A Pathway to Earth-like Worlds:
Overcoming Astrophysical Noise due to Convection

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Dr. Chris Watson, Dr. Sergiy Shelyag, Prof. Mihalis Mathioudakis
A Pathway to Earth-like Worlds:
Astrophysical Noise
Astrophysical Noise

- Star spots, Plages
Astrophysical Noise

- Star spots, Plages
- Stellar Oscillations
Astrophysical Noise

- Star spots, Plages
- Stellar Oscillations
- Granulation
Astrophysical Noise

- Star spots, Plages
- Stellar Oscillations
- Granulation
Stellar jitter from variable gravitational redshift: implications for radial velocity confirmation of habitable exoplanets


Astrophysical Noise

- Star spots, Plages
- Stellar Oscillations
- Granulation
- Variable Gravitational Redshift
Astrophysical Noise

- Star spots, Plages
- Stellar Oscillations
- **Granulation**
- Variable Gravitational Redshift
Current Removal Method

- Average out the noise

An Earth-twin is possible around Proxima Centauri. It also exhibits low stellar activity, similar to the closest stellar system to the Sun, composed of itself, Proxima Centauri A and B. Centauri A and B are both K-type stars (spectral type K1V), and has a smaller mass than our parent star. However, because the orbital inclination of the planet is unknown, the radius of the planet is unknown, with minimum because the orbital inclination of the planet is unknown, and the fractional mass is in the range 0.006-0.01 solar masses. These two conditions ease the detection of an Earth-twin because of the gravitational pull of an orbiting planet is about 0.04 astronomical units from the star (one astronomical unit is the Earth–Sun distance) and has a smaller mass than our parent star than Earth is to the Sun, it is not an Earth twin. However, it is one of the closest to the Solar System found to date.

High-precision measurements were obtained for Proxima Centauri B. Such detections have led to this impressive number of discoveries: the radial-velocity technique, which measures the change in the velocity of the central star due to the gravitational pull of an orbiting planet, is one of the major challenges in the search for exoplanets is the detection of an Earth-twin because of the gravitational pull of an orbiting planet and the signal is overwhelmed by stellar perturbations. Here we report the detection of an Earth-mass planet orbiting our parent star.

Dumusque et al., 2011, A&A, 525, 140
Our Removal Method
Our Removal Method
Parameterisation

- Separate based on:
  - Continuum Intensity
  - Magnetic Field

- Four Components
  - Granules
  - Non-Magnetic Intergranular Lanes
  - Magnetic Intergranular Lanes
  - MBPs
200 G Reconstruction

Best (0°)

Wavelength (Angstroms)

Flux

Avg Rel Err: 0.00048

Original

Reconstruct

Worst (0°)

Wavelength (Angstroms)

Flux

Avg Rel Err: 0.022

Original

Reconstruct
50 G Reconstruction

Best (0°)

Wavelength (Angstroms)

Flux

Original

Reconstruct

Avg Rel Err: 0.0054

Worst (0°)

Wavelength (Angstroms)

Avg Rel Err: 0.017
STEELAR SURFACE MAGNETO-CONVECTION AS A SOURCE OF ASTROPHYSICAL NOISE. I.
MULTI-COMPONENT PARAMETERIZATION OF ABSORPTION LINE PROFILES

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Recovered Granulation RVs from Parameterization

Residuals
Velocities Across the Disc

![Graph showing velocities across the disc. The x-axis represents inclination in degrees, and the y-axis represents velocity in meters per second. Three curves are plotted: original, reconstructed, and oscillation.](image)

- **Original**
- **Reconstructed**
- **Oscillation**
Generating **New** Profiles
Analysing the Profiles

![Graph showing normalised flux over wavelength with marked points V₁, V₂, V₃, V₄, and Aₜ.]
Analysing the Profiles

Velocity (km s$^{-1}$)

Normalised Flux

$\delta F_0(i)$

$\delta RV(i)$

$i \rightarrow i+30$

$i \rightarrow i+30$

$\frac{\delta F_0(i)}{\delta RV(i)}$

$\frac{\delta F_0(i)}{\delta RV(i)}$

$F_0(i)$

RV(i)
Initial Results
Initial Results
Initial Results

As expected, those diagnostics with the strongest correlation with RV reduced the noise to the largest fraction. We also found that those diagnostics with poor correlations with RV actually made the scatter within the RVs worse when attempting to correct for the granulation noise. By far the largest reduction of noise was obtained when using the BIS diagnostic, with a fractional reduction of 20.4%.

The table below shows the noise reduction success for the various diagnostics:

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Fractional Reduction (%)</th>
<th>Pearson's R</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16.2</td>
<td>-0.78</td>
</tr>
<tr>
<td>B</td>
<td>15.5</td>
<td>0.80</td>
</tr>
<tr>
<td>C</td>
<td>13.3</td>
<td>-0.84</td>
</tr>
<tr>
<td>V-asy</td>
<td>9.0</td>
<td>0.91</td>
</tr>
</tbody>
</table>

**Table 7.1**: Granulation Noise Reduction Success for the Various Diagnostics

All of these values, as well as the correlation coefficients, have been calculated as part of the analysis. The standard deviation of the corrected RV measurements was calculated, and this was found to be significantly lower compared to the uncorrected disc-integrated line profile RVs. The effectiveness of each of the granulation noise diagnostics for each of the noise reduction techniques is shown in Table 7.1.
### Initial Results

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$V_\sigma$ (cm s$^{-1}$)</th>
<th>Fractional Reduction (%)</th>
<th>Pearson’s R</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>20.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>BIS</td>
<td>37.8</td>
<td>-85</td>
<td>-0.48</td>
</tr>
<tr>
<td>C</td>
<td>13.3</td>
<td>35</td>
<td>-0.84</td>
</tr>
<tr>
<td>$V_b$</td>
<td>15.5</td>
<td>24</td>
<td>0.80</td>
</tr>
<tr>
<td>$A_b$</td>
<td>16.2</td>
<td>21</td>
<td>-0.78</td>
</tr>
<tr>
<td>bi-Gauss</td>
<td>46.1</td>
<td>-126</td>
<td>-0.40</td>
</tr>
<tr>
<td>$V_{asy}$</td>
<td>9.0</td>
<td>56</td>
<td>0.91</td>
</tr>
<tr>
<td>FWHM</td>
<td>77.0</td>
<td>-277</td>
<td>0.26</td>
</tr>
<tr>
<td>Line Depth</td>
<td>13.0</td>
<td>36</td>
<td>-0.84</td>
</tr>
<tr>
<td>EW</td>
<td>17.4</td>
<td>15</td>
<td>-0.76</td>
</tr>
<tr>
<td>Brightness</td>
<td>10.5</td>
<td>49</td>
<td>-0.89</td>
</tr>
</tbody>
</table>
Next Steps...

- Continue to make observations more realistic:
  - Instrumental profile, photon noise, finite exposures, additional noise sources, various magnetic fields, injecting planets
- Test observationally
  - Solar data, highest RV precision targets
- Expand to a suite of stellar lines with varying:
  - Formation heights, absorption strengths, excitation and ionisation potentials
- Expand to other spectral types