CoRoT Measures Solar-Like Oscillations and Granulation in Stars Hotter Than the Sun

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Oscillations of the Sun have been used to understand its interior structure. The extension of similar studies to more distant stars has raised many difficulties despite the strong efforts of the international community over the past decades. The CoRoT (Convection Rotation and Planetary Transits) satellite, launched in December 2006, has now measured oscillations and the stellar granulation signature in three main sequence stars that are noticeably hotter than the sun. The oscillation amplitudes are about 1.5 times as large as those in the Sun; the stellar granulation is up to three times as high. The stellar amplitudes are about 25% below the theoretic values, providing a measurement of the nonadiabaticity of the process ruling the oscillations in the outer layers of the stars.

The discovery of global oscillations in the Sun (*1*, *2*) opened the way to solar seismology, that is, to sounding the Sun's interior, measuring, for instance, the depth of its convection zone and its rotation at different depths and latitudes (*3*). High-precision photometry from space has long been considered the best way to extend these techniques to other main sequence stars of moderate mass where such oscillations are expected. However, the first attempts were ambiguous (*4*, *5*), casting some doubt on the theoretical estimates of intrinsic amplitudes and questioning to what extent the oscillations might be hidden by stellar granulation. We present here the detection of solar-like oscillations in three stars observed by the CoRoT (Convection Rotation and Planetary Transits) (*6*) space mission, and we characterize their amplitudes and the granulation signature.

Detecting and measuring solar-like oscillations in main sequence stars other than the Sun is challenging. Tracking the variations in the light from a star to one part per million (ppm) requires high accuracy on individual measurements. It also requires long uninterrupted sequences of observations to enhance the statistics of the measurements without being polluted by the spurious frequency components induced by data gaps. Solar-like oscillations have been detected from the ground in radial velocity in several stars (Fig. 1). However, ground-based observations are hampered by diurnal interruptions, weather instabilities, and the annual motion of the Earth. As a result, all existing data sets suffer more or less severely from a limited time base and large gaps in the data, which hamper the measurement of mode characteristics. In addition, radial velocity observations are strongly biased toward low-effective temperature stars (and slow rotators), for they require many narrow spectral lines, and toward subgiant and giant stars, which show oscillations of the same nature as the Sun and other main sequence stars but with larger intrinsic amplitudes. On the other hand, photometric detection of solar-like oscillations has not been possible from the ground because of the higher sensitivity to atmospheric scintillation, and the previous space projects detected only power excess so far [for Procyon and beta Hydri with WIRE (Wide-Field Infrared Explorer) (*7*, *8*) and eta Boo with MOST (Microvariabilité et Oscillations

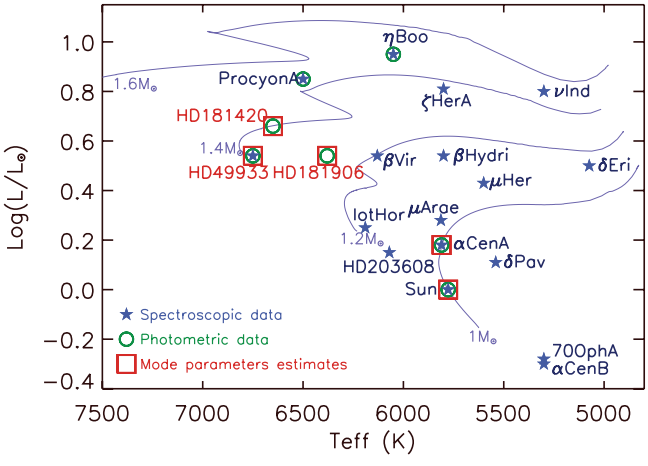

Fig. 1. HR diagram featuring stars for which mode structure has been observed in photometry (red squares), a power excess has been detected in photometry (green circles), and a detection has been performed in radial velocity (blue stars). Stellar evolutionary tracks are taken from (*20*), for solar chemical composition. Red giant pulsators (~6 objects) are out of the upper right corner of the figure.

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Table 1. Parameters obtained in the present analysis, with standard deviation estimates.

Star	A_{bol} (l = 0)(ppm)	B_{bol} (ppm^2/μHz)	C (s)	Δ (μHz)
HD 49933	4.02 ± 0.57	1.97 ± 0.53	1967 ± 431	86 ± 2
HD 181420	3.82 ± 0.40	2.41 ± 0.31	1936 ± 206	77 ± 2
HD 181906	3.26 ± 0.42	1.12 ± 0.20	1650 ± 0276	88 ± 2
Sun PMO6	2.39 ± 0.17	0.85 ± 0.06	1440 ± 86	135 ± 2

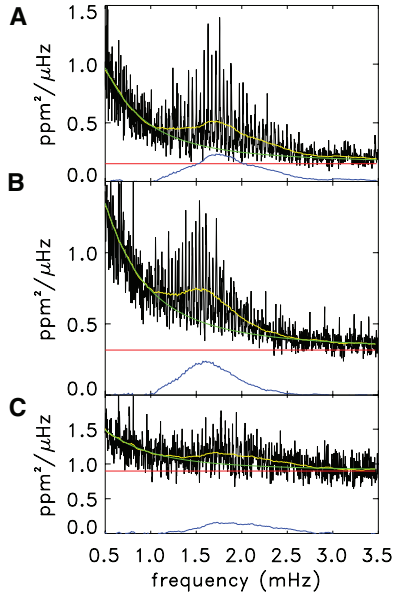

Fig. 2. Instrumental power spectral density. (**A**) For HD49933; a moving mean is applied with a 4-μHz boxcar (black); yellow curve: same spectrum highly smoothed (4 times Δ boxcar); green curve: mean level of the granulation + white noise components; red curve: mean white noise component level alone; blue curve: oscillation mean power density contribution alone. (**B**) Same for HD181420. (**C**) Same for HD181906.

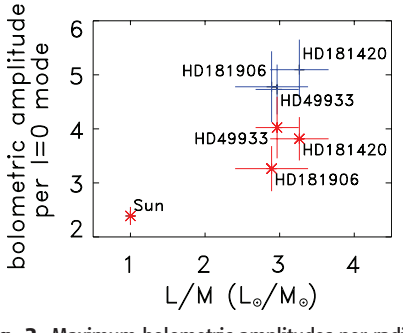

Fig. 3. Maximum bolometric amplitudes per radial mode measured (red) for HD49933, HD181420, HD181906, and for the Sun. Theoretical values are also given (blue). Error bars on amplitudes are standard deviation estimates associated with the accuracy of the measurements (red), and with the error estimate on T_{eff} (blue).

Stellaires) (*9*)]. For alpha Cen A, WIRE (*10*) detected the characteristic comblike pattern of the oscillations, which could be analyzed with the help of complementary velocity data (*11*). However, alpha Cen A is very close to the Sun in terms of its global characteristics. The results here are based on light curves obtained with CoRoT over 60 days for HD49933 and 156 days for HD181420 and HD181906, three main sequence F stars noticeably hotter than the Sun (Fig. 1 and table S1).

The CoRoT satellite was launched on December 2006 in an inertial polar orbit at an altitude of 897 km. The instrument is fed by a 27-cm diameter telescope. During each run, it simultaneously provides light curves (variations in stellar flux with time) from 10 bright stars ($5.5 < m_V < 9.5$) dedicated to seismic studies, while 12,000 fainter stars ($11.5 < m_V < 15.5$) are monitored to search for transits due to planets (*6*). The sampling rate is 1 s for an integration time of 0.794 s. Pointing stability reaches a precision of 0.15″ root mean square. The duty cycle was higher than 93%; the missing data correspond essentially to the time spent in the South Atlantic magnetic anomaly where the perturbations due to energetic particles have not, as yet, been effectively corrected. These gaps, about eight per day, from 5 to 15 min each, have been linearly interpolated (with a 2000-s boxcar on each side of the gap to prevent the introduction of any spurious high frequencies) before we computed the Fourier power spectra, to minimize the aliases of the low-frequency components due to the window. We used synthetic spectra to check that this procedure has no noticeable influence on the measured mean values.

For each of the three stars, the Fourier power density spectra (Fig. 2) show three components that can be understood as (i) a flat white-noise component essentially due to photon counting noise, (ii) a stellar background component (essentially granulation in this frequency domain) following a Lorentzian profile $B/[1+(Cν)^2]$ as suggested in (*12*), and (iii) the stellar oscillation spectrum with its comblike pattern characterized by the large separation Δ (*13*).

Although dedicated analyses are under way to extract individual mode frequencies and profiles for each star, we measure here the contributions of these three components. We follow the method proposed in (*14*) and illustrated in Fig. 2, and we convert these instrumental values into intrinsic bolometric maximum amplitude per radial mode [$A_{bol}(l = 0)$] and bolometric maximum power spectral density B_{bol} (*15*). We apply the same analysis to the solar SOHO/VIRGO/PMO6 (Solar and Heliospheric Observatory/Variability of Solar Irradiance and Gravity Oscillations) data (*16*). The amplitudes of the three stars are larger than in the Sun by a factor of ~1.5 (Fig. 3).

Theoretical predictions suggest that velocity amplitudes follow a scaling law in $(L/M)^{\alpha}$ with $\alpha \sim 0.7$ (L and M standing for luminosity and mass), in broad agreement with the existing velocity measurements (*17*). In the adiabatic approximation (*18*), this would give photometric amplitudes scaling as $(L/M)^{\alpha}$ $(T_{eff})^{1/2}$, where T_{eff} is effective temperature. As shown in Fig. 3 (see also Table 1), the measured values for the three stars are of the same order but significantly lower (by 24 ± 8% globally) than the theoretical values. The measurement of this systematic departure from the adiabatic case, which is not observed in velocity, tells us about the exchange of energy between convection and oscillations in the outer part of the convection zone. This process is responsible for the existence, and the specific amplitudes and lifetimes, of the oscillations. Both radial velocity and photometry measurements are sensitive to the oscillation momentum induced by this energy exchange; the photometric amplitudes are in addition more sensitive to the details of this process, via radiation-matter interaction. These measurements offer the possibility of testing theoretical models of the nonadiabatic effects of the processes governing the oscillations and illustrate the complementary interest of photometry and radial velocity measurements (when they are possible), which probe the oscillations differently.

The spectral signature of granulation is expected to reveal time scales and distance scales characteristic of the convection process in different stars (*12*, *19*). Our data show (fig. S1 and Table 1) that (i) the maximum bolometric power density (B_{bol}), associated with the number of eddies seen at the stellar surface and the border/center contrast of the granules, is higher for the three stars than for the Sun by a factor up to 3; and (ii) the characteristic time scale for granulation (C) associated with the eddy turnover time increases slightly with T_{eff} (up to 30% higher than the Sun).

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Supporting Online Material

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SOM Text
Fig. S1
Table S1
References

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A Large Excess in Apparent Solar Oblateness Due to Surface Magnetism

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The shape of the Sun subtly reflects its rotation and internal flows. The surface rotation rate, ~2 kilometers per second at the equator, predicts an oblateness (equator-pole radius difference) of 7.8 milli–arc seconds, or ~0.001%. Observations from the Reuven Ramaty High-Energy Solar Spectroscopic Imager satellite show unexpectedly large flattening, relative to the expectation from surface rotation. This excess is dominated by the quadrupole term and gives a total oblateness of 10.77 ± 0.44 milli–arc seconds. The position of the limb correlates with a sensitive extreme ultraviolet proxy, the 284 angstrom limb brightness. We relate the larger radius values to magnetic elements in the enhanced network and use the correlation to correct for it as a systematic error term in the oblateness measurement. The corrected oblateness of the nonmagnetic Sun is 8.01 ± 0.14 milli–arc seconds, which is near the value expected from rotation.

Motions within the interior of the Sun affect the location of the photosphere, so the precise measurement of the shape of the solar limb is a long-standing astrometric objective (*1*). The shape also relates to Le Verrier's 1859 observation of an anomalous perihelion precession of Mercury (only some 43″ per century), which could be precisely calculated in Einstein's theory of general relativity (*2*). A discrepancy from the predictions of this theory would point to either a need for a new theory or else to a distortion of the Sun's internal gravity not reflected in the surface rotation. The two leading possibilities for such a gravitational field would be a rapidly rotating core left over from the early stages of star formation—perhaps on an oblique axis—or a strong magnetic field (*3*).

The modern era of measurements of the solar oblateness began in the 1960s with Dicke's Princeton Solar Distortion Telescope (*4*) and other ground-based telescopes (*5*–*8*). Dicke's initial results (*4*) implied that the Sun was much more oblate than the surface rotation predicts. More recent observations have tended to show smaller values, closer to the 7.8 milli–arc sec predicted by the surface rotation (*3*), but the uncertainties in the measurements have remained relatively large. The theoretical estimate is difficult because of the differential nature of solar rotation, both in latitude and in radius. The ground-based data also hinted at time variations in the oblateness (*6*). Including the two data points (1997 and 2001) from the Michelson-Doppler Imager (*9*) on board the Solar Heliospheric Ob-

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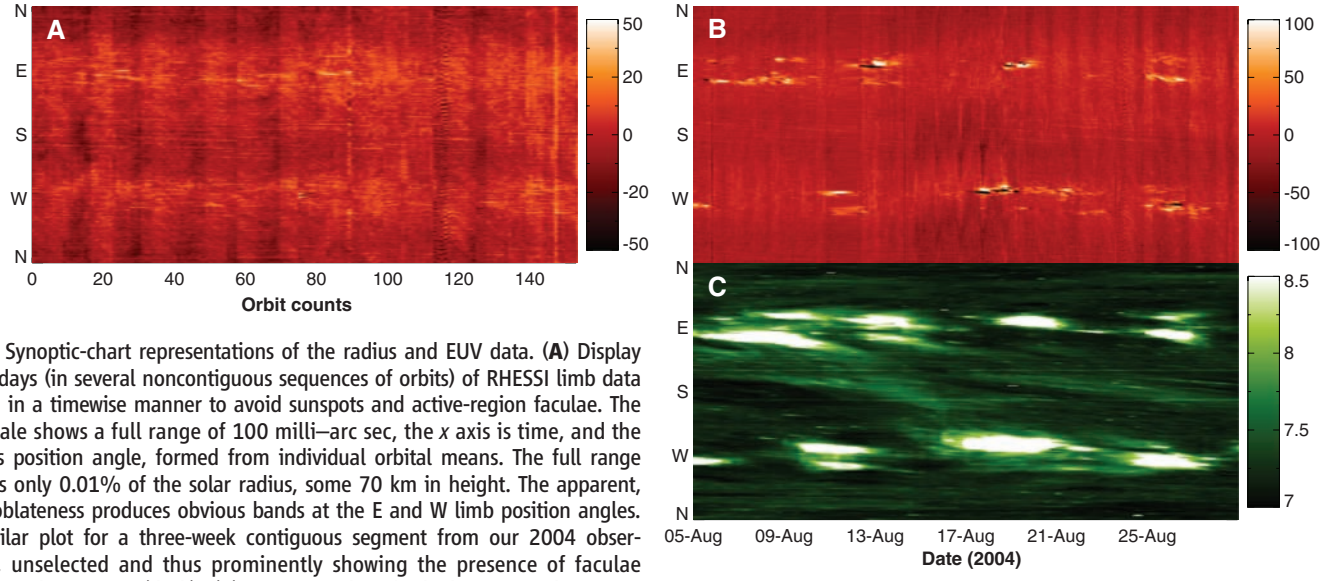

Fig. 1. Synoptic-chart representations of the radius and EUV data. (**A**) Display of ~10 days (in several noncontiguous sequences of orbits) of RHESSI limb data selected in a timewise manner to avoid sunspots and active-region faculae. The color scale shows a full range of 100 milli–arc sec, the *x* axis is time, and the *y* axis is position angle, formed from individual orbital means. The full range shown is only 0.01% of the solar radius, some 70 km in height. The apparent, excess oblateness produces obvious bands at the E and W limb position angles. (**B**) Similar plot for a three-week contiguous segment from our 2004 observations, unselected and thus prominently showing the presence of faculae (bright) and sunspots (dark). (**C**) Corresponding limb data from the SOHO observations in the EUV 284 Å band (*18*), which shows the locations of faculae and other kinds of magnetic activity. The contours of this synoptic map determine the data fraction for our masking analysis, as detailed in the SOM.