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Supporting Online Material for

Solar-like Oscillations in a Massive Star

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This PDF file includes:

SOM Text

Figs. S1 to S5

References

Supporting online material

Solar-like oscillations in a massive star

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I) Data analysis

a) Instrumental effects

As a first test to verify that the structures seen in the frequency domain [100; 250] μHz of the Fourier spectrum of V1449 Aql (HD180642) are not due to some instrumental perturbations, we have considered the fainter (apparent visual magnitude mv=9.14 for HD181072, and mv=8.27 for V1449 Aql (*S1*)) CoRoT target HD181072, which is in the same observation run and same CCD.
HD181072 does not exhibit structures comparable to those observed in V1449 Aql in the abovementioned frequency region. Its frequency spectrum only shows a residual of the orbital frequency with an amplitude around 9.8 ppm and a flat/white noise with an amplitude of 0.6 ppm in 150 days, far below the amplitudes of the structures we are interested in. Furthermore, neither the star background nor the satellite jitter show the structures observed in the stellar V1449 Aql.

b) Prewhitening procedure

To remove the influence of the dominant peaks and associated perturbation due to observational interruptions, we performed a prewhitening of the light curve (hereafter LC) obtained by CoRoT (Fig *S1*). The highest peaks in the time-series are fitted and then removed from the time series. Within each frequency range of 2 μHz, peaks are selected whenever their amplitudes are at least five times the local mean of the power spectrum. A fit to the time series is performed, based on a Levenberg-Marquardt method with a least-square minimization (*S2, S3, S4*). A total of 91 peaks were withdrawn. We find that the large structures in the power spectrum, which we identify as solar-like modes, are unaltered by the prewhitening procedure; their existence is therefore independent of the low frequency opacity-driven modes.

c) Validation using numerical simulations

In order to validate our prewhitening procedure as well as to theoretically investigate the influence of the combined effects of the unstable dominant modes and the observational interruptions, we built two simulated LC using our CoRoT light-curve simulator (*S5*). The first simulation is a temporal signal built by including only the low-frequency unstable modes that have been detected in the LC of V1449 Aql down to the amplitude of 460 ppm. In the second simulation, we also included a set of solar-like oscillations. The frequencies and line widths of these solar-like oscillations are computed using the non-adiabatic numerical code MAD (*S6*) and a stellar model- built with the evolutionary numerical code CLES (*S7*) - that matches the effective temperature and the luminosity of the star (see section II for details). Amplitudes of the included solar-like modes are set to a level representative of the high-frequency stable modes detected in V1449 Aql, that is 300 ppm. Each simulated LC is sampled with the same duty-cycle than that associated with the observations of V1449 Aql and noise is added to the resulting time series. Finally, we filled the gaps in the same way as done by the CoRoT data treatment chain (*S8*).

The prewhitened Fourier spectrum associated with the first simulated LC does not show any structures in the frequency domain we are interested in. This demonstrates that the combined effects of the unstable dominant modes, the window and the filling procedure do not produce spurious structures that could erroneously be interpreted as solar-like oscillations.

The second LC, which includes solar-like modes, has been prewhitened to remove the unstable modes in the same manner than done for V1449 Aql. The Fourier spectrum associated with the second simulated LC is presented in Fig. S2. The simulated solar-like oscillations are recovered in the Fourier spectrum associated with the second simulated LC. This demonstrates that the clean procedure leaves existing solar-like oscillations unaltered.

II) Modelling of solar-like modes

a) Auto-correlation of HD180642

Solar like oscillations are acoustic oscillations whose frequencies are expected to follow more or less closely the asymptotic regime (*S9*). In order to search for such a signature of regular p-mode spacing, we computed the autocorrelation of the Fourier spectrum in the frequency domain 130 μHz – 300 μHz. The domain below 130 μHz is excluded so as to avoid the low-frequency (low-radial order) modes, which in general significantly depart from the regular spacing expected for the high frequency p modes. The result is shown in Fig. S3**,** which clearly reveals three patterns, one centred on ν_0 =5 μHz, the second around ν_1=13.5 μHz and the last one around ν_2=27 μHz. The second pattern is centered at a frequency equal to half ν_2, that is $\nu_1=\nu_2/2$. The autocorrelation function then shows that a regular frequency spacing exists in the Fourier spectrum of the light-curve of V1449 Aql. This is the expected signature of asymptotic p modes with an associated large separation of either ν_2= 27 μHz or half its value, ν_1. We also see that the peak at ν_2 in the autocorrelation function has several components that are distant from ν_2 by a multiple of 2.5 μHz. The same feature, although less pronounced, is also observed in the pattern centred on ν_1. The presence of the peak at ν_0=5 μHz can be interpreted as the signature of mode splitting induced by the rotation of the star.

b) Simulated auto-correlation

An important issue is to verify that the properties of high frequency p modes, which are derived from the observed spectrum, are -at least roughly- consistent with theoretical expectations for solar-like p modes in a massive star. We therefore carried out a modelling of V1449 Aql, which is not fully optimized but sufficient for the present purpose. Future works will be dedicated to an optimized modelling of V1449 Aql.

To simulate an autocorrelation that can be compared with the one derived from the observed V1449 Aql LC, we computed a model that approximately matches the effective temperature of the star (*S1*) (T_{eff}=24500 ± 1000 K, log g = 3.45 ± 0.15). A ten-solar-mass model is obtained, with an effective temperature of 24075 K and a gravity of log g=3.88, using the CLES evolutionary code (*S7*). The associated p-mode frequencies present a large separation of 27 μHz, as suggested by the observed autocorrelation (Fig. S3). In building the simulated light curve, we included modes with angular degree l=0, 1, 2 and 3. We assumed the same theoretical value, σ=1 μHz, obtained with the code MAD (*S6*) for all line-widths of the modes. The radial modes were all given amplitude of 300 ppm, which is representative of the structures observed for V1449 Aql. The amplitude of the non-radial modes were set up to a 300 ppm value modulated by mode visibility factors. We further assumed a constant rotational splitting σ and defined *i* as the inclination angle between the rotation axis and the line of sight. From our set of theoretical frequencies, we simulate a LC using the CoRoT light-curve simulator[15] and computed the associated power density spectrum and the autocorrelation function.

We investigated different values of σ and *i.* An agreement with the observations is found for a rotational splitting of σ= 2.5 μHz and an inclination angle of *i*=90°. The result is shown in Fig S4. The pattern at ν_0 is reproduced. Our theoretical result shows that including p-modes split by a rotation of 2.5 μHz with an inclination angle of i=90° gives an autocorrelation that is compatible with the observed one. In order for the reader to estimate the quality of the agreement, we also show two additional autocorrelation functions in Fig. S5. In the first case we assume i=45° and a splitting of 2.5 μHz (top panel), while in the other case we assume i=90° with no splitting, i.e. keeping only the central component of the rotationally split multiplets (bottom panel). These autocorrelation functions do not reproduce the observed structures seen in Fig. S3.

These results provide a theoretical support to our assumption that the structures observed on the autocorrelation function of V1449 Aql are compatible with the presence of a regular p-mode spectrum. We also find that the main features of the observed autocorrelation function can be reproduced by assuming an internal rotation of 2.5 μHz and a rotation axis that has an inclination of i~ 90° with respect to the observed direction. However, a definite determination of the values of angle i and the rotation frequency is dedicated to a forthcoming work together with an optimized modeling.

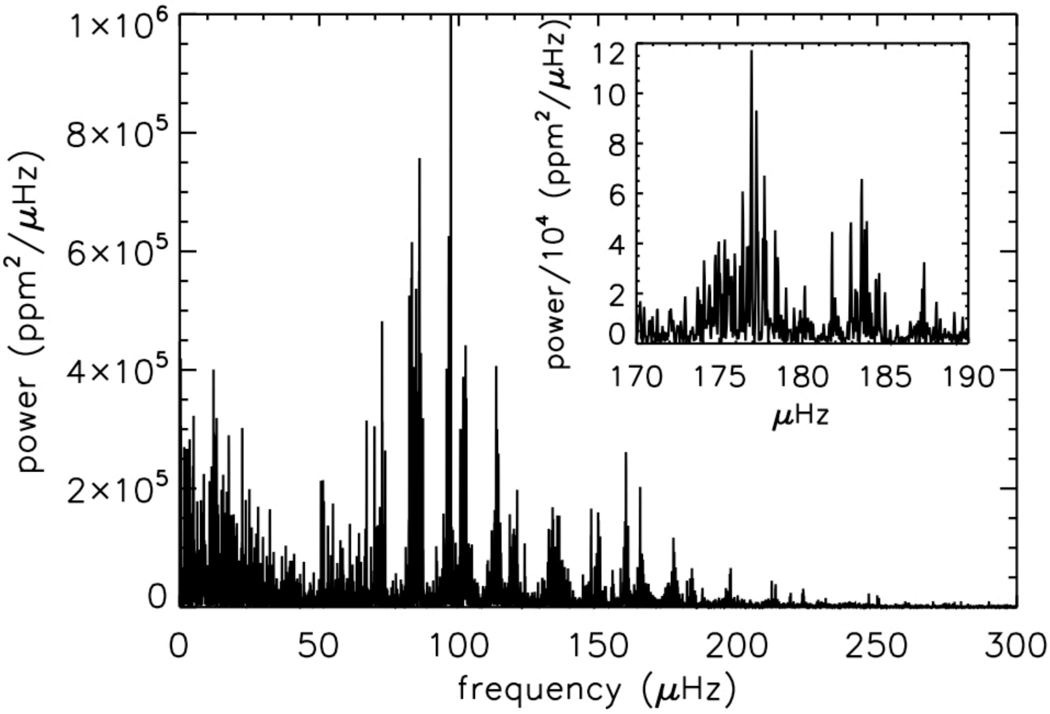

Fig S1: Fourier spectrum of prewhitened light curve obtained from the quasi-uninterrupted 150 days of observations, with a duty-cycle of 90%, of the star V1449 Aql by CoRoT, showing structures that are reproduced. Below 100 μHz, we enter the bulk regime of unstable modes and the possible existence of many such modes in this frequency domain then makes the deciphering of unstable versus stable modes quite delicate. Below 50 μHz, one notes an increase of the power toward low frequencies that is not yet identified as due to coloured noise, and/or g modes, and/or rotation. (Inset) Enlarged part of the spectrum.

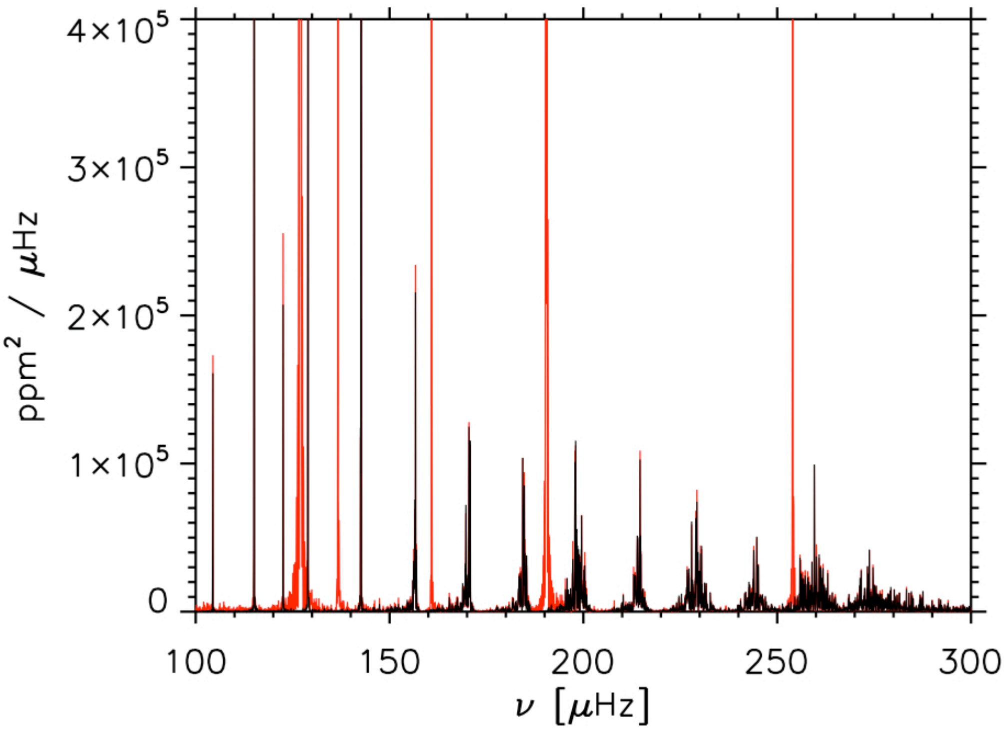

Fig S2: Power spectral density of the *simulated* LC that includes both unstable modes and solar-like oscillations. In black: prewhited LC. In red: original LC

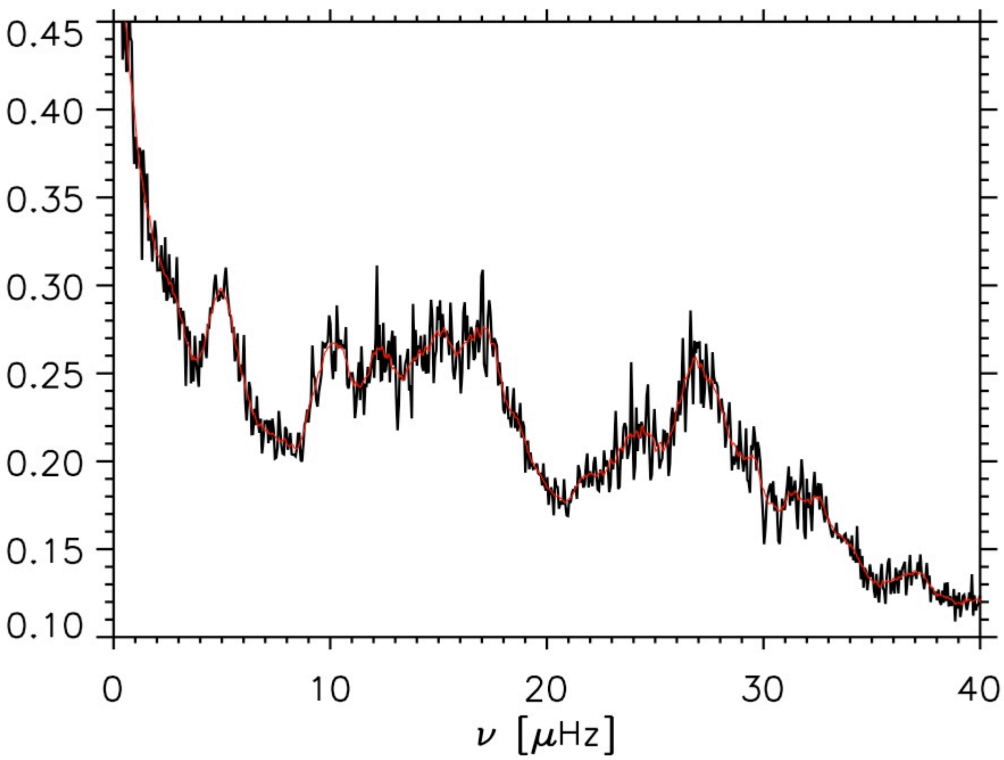

Fig S3: Autocorrelation of the power density spectrum associated with the observed lightcurve of V1449 Aql. The autocorrelation has been computed between 130 μHz and 300 μHz.

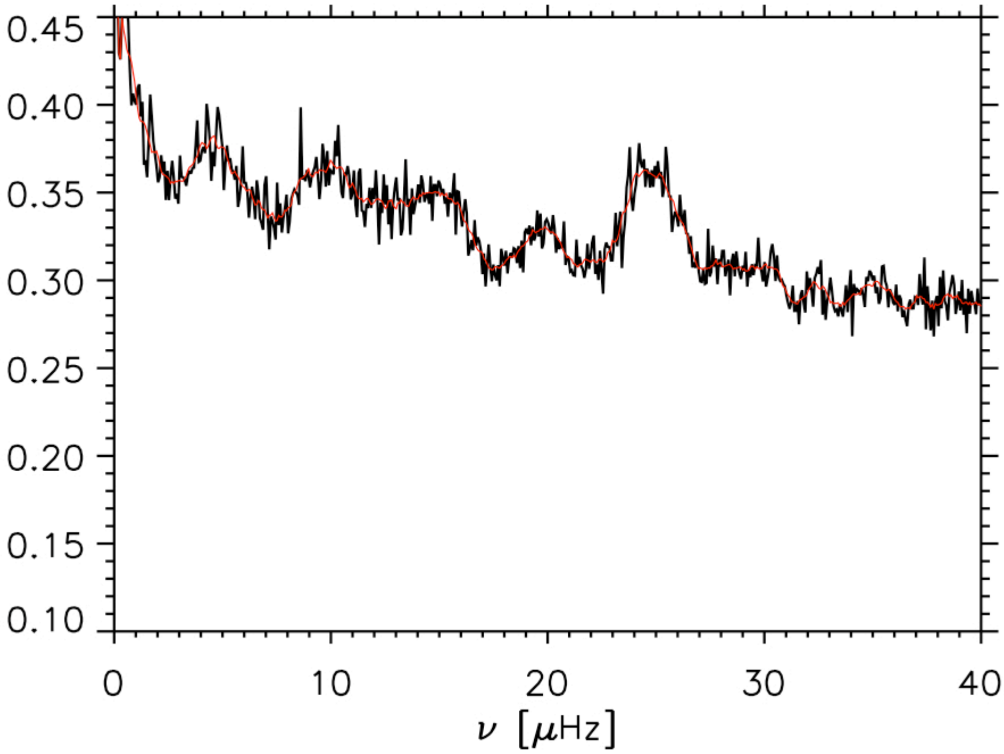

Fig S4: Autocorrelation function of the *simulated* power density spectrum associated with the stellar model that matches the effective temperature of V1449 Aql and that has a large separation of 27 μHz. It includes the modes l=0,1 and 2, with i=90° and a splitting of 2.5 μHz.

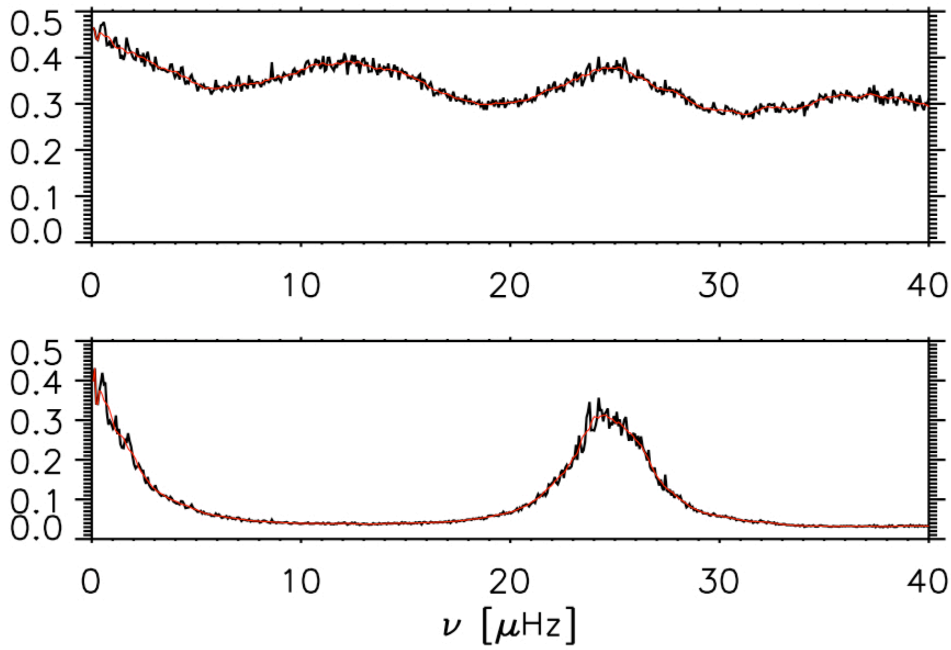

Fig S5: Autocorrelation function of simulated power density spectrum associated with the stellar model that matches the effective temperature of V1449 Aql and that has a large separation of 27 μHz. At the top panel, the simulation includes the modes l=0,1 and 2, with i=45° and a splitting of 2.5 μHz. At the bottom panel, the simulation includes the modes l=0,1 and 2, with i=90° and no splitting.

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