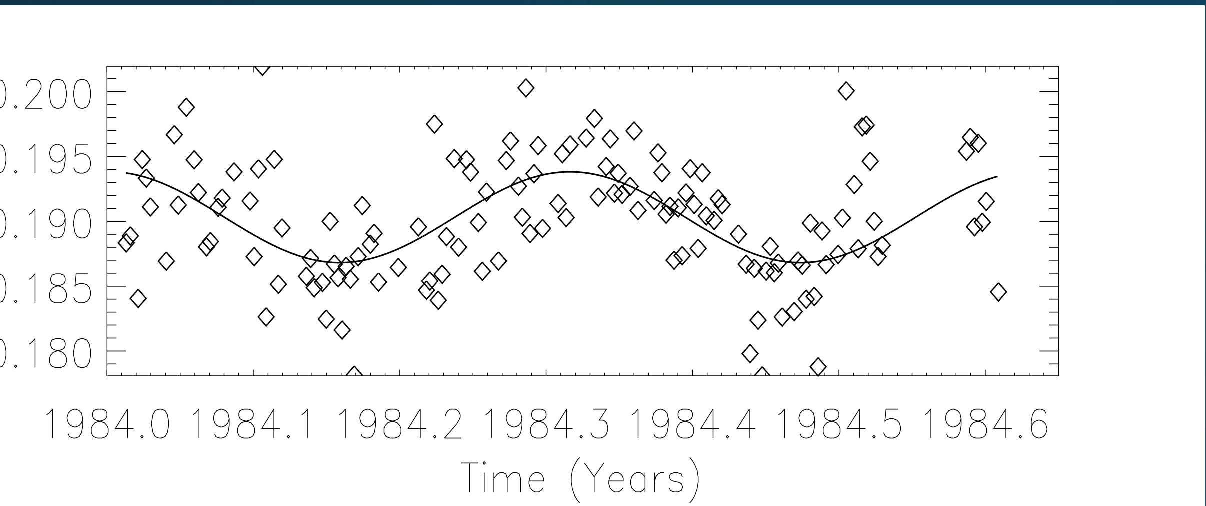
- Limit our search from the ground to cycles longer than 1-3 years depending on the time sampling of the time series (its spectral window provides information on spurious periodicities);

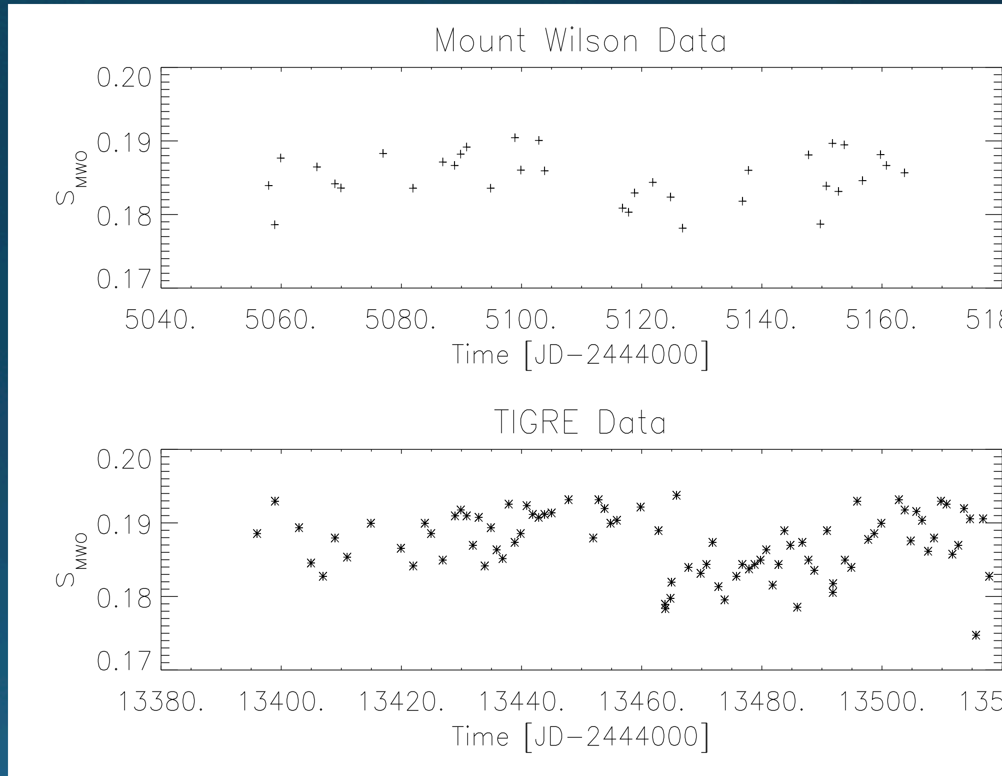
- Extract all the different frequencies present in the light curve modulation and check their amplitudes: this requires a frequent and continuous time sampling not easy to obtain from the ground.

The case of τ Bootis (HD 120136)

- A long-term cycle with a period of about 11-yr (11. 6 ± 0.6 yr) is found by Baliunas et al. (1995), although it is not highly significant; activity index: log R'_{HK} = -4.47 (Noyes et al. 1984).
- A short-term periodicity of 110-120 days persisted for at least 25 yr (Baliunas et al. 1997; Henry et al. 2000; Schmitt & Mittag 2017);
- Phase jump episodes sometimes observed;
- Reversals of the global magnetic field polarity with cycles of 240 or 740 (Fares et al. 2009; 2013; Mengel et al. 2016);
- **τ** Boo shows differential rotation with P_{rot} = 3.0 days at the equator and 3.9 days at the pole (a 24% relative amplitude; Donati et al. 2008) .
- The star is accompanied by a massive planet (5.95 ± 0.28 M_{jup}) on a synchronous orbit with a period of 3.312 days; the star shows differential rotation with P_{rot} = 3.0 days at the equator and 3.9 days at the pole (a 24% relative amplitude; Donati et al. 2008) .

Short-term cycle of τ Bootis





One short-term cycle in τ Boo (left) and two examples of phase jumps (Schmitt & Mittag 2017

α Com: another short-term cycle ?

The persistent sub-yearly period in the activity of τ Bootis was unprecedented (Baliunas et al. 1997);

Therefore, Maulik, Donahue & Baliunas searched the time series of other 40 mid-to-late F dwarfs for similar phenomena (SAO Technical Reports 1997, never published in a referred journal);

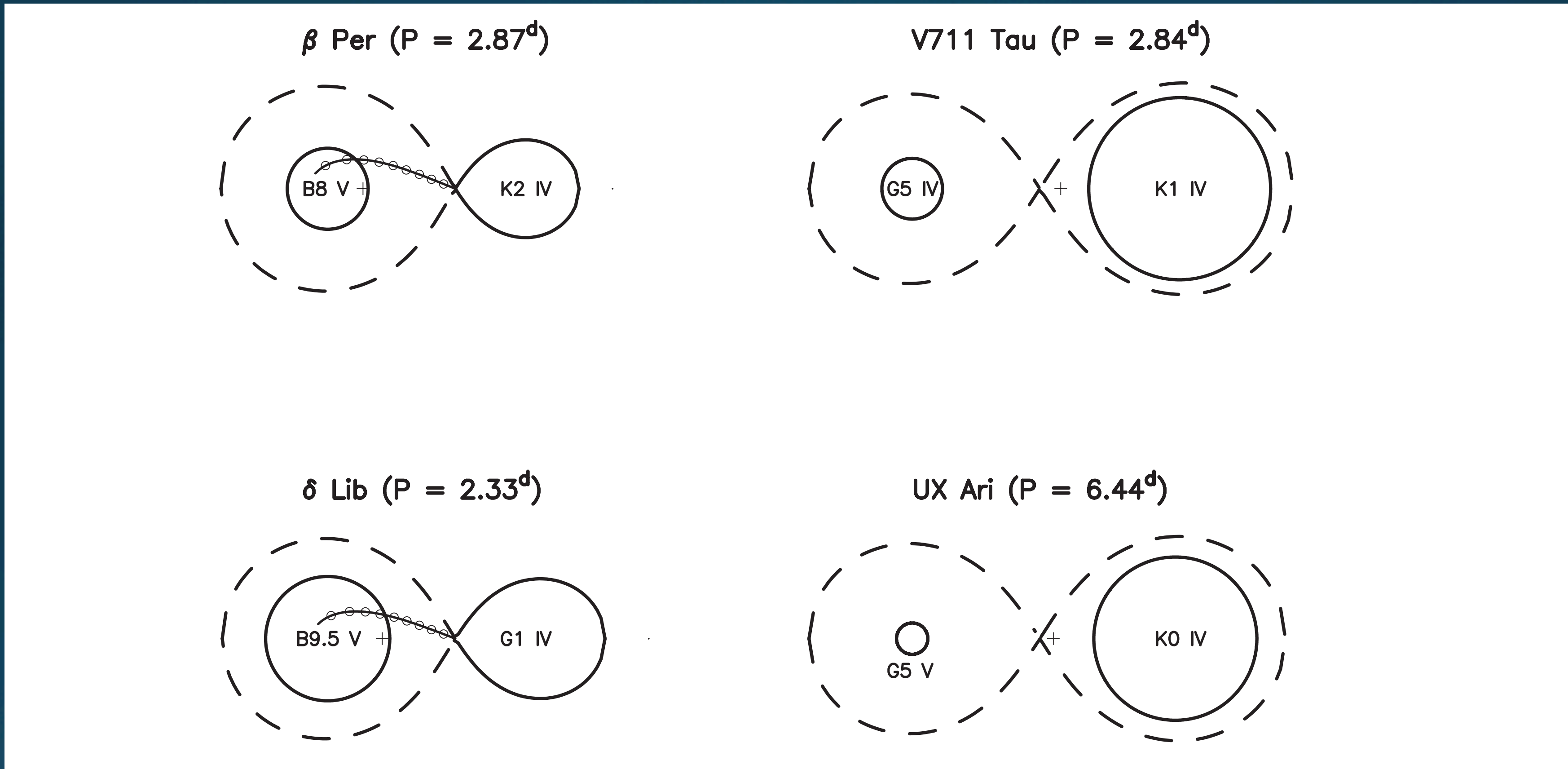
Only α Comae (HD 114378) was found to have a period of about 132 days;

No planet has been detected around this star as of February 4 2017; its mean rotation period is 3.02 days with hints of differential rotation with a relative amplitude of ~ 15% (cf. Donahue et al. 1996); Hempelma et al. (2016) give a rotation period of about 4.3 days; activity index: log R'_{HK} = -4.34 (Noyes et al. 1984).

For both stars, the variations were checked for persistence and coherence suggesting that neither rotati nor active region evolution are producing the modulation;

Since the entire Mt. Wilson project dataset became recently public, it would be interesting to re-examin this star.

Close binary systems

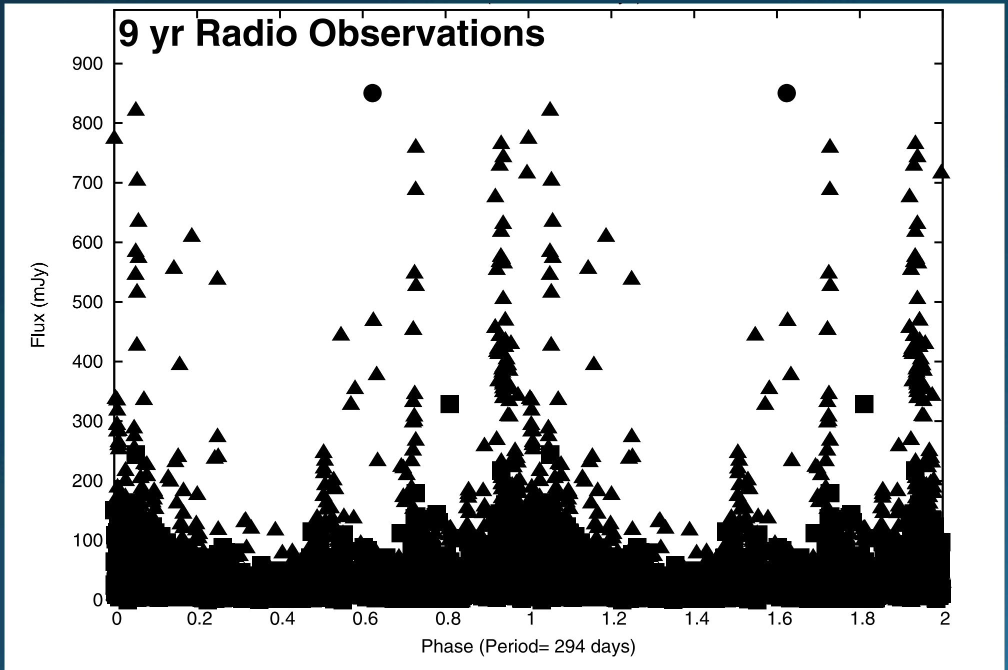


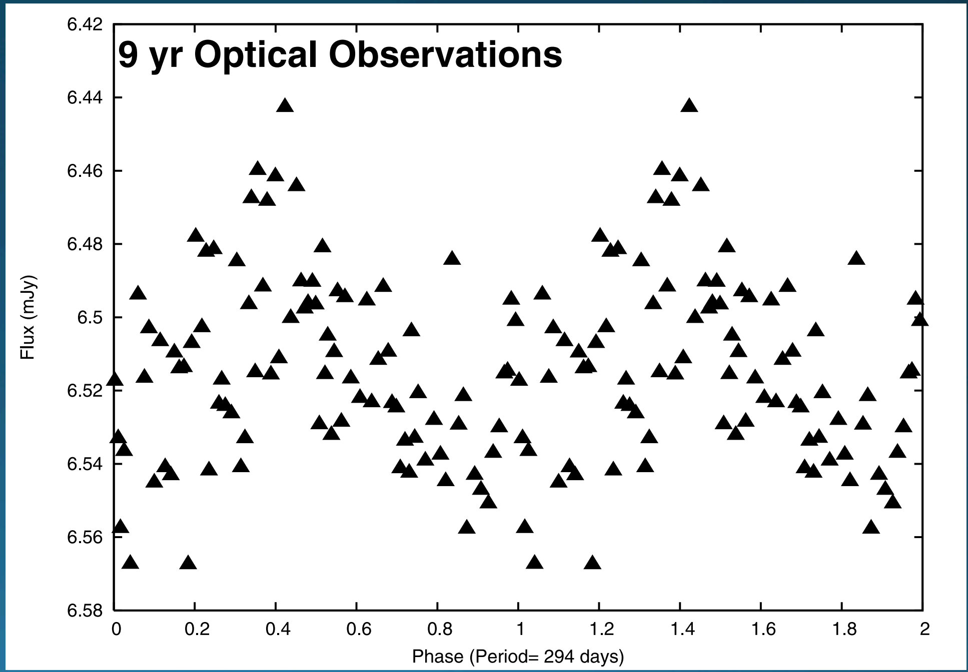
Algol (semi-detacted) binaries are on the left, while RS Canum Venaticorum (RS CVn; detacted binaries) are on the right (after Richards et al. 2003).

Rieger cycle in UX Arietis

Massi et al. (2005) found a Rieger-like cycle in the radio (1.4-43 GHz) flaring activity of this close binary syst
belonging to the RS CVn class;

The period is 294 days and is supported by the folded optical light curve. It cannot be produced by starspot migrat
because it would imply a migration rate of 1.24 yr^{-1} while the maximum observed migration rate is 0.26 yr^{-1} (Aar
Ulvas & Henry 2003).





Possible cycles in other close binaries

- Richards et al. (2003) monitored four close binary systems at 2.3 and 8.3 GHz f a total of 2096 days with interruptions;
- The strongest periodicities were 49 ± 1.7 days for β Persei (Algol), 121 ± 3.5 da for V711 Tau (RS CVn), and 141.4 ± 4.5 days for UX Ari (RS CVn);
- The periodicities detected in δ Librae are related to the time sampling and a not real;
- Note the difference in the period of UX Ari with the work of Massi et al. (20 based on a longer dataset; this reveals the limitations related to the tir sampling of the observations;

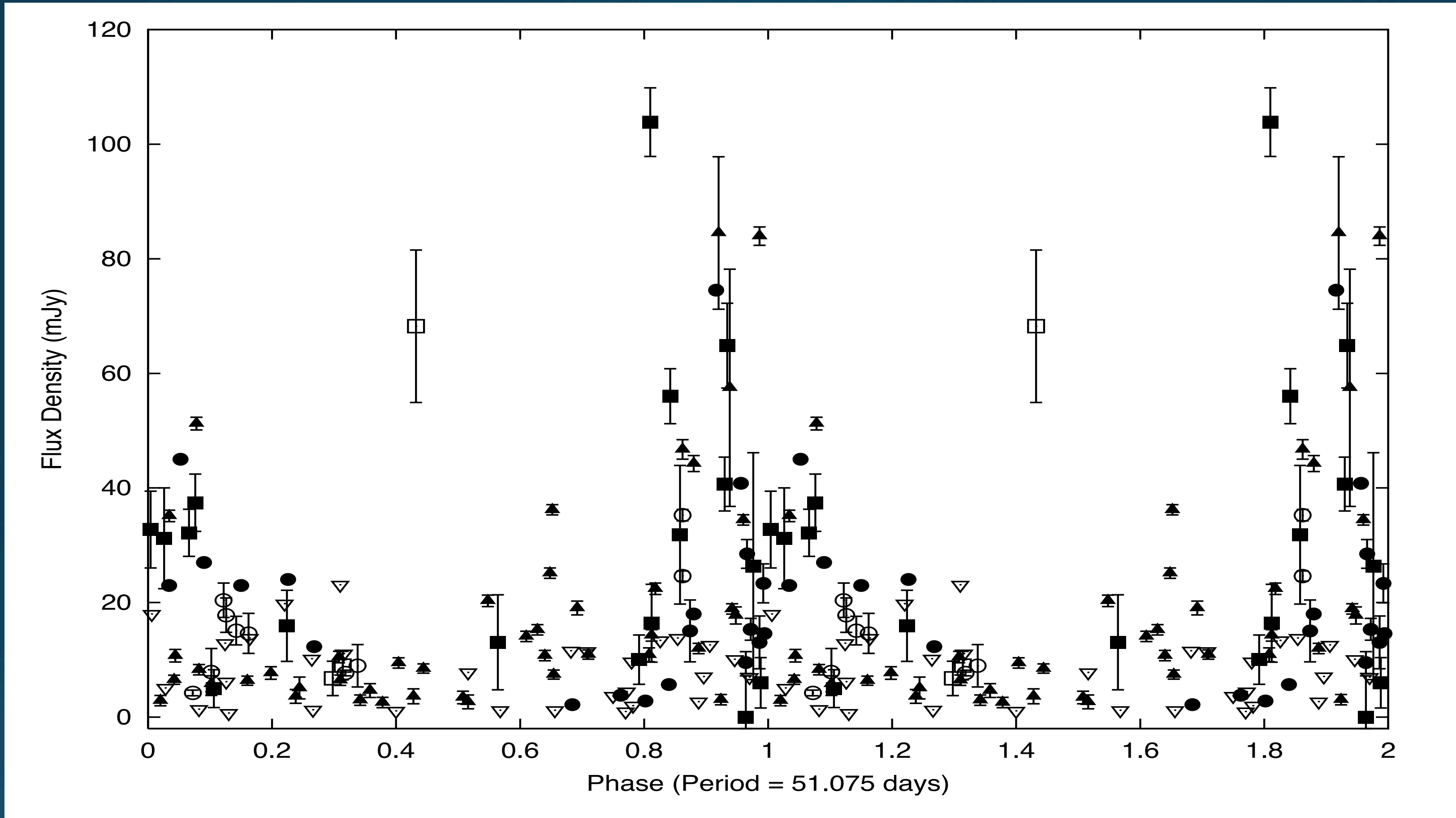
The case of V773 Tauri

This is a binary systems consisting of pre-main-sequence stars on a
eccentric orbit (P_{orb} = 51.075 days; e = 0.27);

They show a strong flaring activity concentrated at periastron an
interpreted as originating from the interaction of large coronal loops o
helmet streamers because the separation at periastron is about 30 stella
radii (Massi et al. 2002; 2008);

However, could it arise from the preferential emergence of new magnet
flux close to the periastron rather than from large loop interaction ?

V773 Tauri radio flaring



ed radio observations of V 773 Tau; different symbols refer to different wavelengths between 0.7 and 3.6 cm; triangl
pper limits (after Massi et al. 2002).

Rieger cycles in ASAS photometry

- Savanov (2012) analysed 31 M dwarf stars finding cycles with periods from hundreds to thousands of days without correlation with the star mass or rotation period;

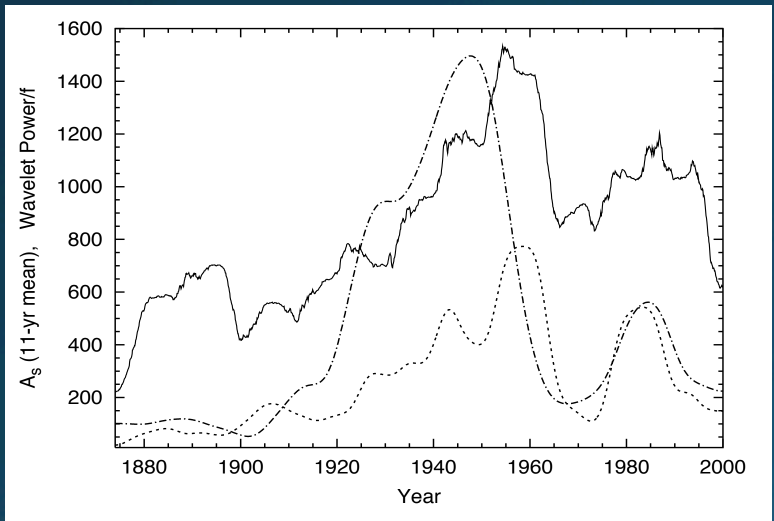
- Suarez-Mascareño et al. (2016) searched for cycles in a sample of 125 main-sequence stars (from late A to mid M); their shortest cycle is 2.5 yr;

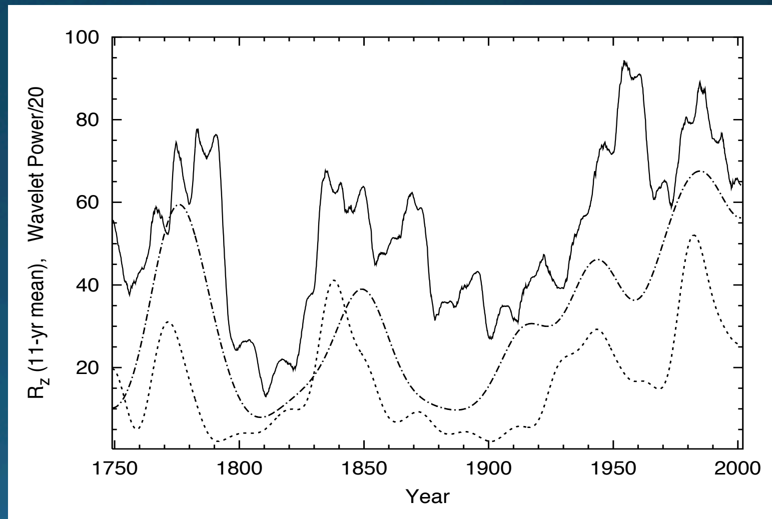
- A sample of 90 stars of types G5-M4 belonging to young associations with ages between 4 and 95 Myr (Distefano et al. in prep.);

- Approximately 40% of the sample show possible cycles shorter than 300 days, but generally only a couple of consecutive oscillations are observed and the data are affected by the yearly gaps.

Short-term activity cycles and Rieger cycles

- The possible connection between the solar biennial oscillation and the Rieger cycles suggested by Krivova & Solanki (2002) makes the search of short-term cycles (1-3 yrs) in solar-like stars of interest.

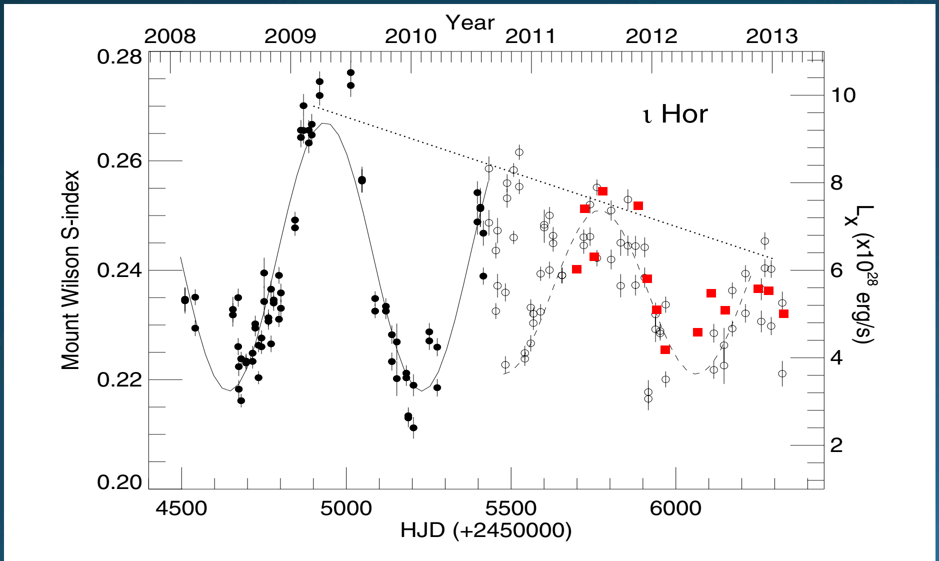




Left: The 22-yr running mean of sunspot areas (solid line) and of the corresponding wavelet power spectrum of the periods of 1.3 yr (dot-dashed line) and of 156 days (dotted line). *Right:* The same as left, but for the sunspot number (after Krivova & Solanki 2002).

Short-term activity cycles

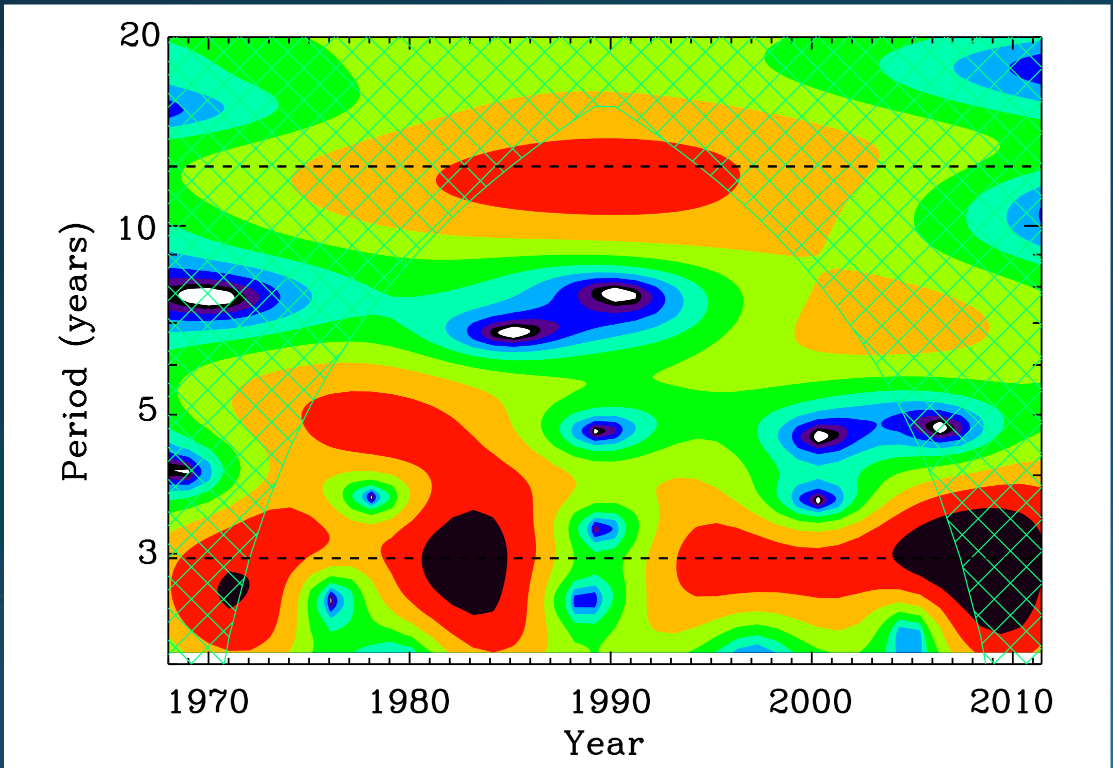
- The Mt. Wilson survey found the shortest cycles in HD 76151 (2.52 yrs) and HD 190406 (2.60 yrs) (Baliunas et al. 1995);
- Metcalfe et al. (2010) and Sanz-Forcada et al. (2013) detected a cycle of 1.6 yrs in the F8V star ι Horologii, showing some phase jumps; also a longer-term cycle is suggested;
- The star has P_{rot} = 8.5 days (Metcalfe et al. 2010) and is accompanied by a planet with a mass of 2 M_{jup} with an orbital period of 303 days.



Filled symbols: data from Metcalfe et al. (2010); open symbols: additional data from Sanz-Forcada et al. (2013); red symbols: scaled X-ray flux from the stellar corona (after Sanz-Forcada et al. 2013).

ε Eridani

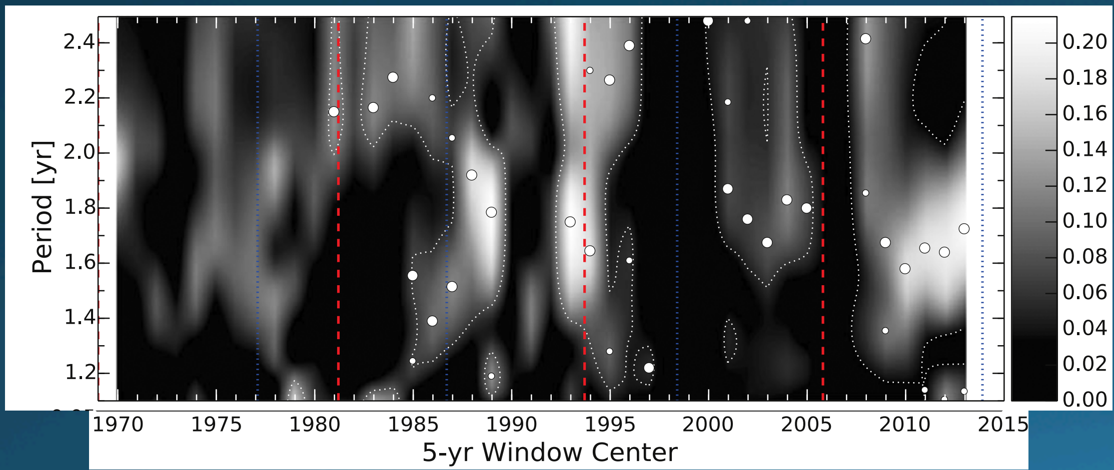
- Another interesting target is the K2V star ε Eri that shows two cycles of 2.95 ± 0.03 yr and 12.7 ± 0.3 yr based on the Ca II H&K chromospheric flux (Metcalfe et al. 2013);
- The star has a mean rotation period of 11.4 days with indication of a ~ 2% differential rotation (Croll et al. 2006) and is accompanied by a planet of ~ 1 M_{jup} with a period of ~ 2500 days.



Wavelet spectrum of ε Eri from 1968 to 2012; we signals in white and blue, strongest signals in rec black (after Metcalfe et al. 2013).

HD 30495

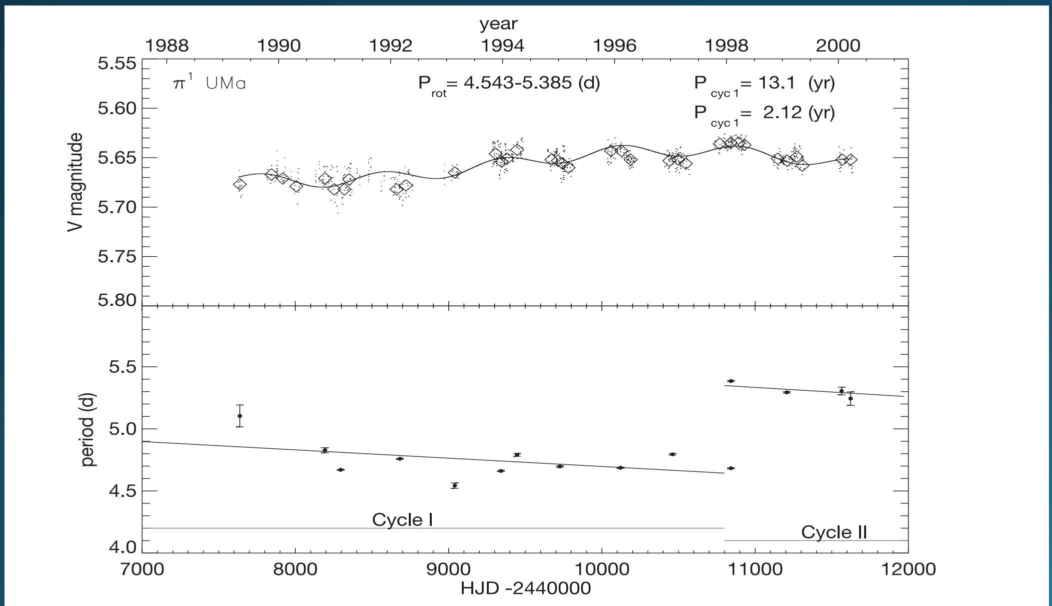
- The young (~ 1 Gyr) G1.5V star HD 30495 has a rotation period of about 11 days;
- It shows two chromospheric cycles of ~ 1.7 ± 0.4 yr and ~ 12 ± 3 yr; the former periodicity is intermittent and does not appear to correlate with the longer cycle (Egeland et al. 2015).

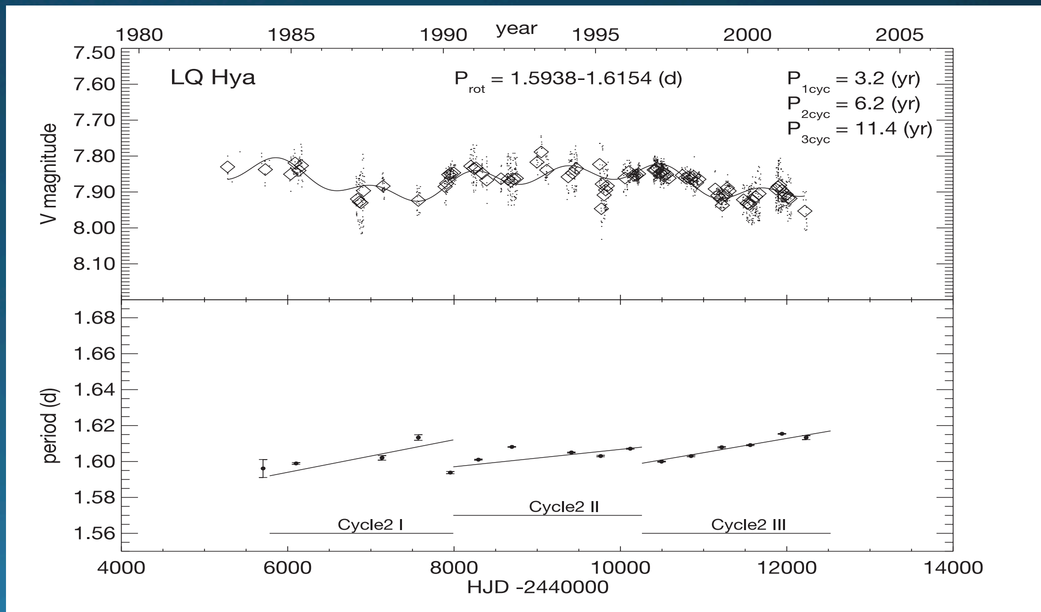


Short-term Lomb-Scargle periodogram power computed in 5-yr intervals shifted by 1 yr along the time series of the S index. The blue and red vertical dashed lines mark the minima and the maxima of the long-term cycle, respectively (after Egeland et al. 2015).

π¹ Ursae Maioris and LQ Hydrae

- π¹ UMa is a young G1.5V star with a mean rotation period of 4.9 days and indication of differential rotation with a relative amplitude of ~ 12%;
- It shows two activity cycles of 2.1 yr and 13.1 yr, the latter associated with a variation of the rotation period interpreted as the consequence of the migration of the activity belts;
- A similar behaviour, although with a more complex long-term modulation, is shown by LQ Hya (spectral type K2V) whose rotational modulation varies with the 6.2-yr cycle (Messina & Guinan 2003).

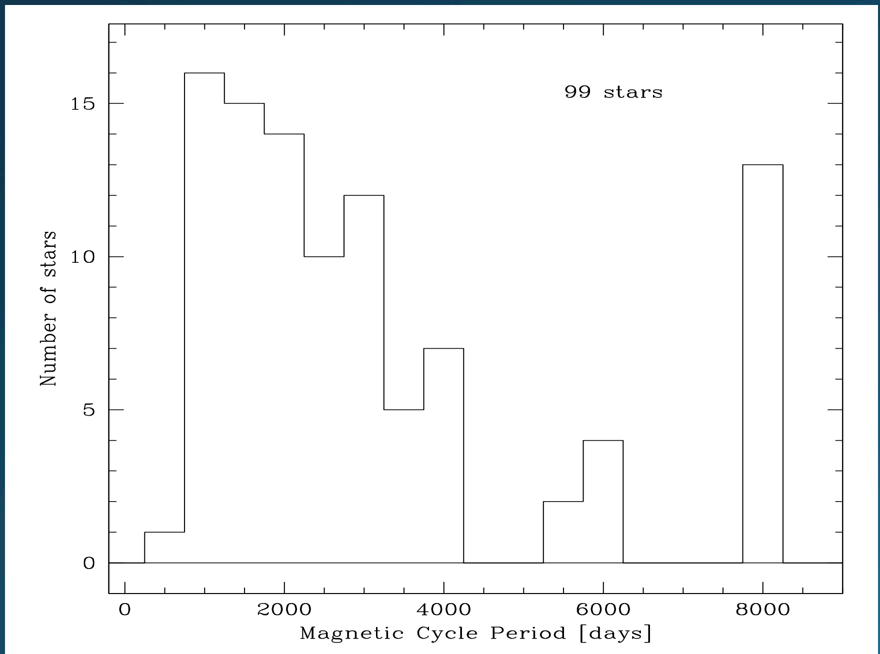




Activity cycles in RV planet searches

Lovis et al. (2011) found cycles with periods down to 3-5 yrs in a sample of old (low activity) late-type s
searched for exoplanets; the shortest period is about 700-750 days;

Robertson et al. (2013) observed 93 K5-M5 dwarf stars for about a decade finding cycles with P > 1
about 5% of the sample; GJ 708 show a period of only 296 days, but its FAP is 0.03.



Cycle period distribution for the stars of Lovis et al. (2011)

Space-borne photometry

- CoRoT and Kepler opened a new era in stellar photometry from space;

- CoRoT was designed for asteroseismology and the search of planets through the method of transits;

- Kepler was a planet-search mission looking for transits and with asteroseismic capabilities for bright targets (V < 12-13).

CoRoT

- CoRoT was launched in Dec 2006 and has been in operation till 2 Nov 2012; its telescope aperture is 27 cm;
- It performed short runs (typically 20-40 days) and long runs (130-160 days) in several fields in two regions of th sky;
- The cadence of the observations is 32 or 512 s, with a white-light passband from ~ 450 to ~ 900 nm (FWHM);
- Short gaps (< 1500 s) are due to the crossing of the SAA of the Earth magnetic field;
- In addition to short-term effects (mostly corrected in the N2 and N3 data releases), long-term instrumental trends are present (Auvergne et al. 2009);
- Long-term trends are usually corrected by fitting a low-order polynomial and dividing by the best fit.

Kepler

epler was launched in March 2009;

l end of May 2014, it observed a fixed field in the Cygnus constellation, then it started the so-
lled K2 mission observing fields along the ecliptic for ~ 75 days each;

he telescope aperture is 95 cm, the passband 430-890 nm (FWHM);

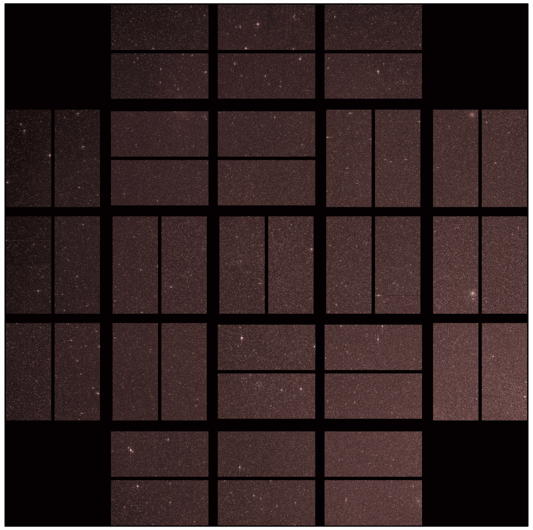
uring the main mission, the spacecraft was rolled every 90 days (a quarter) with a correspondin
tation of the focal plane;

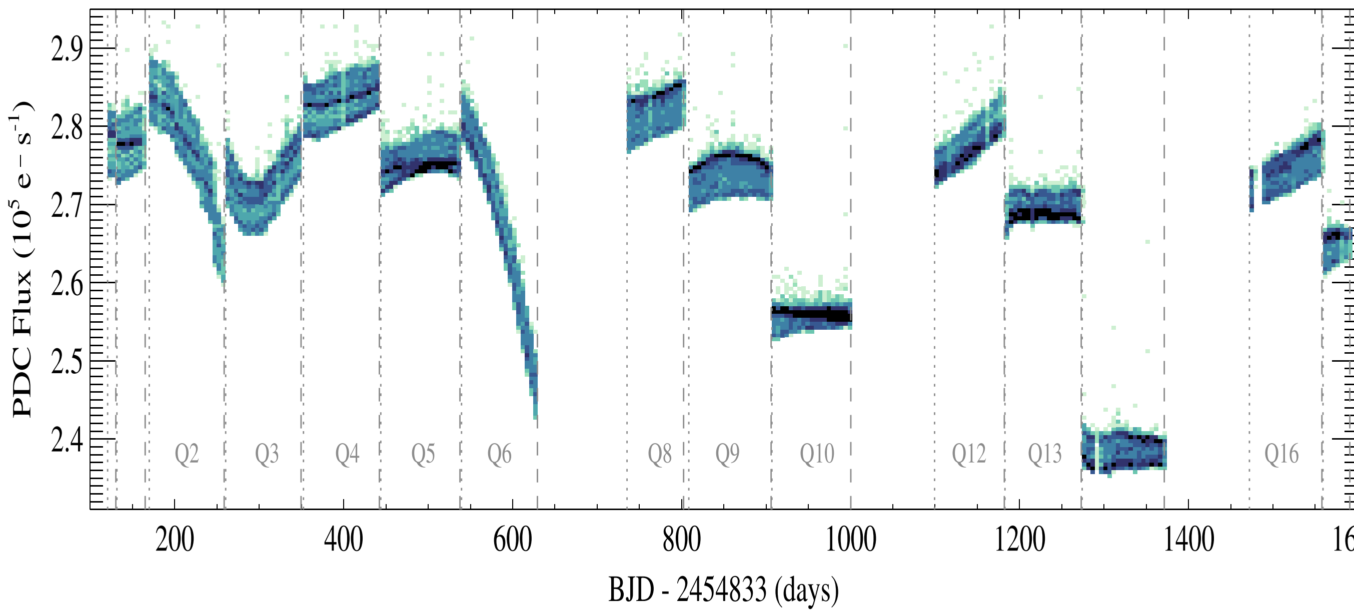
his produced large jumps in photoelectron counts for each target from one quater to the next;

oreover, smaller instrumental variation were present, especially every ~ 30 days when data we
ownloaded to Earth;

orrections have been developed with the purpose of preserving variations on short time scales
om a few hours to a few days).

Kepler photometry





: The 42 CCDs on Kepler focal plane; Right: the raw light curve of GJ 1243 (Davenport et al. 2015).

ndard methods were developed to correct for instrumental effects, but they are optimized to extract transit s
pressing also most of the stellar intrinsic variations.

HD 49933 as observed by CoRoT

Garcia et al. (2010) found a short-term (~ 120 days) cycle in this F5V star (P_{rot} = 3.45 d) both with a photometric index and the variation of the p-mode frequencies (see also Salabert et al. 2011).

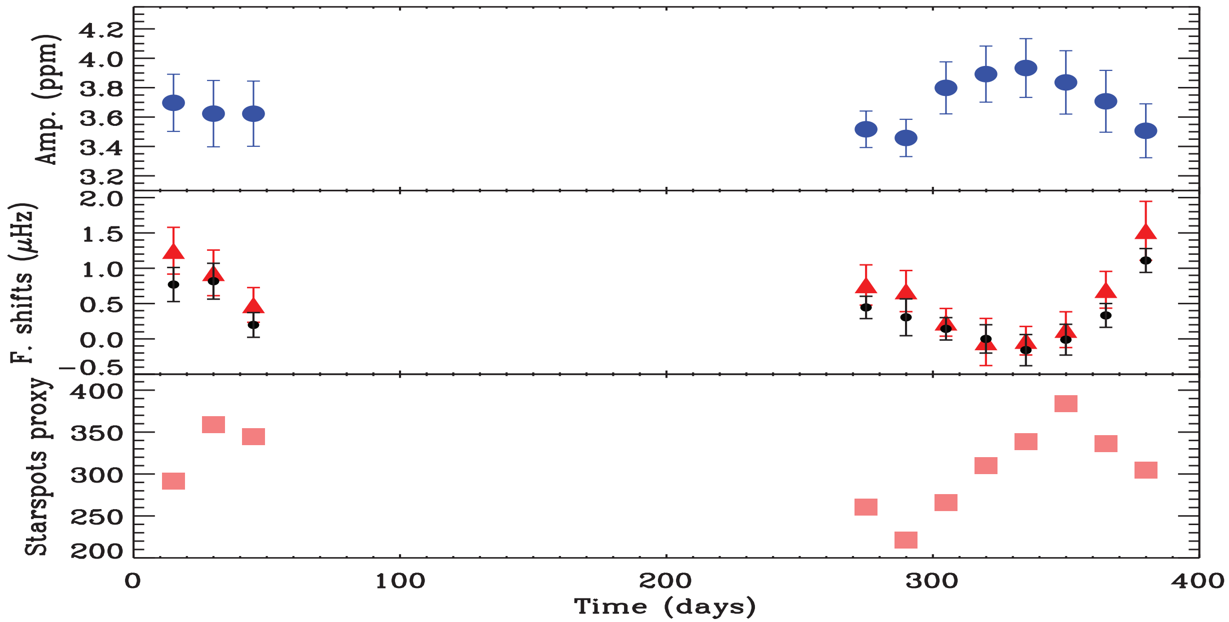
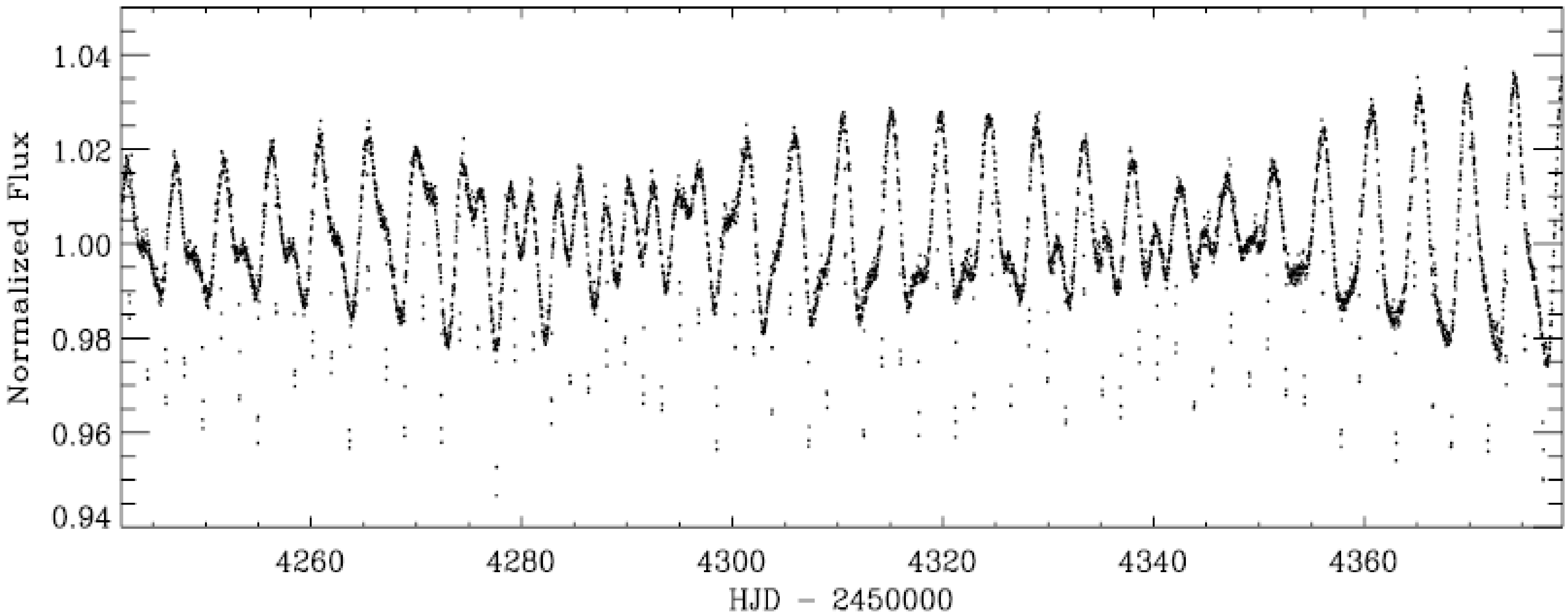


Fig. 1. Time evolution beginning 6 February 2007 of the mode amplitude (**top**); the frequency shifts using two different methods (**middle**), cross correlations (red triangles) and individual frequency shifts (black circles); and a starspot proxy (**bottom**) built by computing the standard deviation of the light curve (*7*). All of them were computed by using 30-day-long subseries shifted every 15 days (50% overlapping). The corresponding 1σ error bars are shown.

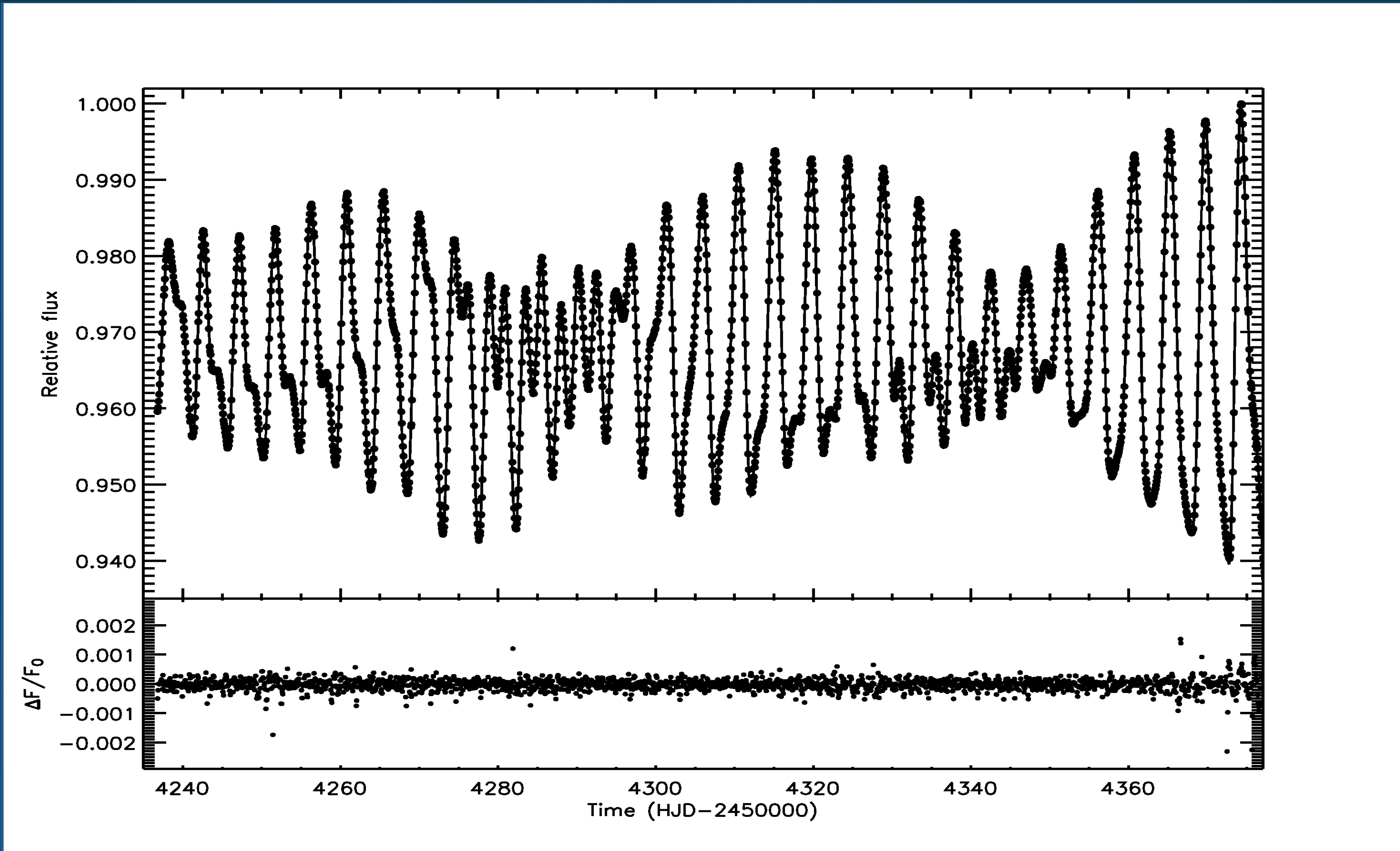
CoRoT-2

- CoRoT-2 is a G7V star accompanied by a massive planet on a 1.743-d orbit (Alonso et al. 2008; Bouchy et al. 2008);
- It was one of the brightest CoRoT targets with a planet and was therefore the subject of several investigations;
- The mean rotation period is 4.52 days and there are hints of differential rotation (see below).

CoRoT-2 light curve

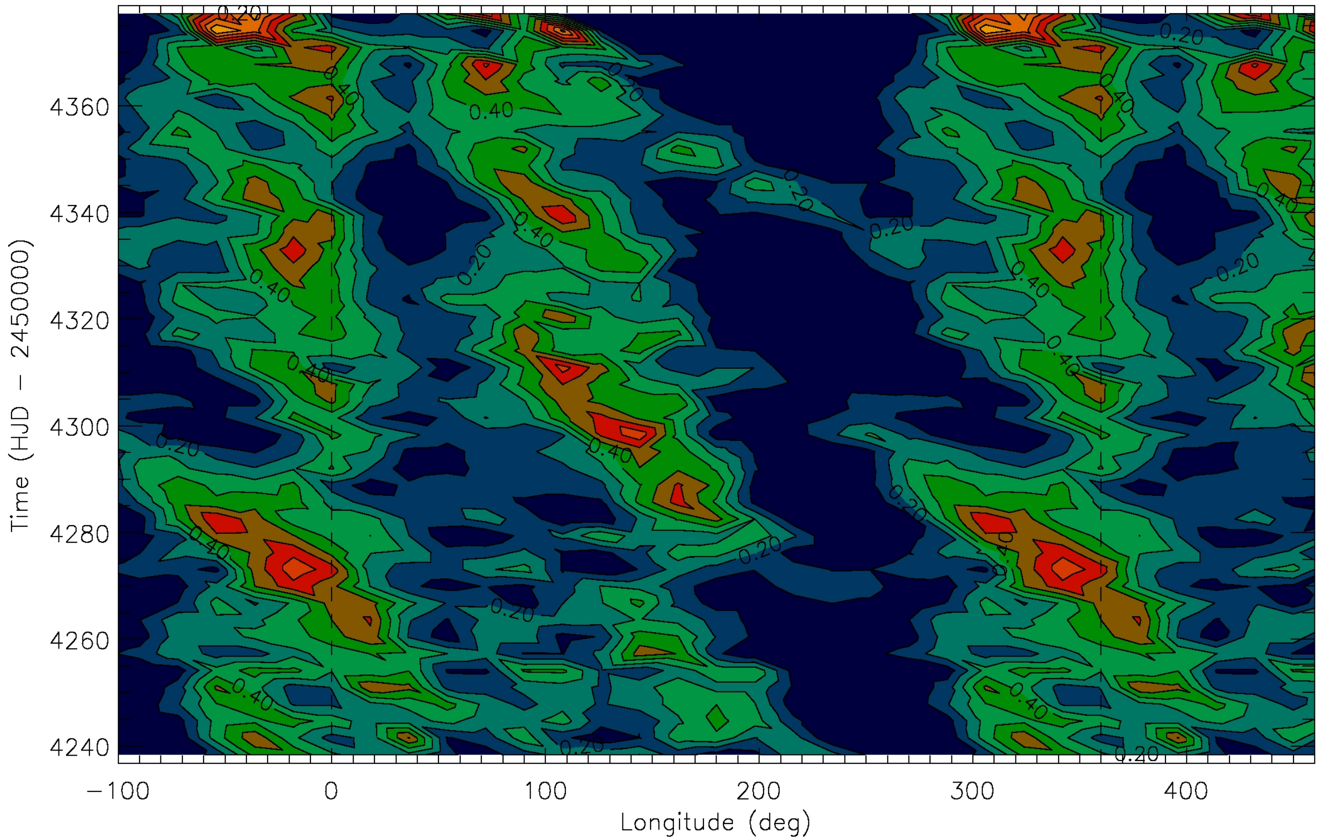


aximum Entropy spot model best fit of the out-of-transit light cu



ata points obtained by binning the flux measurements along each satellite orbital period of 6184 s; Lanza et al 200

Spot area vs. longitude and time



(The rotation period of the longitude reference frame is 4.5221 days)

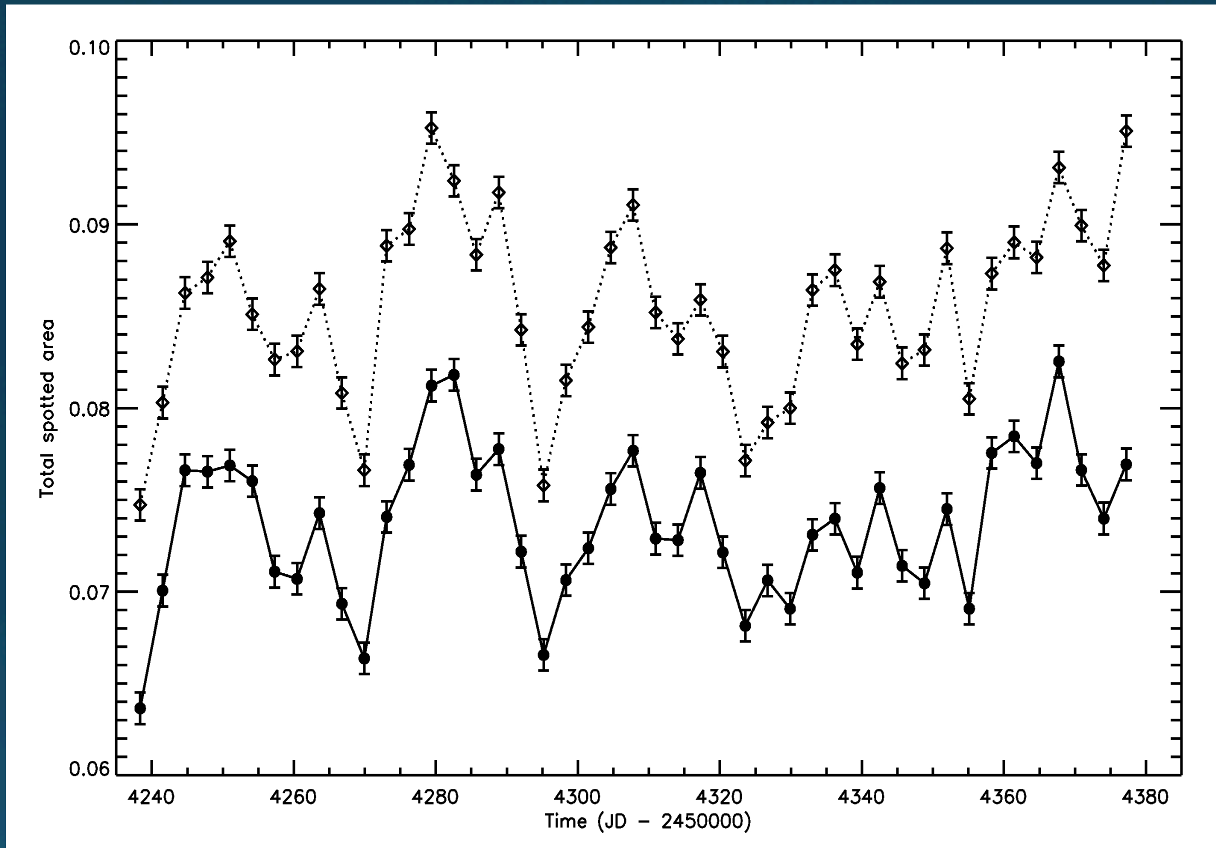
Differential rotation in CoRoT-2

- Individual spot groups migrate backward in longitude during their lifetime, i.e., their angular velocity is lower than that of the active longitudes (cf. *sunspot group braking*; Zappalà & Zuccarello 1991; Schuessler & Rempel 2005);

- One of the *active longitudes* is almost fixed while the other migrates backward, suggesting a surface differential rotation with a relative amplitude $\Delta\Omega/\Omega \approx 0.9$ percent (this is actually *a lower limit* to $\Delta\Omega/\Omega$);

- Modelling the migration of *individual spots*, a higher differential rotation is derived: $\Delta\Omega/\Omega \approx 8$ percent (Fröhlich et al. 2009; Huber et al. 2010).

Variation of the spot area vs. time (a Rieger cycle ?



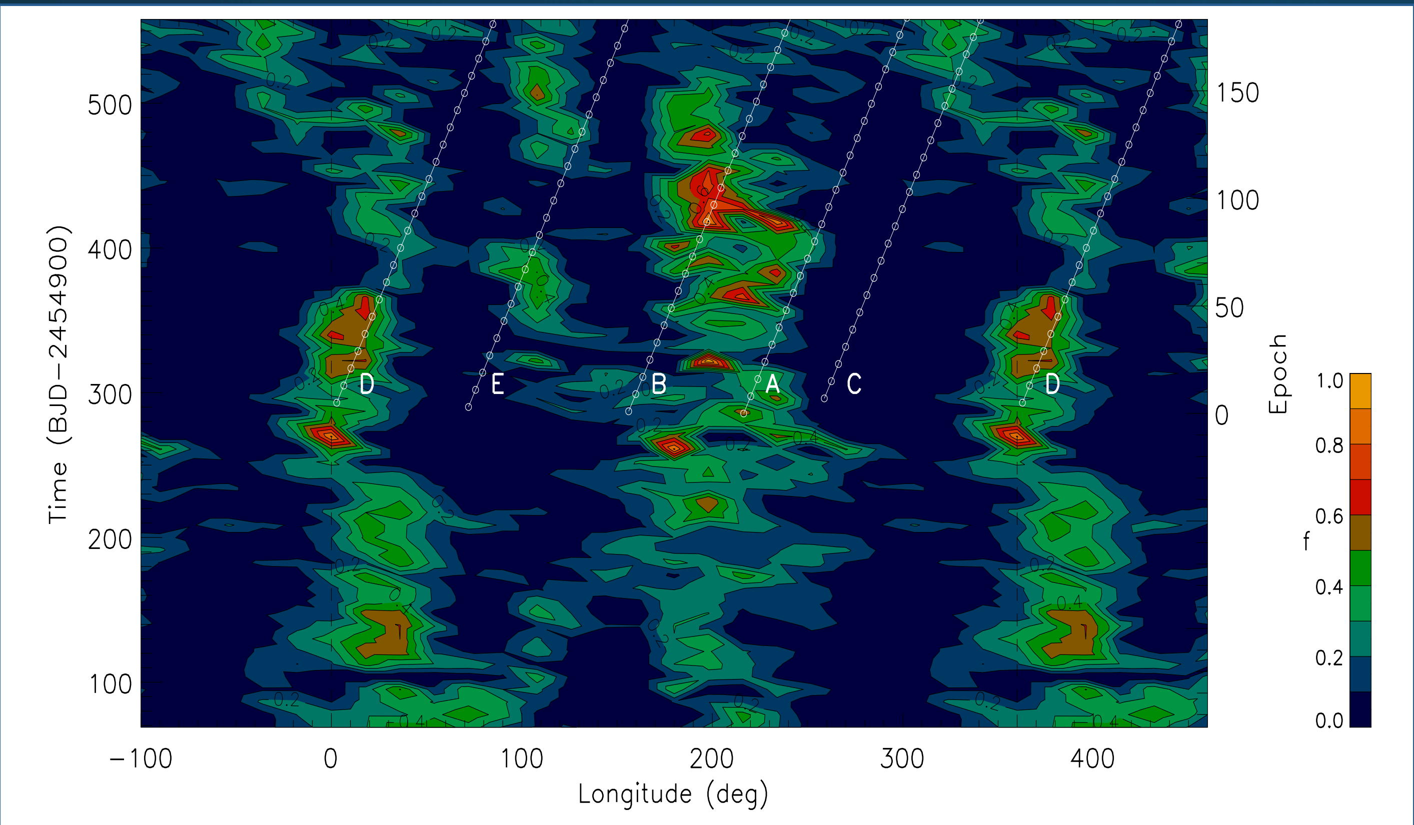
Spots only (solid line): P_{cyc} = 28.9 ± 4.8 days;
Spots and faculae with $Q = A_f/A_s$ = 1.5 (dot-dashed line): P_{cyc} = 29.5 ± 4.8 days (after Lanza et al. 2009);

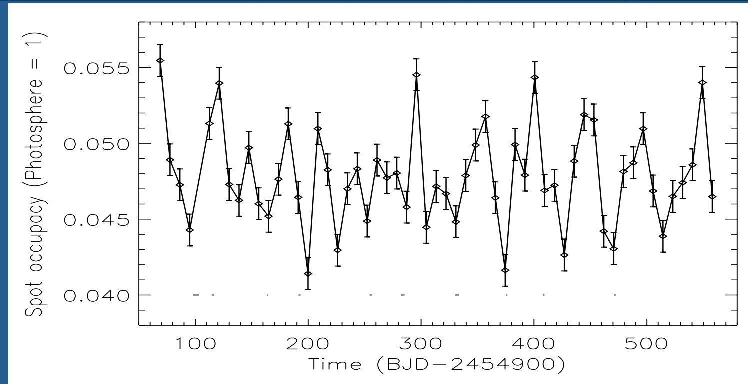
Kepler-17

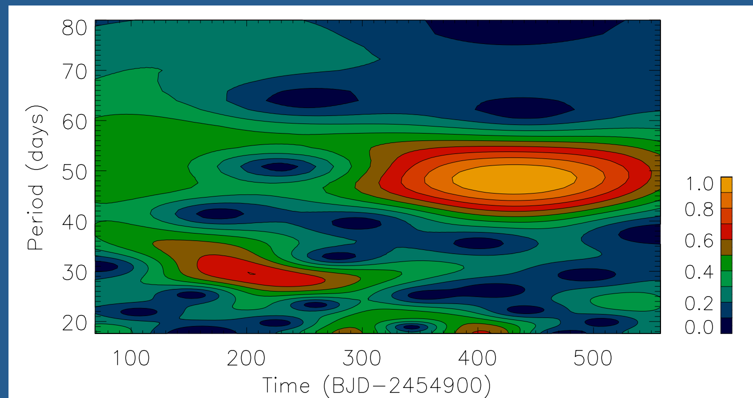
onomo & Lanza (2012) fitted the out-of-transit light curve of Kepler-17, a G2V star with P_{rot} = 12.0 day
ccompanied by a hot Jupiter with an orbital period of 1.486 days ;

hey found active longitudes in Kepler-17 and a general correspondence with the spots occulted by th
lanet during transits;

Rieger-like cycle with a period of ≈ 48 days was detected in the second half of the dataset.





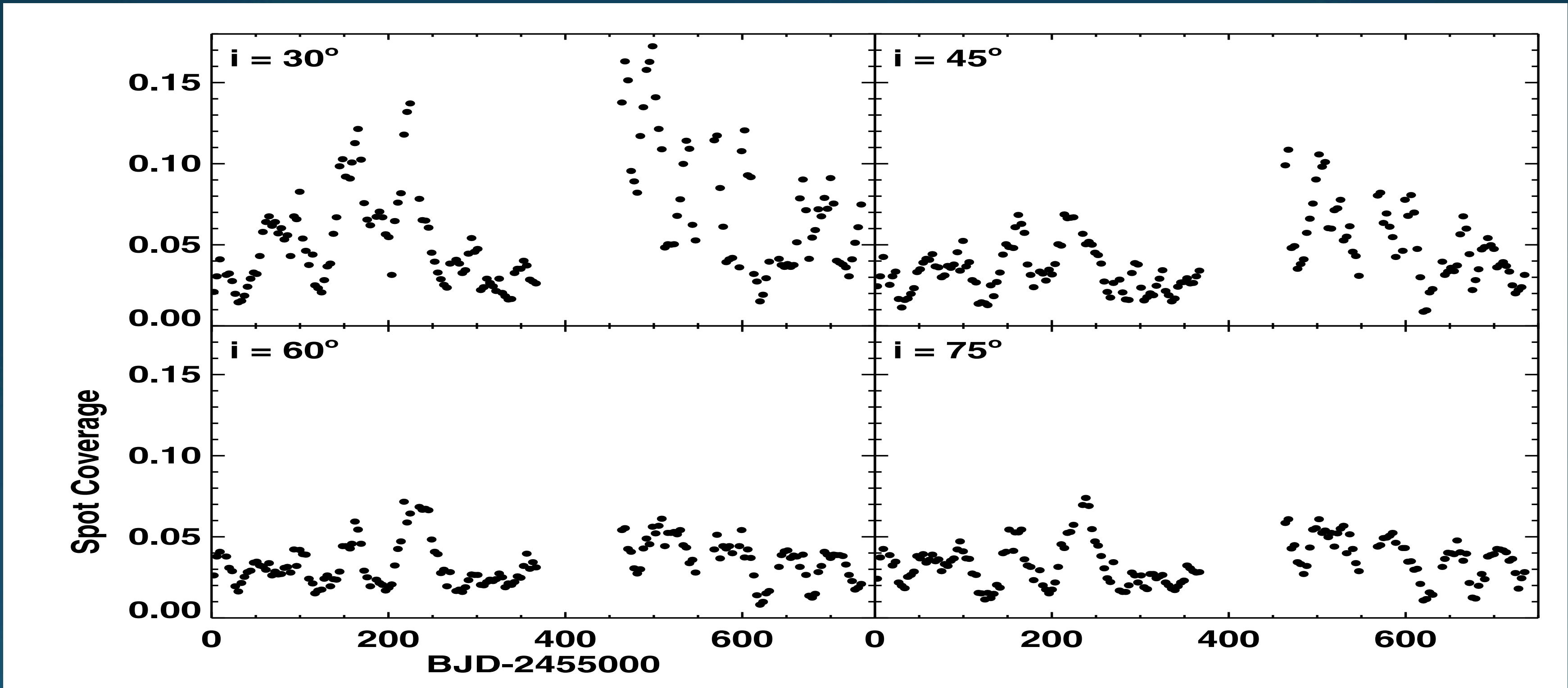


KIC 5110407

Roettenbacher et al. (2013) modelled the light curve of this KV star with a rotation period of 3.47 days;

The star shows hints of surface differential rotation from the migration of its active longitudes;

The modulation of the spot area is difficult to characterize due to the unknown inclination, but possibl cycles of about 70-80 days could be present.



Short-term cycles in Kepler and CoRoT targets

- Mathur et al. 2014 (Kepler);
- Vida et al. 2014 (Kepler);
- Arkhypov et al. 2015 (Kepler);
- Ferreira Lopez et al. 2015 (CoRoT).

Mathur et al 2014

They consider a sample of 22 F-type stars (T_{eff} > 6000 K) with P_{rot} < 12 days and etected p-modes;

They consider two activity proxies:

- The standard deviation of the flux along intervals of 5 P_{rot} ;
- The projection of the Morlet wavelet amplitude over a short interval centred around P_{rot} (Scale Average Variance or SAV);

They find 6 stars with long-lived surface features (~ 1000 days) that can produce beatings of the amplitude of the rotational modulation;

Only two stars show some hints of a cycle: KIC 3733735 with a period of ~ 1400 da and also a shorter period of 90 days produced by beatings); and KIC 10644253 with a period of ~ 650 days, two maxima of which have been observed.

Vida et al. (2014)

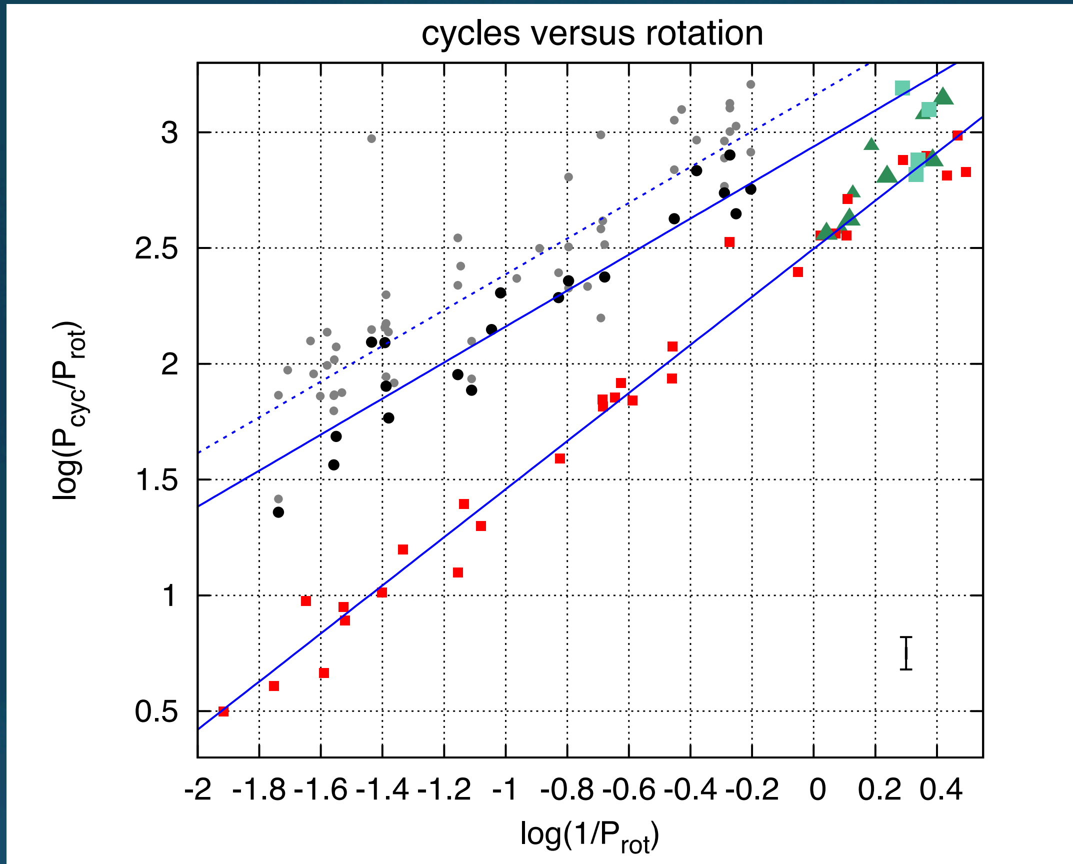
- They select stars with $T_{eff} < 4500$ K, $\log g < 4.5$ cm s^{-2}, $P_{rot} < 1$ day, apparently single and with low contamination by nearby objects;

- Out of 39 targets they find short-term cycles in 9 stars by detecting a modulation of their rotation period that is attributed to a latitudinal migration of the starspots on a differentially rotating star;

- The cycle periods are between 300 ± 50 and 600 ± 300 days;

- Previously, Vida et al. (2013) found cycles between 300 and 530 days in three rapidly rotating (P ~ 0.5 d) M-type dwarf stars;

Vida et al. 2014

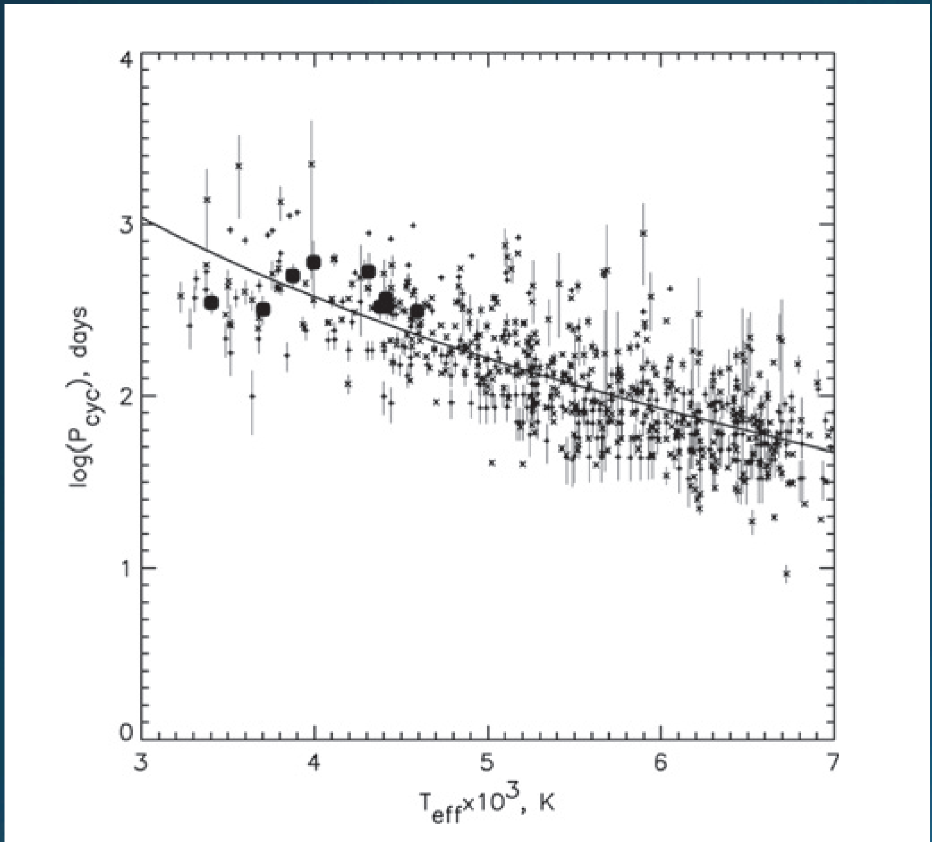


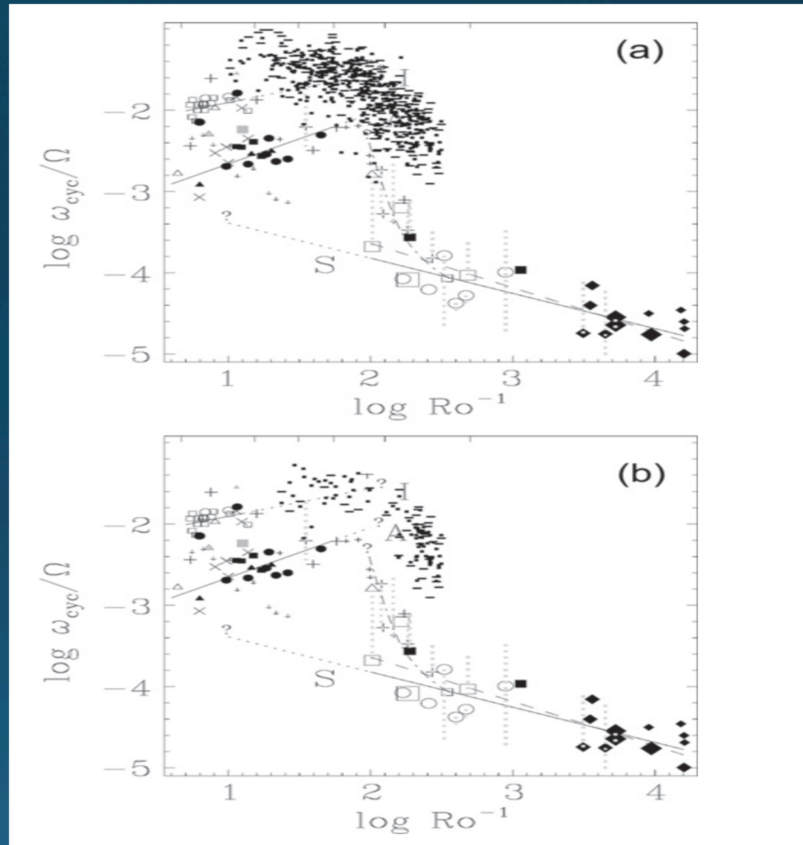
black dots, green squares, and green triangles stand for the shortest cycles from Olah et al. (2009), results from Vida et al. (2013), and Vida
respectively. Smaller grey dots are data from different survey already used in Olah et al. (2009). Smaller triangles indicate less certain p
ida et al. (2014); red filled squares are M dwarf stars from Savanov (2012). The dotted line represents the best fit to all the data excludi
while the solid lines represent the fits to the shortest cycles, the lower one including the M dwarfs by Savanov (2012) that do not sho
dence on the inverse of the rotation period.

Arkhypov et al. 2015

- They analysed apparently single stars with $1 < P_{rot} < 4$ days, $3500 < T_{eff} < 6750$ K with irregular and gradual variations in their light curve selecting a sample of 513 stars;
- They looked for variation in the amplitude of the fundamental periodicity of the light curve, i.e., that corresponding to the rotation period as measured by Nielsen et al. (2013);
- They found cyclic oscillations in 462 objects out of 519 (~ 90%);
- A test performed with the total solar irradiance finds the period of the 11-yr cycle as well as some hints of the Rieger period of ~ 150 days and of a 3-yr period, although this third periodicity is very marginal;
- An analysis was performed to look for possible beating effects finding no cases;
- The authors discuss the new cycle period in the framework of previous correlations between P_{cyc} and P_{rot} by Saar & Brandenburg (1999).

Arkhypov et al. 2015





eft: Cycle periods P_{cyc} vs. T_{eff} ; cycles by Vida et al. (2014) are shown by the black dots; *Right:* ω_{cyc}/Ω = $_{rot}/P_{cyc}$ vs. the inverse Rossby number Ro^{-1} = $4 \pi t_{MLT} / P_{rot}$ in the diagram proposed by Saar & randenburg. The new cycles seem to follow a different branch with respect to those previously founc ndicated by the solid lines.

Ferreira Lopes et al. 2015

hey analyze ~ 264 days of CoRoT photometry spanning a total of ~ 1880 days (~ 5.1
electing 16 FGK stars with clear rotational modulation ($1 < P_{rot} < 13$ days) and good S/N

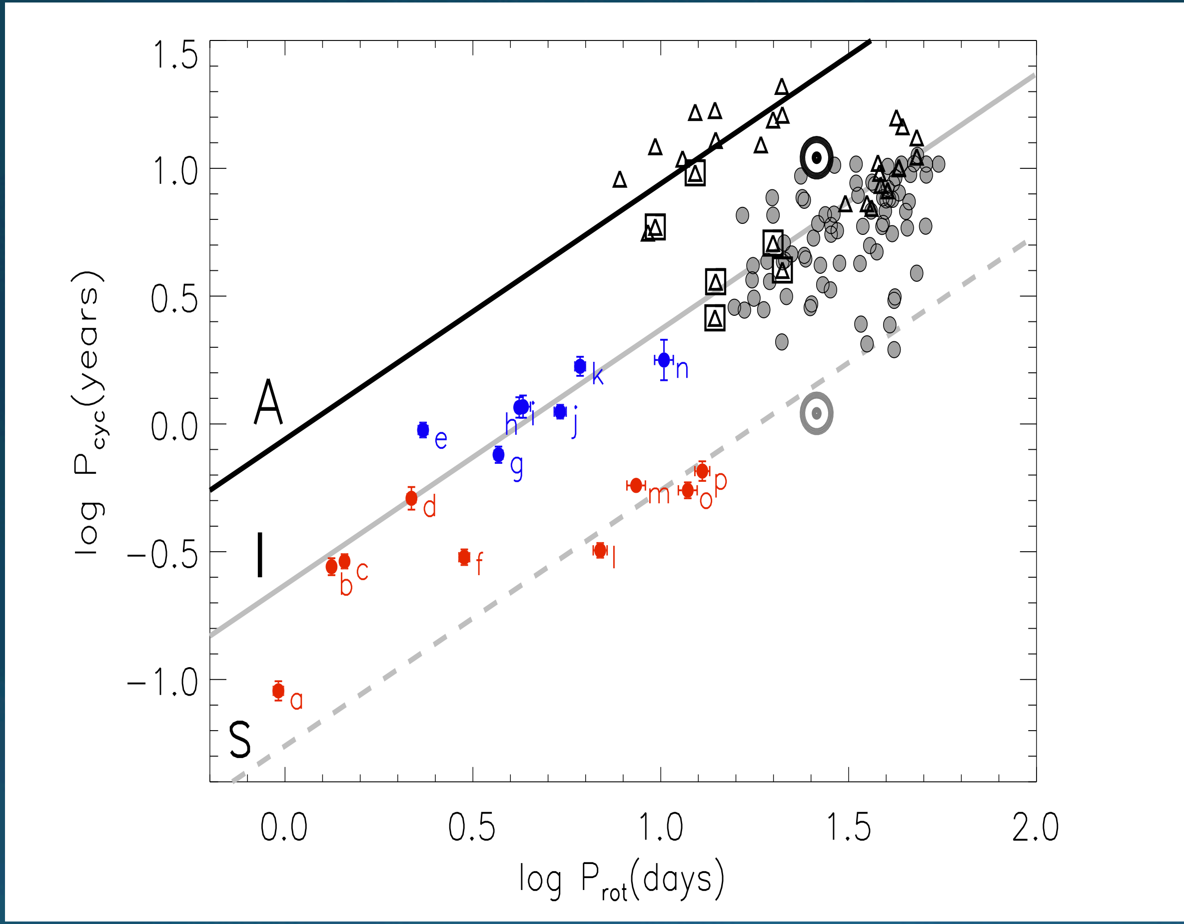
hey perform a fit with a trigonometric polynomial at the rotation period and the fi
armonic to study the variation of the best fit amplitude *A(t)* vs. the time *t*;

sing a Lomb-Scargle periodogram technique, they look for cyclic variations of *A(t)* w
AP < 0.01;

hey find cycle periods ranging from 33 to ~ 650 days, thus extending to shorter P_{rot} a
$_{cyc}$ the results of Lovis et al. (2011);

detailed study of the effect of the gaps in the CoRoT time series and of possible beati
ffects is postponed to a future work.

Ferreira Lopes et al. 2015



Ferreira Lopes et al. data are represented by red (Q > 0.75) and blue (Q < 0.75) circles, Saar & Brandenburg (1999) by black triangles, and data from Lovis et al. (2011) by gray circles. The squares indicate the sources with secondary periods according to Saar & Brandenburg (1999). The solar 11-yr and 1.1-yr cycles are indicated with the solar symbol. The solid lines show the empirical relationships for the A (active) and I (inactive) sequences of Bohm-Vitense (2007).

Conclusions

- Stellar analogues of the solar Rieger-like cycles have been detected in a few stars, but with shorter time series;
- UX Ari, CoRoT-2, Kepler-17, and possibly τ Boo appears to be the best examples;
- Other interesting cases, but with a modulation of a few years, have also been found, e.g., π^1 UMa;
- Preliminary investigations of the CoRoT and Kepler databases suggest several cases of Rieger-like (hundreds of days) or short-term activity cycles (P_{cyc} < 1-3 yr);
- Nevertheless, the role of beatings, active region evolution, and long-term instrumental effects must be investigated in detail before accepting the proposed cases;
- Clarifying the connection between the solar biennial oscillations and the Rieger cycles would be of great importance in interpreting any possible connection between stellar short-term cycles and Rieger-like cycles.

Additional material

GJ 1243 as observed by Kepler

- GJ 1243 is a mid-M dwarf with P_{rot} = 0.5926 days and an estimated mass of 0.24 $M_{\odot}$ (Davenport et al. 2015);
- It shows persistent active longitudes the migration of which can be used to estimate a lower limit for the surface differential rotation;