Evidence for global pressure oscillations in Procyon and α Centauri

B. GELLY; G.GREC and E. FOSSAT
Département d'Astrophysique de l'IMSP
Université de Nice
Parc Valrose
F - 06034 NICE CEDEX

Abstract. Helioseismology has proved to be a powerful tool to probe the internal structure of the sun. With a new adapted optical resonance spectrophotometer, an extension has been attempted to two bright stars, namely α Centauri A and Procyon. Results obtained from two observing runs on α Centauri A in May 1983 and May 1984 at La Silla, and one observing run on Procyon in February 1984 at Hawaii are presented. In both cases, solar-like pressure oscillations have been detected. The complete analysis is presented, which leads to determine essentially five parameters: the frequency range, the amplitudes, the mean equidistance $\Delta\nu$, the departure around this equidistance (curvature of the echelle-diagram) and the fine frequency spacing between modes of degree 0 and 2. For Procyon, all results are consistent with theoretical predictions, including excitation of oscillations, mass, radius, and age of the star. For α Centauri, all the results are consistent together and are confirmed by the 1984 observations. They suggest that α Cen might be younger than estimated, consistent with a zero age main sequence star.

This is the abstract of a paper recently published in Astronomy and Astrophysics. We have selected here under some parts of this paper. For more detail, it is recommended to refer to this journal.

1. Step by step description of the data analysis.

a- Low frequency filtering of the data, with a cut-off at about 0.3 to 0.5 mHz, to reduce the atmospheric and instrumental noise.

b- FFT spectrum $P(\nu)$ of this filtered data, taken as one single time series, filled with zeroes when observation is not available.

c- Search, in this $P(\nu)$, of a frequency range whose Fourier analysis provides a cha-function, multiplied by the window function autocorrelation.

d- Calculation of the Fourier transform of the frequency range found in c. This is the squared autocorrelation function of the stellar signal filtered in this frequency range.

e- Determination, along the autocorrelation time axis, of

J. Christensen-Dalsgaard and S. Frandsen (eds.), Advances in Helio- and Asteroseismology, 249–252.

narrow bands containing the cha-function defined in c.

f- Fourier transform of the complete power spectrum $P(\nu)$, and restriction of this Fourier transform to the narrow bands defined in c by replacing the complex amplitudes by zeroes between these bands.

g- Inverse Fourier transform, of the function defined in f, showing the discrete pattern searched in $P(\nu)$.

h- From g, determination of the power envelope of the assumed p-mode set of dicrete frequencies

i- Echelle-diagram of the filtered power spectrum obtained in g, and measurement of the eventual curvature of the set of modes on this diagram.

j- Straightening of the echelle-diagram by a polynomial fitting of the curvature.

k- Vertical sum on the echelle-diagram of the unfiltered power spectrum, to search for the eventual frequency separation of modes of degree 0 and 2 (separation impossible on the filtered spectrum).

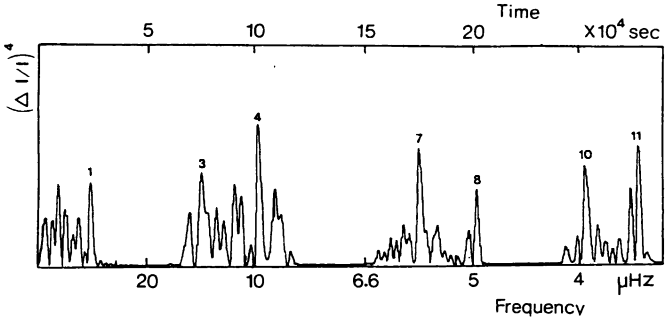

Figure 1. Power spectrum of the 1.17-1.65 mHz range of the power spectrum of four nights of Procyon data. The autocorrelation of the window function is clearly visible, as well as a regular pattern of equidistant peaks. The period of the fundamental defines the spacing $\Delta\nu/2 = 39.7$ μHz.

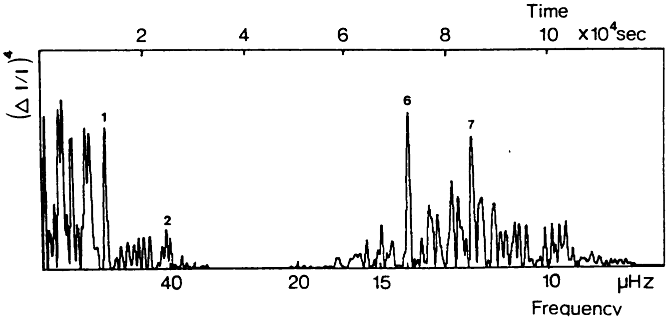

Figure 2. Same for the 2.3 -3.8 mHz range of the power spectrum of 3 nights of α Cen data. In this case, the period of the fundamental defines a spacing of $\Delta\nu = 82.7$ μHz.

2. Discussion of results.

Two recent studies (Christensen-Dalsgaard & Frandsen, 1983 and Christensen-Dalsgaard, 1984) give us interesting points of comparison between our results and the theoretical predictions. The three main results of these studies are based upon the expected measurements of the two parameters $\Delta\nu$ and D_0 in the asymptotic equation. First it is found that for any zero age main sequence model of star (ZAMS), $R\Delta\nu \simeq$ constant, R being the radius of the star. Then, during its evolution in the main sequence, the star follows the homologuous scaling law $R^{3/2}\Delta\nu \simeq$ constant. These laws can be calibrated against the solar values.

The third result is the diagnostic value of the parameter D_0, which depends strongly on the gradient of the sound speed near the center. As the star burns its hydrogen, the central molecular weight increases, consequently the central sound speed and D_o decrease with age.

For Procyon, asssuming a mass of 1.5 (in solar mass unit) (Demarque et al, 1985), the $\Delta\nu$ computed for the ZAMS model is $\simeq 95$ µHz

As R increases along the main sequence evolution of the star, $\Delta\nu$ has to decrease and our value of 79.4 µHz is then consistent with a star quite much evolved. From the calibration with the solar value, the ZAMS sequence of model must verify $R\Delta\nu = 145$. This gives for Procyon an initial radius of 1.67. The law $R^{3/2}\Delta\nu \simeq$ cst gives then a present radius of 1.87. If some credit can be given to the non resolution of the $\ell=0,\ell=2$ spacing, then $D_o < 0.6$. This value seems to indicate that Procyon is more evolved than the sun, consistent with the best model computed by Demarque who finds a star close to the end of its hydrogen burning main sequence life (Demarque et al.,1985).

Regarding the frequency range and the amplitudes, two different possibilities of excitation have been suggested, namely the κ-mechanism (Unno et al.,1979), or the stochastic excitation by interaction with the convection (Goldreich and Keeley,1977). The two suggestions can hardly be distinguished on the sun, because they both predict quite well the observations. In the case of Procyon, however, they are quite diverging and our result is strongly favouring the stochastic excitation (Christensen-Dalsgaard & Frandsen,1983), agreeing both with the frequency range and the expected amplitudes.

Now, if the general agreement between theory and observation, is quite satisfactory on Procyon, the results obtained on α Centauri A are really puzzling. Being a member of the closest multiple star system in our neighbourhood, this star has a well measured mass of 1.09. Given the precise measurement of its temperature and of its distance, it has an estimated radius of 1.23 ± 0.04 (Blackwell and Shallis,1977). According to Christensen-Dalsgaard & Frandsen (1983) and as already noticed by Gough (1985), $\Delta\nu$ should have been 142 µHz when such a star was at zero age on the main sequence, its radius should have been 1.03. With the measured value of 165.5 µHz, one can deduce from homologuous scaling a present radius of 0.93. There is an evident contradiction as our result seems to imply that the star has shrunk since its zero age. Even assuming that this star could be much younger than the sun, down to zero age, we have to assume a mass of 1.0 to fit with the theory. There is indeed a general disagreement about the age of α Centauri (Demarque,1985; Flannery and Ayres,1978; Morel and Baglin,1983) and the idea that that the star is at its zero age evolution stage can perhaps not be rejected. But can the knowledge of the mass be wrong by 9% ? It must be noted here, that if once again some credit is given to the measurement of the spacing $\ell=0,\ell=2$, then $D_o \simeq 2.65$ and the whole figure becomes exactly consistent with a zero age solar mass star (Christensen-Dalsgaard, 1984, Fig. 10).

The frequency range, centered around 3 mHz, is the only quantity which agrees quite well with predictions. The amplitudes, 5 to 10 times too large are also puzzling. Now if we want to explain all the results, the structure of α Centauri has really to be quite different from expectations, and then a mismatch of oscillations amplitude by such a factor is not too surprising.

3. Conclusion.

In contrast to "classical" variable stars, where one or at most two differents eigenmodes are typically found, Christensen-Dalsgaard proposes to use the term seismology only when a fairly large number of modes are observed (Christensen-Dalsgaard,1984). In this respect, one can say that the results presented here, together with those of Noyes et al. on ϵ Eridani (1984) and those of Kurtz et al. on Ap stars (1983) mark the real birth of stellar seismology. It is obvious that the observation is extremely more difficult in this case than it is on the sun. The present results are at the limit of the noise level, and one cannot completely exclude the possibility of a misinterpretation, in spite of the care of the analysis.

Now comes the question: How will it be possible to do much better in the the nearest possible future. This question has already be debated in several recent meetings or workshops (for example Meudon 1984, San Diego 1984, Cambridge 1985). All these debates lead us to have the following feeling, which will be our conclusion of this short presentation.

We definitely have the optimistic hope that trough this open door of stellar seismology, many results will come out in the next few years, providing a real new dimension to the tests of stellar evolution theory. And the perhaps less enthousiastic point of view that even if in principle, stellar observations can be as precise (or even more precise) than solar observations, it will take some time before that becomes a reality.

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