Sciencexpress Report

Asteroseismology of HD 129929: Core Overshooting and Nonrigid Rotation

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We have gathered and analyzed 1493 high-quality multicolor Geneva photometric data (obtained with the Swiss 0.7-meter telescope at La Silla Observatory, Chile) taken over 21 years of the B3V star HD 129929. We detect six frequencies, among which appear the effects of rotational splitting with a spacing of ~0.0121 cycles per day, implying that the star rotates very slowly. A nonadiabatic analysis of the oscillations allows us to constrain the metallicity of the star to $Z \in [0.017,0.022]$, which agrees with a similar range derived from spectroscopic data. We provide evidence for the occurrence of core convective overshooting in the star, with $\alpha_{ov} = 0.10 \pm 0.05$, and we rule out rigid rotation.

Stars are composed of multiple gas layers with different temperatures, pressures, and chemical compositions. During their main-sequence phase, that is, while they transform hydrogen into helium in their core, a number of massive stars undergo oscillations. Through the study of these oscillations, scientists have a unique opportunity to probe the structure of specific layers of those stars. This type of investigation is termed asteroseismology. Here, asteroseismology is used to study the interior structure of a 10 solar mass star of spectral type B, HD 129929. Such a massive B star has a well developed convective core, the extension of which is uncertain as it depends on a poorly known phenomenon called core overshooting (inertial mixing of material from the convective core to the convectively stable upper layer). Moreover, the rotation of the star may be a source of mixing between the core and the outer layers. Both effects, which are in general difficult to disentangle from each other (*1*), affect the evolutionary path of the star; that is, they determine the way in which the star evolves to its supernova stage. In the case of HD 129929, we would like to determine the effectiveness of the overshooting phenomenon, technically measured by the overshooting parameter.

Oscillating main-sequence B stars more massive than 8 solar masses are called β Cephei variables. Their individual oscillation modes, which are driven by an opacity mechanism acting in the metal opacity bump at a temperature of some 200,000° (*2*), have multiple periods between 2 and 8 hours. This condition leads to beat periods of order several months, which are much longer than the beat-periods of main-sequence stars that exhibit solar-like oscillations or of the oscillations in compact stars such as white dwarfs. Moreover, the oscillation frequencies in solar-like stars and in white dwarfs are more numerous and obey certain regular patterns (*3*, *4*), which makes their modes much easier to identify than opacity-driven modes in massive stars. This is one of the reasons why seismic studies of solar-like stars and of white dwarfs are much further advanced than those of opacity-driven oscillators.

HD 129929 (visual magnitude of 8.1, spectral type of B3V) was discovered to be a microvariable by (*5*). Three close frequencies were established by (*6*, *7*) in multicolor photometry of the star which led (*6*) to classify the object as a new β Cephei star. We have continued the photometric monitoring of the star and have assembled 1493 high-quality (error < 5 mmag) multicolor data points during several three-week runs throughout 21.2 years. All data were gathered with the 7-passband Geneva photometer P 7 attached to the 0.7-m Swiss telescope at La Silla Observatory in Chile. The effective temperature and the gravity of HD 129929 are available from calibrations of photometric systems (*8*, *9*). These parameters and the metallicity of the star were also derived from low-resolution spectra taken with the International Ultraviolet Explorer (*10*). The overall range in quoted values of the temperature and gravity is respectively $\log T_{\rm eff} \in [4.35,4.38]$ and $\log g \in [3.87,3.94]$ and the metallicity found by (*10*) is $Z = 0.018 \pm 0.004$. We have used these estimates as starting point of our model grid calculations but we stress that our modeling results are independent of this particular result. In fact, we improve the estimates of the temperature and the gravity considerably with our seismic analysis.

We have performed both phase dispersion minimization (*11*) and fourier analysis (*12*) on the time series of 1493 data points in each of the seven Geneva filters (Fig. 1). The six frequencies which result were found by both of these independent techniques and all six frequencies are found independently of the order of prewhitening (i.e., subsequent sine curve subtraction). The periodograms (Fig. 1 and Table 1) show that $f_1 – f_3 \cong f_2 – f_6 \cong f_4 – f_2 \cong 0.0121$ c d^{-1}; i.e., two frequency multiplets due to rotational splitting appear in the data. We note that the highest peaks in the periodograms do not occur for f_5 and f_6 but for their one-day alias (Fig. 1). We can be sure of this both for physical reasons and for reasons related to our models. All models that obey $f_1,\ldots,f_4$ do not lead to a low-degree mode at $f_5 - 1$ or any other alias of f_5, while they result in the radial fundamental mode at f_5. Similarly there is no low-degree mode available near $f_6 + 1$ while f_6 corresponds to the $l = 1$, p_1 mode shifted by the rotation. The frequencies that show up after prewhitening with $f_1,\ldots,f_6$ no longer coincide for the different Geneva filters and/or for the different analysis methods. We hence regard them as ambiguous and we only make use of the six established frequencies (Fig. 2), which consist of one isolated frequency and (parts of) two multiplets.

We modeled the interior structure of HD 129929 using two independent evolutionary codes, namely the Code Liégeois d'Évolution Stellaire (*13*) and the Warsaw-New Jersey Evolutionary Code (*14*). We have considered a large range in log $T_{\rm eff}$ and in log g and allowed $X \in [0.68,0.74]$, $Y \in [0.24,0.3]$ and $Z \in [0.015,0.03]$. We used the OPAL opacities (*15*) completed with the Alexander & Ferguson opacities (*16*) below $\log T = 3.95$ and the standard heavy-element mixture (*17*). For all these models, we have calculated the oscillation modes using also two independent codes for linear nonadiabatic oscillations (*18*, *19*). All the results obtained from these independent codes are the same to a high degree of accuracy.

The second step in a seismic analysis consists of mode identification of the detected frequencies, that is, to derive the wavenumbers (n,l,m) of the modes. The degree l of the modes can be derived from the amplitude ratios and phase differences of multicolor photometry. We have used the two nonadiabatic oscillation codes (*18*, *19*) to do so and found agreement for the identifications (Table 1). These identifications are unambiguous because of the sparse frequency distribution due to the slow rotation of HD 129929. Following (*20*, *21*), who provided a method to derive constraints on the metallicity of the star from the observed amplitude ratios in B stars, we find that $Z < 0.022$ is needed to meet the observed amplitudes and their errors. Moreover, for $Z < 0.017$ the modes corresponding to the observed frequencies are not excited by the opacity mechanism. This seismically determined interval $Z \in [0.017,0.022]$ is consistent with the one derived from the independent spectroscopic observations. The physical behavior of the modes of HD 129929 (fig. S2) is representative of the nature of the propagation zone in which they are trapped.

We have computed numerous stellar models, and only a few of them lead to the observed frequencies f_5 and f_2, which correspond to the radial and axisymmetric dipole modes—modes that are unaffected by the rotation of the star (fig. S3). For all the models that explain f_5 and f_2 well, we have also calculated the frequency of the $l = 2$, g_1 axisymmetric mode and compared its value to the possible values for that mode for the case $X = 0.7$ (Fig. 3, left panel). We conclude that the overshooting parameter $\alpha_{\rm ov}$ cannot be equal to 0.2, as this results in a value for the frequency of the $l = 2$ axisymmetric mode which is too small. Similarly, it cannot be 0, as this value gives results which are inconsistent with the photometric amplitude ratios. The value $\alpha_{\rm ov} = 0.1$ is, on the other hand, totally acceptable, and for this value we derive $M \in [9,9.5]\ M_\odot$ (Fig. 3, right panel). The same results are obtained for models with other values of the parameter $X \in [0.68,0.74]$. The corresponding ages of the allowed models are between 1.6 and 1.8×10^7 years. These models are situated between those indicated by arrows in fig. S3.

The observation of the triplet of frequencies (f_6,f_2, f_4) of the $l = 1$, p_1 mode and of the two components (f_3, f_1) of the quintuplet of the $l = 2$, g_1 mode (Fig. 2) also allows us to determine the rotation frequency of the star. The rotational splitting Δf is linked to the internal rate of rotation of the star $\nu_{\rm rot}$ through the linear relation $\Delta f = \int K_{nl}(r)\nu_{\rm rot}(r){\rm d}\,r$, where the kernel $K_{nl}(r)$ is completely defined by the mode identification and by the stellar model. The observed splittings $\Delta f = 0.0121295{\rm c\ d^{-1}}$ for the $l = 1$, p_1 mode and $\Delta f = 0.012109{\rm c\ d^{-1}}$ for the $l = 2$, g_1 mode are incompatible with a rigid rotation of the star for the accepted stellar models. Indeed, the first one would imply $\nu_{\rm rot} = 0.012653{\rm c\ d^{-1}}$ while the second one would imply $\nu_{\rm rot} = 0.014730{\rm c\ d^{-1}}$. On the other hand, both modes have amplitudes that are too low in the inner regions of the star to give any information on the rotation inside the core. In order to estimate the rotational behavior in the outer layers, we have assumed the behavior of $\nu_{\rm rot}$ to follow a linear law of the form $\nu_{\rm rot}(r) = \nu_{\rm rot,0} + (r/R-1)\nu_{\rm rot,1}$. We then get $\nu_{\rm rot,0} = 0.00713{\rm c\ d^{-1}}$ and $\nu_{\rm rot,1} = -0.01856{\rm c\ d^{-1}}$. These values imply a low equatorial rotation velocity of 2.04 km s^{-1}.

We note that no model calculation using the OP opacity tables (*22*) leads to the observed frequencies for appropriate ranges in the stellar parameters of HD 129929. It is at present unclear whether this is due to the 2.5% higher iron fraction or to the different physics used to calculate the OP tables in comparison with the OPAL tables.

Convective core overshooting is not considered in some evolutionary model calculations of massive main-sequence stars (*23*). The reason is that it does not seem to be a necessary ingredient to explain the observed properties of such stars. However, we have found evidence for the presence of overshooting with $\alpha_{\rm ov} \in [0.05,0.15]$ in HD 129929 because the star has an extremely low rotational velocity and so rotational effects can be neglected. We have adopted the standard solar mixture in our model calculations and an important open question, for any asteroseismic analysis, is how much the results may change if a different mixture is considered.

References and Notes

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24. The authors are much indebted to all researchers from Leuven and Geneva who contributed to the gathering of the data over the course of 21 years. C.A. and C.W. acknowledge financial support from the Fund for Scientific Research of Flanders (FWO). A.T., R.S.,

M.A.D., and A.N. acknowledge financial support from the Pole d'Attraction Interuniversitaire Contract #P5/36, from the Prodex-ESA Contract #15448/01/NL/SFe (IC), and from FRIA (Belgium). A.T. acknowledges financial support received from the Fonds National de la Recherche Scientifique, Belgium. J.D. acknowledges financial support from the Belgian Federal Office for Scientific, Technical, and Cultural Affairs.

Supporting Online Material
www.sciencemag.org/cgi/content/full/1084993/DC1
Figs. S1 to S3

27 March 2003; accepted 14 May 2003
Published online 29 May 2003; 10.1126/science.1084993
Include this information when citing this paper.

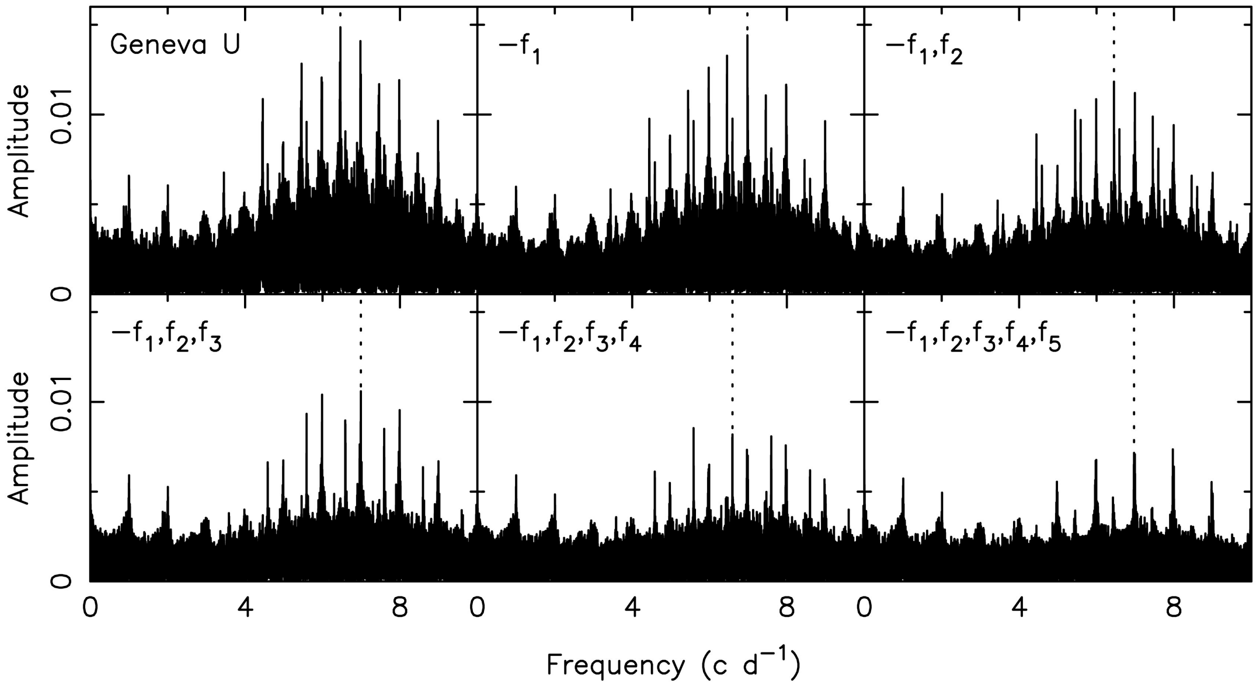
Fig. 1. Periodograms for the Geneva U data for subsequent stages of prewhitening. The amplitude is expressed in magnitudes. For the values of the frequencies, we refer to Table 1. The dotted lines indicate the selected frequencies.

Fig. 2. Final amplitude spectrum of HD 129929.

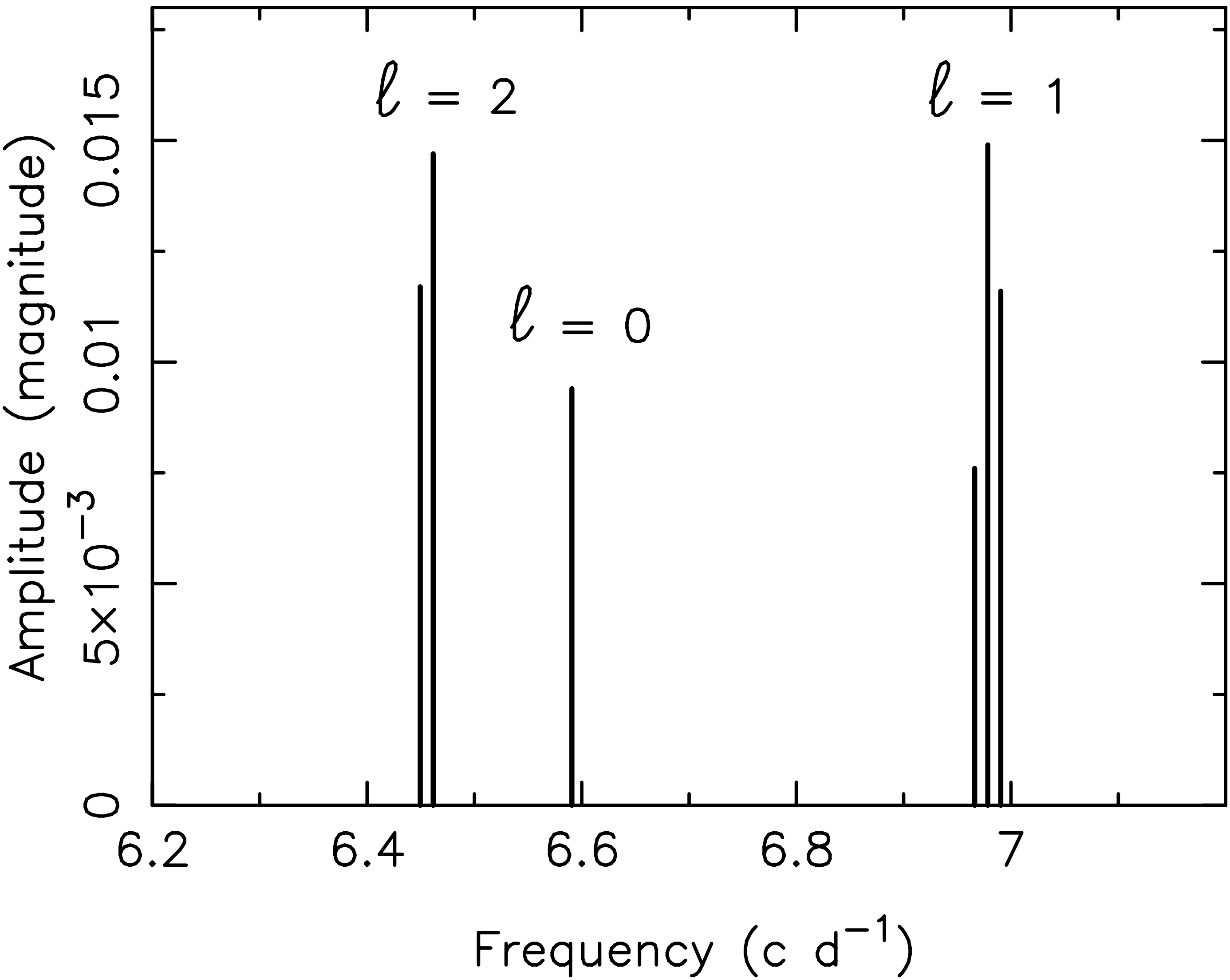
Fig. 3. Frequency of the $l = 2$ axisymmetric mode for the models with $X = 0.7$ that fit the frequencies f_5 and f_2. The squares, dots, and triangles are obtained for $\alpha_{ov} = 0, 0.1, 0.2$ respectively. The four horizontal lines are the possible values derived from the observations for this axisymmetric mode. (**Left**) Frequency as a function of metallicity Z. The seismic constraints on Z are represented as vertical lines. (**Right**) Frequency as a function of mass M for models with $\alpha_{ov} = 0.1$. The constraints on the mass obtained by imposing $0.017 < Z < 0.022$ and that the $l = 2$ frequency must be consistent with the observations are represented as dashed vertical lines.

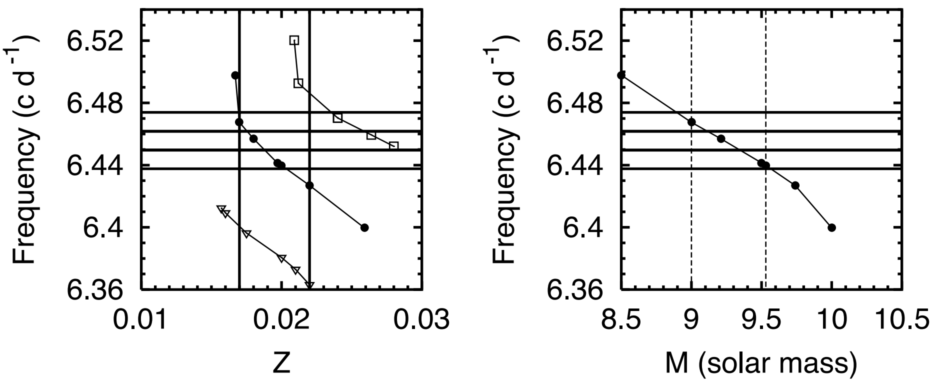
Table 1. Accepted frequencies f_i, $i = 1,\ldots,6$ for HD 129929. The standard error is less than 10^{-6} c d^{-1} (cycles per day) for all listed frequencies. l and m denote the degree and the azimuthal number of the oscillation modes. The amplitudes are expressed in millimagnitudes.

Oscillation Frequencies	Amplitude in U	Amplitude in V	Mode Identification	Frequency Splitting
$f_1 = 6.461699$ c d^{-1}	14.7 ± 0.6	11.8 ± 0.4	$l = 2$, $m = ?$, g_1	
$f_2 = 6.978305$ c d^{-1}	14.9 ± 0.8	10.3 ± 0.5	$l = 1$, $m = 0$, p_1	
$f_3 = 6.449590$ c d^{-1}	11.7 ± 0.6	9.1 ± 0.4	$l = 2$, $m = ?$, g_1	
$f_4 = 6.990431$ c d^{-1}	11.6 ± 0.8	7.5 ± 0.5	$l = 1$, $m = +1$, p_1	$f_1 - f_3 = 0.012109$ c d^{-1}
$f_5 = 6.590940$ c d^{-1}	9.4 ± 0.8	4.9 ± 0.5	$l = 0$, $m = 0$, p_1	$f_4 - f_2 = 0.012126$ c d^{-1}
$f_6 = 6.966172$ c d^{-1}	7.6 ± 0.6	4.8 ± 0.5	$l = 1$, $m = -1$, p_1	$f_2 - f_6 = 0.012133$ c d^{-1}



Geneva U
$-f_1$
$-f_1,f_2$
$-f_1,f_2,f_3$
$-f_1,f_2,f_3,f_4$
$-f_1,f_2,f_3,f_4,f_5$
Amplitude
0.01
0
0
4
8
Frequency (c d^{-1})


ℓ = 2
ℓ = 0
ℓ = 1
Amplitude (magnitude)
0
5×10⁻³
0.01
0.015
6.2
6.4
6.6
6.8
7
Frequency (c d⁻¹)



Frequency (c d^{-1})
6.52
6.48
6.44
6.4
6.36
0.01
0.02
0.03
Z
Frequency (c d^{-1})
6.52
6.48
6.44
6.4
6.36
8.5
9
9.5
10
10.5
M (solar mass)