Starspots from time series analysis

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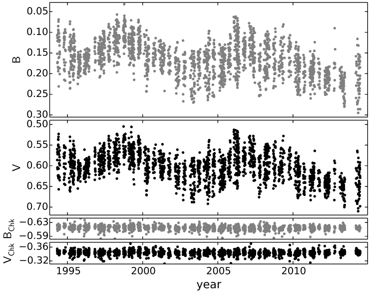
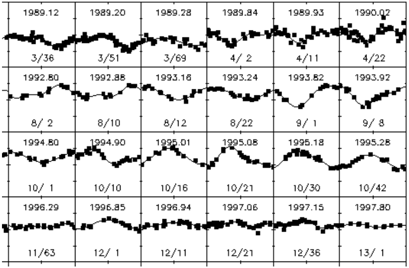
Lightcurve modelling

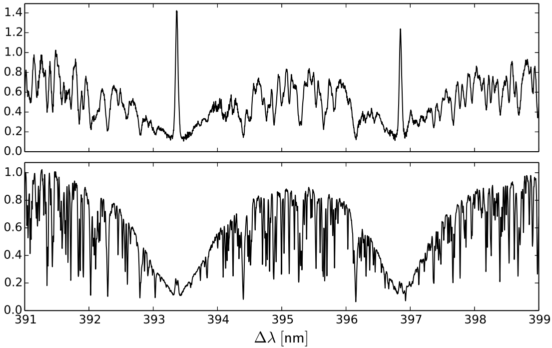
- Starspots on a rotating star cause brightness modulation that can be modelled as a low order harmonic
  $\hat{y}(t_i) = M + \sum_{k=1}^{K} \left[B_k \cos(k2\pi f t_i) + C_k \sin(k2\pi f t_i) \right]$
  - $\Rightarrow$ Light curve mean M, amplitude A, period $P = f^{-1}$, and minimum phases ϕ_{min} in a given rotation frame.





Chromospheric emission

- Chromospheric activity can be observed specroscopically ($H\alpha$, Ca II H&K etc.), typically though the $\log R'_{HK}$ index.
- Allows both the quantification of the activity level and the monitoring of activity variations.



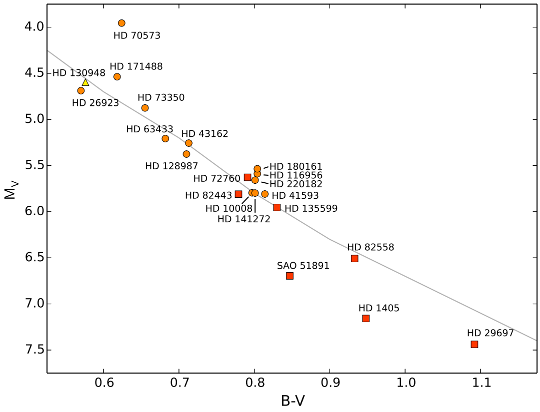
SAO 51891 & HD 26923

Observations

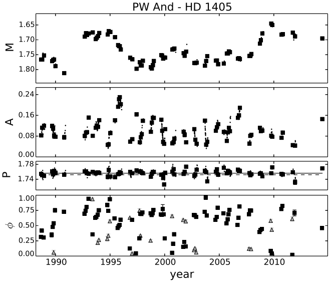
- T3 0.4 m Automated Photoelectric Telescope, Fairborn Observatory, AZ, USA
- Nordic Optical Telescope, 2.5 m, La Palma, Spain

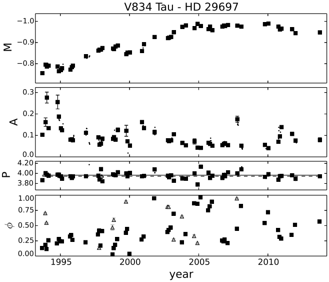
Sample

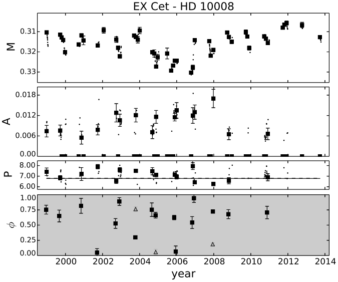
- 21 single F9 – K4 type main sequence stars with ages roughly between 5 Myr and 0.6 Gyr.
- Photometric record spanning 16 to 27 yr.

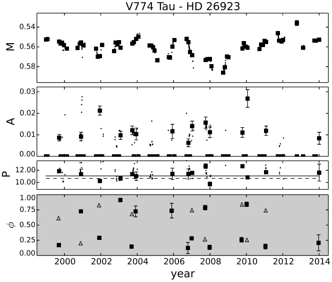


CPS results

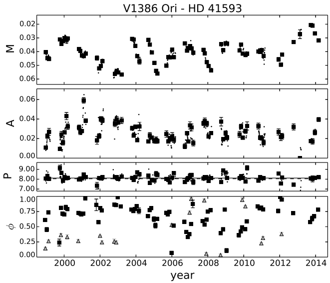

PW And - HD 1405
M
A
P
φ
year


V834 Tau - HD 29697
M
A
P
φ
year

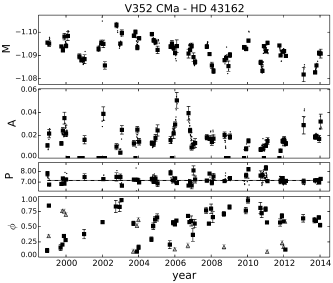

EX Cet - HD 10008
M
A
P
φ
year


V774 Tau - HD 26923
M
A
P
φ
year

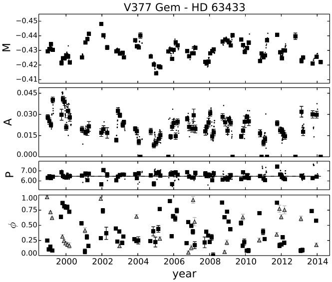
CPS results



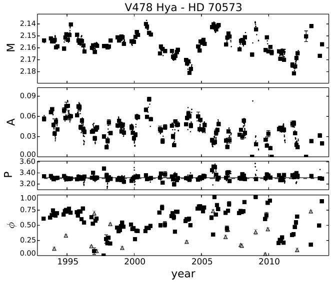
V1386 Ori - HD 41593
M
A
P
ϕ
year



V352 CMa - HD 43162
M
A
P
ϕ
year

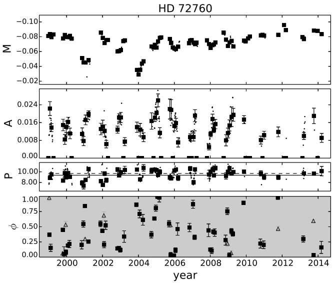


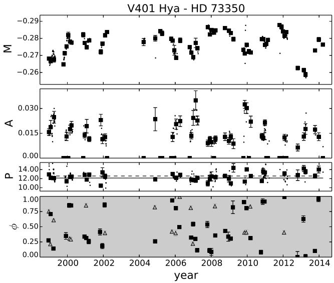
V377 Gem - HD 63433
M
A
P
ϕ
year

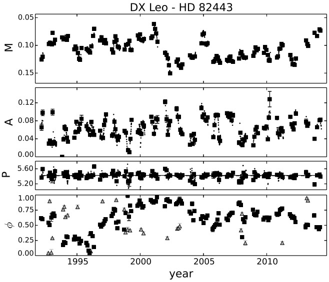


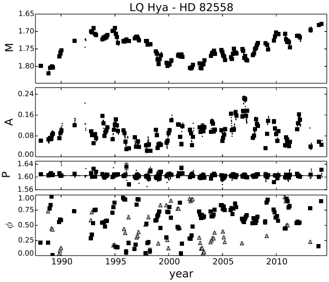
V478 Hya - HD 70573
M
A
P
ϕ
year

CPS results


HD 72760
M
−0.10
−0.08
−0.06
−0.04
−0.02
A
0.024
0.016
0.008
0.00
P
10.00
8.00
ϕ
1.00
0.75
0.50
0.25
0.00
2000 2002 2004 2006 2008 2010 2012 2014
year

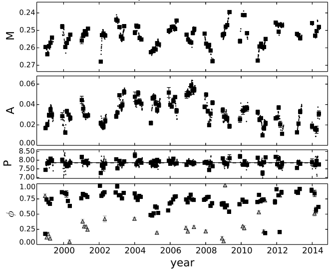

V401 Hya - HD 73350
M
−0.29
−0.28
−0.27
−0.26
A
0.030
0.015
0.00
P
14.00
12.00
10.00
ϕ
1.00
0.75
0.50
0.25
0.00
2000 2002 2004 2006 2008 2010 2012 2014
year


DX Leo - HD 82443
M
0.05
0.10
0.15
A
0.12
0.08
0.04
0.00
P
5.60
5.20
ϕ
1.00
0.75
0.50
0.25
0.00
1995 2000 2005 2010
year

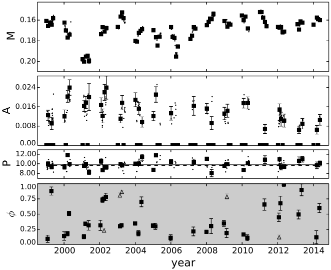

LQ Hya - HD 82558
M
1.65
1.70
1.75
1.80
A
0.24
0.16
0.08
0.00
P
1.64
1.60
1.56
ϕ
1.00
0.75
0.50
0.25
0.00
1990 1995 2000 2005 2010
year

CPS results

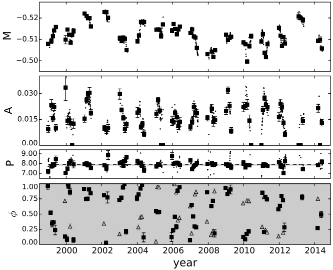
NQ UMa - HD 116956



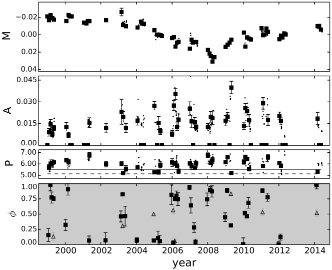
KU Lib - HD 128987



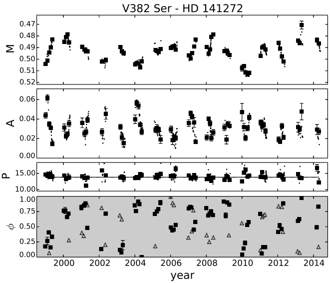
HP Boo - HD 130948

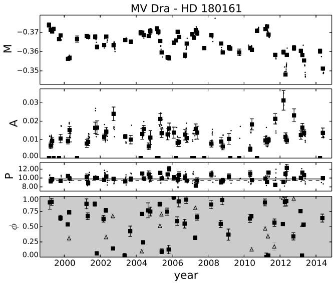


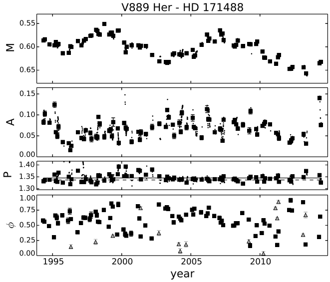
V379 Ser - HD 135599

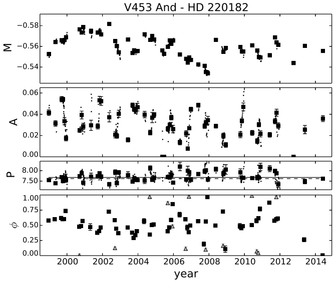


CPS results

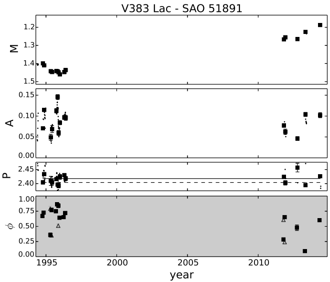

V382 Ser - HD 141272
M
A
P
ϕ
0.47
0.48
0.49
0.50
0.51
0.52
0.06
0.04
0.02
0.00
15.00
10.00
1.00
0.75
0.50
0.25
0.00
2000
2002
2004
2006
2008
2010
2012
2014
year


MV Dra - HD 180161
M
A
P
ϕ
−0.37
−0.36
−0.35
0.03
0.02
0.01
0.00
12.00
10.00
8.00
1.00
0.75
0.50
0.25
0.00
2000
2002
2004
2006
2008
2010
2012
2014
year


V889 Her - HD 171488
M
A
P
ϕ
0.55
0.60
0.65
0.15
0.10
0.05
0.00
1.40
1.35
1.30
1.00
0.75
0.50
0.25
0.00
1995
2000
2005
2010
year


V453 And - HD 220182
M
A
P
ϕ
−0.58
−0.56
−0.54
0.06
0.04
0.02
0.00
8.00
7.50
1.00
0.75
0.50
0.25
0.00
2000
2002
2004
2006
2008
2010
2012
2014
year

CPS results



V383 Lac - SAO 51891
M
1.2
1.3
1.4
1.5
A
0.15
0.10
0.05
0.00
P
2.45
2.40
ϕ
1.00
0.75
0.50
0.25
0.00
1995
2000
2005
2010
year

Issues to think about – Differential rotation

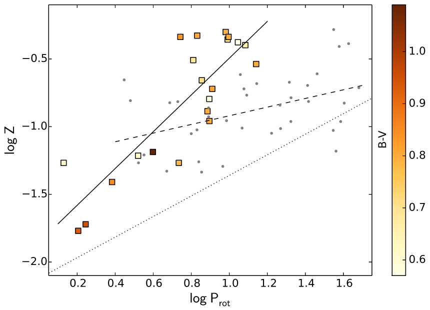
- We observe

$$Z = \frac{6\,Std(P)}{P} \propto k = \frac{\Delta\Omega}{\Omega}$$

and get

$k \propto P^{\mu} = P^{1.36}$,

$\Delta\Omega \propto \Omega^{\nu} = \Omega^{-0.36}$.

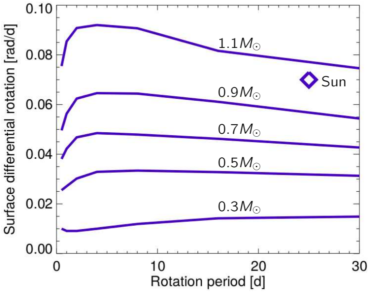


- How much does increased activity level on the fast rotators decouple the spots from the differential rotation?
- How can we get more certain values for μ and ν?

Issues to think about – Differential rotation

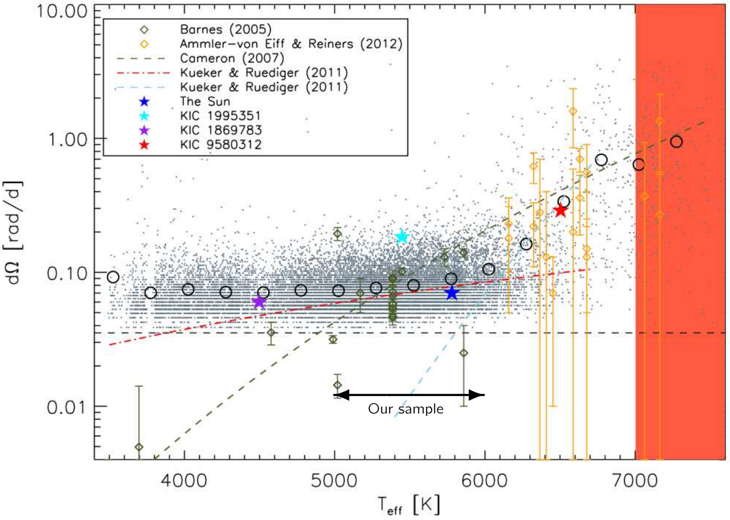
$$k \propto P^{\mu}$$
$$\Delta\Omega \propto \Omega^{\nu}$$

μ	ν	
0.76	0.24	Henry et al. (1995)
0.3	0.7	Donahue et al. (1996)
0.85	0.15	Barnes et al. (2005)
0.71	0.29	Reinhold & Gizon (2015)
1.36	−0.36	Lehtinen et al. (2016)



Küker & Rüdiger (2011)

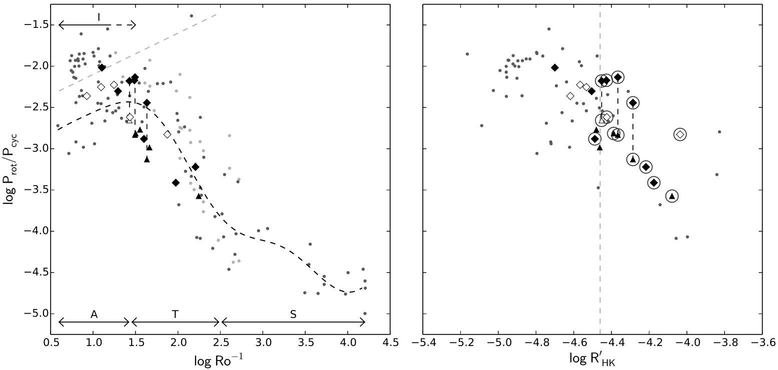
Issues to think about – Differential rotation



Reinhold et al. (2013)

Issues to think about –
Activity cycles & active longitudes

- New structure seen in cycle length sequences.
- Sharp boundary at $\log R'_{\mathrm{HK}} = -4.46$
  limiting active longitudes to its more active side.



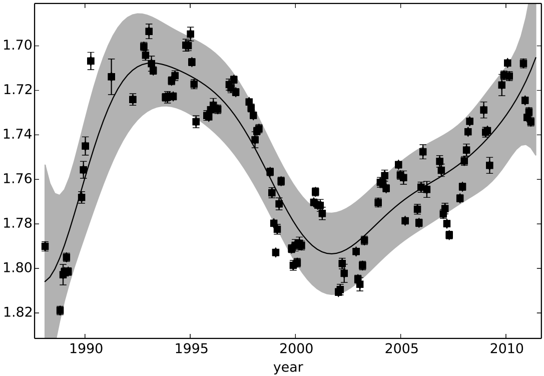
Issues to think about – Activity cycles & active longitudes

However:

- Currently cycles are searched using a sinusoidal model when the actual cycle profiles are more complex.
  - Not all cycles may be recovered.
- The detection limits for cycles and active longitudes also suffer from subjectivity.
  - Affects especially the cutoff limit between stars with and without active longitudes.

Issues to think about – Activity cycles

- A ~ 3 yr low amplitude cyclicity on LQ Hya which escapes the Lomb-Scargle period search.



Issues to think about – Activity cycles

- Modelling the cycle data as a Gaussian process could facilitate the finding of more elusive cycles by not assuming a strict model shape,

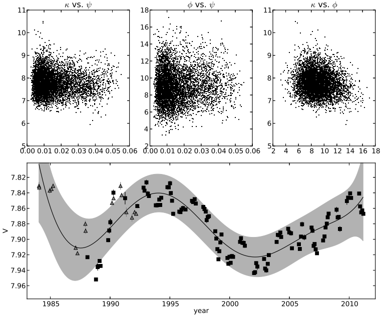
  $$y(t) = f(t) + \epsilon,\ \ \epsilon|\theta \sim \mathcal{N}[0, \Sigma(\theta)],\ \ \Sigma(\psi, \kappa, \phi) = \psi I + \kappa K(\phi)$$

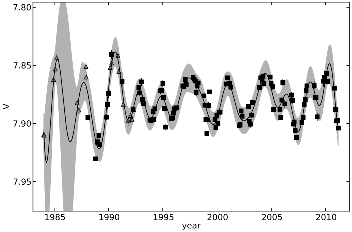
  with periodic and non-periodic kernels of e.g.

  $$K(\phi) = \cos\left[(t_i - t_j)/\phi\right],\ \ K(\phi) = \exp\left[(t_i - t_j)^2/\phi\right]$$

- Rasmussen & Williams,
  Gaussian Processes for Machine Learning
  `www.GaussianProcess.prg/gpml`

Issues to think about – Activity cycles





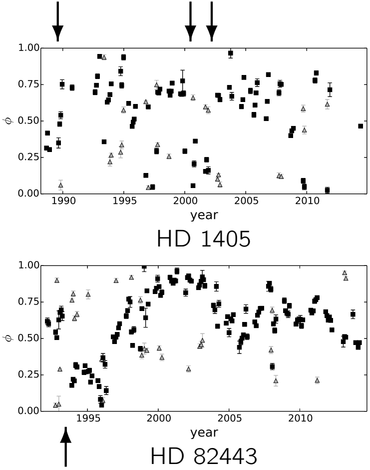
Issues to think about – Activity cycles

- The variable fit may be checked against a constant model with the Bayesian Information Criterion,

$$BIC = 2n \ln \sigma_\epsilon^2 + N_\theta \ln n$$

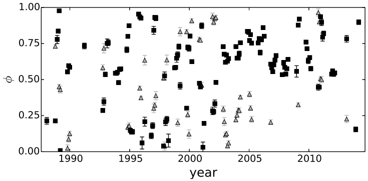
- Data accuracy has to be taken correctly into account to separate variability from non-variability.

- Do we need more robust definitions for what we mean by active longitudes and flip-flops?
- Both appear more common when you look at the data more closely.

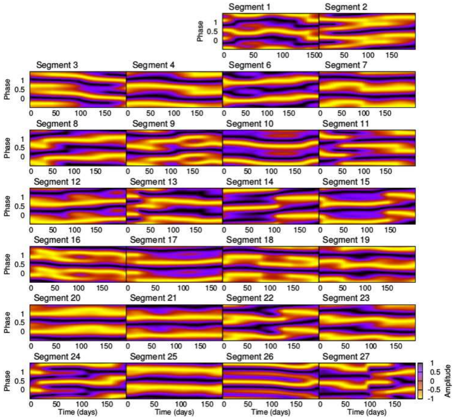


Issues to think about – Active longitudes

Two views on the active longitudes and flip-flops on LQ Hya



Lehtinen et al., (2016)



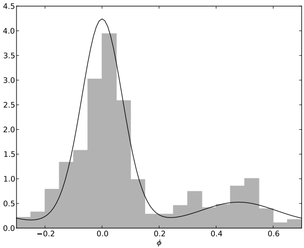
Olspert et al., (2015)

Issues to think about – Active longitudes

- More self consistent solution by modelling the phase distribution by von Mises distributions

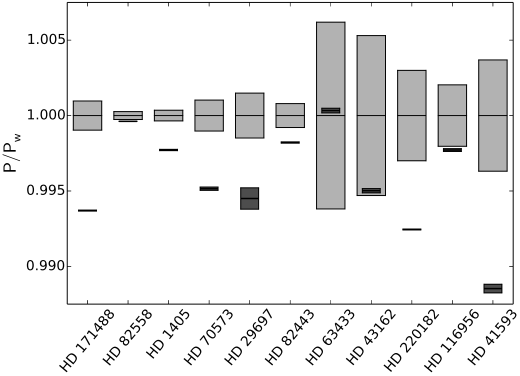
$$vM(\phi|\mu,\kappa) = \frac{\exp\left[\kappa\cos\left(\phi-\mu\right)\right]}{2\pi I_0(\kappa)}$$

- Comparison with an even distribution may require Reversible Jump MCMC.
- Possibility for change point models
(detection of flip-flops, active longitudes disappearing etc.)



Issues to think about – Active longitudes

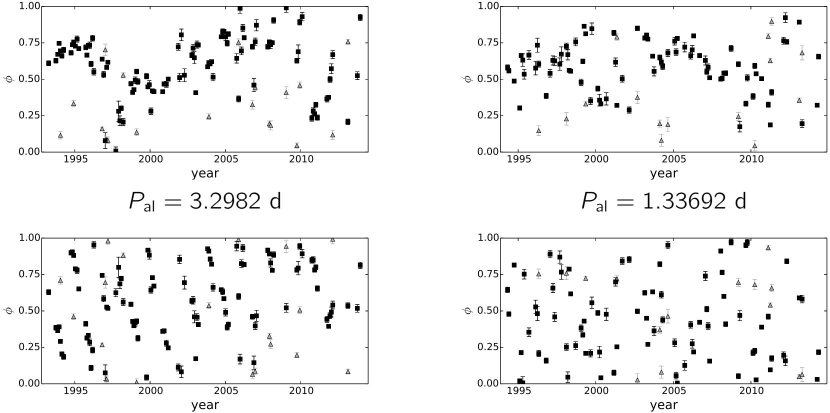
- Active longitude periods are systematically below photometric rotation periods.
- May indicate an azimuthal dynamo wave.



Issues to think about – Active longitudes

HD 70573

HD 171488



$P_{\rm al} = 3.2982$ d

$P_{\rm al} = 1.33692$ d

$P_{\rm rot} = 3.3143$ d

$P_{\rm rot} = 1.3454$ d