STELLAR VARIABILITY: IMPACT ON THE DETECTION AND CHARACTERIZATION OF EXOPLANETS

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in collaboration with:
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INTRODUCTION

Motivations

Various phenomena of stellar variability

Main subject

Focus on the stellar activity problem on its short and long term variations

Focus on low-mass M-dwarfs

Futur

Stellar activity and transit determination

Conclusion and perspectives
PHENOMENA OF STELLAR VARIABILITY

- Granulation, Pulsation
- Stellar activity
- Active cycle
- Surface flows

@NASA/SDO/AIA
NON-RADIAL PULSATION

- Pressure waves (p-modes)
- **Time scales:** 5 to 15 min
- **RV amplitude:** 0.1 to 4 m/s
- Amplitude and period increase with temperature for dwarf stars

(Dumusque et al. 2010)

**RV strategy:**
15 mins time exposure
--> average pulsation

Arentoft et al. 2008
Convective nature of solar-type stars

- **Time scales** from minutes to hours
- **RV amplitude** 0.1 to 2 m/s
- Amplitude increase with temperature for dwarf stars

(Dumusque et al. 2010)

**RV strategy:**
3 obs. of 10 min per night  --> average granulation
STELLAR ACTIVITY

- Dark spots and bright plages
- **Timescale:** rotational period of the star (days to weeks)
- **RV amplitude** from km/s to <1m/s
- Level of stellar activity
  - $\text{LogR'HK}$ (emission in CaII lines)
- Sun: low-active star
STELLAR ACTIVITY

◆ Photometric variability / Stellar activity level

CoRoT  
Affer et al. 2009

Kepler  
Basri et al. 2010,11,13

--> ~30% of G-type dwarfs more variable than the Sun

--> greater percentage for K and M dwarfs

Sun at maximum activity

--> 30% of solar-type stars are more active than the Sun

i.e. logR’HK > -4.75

ex: CoRoT-2, HD189733,...
MAGNETIC CYCLE

Baliunas et al. 1995
SURFACE FLOWS

Makarov et al. 2010
# OUTLINE

**Introduction**
- Motivations
- Various phenomena of stellar variability

**Main subject**
- Focus on the stellar activity problem on its short and long term variations
- Focus on low-mass M-dwarfs

**Futur**
- Stellar activity and transit determination
- Conclusion and perspectives
RADIAL VELOCIMETRY

- Minimal mass \( msini \)

\[
m \sin i [M_{\text{Jup}}] = \frac{1}{203} M_\star^{-2/3} [M_\odot] P^{-1/3} [j] K [\text{ms}^{-1}] \sqrt{1 - e^2}
\]

- 12 m/s (Jupiter) \( \approx 0.12 \text{ mÅ} \approx 1/100 \text{ line width} \approx <1/100 \text{ px} \)
RADIAL VELOCIMETRY

- Minimal mass $m \sin i$
  \[ m \sin i \left[ M_{\text{Jup}} \right] = \frac{1}{203} M_*^{-2/3} M_\odot P^{-1/3} K [\text{ms}^{-1}] \sqrt{1 - e^2} \]

- 12 m/s (Jupiter) $\approx 0.12$ mÅ $\approx 1/100$ line width $\approx <1/100$ px

- Solar-type stars and slow rotators
RADIAL VELOCIMETRY

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$$m \sin i [M_{\text{Jup}}] = \frac{1}{203} M_*^{-2/3} [M_\odot] P^{-1/3} [\text{J}] K [\text{ms}^{-1}] \sqrt{1 - e^2}$$

- 12 m/s (Jupiter) $\approx$ 0.12 mÅ $\approx$ 1/100 line width $\approx$ <1/100 px

- Solar-type stars and slow rotators

@ Bouchy
HOW SPOTS (AND PLAGES) Creates RV Fake Variations

- CCF $\approx$ mean line of the spectra
- Fitted with a Gaussian
- Spots or plages deform the CCF

Induced variations of the measured RV
DIAGNOSTICS OF STELLAR ACTIVITY

- Line bisector variations $V_{\text{span}}$, line deformations FWHM

$V_{\text{span}} = V_{\text{top}} - V_{\text{bottom}}$

Queloz et al. 2001

Bisector scale 10 times RV scale

Fig. 7. Radial velocity of each CCF versus the bisector span ($V_r - V_b$) of the CCF profile. The dotted line is the best linear fit to the data.
DIAGNOSTICS OF STELLAR ACTIVITY

- Line bisector variations $V_{\text{span}}$, line deformations FWHM
- Active lines CaII, Hα, HeI, NaI (M dwarfs)

Boisse et al. 2009
DIAGNOSTICS OF STELLAR ACTIVITY

- Line bisector variations $V_{span}$, line deformations FWHM
- Active lines CaII, Hα, HeI, NaI (M dwarfs)
- Photometry

Boisse et al. 2009
CHARACTERIZE STELLAR ACTIVITY

- HD166435
  Queloz et al. 2001
  Prot ~ 3.8 days
  Age ~ 200 Myr

- M dwarfs
  GJ674 Bonfils et al. 2007
  Prot ~ 35 days
  Gl176 Forveille et al. 2008
  Prot ~ 3.8 days
CHARACTERIZE STELLAR ACTIVITY

- Dedicated Observations -

- Simultaneous observations of the active planet host star HD189733 spectroscopy with SOPHIE photometry with MOST

Boisse et al. 2009
CHARACTERIZE STELLAR ACTIVITY
- Dedicated Observations -

◆ Simultaneous observations of the active planet host star HD189733 spectroscopy with SOPHIE photometry with MOST
---> Dominated by a spot associated to a faculae
---> Better determination of the planetary parameters cf. also Melo et al. 2007

◆ Reference data set
e.g. Lanza et al. 2011
    Aigrain et al. 2012

Anticorrelated
More active
Lower flux

RV
Vspan
Hα
Flux
Boisse et al. 2009

Reference data set
CHARACTERIZE STELLAR ACTIVITY

- Dedicated Observations -

• Simultaneous observations of the active planet host star HD189733 spectroscopy with SOPHIE
  photometry with MOST

• Reference data set: Lanza et al. 2011
• New observations
  cf. also Melo et al. 2007
  Aigrain et al. 2012

- New observations

• More active
• Lower flux

• Anticorrelated

Boisse et al. 2009
CHARACTERIZE STELLAR ACTIVITY
- Dedicated Observations -

Transiting planet: CoRoT-7b
Léger et al. 2009

RV follow-up: masses and CoRoT-7c
Queloz et al. 2009

Several studies and different techniques

CoRoT-7d?

New observations in Jan. 2012
Simultaneous HARPS & CoRoT

RV dominated by stellar activity
CHARACTERIZE STELLAR ACTIVITY

- Dedicated Observations -

Transiting planet: CoRoT-7b

Léger et al. 2009

RV follow-up: masses and CoRoT-7c

Queloz et al. 2009

Several studies and different techniques


New observations in Jan. 2012

Simultaneous HARPS & CoRoT

Lower level of stellar activity

--> use Aigrain et al. 2011 model to remove active jitter and confirm 3rd planet(?)

Haywood et al. in prep., Barros et al. in prep., Lanza et al. in prep., Hatzes et al. in prep.
CHARACTERIZE STELLAR ACTIVITY

- Simulations -

◆ Tool SOAP

Fast tool to calculate the impact of spots and plages on radial-velocity and photometry

Available for use at http://www.astro.up.pt/soap

| Star        | radius and Prot equiv. $v \sin i$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inclinaison of rotation axis</td>
</tr>
<tr>
<td></td>
<td>limb-darkening</td>
</tr>
<tr>
<td>Spot</td>
<td>number</td>
</tr>
<tr>
<td></td>
<td>radius and brightness</td>
</tr>
<tr>
<td></td>
<td>latitude and longitude</td>
</tr>
<tr>
<td>Spectro.</td>
<td>resolution power</td>
</tr>
<tr>
<td></td>
<td>CCF calculation</td>
</tr>
</tbody>
</table>

Boisse et al. 2012b
CHARACTERIZE STELLAR ACTIVITY
- Simulations -

- **Amplitude:**
  \( v_{\text{sini}} \), spot size, stellar age  
  FeI line Saar & Donahue 1997   Hatzes 2000, 2001
  spectrograph resolution, spot temperature  
  spectre visible Desort et al. 2007

- **Shape:** depends on stellar \( I \) and spot latitude \( \delta \)

Boisse et al. 2011
CHARACTERIZE STELLAR ACTIVITY
- Simulations -

- Harmonic decomposition

Fit the rotational stellar variability in RV with three sinusoids

\[ P_{\text{rot}} / 3 P_{\text{rot}}/2 P_{\text{rot}} \]

Boisse et al. 2011
CHARACTERIZE STELLAR ACTIVITY

- Simulations -

◆ Harmonic decomposition

Alpha Cen B b  
Dumusque et al. 2012

smallest mass planet, \( m \ sini = 1.13 \ m_{\text{Earth}} \)
close and bright star

-->  Stellar activity dominates the RV signal

Use the harmonic decomposition of Boisse et al. 2011

Prot=39.76d  
Prot=37.80d  
Prot=36.71d
STELLAR ACTIVITY
AND LONG-PERIOD PLANETS

◆ Magnetic cycles:
  Time variation of spot coverage and convective pattern

Magnetic field: block convection

- Granule $\text{Teff} \approx 5800$ K
- Penumbra $\text{Teff} \approx 5500$ K, Sun
- Umbra $\text{Teff} \approx 4500$ K

Magnetic field lines
STELLAR ACTIVITY 
AND LONG-PERIOD PLANETS

**Magnetic cycles:**
Time variation of spot coverage and convective pattern

Based on Sun data and simulations, estimated the combined effect of spot, plages and convective blueshift during the magnetic cycle

- Lagrange et al. 2010, Meunier et al. 2010a,b
- Dumusque et al. 2011

**RV strategy:**
1 obs. each 3 nights during a month
--> average rotational stellar activity

→ RV variations dominated by convective blueshift?
STEELAR ACTIVITY AND LONG-PERIOD PLANETS

RV

logR’_{HK}

Planet

Magnetic variation

Dumusque et al. 2011b
STELLAR ACTIVITY
AND LONG-PERIOD PLANETS

- Magnetic cycles:
  Time variation of spot coverage and convective pattern

Observations to look for correlation between activity indicators and RV measurements

Santos et al. 2010
Gomes da Silva et al. 2012
Lovis et al. 2011
Magnetic cycles:

Time variation of spot coverage and convective pattern

Observations to look for correlation between activity indicators and RV measurements

- Santos et al. 2010
- Gomes da Silva et al. 2012
- Lovis et al. 2011

Dependance with spectral type?
**STELLAR ACTIVITY AND LONG-PERIOD PLANETS**

- **Magnetic cycles:**
  - Time variation of spot coverage and convective pattern

  ![Graph of Radial Velocity vs. Year](image)
  - Wright et al. 2008

  ![Graph of Mount Wilson S vs. Date](image)
  - Dumusque et al. 2012

  Observations to look for correlation between activity indicators and RV measurements
  - Santos et al. 2010
  - Gomes da Silva et al. 2012
  - Lovis et al. 2011

- **Dependance with spectral type?**

- **Impact for long period planets?**
  - Dumusque et al. 2012
  - Wright et al. in prep.
STELLAR ACTIVITY AND LONG-PERIOD PLANETS

Surface flows:

Makarov et al. 2010

From Mont Wilson Doppler measurements but only one Fe line

Meridional flow + convective limb shift

0.1 - 10 yrs  \[ \text{sig(RV)} \sim 1.4 \text{ m/s} \]
Simulations from sunspots and plages properties over one solar cycle

Lagrange et al. 2011 10 pc seen from equator --> 0.2 μas (rms = 0.07 μas)

To compare to an Earth-mass planet in the HZ 0.3 μas

<table>
<thead>
<tr>
<th>Period</th>
<th>rms(ΔX)</th>
<th>rms(ΔY)</th>
<th>rms(RV) without conv.</th>
<th>rms(RV) with conv.</th>
<th>rms(TSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>0.07</td>
<td>0.05</td>
<td>0.33</td>
<td>2.4</td>
<td>3.6 × 10⁻⁴</td>
</tr>
<tr>
<td>high1</td>
<td>0.09</td>
<td>0.06</td>
<td>0.42</td>
<td>1.42</td>
<td>4.5 × 10⁻⁴</td>
</tr>
<tr>
<td>high2</td>
<td>0.08</td>
<td>0.05</td>
<td>0.37</td>
<td>1.62</td>
<td>3.9 × 10⁻⁴</td>
</tr>
<tr>
<td>low</td>
<td>0.02</td>
<td>0.01</td>
<td>0.08</td>
<td>0.44</td>
<td>1.2 × 10⁻⁴</td>
</tr>
</tbody>
</table>

in agreement with Makarov et al. (2010)

see also Makarov et al. 2009, Catanzarite et al. 2008
Assuming circular orbit:

\[ \alpha = \left( \frac{M_p}{M_{\text{sun}}} \right) \left( \frac{M_{\text{sun}}}{M_*} \right) \left( \frac{a_p}{1 \text{ AU}} \right) \left( \frac{1 \text{ pc}}{d} \right) \text{ arcsec} \]

- \( \alpha \)  apparent semi-major axis of the stellar orbit
- \( a_p \)  semi-major axis of the planetary orbit
- \( d \)   distance to the Solar System

More sensitive to long-period massive planets

- Broke the \( m_p \) \( \sin i \) degeneracy
  - access to the entire set of seven orbital elements

- Young active stars and shorter period low-mass planet could be a problem
ASTROMETRY

During low activity period
(one single structure)

Photometry or RV:
dark or bright dominated

Lagrange et al. 2011

Movement of the photocenter
---
> direction of the star’s rotational axis in the plane of the sky
ASTROMETRY

-- Can be used to estimate the level of convection on the star?

But no correlation with photometric variation
(because not dependent on spot/plage locations)

without convection effect simulated for RV

Lagrange et al. 2011

with convection effect simulated for RV
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FOCUS ON M DWARFS

Low mass advantage for detection

RV signal $\propto M_\star$
Transit depth $\propto R_\star^{-2/3}$

Low mass advantage for habitable zone

Low mass stars are most numerous

$0.07 < \text{mass} < 0.6 \ M_{\odot}$
FOCUS ON M DWARFS

Low mass advantage for detection

RV signal $\propto M_\star$

Transit depth $\propto R_\star^{-2/3}$

0.07 < mass < 0.6 $M_{\text{sun}}$

Low mass advantage for habitable zone

Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Observing Details</th>
<th>Period</th>
<th>Stars</th>
<th>RV Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIRou</td>
<td>RV @ CFHT</td>
<td>980-2400 nm</td>
<td>2016</td>
<td>~300 stars &gt; M4</td>
</tr>
<tr>
<td>CARMENES</td>
<td>RV @ 3.5m Carlo Alto</td>
<td>520-1700 nm</td>
<td>2015</td>
<td>~300 stars M0 to &gt;M4</td>
</tr>
<tr>
<td>Mearth</td>
<td>Transit (ground)</td>
<td>&gt; 715- ? nm</td>
<td>ongoing</td>
<td>2000 stars</td>
</tr>
</tbody>
</table>

1 m/s
FOCUS ON M DWARFS

Low mass advantage for detection

RV signal $\propto M\star$

Transit depth $\propto R\star^{-2/3}$

Low mass advantage for habitable zone

Low mass stars are most numerous

0.07 < mass < 0.6 M$_{\text{sun}}$

But

difficult to estimate stellar parameters
activity

faintness
FOCUS ON M DWARFS

Low mass advantage for detection

RV signal $\propto M_\star^{\alpha}$

Transit depth $\propto M_\star^{-2/3}$

Low mass advantage for habitable zone

Low mass stars are most numerous

But faintness difficult to estimate stellar parameters

activity

Activity

Fraction Active

Spectral Type

West et al. 2004
FOCUS ON M DWARFS

Combining nIR and visible RV

Dark bodies
1 spot of 2% of the surface
1000K lower temperature than the surface
FOCUS ON M DWARFS

Combining nIR and visible RV

Dark bodies
1 spot of 2% of the surface
1000K lower temperature than the surface

Prato et al. 2008
Huélamo et al. 2008
Figueira et al. 2010

Also useful for very active / young stars

Martin et al. 2006
FOCUS ON M DWARFS

Combining nIR and visible RV

Dark bodies
1 spot of 2% of the surface
1000K lower temperature than the surface

Prato et al. 2008
Huélamo et al. 2008
Figueira et al. 2010

Also useful for very active / young stars

Using spectropolarimetry to characterize activity jitter?

Impact of Zeeman broadening in the infrared? Reiners et al. 2013
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IMPACT OF STELLAR ACTIVITY ON TRANSIT DETERMINATION

Active host-star

Planet conceals a portion of the star brighter than the average brightness of the star

see also Sing et al. 2009, Désert et al. 2011, Knutson et al. 2011, Sing et al. 2011a,b, Berta et al. 2011, Cegla et al. 2013, ...
IMPACT OF STELLAR ACTIVITY ON TRANSIT DETERMINATION

Active host-star

Planet conceals a portion of the star brighter than the average brightness of the star

\[
\frac{R_p}{R_*} = \sqrt{\frac{\Delta F}{F}}
\]

the measured radius is overestimated for a star with spots

@Parmentier&LeCavelier

see also Sing et al. 2009, Désert et al. 2011, Knutson et al.2011, Sing et al. 2011a,b, Berta et al. 2011, Cegla et al. 2013,...
IMPACT OF STELLAR ACTIVITY ON TRANSIT DETERMINATION

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the measured radius is overestimated for a star with spots

Planet may occult stellar inhomogeneities

impact on radius and atmospheric components determination

see also Sing et al. 2009, Désert et al. 2011, Knutson et al.2011, Sing et al. 2011a,b, Berta et al. 2011, Cegla et al. 2013,...
IMPACT OF STELLAR ACTIVITY ON TRANSIT DETERMINATION

Out-of-transit lightcurve

Simultaneous photometry

Estimate stellar spots coverage

Correct the lowered transit depth

Ballerini et al. 2012

Czesla et al. 2009, Pont et al. 2012,...
DEVELOPMENT OF SOAP

- **SOAP-T**: Planet in transit  
  Oshagh et al. 2012b

  Lighcurve and Rossiter-McLaughlin effect

Impact of spots on transit parameters  
Oshagh et al. 2013

see next talks
### RESUME

**Overcome the stellar variability**

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Year</th>
<th>Resolution</th>
<th>Velocity</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIRou @ CFHT</td>
<td>2016</td>
<td>100 000</td>
<td>1 m/s</td>
<td>nIR</td>
</tr>
<tr>
<td>ESPRESSO @VLT</td>
<td>2016</td>
<td>140 000</td>
<td>10 cm/s</td>
<td>visible</td>
</tr>
<tr>
<td>HIRES @ E-ELT</td>
<td>&gt;2020</td>
<td>150 000</td>
<td>2 cm/s</td>
<td>visible/nIR</td>
</tr>
</tbody>
</table>

→ Simultaneous observations in RV - Photometry - Polarimetry

→ Next instrumentations: new ranges of instrumental and stellar noises
RESUME

Overcome the stellar variability

- Different frequencies: observational strategy
- Comparable frequencies: diagnostics and models

Perspectives

- Use several indices
- Develop tools SOAP / SOAP-T

- Simultaneous observations in RV - Photometry - Polarimetry
- Next instrumentations: new ranges of instrumental and stellar noises
- Improve our stellar variability understanding