Acne at the Bottom of the Main Sequence

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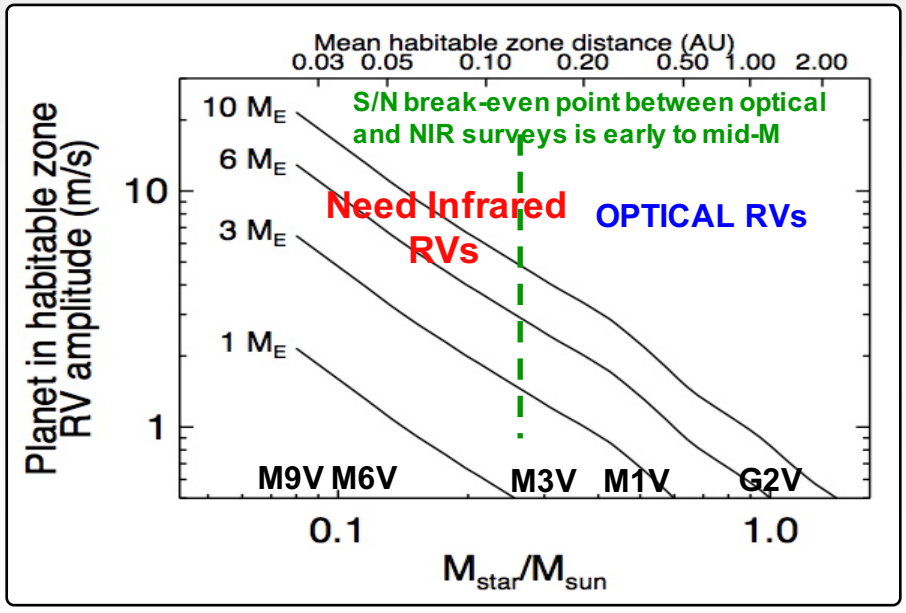
Credit: ESO/L. Calçada

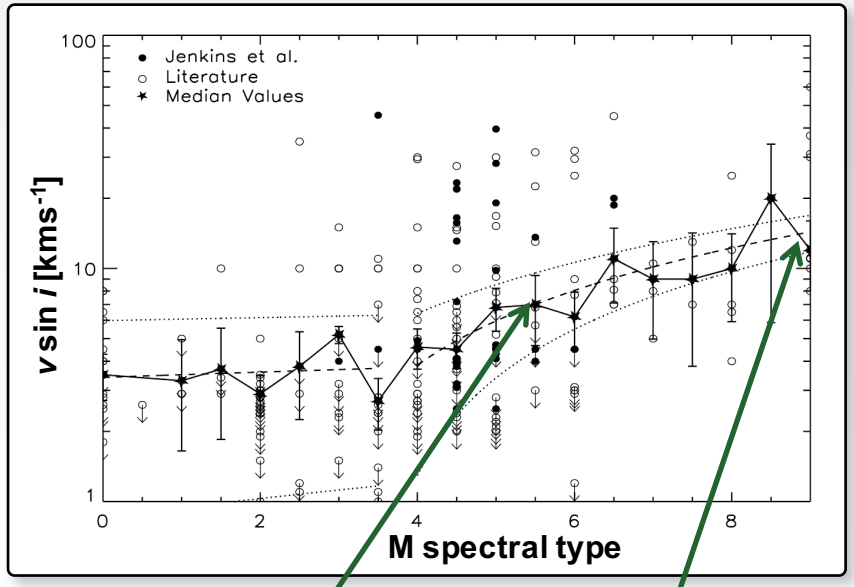
Precision RVs & M dwarf rotation

- RV surveys focusing on searches for rocky planets orbiting M dwarfs, including M5V - M9V
  - Planet formation at the bottom of the main-sequence
  - Occurrence rate of exoplanets



- Habitable zone planet orbiting M6V (0.1 $M_\odot$) star – $K_* \sim 1.7$ ms^{-1}
  - Orbits of a few days to a few days to ~20 days

- BUT: What about activity induced RV jitter?



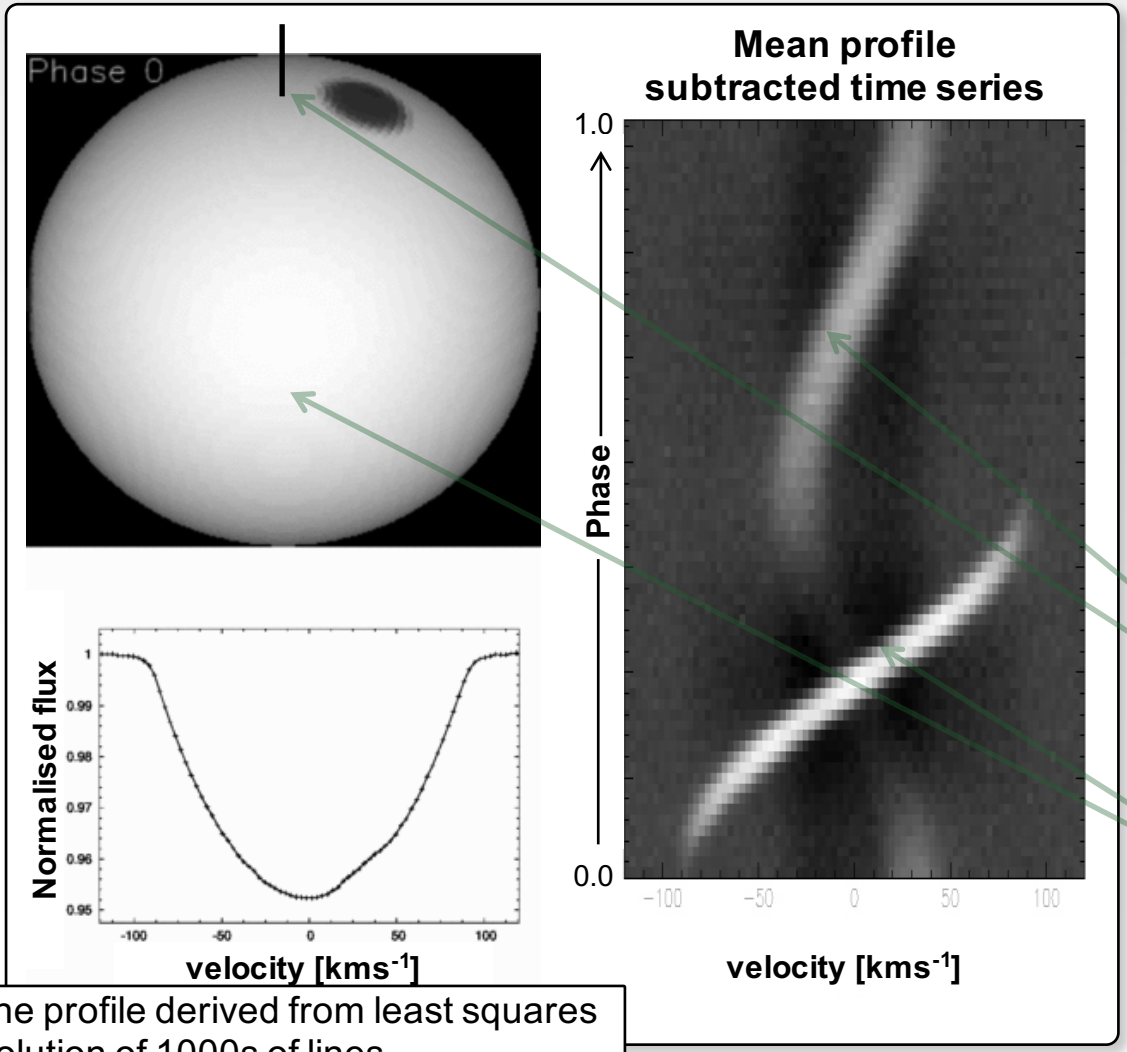
M5V
$v \sin i \sim 5$ kms^{-1}

M9V
$v \sin i \sim 15$ kms^{-1}

Probing spot distributions with Doppler imaging

- Time series profiles modelled with 2-temperature model spot filling factor

Image reconstruction with maximum entropy regularisation minimises spurious noise artefacts



Mean line profile derived from least squares deconvolution of 1000s of lines

- Line distortions (in white due to spots)
- Spot "bump" at 0 kms^{-1} is located on the meridian of the star → enables spot longitude to be determine
- Behaviour of spot feature in line profile (gradient/ velocity-extent) informs us of the stellar latitude

High latitude

Low latitude

M dwarf targets

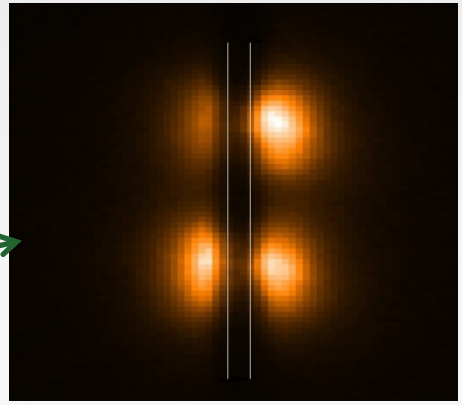
- Previous M1-M2V (Barnes et al. 2001, 2004) images and M4V stars at the fully convective boundary (Donati et al. 2006, Morin et al. 2008, Phan-Bao et al. 2009) to the latest M dwarfs

GJ 791.2A (HU Del) – **M4.5V** flare star. Astrometric binary *P* = 1.473 yrs

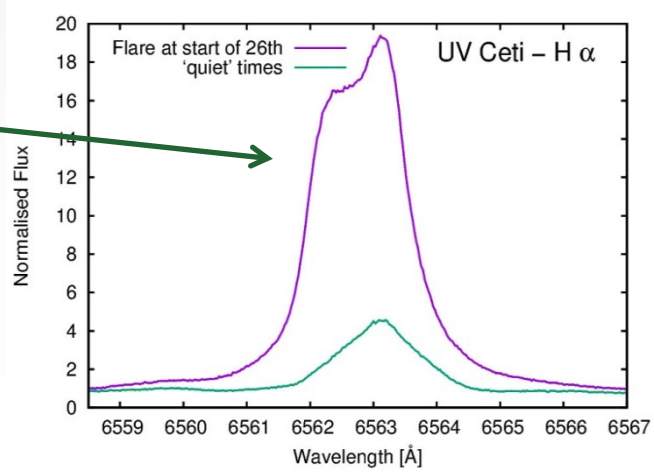
- Nearby young disk system - *d* = 8.84 pc

GJ 65 (Lutyen 726-8) – Visual binary, *P* = 26.52 year

- *d* = 2.68 pc. 6th closest system (recons.org)
- In 2015, the components were separated by 2.16´´ → 'buy one get one free'



- **GJ 65A** (BL Ceti) - **M5.5V** flare star
- **GJ 65B** (the infamous UV Ceti) - **M6V** flare star



LP 944-20 M9V

- At 6.41 pc is the 57th closest system to the Sun

Observations

- UVES @ VLT with wavelength range : λλ ~ 0.64 – 1.03 μm (excluding tellurics and chromospheric lines – Ca II IR triplet, H ✔, He I

GJ 791.2A time series

SpType M4.5V

Deconvolved line
SNR ~ 1900

***v sin i* = 35.3 kms^{-1}**

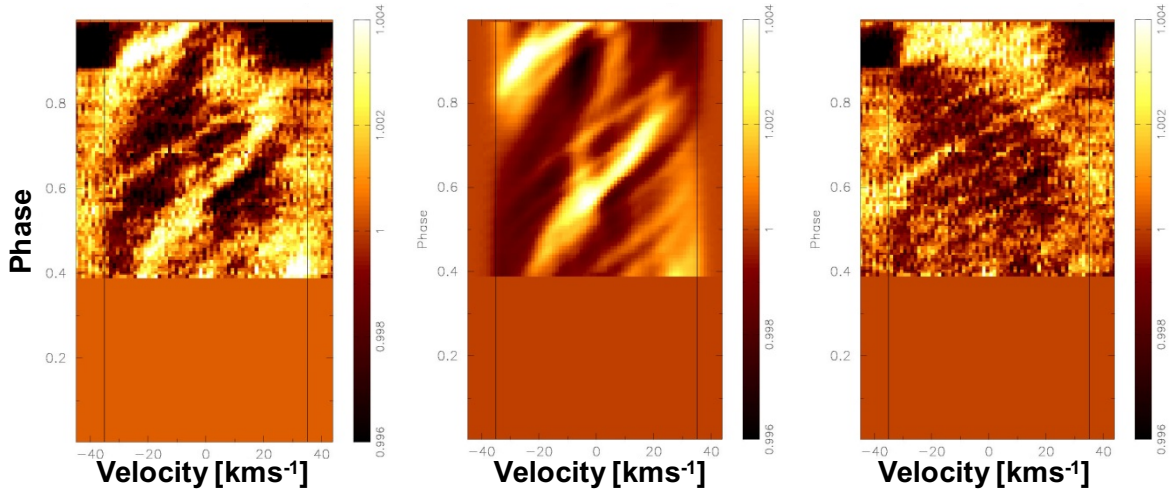
***P* = 8.2 hrs**

***i* = 51°**

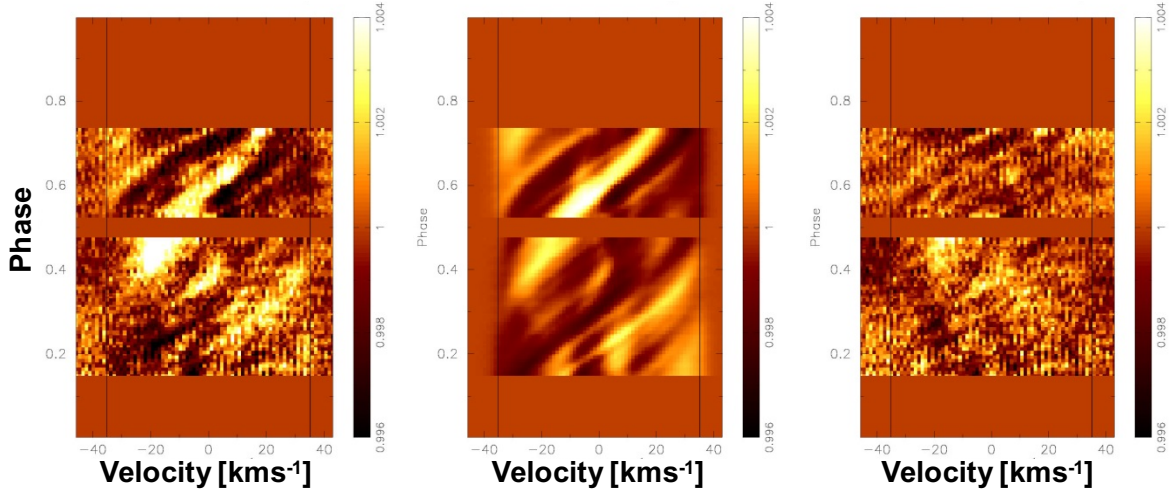
Fit
2015 Sept 25 & 28
χ^2 = 1.41

Mean line subtracted time series | **Maximum entropy regularised fits** | **Residual time series**

2015 Sept 25 (χ^2 = 1.54)

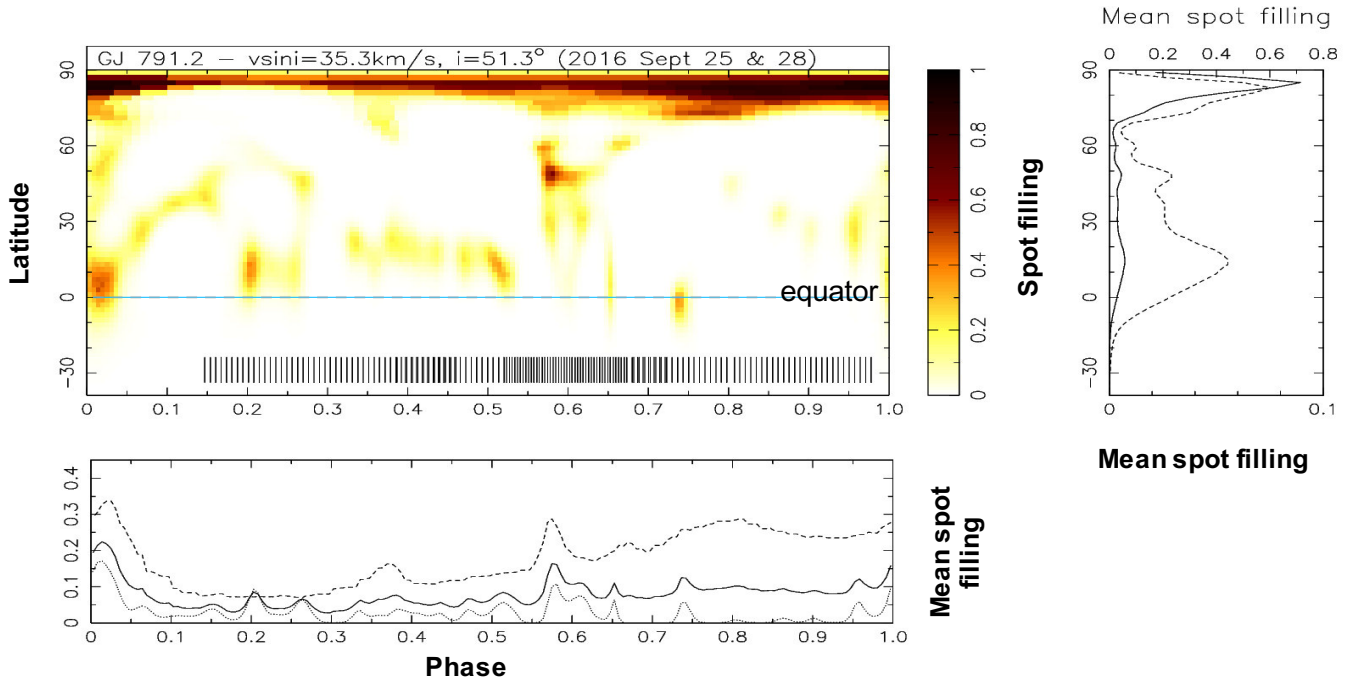


2015 Sept 28 (χ^2 = 1.05)



GJ 791.2A image (2015)

- T_{eff} = 3000K, T_{spot} = 2600K, I^c_{spot} / I^c_{phot} = 0.32,
  i = 51°, P = 0.3428 d (8.23 hrs), $v \sin i$ = 35.3 km s^{-1}



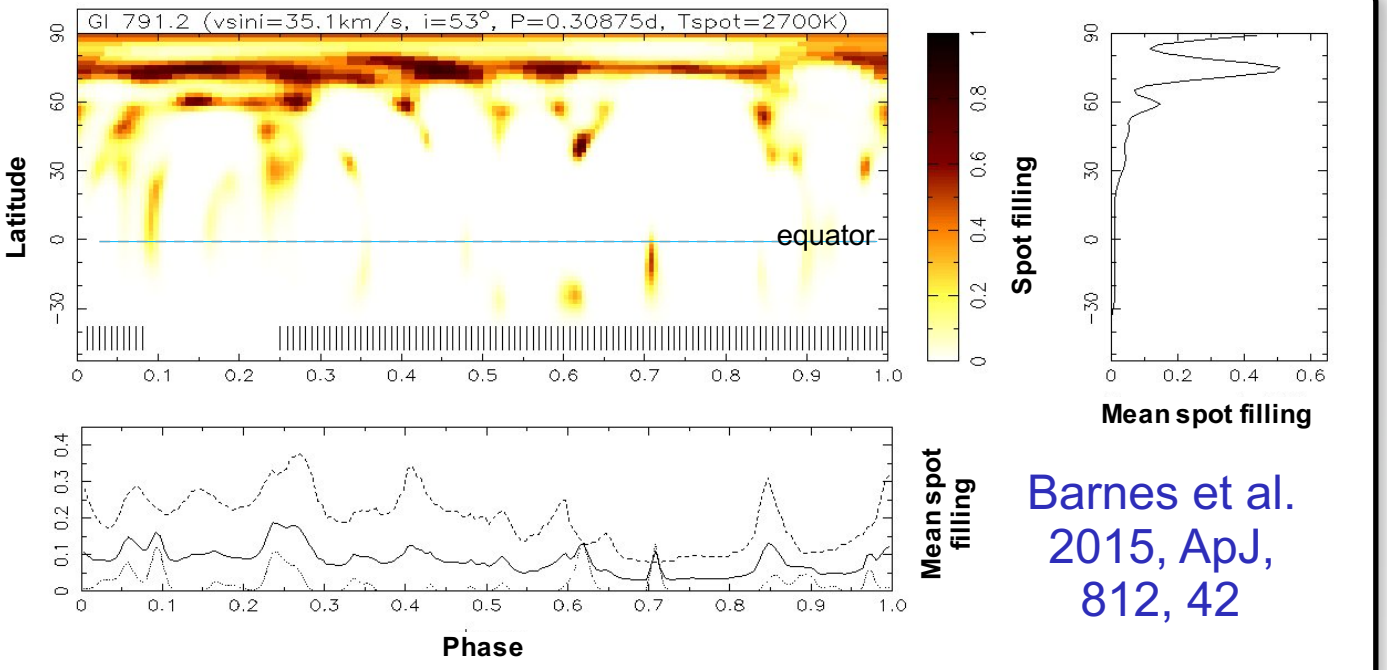
0.00 0.25 0.50 0.75

- Better phase overlap on both nights → slightly different optimised parameters
- Spot coverage similar
- Larger circum-polar spot
- Low latitude filling predominantly at latitude ~15°
- Mean spot filling = 2.7%
- Max spot filling = 92%

(χ^2 = 1.41)

GJ 791.2A image (2014)

- T_{spot} = 2700K, I^c_{spot} / I^c_{phot} = 0.42
- 59% (26th) & 57% (29th) phase coverage - 33% phase overlap



Deconvolved line SNR ~ 3600

Barnes et al. 2015, ApJ, 812, 42

- Spots located at a range of longitudes and latitudes
- Weak spot filling weak at low latitudes, increases at high latitudes
- Mean filling factor 3.2%
- Max filling factor 82.3%

(χ^2 = 1.4)

GJ 65A / BL Ceti time series

SpType M5.5V

Deconvolved line
SNR ~ 2500

$v \sin i$ = 28.6 kms^{-1}

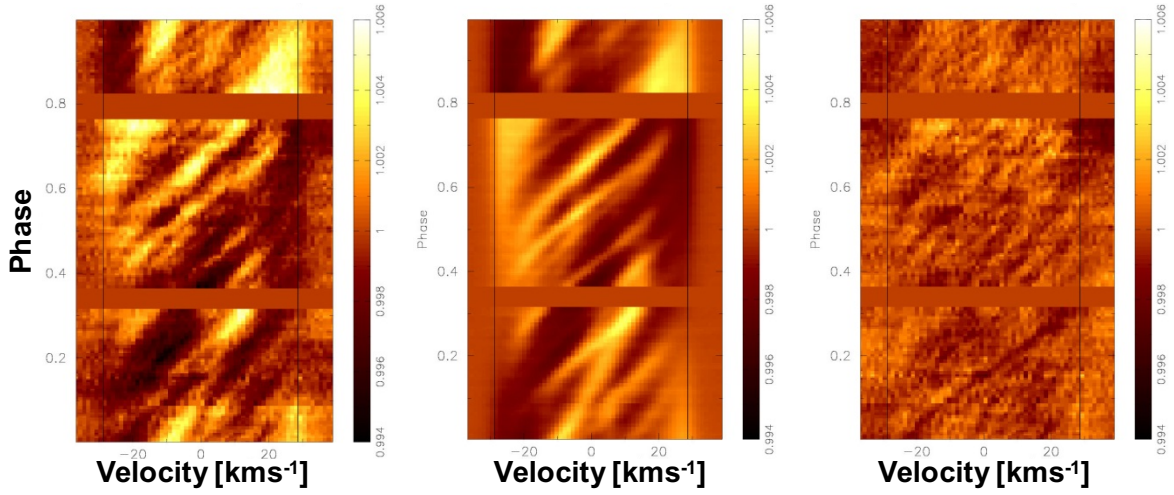
P = 5.84 hrs

i = 59°

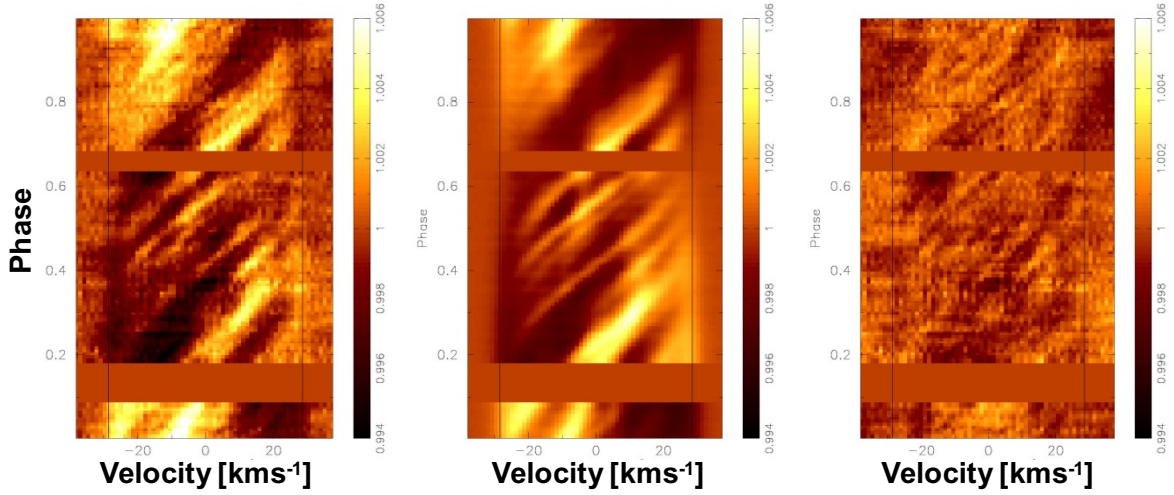
Fit
2015 Sept 26 & 29
χ^2 = 1.29

Mean line subtracted time series	Maximum entropy regularised fits	Residual time series

2015 Sept 26 (χ^2 = 1.09)

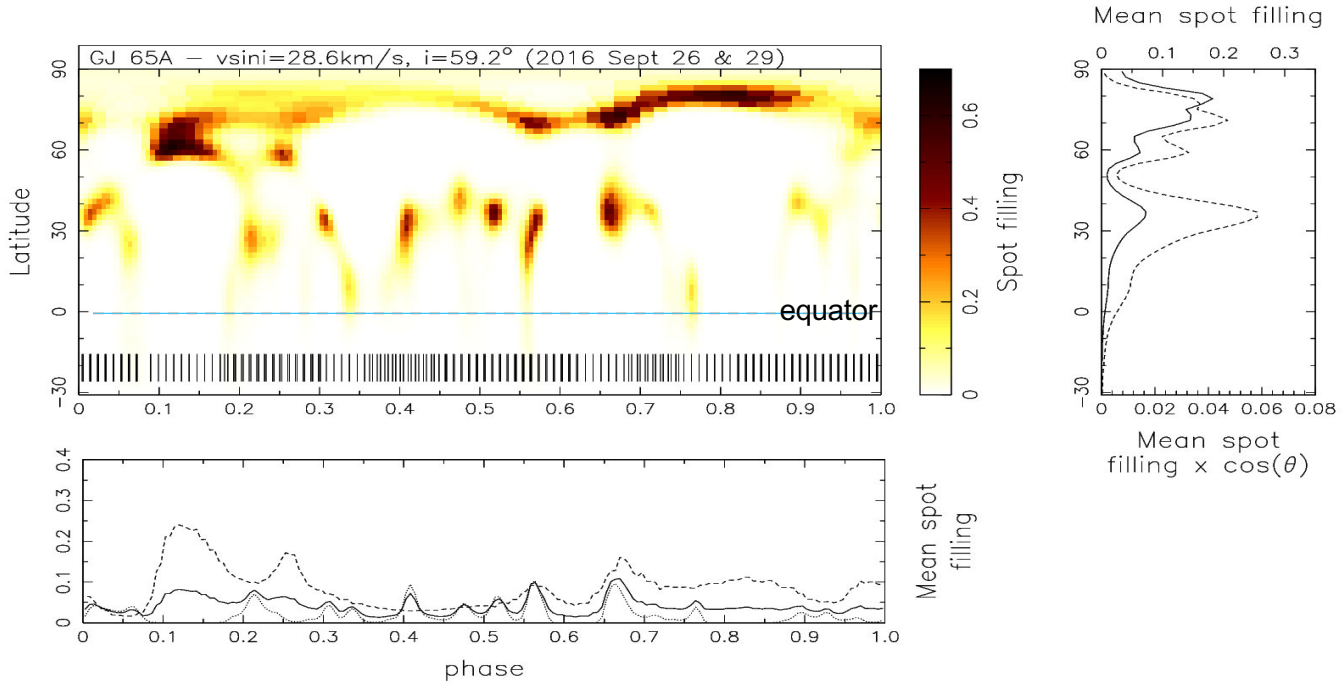


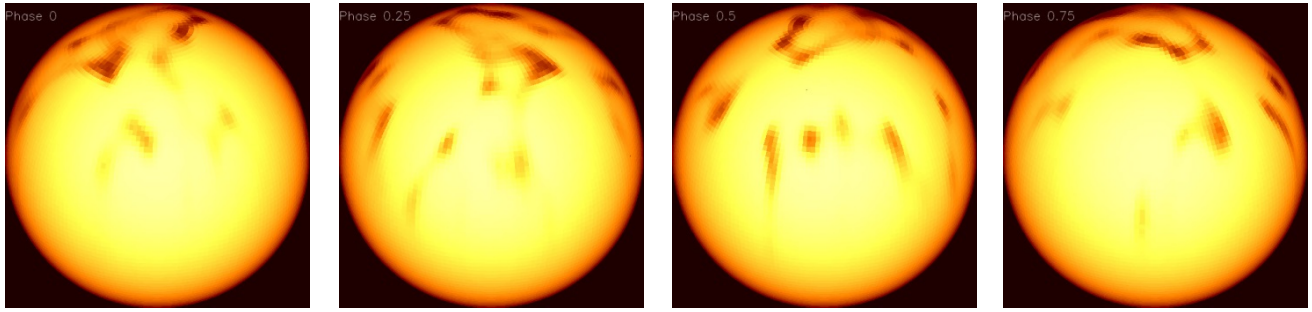
2015 Sept 29 (χ^2 = 1.02)



GJ 65A / BL Ceti image (2015)

- T_{eff} = 2800K, T_{spot} = 2400K, Ic_{spot} / Ic_{phot} = 0.26, i = 59°, P = 0.2432 d (5.84 hrs), $v \sin i$ = 28.6 km s^{-1}





0.00 0.25 0.50 0.75

- T_{spot} = 2500K, Ic_{spot}/Ic_{phot} = 0.39

→ max spot filling ~ 0.8

- 93% (26th) & 89% (29th) phase coverage - 82% phase overlap
- Large spots at high latitude
- Low latitude filling predominantly at latitude ~35°
- Mean spot filling = 1.9%
- Max spot filling = 64%

(χ^2 = 1.29)

GJ 65B / UV Ceti time series

SpType M6V

Deconvolved line
SNR ~ 1900

$v \sin i$ = 32.0 kms^{-1}

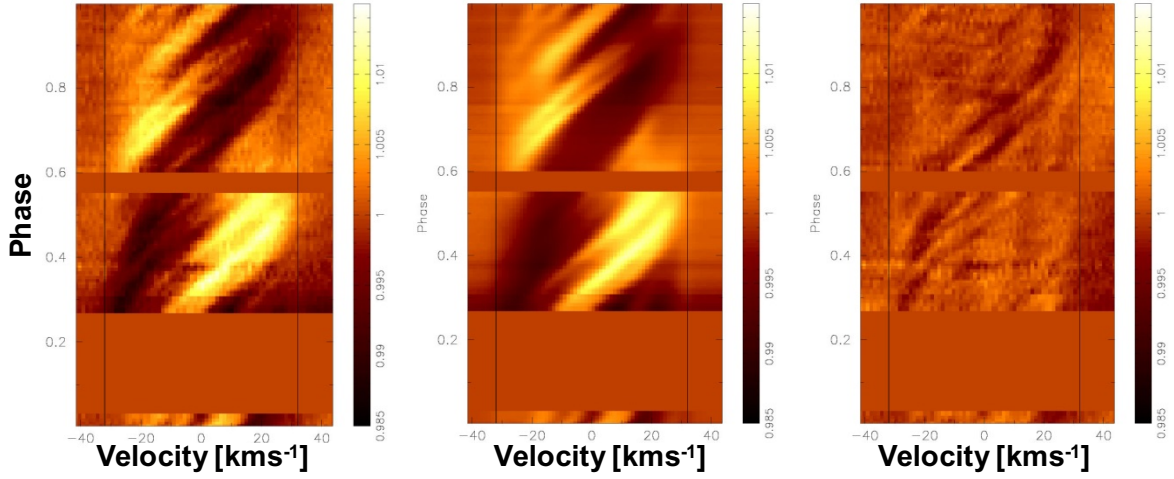
P = 5.45 hrs

i = 61°

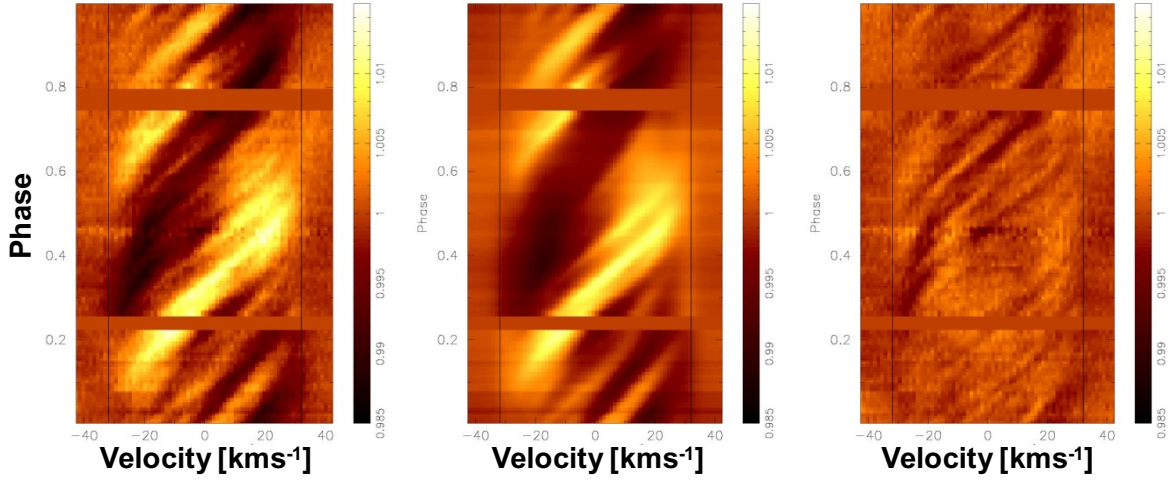
Fit
2015 Sept 26 & 29
χ^2 = 1.48

Mean line subtracted time series	Maximum entropy regularised fits	Residual time series

2015 Sept 26 (χ^2 = 1.33)

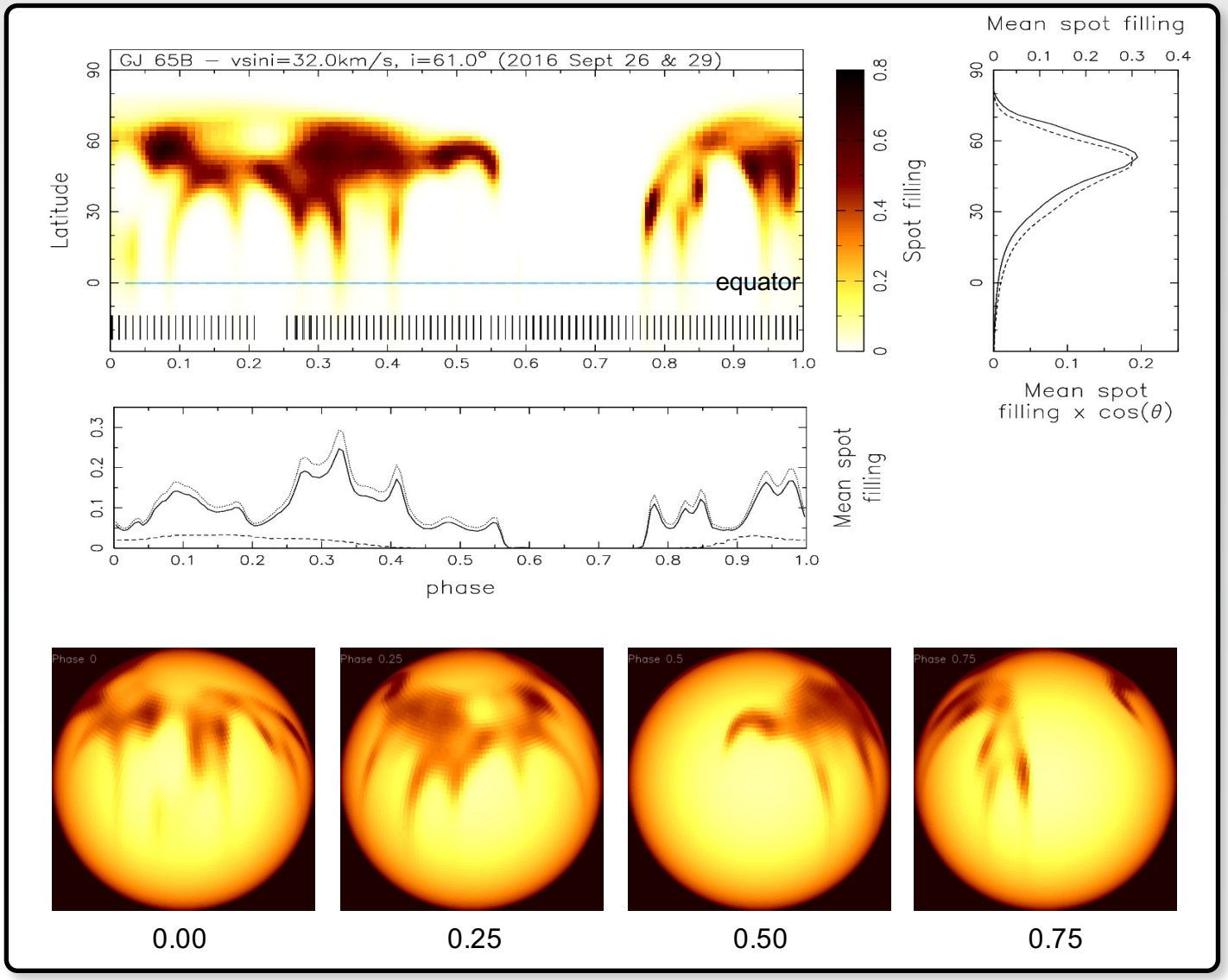


2015 Sept 29 (χ^2 = 1.46)



GJ 65B / UV Ceti image (2015)

- T_{eff} = 2800K, T_{spot} = 2400K, Ic_{spot} / Ic_{phot}=0.26, i = 61°, P = 0.2269 d (5.45 hrs), $v \sin i$ = 32.0 km s^{-1}



- 74% (26th) & 95% (29th) phase coverage - 74% phase overlap
- High degree of spot filling in spots clustered at latitude ~55°
- Notable lack of spots at pole and phases 0.55-0.75
- Mean spot filling = 5.3%
- Max spot filling = 73%

(χ^2 = 1.48)

LP944-20 image (2014)

SpType M9V

$v \sin i$ = 30.8 km s^{-1}

P = 3.88 hrs

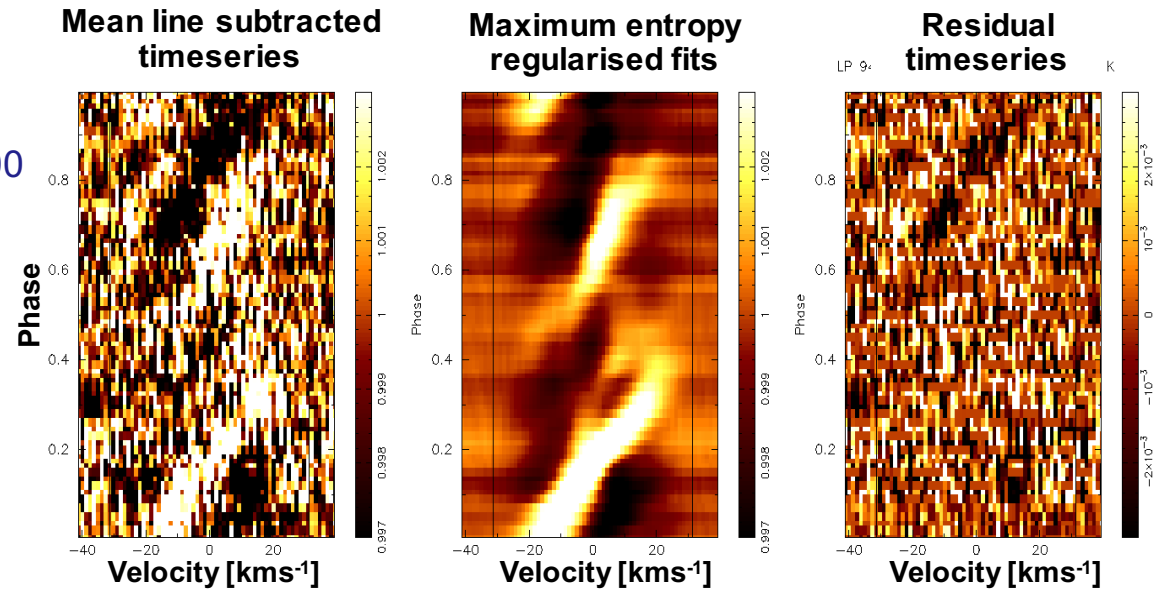
i = 55^{o}

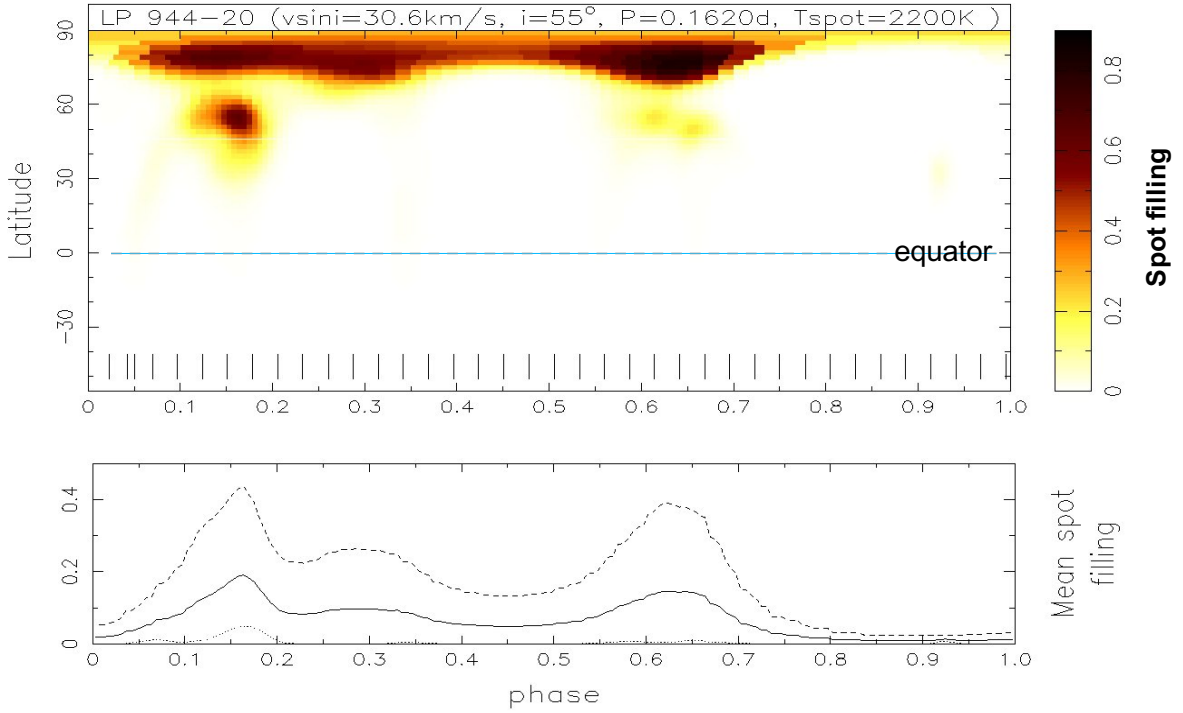
$I^{c}_{spot} / I^{c}_{phot}$ = 0.64

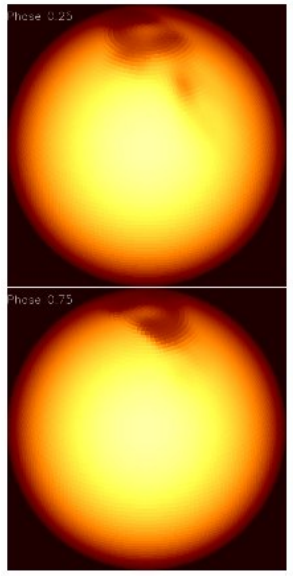
Max spot filling = 89%

Mean spot filling = 2.2%

Deconvolved line SNR ~ 600



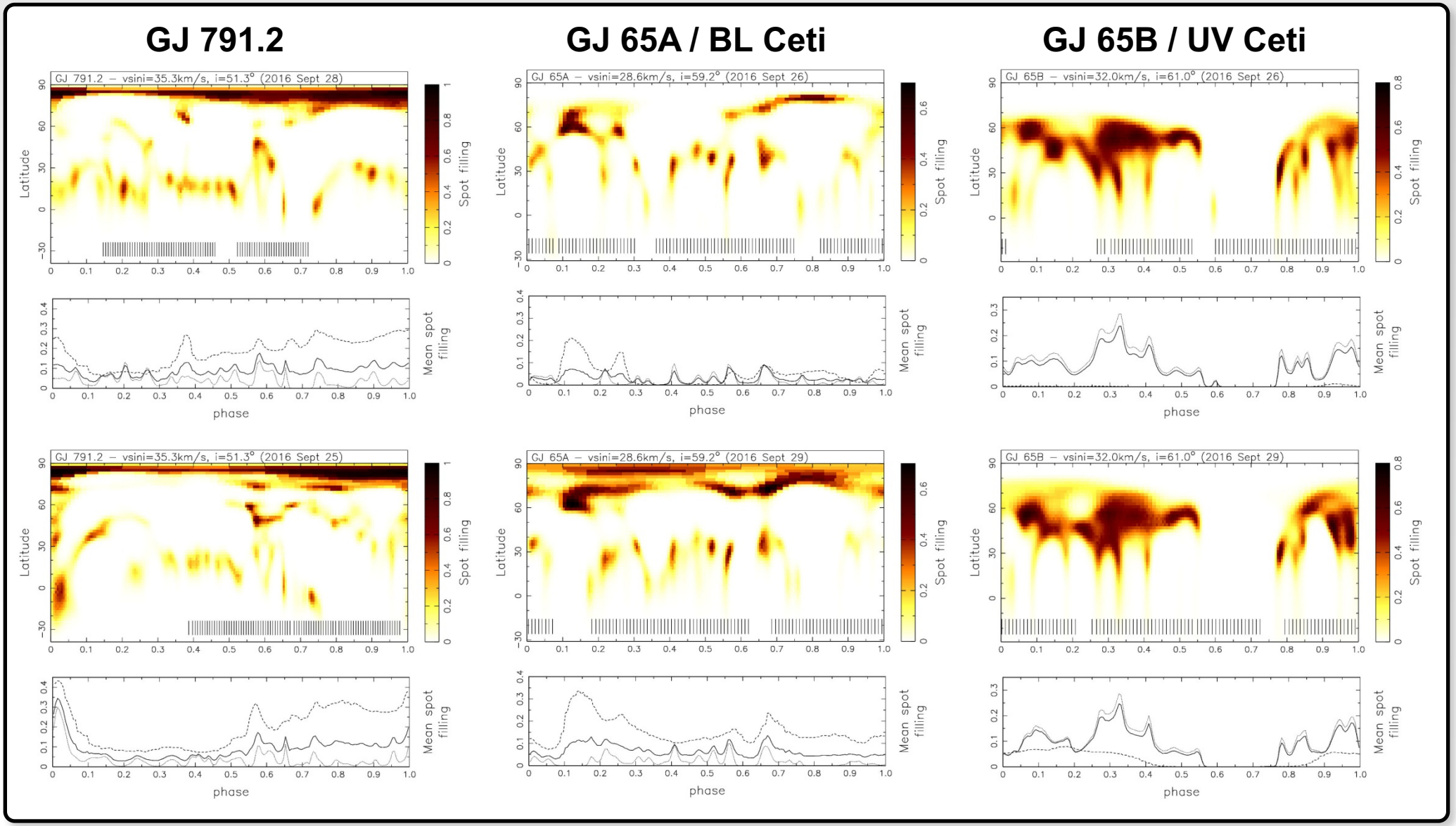




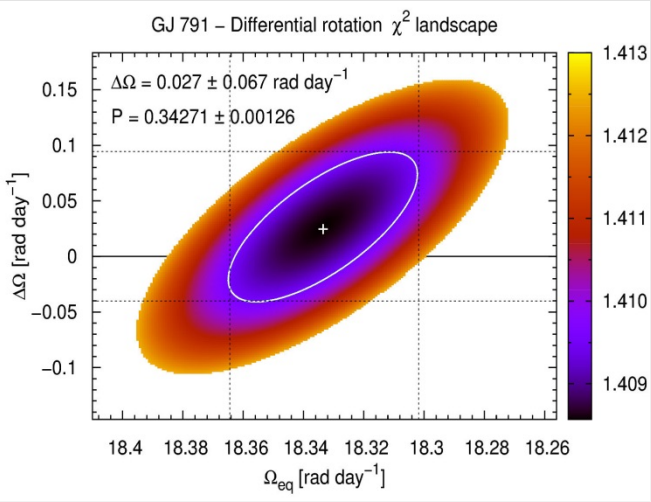
Barnes et al. 2015, ApJ. 812, 42

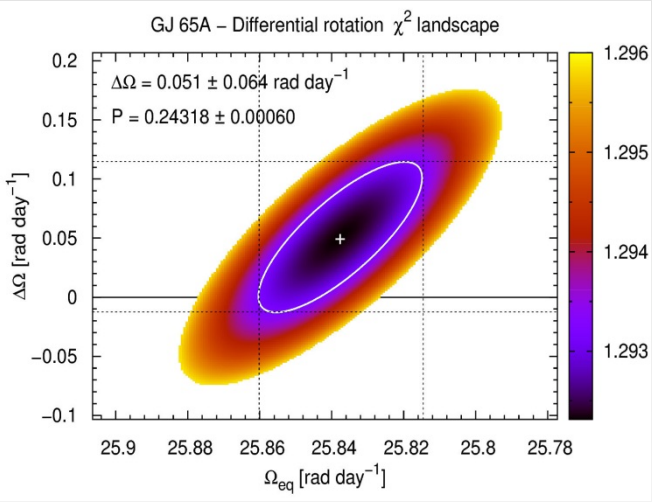
Spot evolution

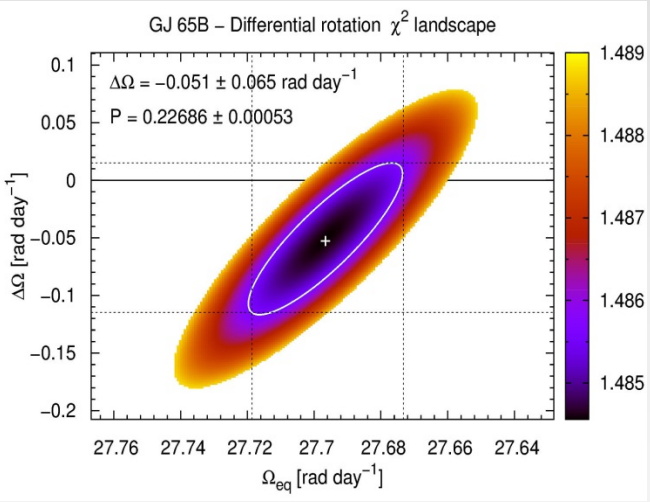
- Spot patterns coherent on time scales of 3 nights
- Some evolution – growth/decay of spot structure



Differential rotation



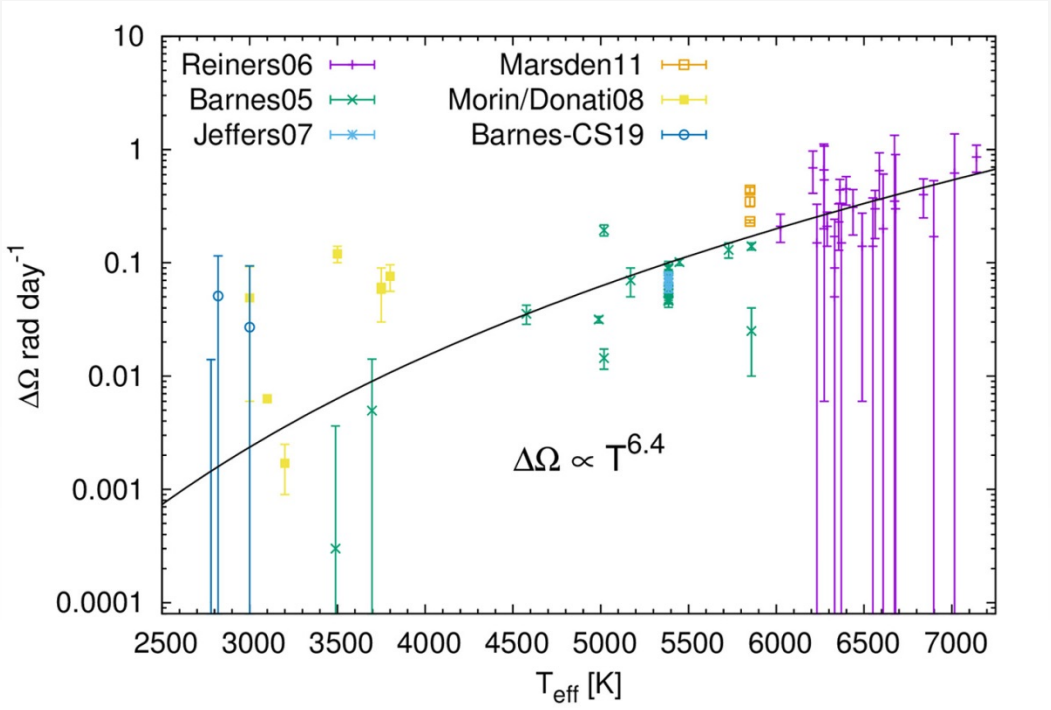




- Sheared-image method to obtain an estimate of the differential rotation

  $\Omega(\theta) = \Omega_{eq} - \Delta\Omega \sin^2 \theta$

- $\Delta\Omega \propto T^{8.9}$ (Barnes, 2005)
- $\Delta\Omega \propto T^{8.3}$ (Collier Cameron, 2007)
- **With M dwarfs → $\Delta\Omega \propto T^{6.4}$**

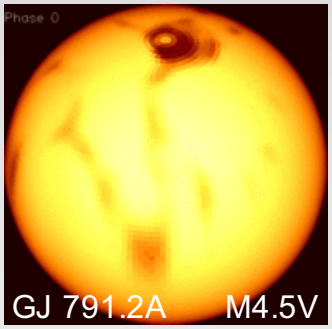


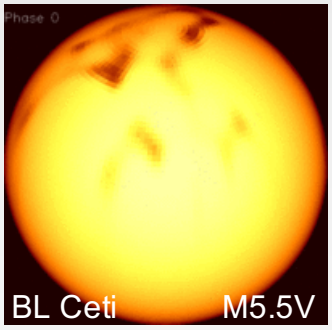
Summary

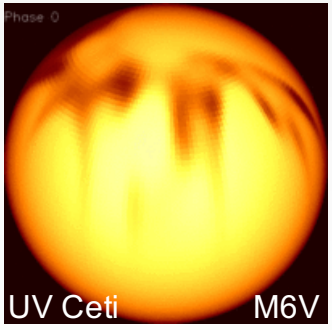
- Mid-Late Ms show 2.2 – 5.3% spot filling factors all the way to M9V
  - GJ 791.2 and GJ 65A spots at all latitudes, but preferentially at intermediate and high latitudes
  - Is UV Ceti (an extreme case?) with high degree of intermediate latitude spot filling
  - M9V spots at circumpolar latitudes only lower contrast and spot filling
- Comparison of magnetic and brightness images difficult because of contrast effects (Zeeman Doppler imaging sensitive to large scale field)
  - Next generation instruments such as SPIROU working at NIR wavelength will provide exciting opportunities to probe this relationship further
- GJ791 RV variability – 138 m/s, correctable with DI to 73 m s (factor 1.9)

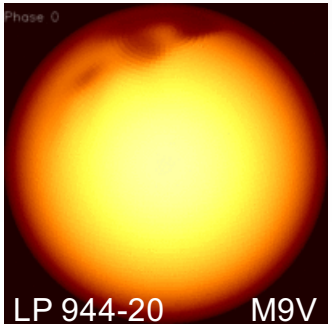
  Typical M dwarf with $v \sin i$ = 5 or 10 km s^{-1} expect respective upper limit RV variabilities of 39 & 18 m s^{-1}, correctable to 18 / 9 m s^{-1}
- Campaigns targeting stars with moderate rotation are most likely to recover planets by intensive monitoring on timescales of days to weeks – i.e. strategy to enable modelling of spot jitter

Habitable Zone planets expected in large numbers in 5 – 20 day orbits



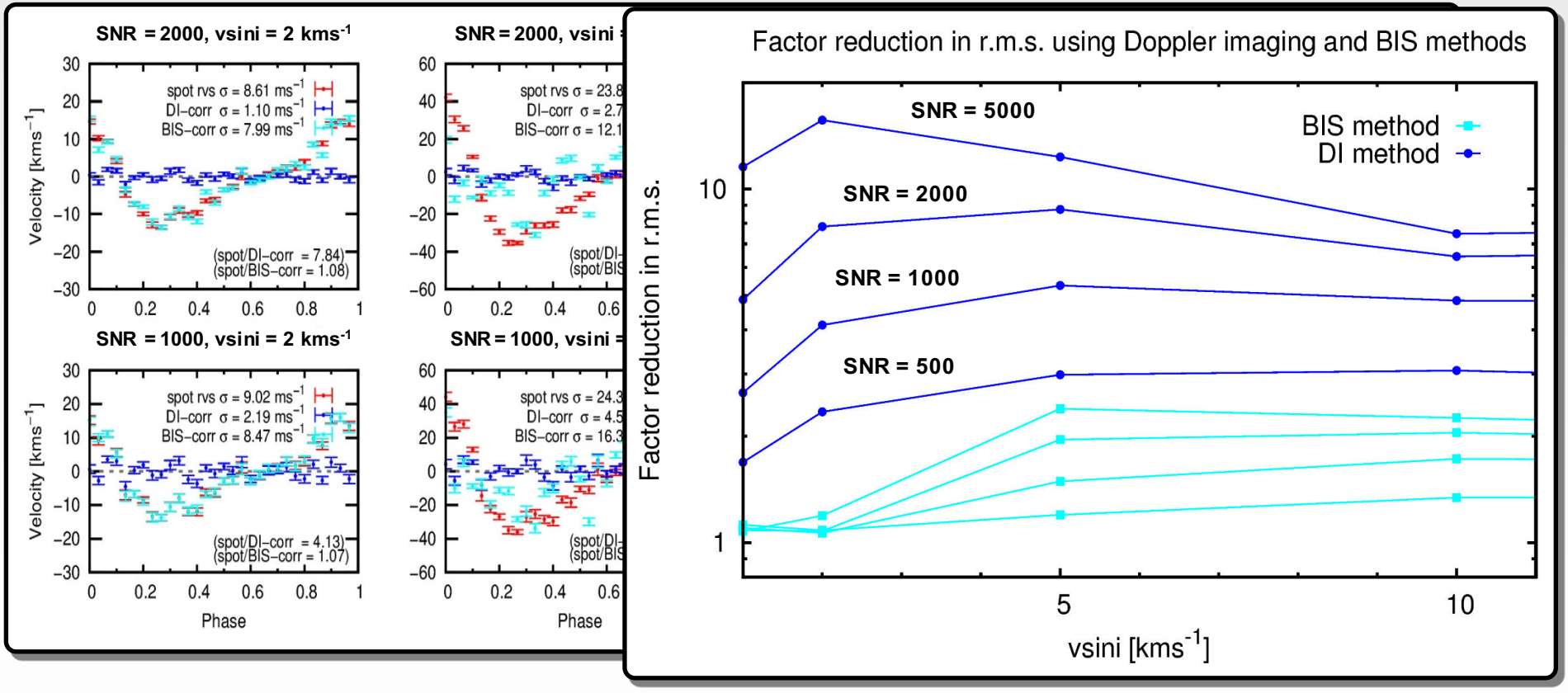






Mitigating spot induced jitter

- Generate 30 line profiles from GJ 791.2A image with known *v*sin *i* and SNR
- Fit line profiles via imaging, calculate weighted velocities to subtract from RVs

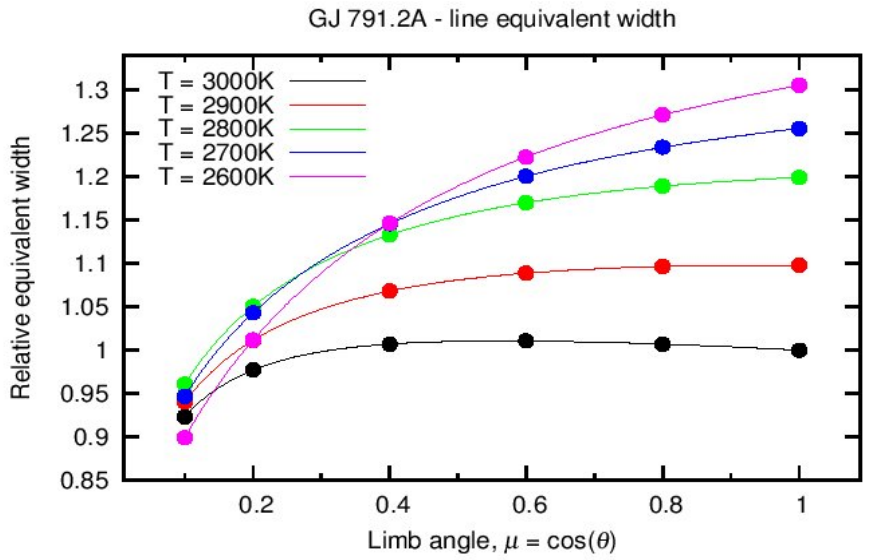


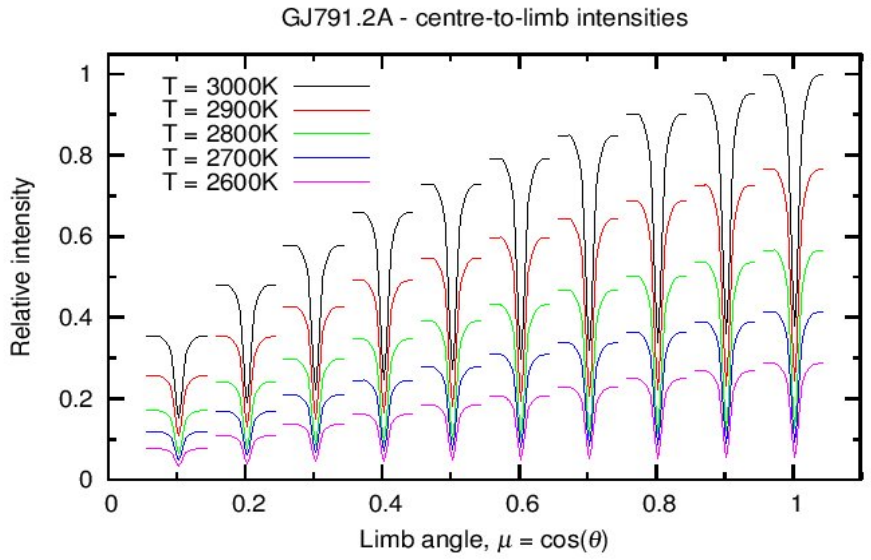
- GJ 791.2 model: assumed f = 3.2%, spot radii = 5° - 7°

e.g. *v*sin *i* = 5 kms^{-1}, SNR = 2000 **Jitter = 23.8 ms^{-1} (r.m.s.)** →
BIS → **12.17ms^{-1}** (/2.0)
DI → **2.72 ms^{-1}** (/8.8)

Centre-to-limb & EW variation

GJ 791.2 (M4.5V)





LP 944-20 (M9V)