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 \( \sim 20 \) days

- BUT: What about activity induced RV jitter?

S/N break-even point between optical and NIR surveys is early to mid-M

Need Infrared RVs

M6V M3V M1V G2V

Optical RVs

\( v \sin i \) ~ 5 kms\(^{-1}\)

\( v \sin i \) ~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
- 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 determined
- Behaviour of spot feature in line profile (gradient/velocity-extent) informs us of the stellar latitude

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


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 (Luyten 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 : $\lambda \lambda \sim 0.64 - 1.03 \mu m$ (excluding tellurics and chromospheric lines – Ca II IR triplet, Hα, He I)
GJ 791.2A time series

SpType M4.5V

Deconvolved line
SNR ~ 1900

$\nu sin i = 35.3$ km s$^{-1}$
$P = 8.2$ hrs
$i = 51^\circ$

Fit
2015 Sept 25 & 28
$\chi^2 = 1.41$

2015 Sept 25 ($\chi^2 = 1.54$)

2015 Sept 28 ($\chi^2 = 1.05$)
• $T_{\text{eff}} = 3000\text{K}$, $T_{\text{spot}} = 2600\text{K}$, $I_{\text{c, spot}} / I_{\text{c, phot}} = 0.32$, $i = 51^\circ$, $P = 0.3428 \text{ d (8.23 hours)}$, $v \sin i = 35.3 \text{ km s}^{-1}$

• Better phase overlap on both nights $\rightarrow$ slightly different optimised parameters

• Spot coverage similar

• Larger circum-polar spot

• Low latitude filling predominantly at latitude $\sim 15^\circ$

• Mean spot filling $= 2.7\%$

• Max spot filling $= 92\%$ ($\chi^2 = 1.41$)
• $T_{\text{spot}} = 2700 K$, $I_{\text{spot}}^c / I_{\text{phot}}^c = 0.42$
• 59% (26th) & 57% (29th) phase coverage - 33% phase overlap

Deconvolved line
SNR ~ 3600

• 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% ($\chi^2 = 1.4$)
**GJ 65A / BL Ceti time series**

**SpType** M5.5V

Deconvolved line
SNR ~ 2500

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

$P = 5.84$ hrs

$i = 59^\circ$

Fit

2015 Sept 26 & 29

$\chi^2 = 1.29$

2015 Sept 26 ($\chi^2 = 1.09$)

2015 Sept 29 ($\chi^2 = 1.02$)
GJ 65A / BL Ceti image (2015)

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

- $T_{\text{spot}} = 2500\,\text{K}$, $I_{c,\text{spot}}/I_{c,\text{phot}} = 0.39$  
  $\rightarrow$ max spot filling $\sim 0.8$

- 93% ($26^{\text{th}}$) & 89% ($29^{\text{th}}$) phase coverage - 82% phase overlap
- Large spots at high latitude
- Low latitude filling predominantly at latitude $\sim 35^\circ$
- Mean spot filling $= 1.9$
- Max spot filling $= 64$
  ($\chi^2 = 1.29$)
GJ 65B / UV Ceti time series

**SpType** M6V

Deconvolved line
SNR ~ 1900

$v sin i = 32.0$ kms$^{-1}$
$P = 5.45$ hrs
$i = 61^\circ$

Fit
2015 Sept 26 & 29
$\chi^2 = 1.48$

2015 Sept 26 ($\chi^2 = 1.33$)

2015 Sept 29 ($\chi^2 = 1.46$)
• $T_{\text{eff}} = 2800\text{K}, \ T_{\text{spot}} = 2400\text{K}, \ I_{\text{c spot}} / I_{\text{c phot}} = 0.26$, 
  $i = 61^\circ, \ P = 0.2269 \text{ d (5.45 hrs)}, \ \nu \sin i = 32.0 \text{ km s}^{-1}$

• 74% (26th) & 95% (29th) phase coverage - 74% phase overlap

• High degree of spot filling in spots clustered at latitude $\sim 55^\circ$

• Notable lack of spots at pole and phases 0.55-0.75

• Mean spot filling = 5.3%

• Max spot filling = 73% 
  ($\chi^2 = 1.48$)
SpType M9V

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

$P = 3.88$ hrs

$i = 55^\circ$

$I_c^{\text{spot}} / I_c^{\text{phot}} = 0.64$

Max spot filling = 89%

Mean spot filling = 2.2%

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
• 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 \( \Rightarrow \Delta \Omega \propto T^{6.4} \)
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 = $5^\circ$ - $7^\circ$

<table>
<thead>
<tr>
<th>SNR</th>
<th>$v \sin i$</th>
<th>Jitter (r.m.s.)</th>
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<tbody>
<tr>
<td>2000</td>
<td>2 kms$^{-1}$</td>
<td>23.8 ms$^{-1}$</td>
</tr>
<tr>
<td>2000</td>
<td>5 kms$^{-1}$</td>
<td>12.17 ms$^{-1}$</td>
</tr>
<tr>
<td>2000</td>
<td>10 kms$^{-1}$</td>
<td>2.72 ms$^{-1}$</td>
</tr>
<tr>
<td>2000</td>
<td>20 kms$^{-1}$</td>
<td></td>
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e.g. $v \sin i = 5$ kms$^{-1}$

SNR = 2000
Centre-to-limb & EW variation

GJ 791.2 (M4.5V) LP 944-20 (M9V)

GJ 791.2A - line equivalent width

LP944-20 - line equivalent width

GJ791.2A - centre-to-limb intensities

LP944-20 - centre-to-limb intensities