

Measuring Solar Oscillations using High-Precision Temperature Variations from SONG Spectra

Roar Holmberg^{1,2}, Hans Kjeldsen¹, Frank Grundahl¹

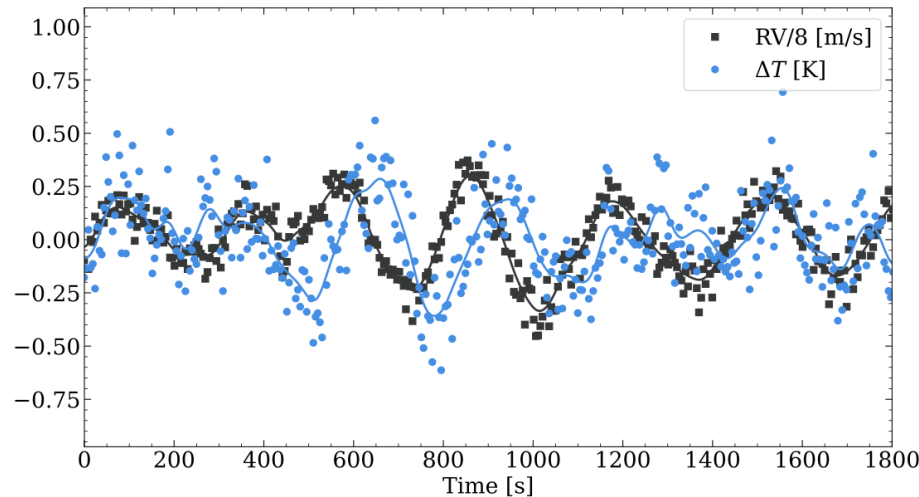
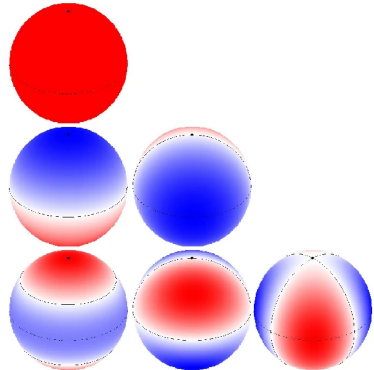
¹ Aarhus University, Denmark

² Nordic Optical Telescope, Spain



- Solar-like oscillations are usually observed in **RV** or **photometry**.

- Here: measure both RV and ΔT from the very same high-resolution spectra.



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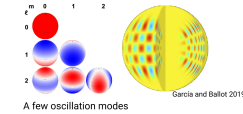
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Asteroseismology using simultaneous radial velocity and temperature variations

Solar-like oscillations are pressure waves oscillating at a star's natural frequencies driven by turbulence near the surface.



Mechanisms for observing solar-like oscillations:

1. Movement → Radial velocity (RV)
Ground-based
2. Temperature → Brightness (photometry)
Space-based
3. Temperature → Absorption line strengths
Ground-based

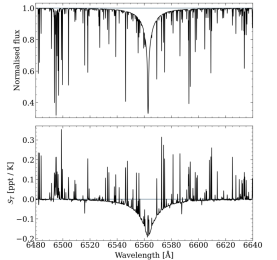
Typically, only RV and photometry are used in asteroseismology and these are used separately.

When available, simultaneous measurements allow for different studies comparing oscillation amplitude ratios and phase shifts.

We have developed a method of measuring precise temperature variations ΔT from high-resolution spectra obtained originally only for high-precision RV measurements. With this method, we are able to get simultaneous and precise RV and ΔT measurements from the very same data.

To measure ΔT we need the temperature response function $S = \partial F / \partial T$, where F is the normalised flux.

- The temperature response function for the specific star is generated from synthetic spectra. Most absorption lines in stellar spectra are sensitive to temperature changes.



Spectroscopic temperature variations from sensitive absorption lines

Reduction method applied to each echelle order:

1. Remove iodine spectrum used for wavelength calibration for precision RVs
2. Normalise spectrum to stellar continuum
3. Average all reduced spectra for each day, around 8000 spectra
4. Subtract average to obtain residual spectrum for each observation

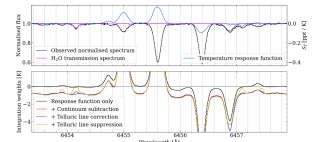
We calculate ΔT as a weighted integration of the residual spectrum:

$$\Delta T = \sum_i w_i R_i$$

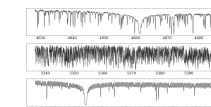
i : pixels

w_i : integration weights

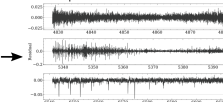
R_i : residual spectrum



Observed spectrum in three echelle orders



Residual spectrum from the same observation



We derive integration weights independently for each echelle order each observation to minimise noise while satisfying:

1. ΔT is measured in K according to the temperature response function
2. The continuum background is subtracted such that ΔT is insensitive to scaling variations in the spectrum
3. The effect of telluric lines, and thus also telluric line variations, is neutralised across the echelle order. This relies on telluric template spectra for H₂O and O₂

High-precision temperature variations from 40,000 solar spectra

Solar spectra observed with SONG-Tenerife

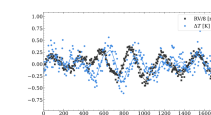
4351 - 6828 Å, R=120,000

4.9 s cadence

40,000 observations over 5 days

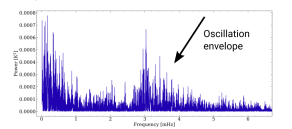
After measuring all ΔT s, the time series is post-processed by:

1. Rejecting observations obscured by clouds
2. Combining ΔT measurements from all echelle orders into one using a weighted average based on measured statistical errors
3. Generating the power spectrum

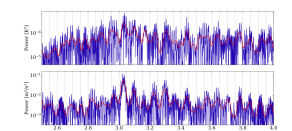


RV and ΔT measurements over 30 min showing phase-shifted solar oscillations

- Per-observation error:
 - Measured statistical error=0.14 K
 - Photon noise floor=0.086 K
- Oscillation envelope very clearly visible.
- The S/N of the oscillations can be measured from the power spectrum. Based on this, the S/N from ΔT is 1/5 the S/N from RV measurements from the same observations.



- The Sun's brightness allows for high-S/N, high-cadence spectra, ideal for testing and demonstration
- The intention is that the method can be used for any star with a similar dataset
- There are many years of observations for a number of oscillating stars in the SONG archive. These already have extracted RVs
- Applying this method to stars in the archive promises not just more signal from the same observations, but an entirely new pathway to studying stellar photospheres and stellar oscillations.



Comparison with power spectrum from RV measurements from the same data show the same oscillation frequencies