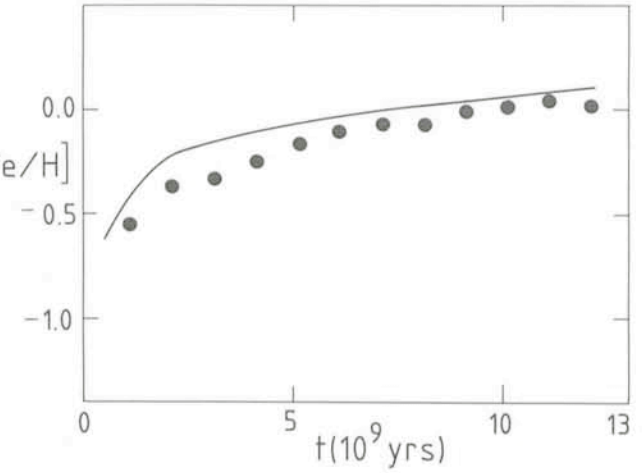

Fig. 4: *The theoretical age-metallicity ([Fe/H] is a logarithmic measure of the Iron abundance relative to the sun) relationship compared with the observational data of Twarog (1980) for solar neighbourhood stars (full dots). The time is in units of 10^9 years. The mean metallicity in the solar vicinity increased by about a factor of 5 between 12 and 5 billion years ago, and has increased only slightly since then.*

as a function of time is found to be in good agreement with the age-metallicity relationship for solar neighbourhood stars (Twarog 1980), as shown in Fig. 4. This indicates that the Iron produced by intermediate mass stars, in addition to the massive ones, does not lead to an overproduction of this element when the corresponding yield is a decreasing function of time.

Finally, I want to mention that, from an observational point of view, the possibility that low and intermediate mass stars can produce Iron peak and other heavy nuclei is suggested by the spectra of type I SNe (Branch, 1980), which are believed to originate from this stellar mass range. However, the progenitors of these SNe are still uncertain and two classes of them can be envisaged: single intermediate mass stars and white dwarfs in binary systems (Iben and Tutukov, 1983). In both cases the nucleosynthesis products would be the same because they come from the destruction of a C-O core of 1.4 $M_\odot$ exploding by carbon deflagration.

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Stellar Seismology: Five-Minute P Modes Detected on Alpha Centauri

E. Fossat, Observatoire de Nice
G. Grec, B. Gelly and Y. Decanini, Département d'Astrophysique de l'Université de Nice

A short note in a recent issue of the *Messenger* (Fossat et al., 1983) described the first test of a new spectrophotometer specially designed for extending to a few bright stars the results already obtained in solar seismology. Since the late seventies, we know that the sun is pulsating within a certain range of eigenmodes, the most famous having periods around five minutes. The most striking results in this field have been obtained by the observation of integrated sunlight. Indeed in this case, the angular filtering is so severe that only radial and weakly non radial (degree $l \leqslant 3$) eigenmodes can be observed. Their number is limited enough to make the identification possible despite the absence of any angular resolution in the observation. More than 80 of such eigenmodes, attributed to the pression acting as a restoring force, have been thus identified in the five-minute range in the case of the sun (Grec et al., 1983). Once identified in angular degree, radial order and temporal frequency, these eigenmodes make possible a real seismological investigation of the internal solar structure (Gough, 1984).

Because important results have been obtained in integrated sunlight, observing the sun "as a star", it was tempting to try to achieve similar results on other stars. Evidently, the 10^{11} flux reduction factor for the brightest stars makes the task highly difficult, because the oscillation amplitudes to be detected are below 1 ms^{-1} in Doppler shift measurements. It is for this special goal that we have designed a special spectrophotometer, using again the principle of optical resonance spectroscopy. The conclusion of the first test of this new instrument was that if the observation can be photon noise limited (i.e. in total absence of any instrumental source of noise), the five-minute solar oscillation could still be detected by removing the sun far enough for its magnitude to reach about zero.

Such a situation is very closely represented by the observation of Alpha Centauri A, because it is a G2 V star, very similar to the sun, with a mass of 1.1 $M_\odot$. Six nights were granted to this programme on the ESO 3.6 m telescope, 22–28 May 1983. Two and a half nights provided over 20 hours of data of photometric quality good enough for analysis. In fact these data consist of two signals:

- The monochromatic intensity (about 0.08 Å bandwidth) in the red wings of the Na D1 and D2 lines.

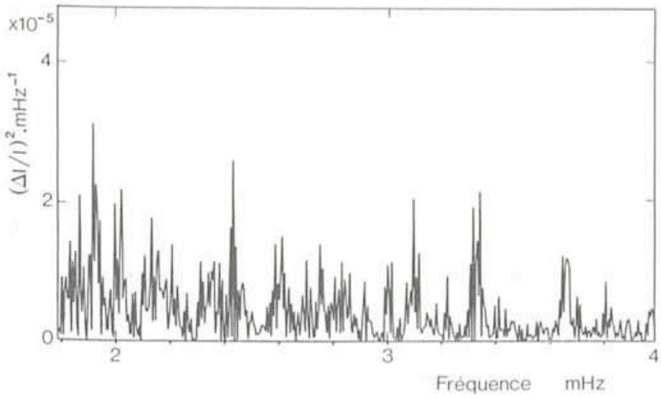

Fig. 1: *Part of the power spectrum of the data consisting in the monochromatic intensity in the red wings of the Alpha Centauri A Na D lines, recorded during three consecutive nights (May 1983) at the Cassegrain focus of the ESO 3.6 m telescope.*

– A reference channel, which contains the whole 20 Å passband of the interference prefilter.

The first step of the analysis consists in dividing the monochromatic intensity by the reference signal, in order to minimize the effect of atmospheric transparency fluctuations. This has proved to be sufficient in the presence of clouds, absorbing as much as 60 % of the light. With thicker clouds, the diffusion of the moonlight makes the division inaccurate.

A harmonic analysis is then performed by Fourier analysis, whereby the whole data set is regarded as one single time series, including zeroes when data are not available. Fig. 1 shows the resulting power spectrum in the five-minute range where spectral peaks are looked for. Having the solar result in mind, we are looking for a set of equidistant peaks representing the resolution of alternatively even and odd degree eigenmodes. This power spectrum is evidently much noisier than the corresponding solar one (Grec et al., 1983). However, a regular pattern of about 80 μ Hz seems to be present just around 3 mHz. In order to check the significance of this possible pattern, the next step consists in looking for a periodicity by calculating the power spectrum of a given section of this power spectrum. This has the dimension of the square of an autocorrelation and therefore, the result shown in Fig. 2 has been corrected of the square of the autocorrelation of the temporal observing window. It shows convincingly that only one periodicity is present in the range 2.3–3.8 mHz of the power spectrum, with a period of 81.3 μHz.

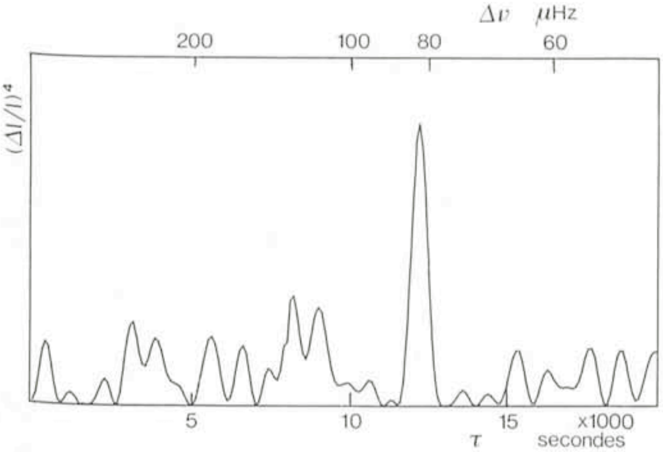

Fig. 2: *Power spectrum of the power spectrum limited to the frequency range 2.3–3.85 mHz, corrected of the square of the window function autocorrelation. The major peak, at 81.3 μHz, means that the expected periodicity in the signal spectrum is indeed present.*

Although significantly different, this result is of the same order of magnitude as the 68 μHz obtained in the solar case. It is then to be regarded as a very convincing evidence for the detection of five-minute p-modes on Alpha Centauri.

Now, once admitted the existence of a pattern of equidistant peaks in the power spectrum, the data analysis can be pursued one step further by trying to extract this pattern from noise. This is done by using the knowledge of the periodicity (81.3 μHz) and phase of this period provided by the Fourier analysis whose result is displayed in Fig. 2. An adapted filtering with this period and this phase is made on the power spectrum of Fig. 1 and with a resolution of 0.32 mHz (Sinus fitting at locked phase on 0.32 mHz wide slices of the power spectrum). The result, shown in Fig. 3, is compared to the envelope of the solar spectrum obtained with the same resolution (from Fossat et al., 1978). The similarity is really striking and does not leave any room for doubt about the significance of the result obtained on Alpha Centauri.

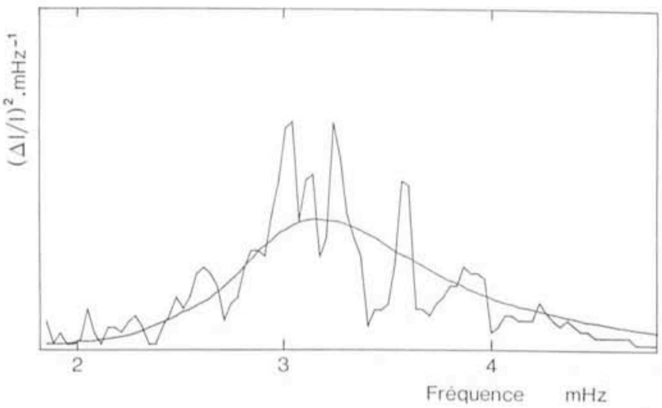

Fig. 3: *Using an adapted filtering, locked in frequency and phase, it is possible to extract from surrounding noise the power contained in the discrete pattern which is present in the power spectrum of Fig. 1 (black part). The continuous line shows, for comparison, the same envelope measured with an identically resolved solar power spectrum.*

Theoretical implications of this result must now be investigated. At first order, one can probably say that if the five minute p-modes are convectively excited, the close similarity of the two curves in Fig. 3 indicates that Alpha Centauri and the sun have presumably almost identical external layers, as their identical spectral type suggests. However, the frequency spacing within this envelope is significantly different. This spacing being directly related to the inverse of a sound wave travel time from centre to surface, the two stars are certainly notably different in their deeper layers. The sound travels faster in Alpha Centauri, which has then to be denser than the sun. Also, in the same frequency range, the radial order of excited eigenmodes is slightly smaller in the case of Alpha Centauri. For example, the major peak at about 3.3 mHz can be tentatively attributed to a $n = 19$, $l = 0$ or 1 mode while in the solar spectrum this is the frequency of the radial $n = 23$ mode.

We hope to obtain more data during the next observing runs, in order to resolve the pairs of odd and even peaks, like in the solar case.

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A Close Look at Our Closest Neighbor: High Resolution Spectroscopy of Alpha Centauri

D. R. Soderblom, Harvard-Smithsonian Center for Astrophysics, Cambridge MA, USA

As most astronomers will tell you, most of the telescopes are in the northern hemisphere, and most of the interesting objects are in the south. The Magellanic Clouds, the largest globular clusters, and the center of our Galaxy are among the celestial objects that must be studied from south of the equator. Also in the deep south are the Sun's nearest neighbors – the α Centauri system. It contains three stars: (1) α Cen A has the same spectral type as the Sun, although it is slightly more massive; (2) α Cen B is a little less massive than the Sun and orbits α Cen A with a period of 80 years; and (3) Proxima Cen is a very low mass star that is slightly closer to us than either of the other two. Proxima Cen is moving through space in the same direction and at the same rate as α Cen A and B, but is very distant from them.

None of these three stars is particularly unusual – they certainly show none of the bizarre behavior of some astronomical objects. But it is their very ordinariness that makes them so interesting. Here are assembled three excellent examples of the lower main sequence, and they are much brighter than most stars, hence easier to observe. These stars, particularly α Cen A, bear a striking resemblance to our Sun, and so we naturally want to study them in great detail, in order to draw comparisons.

New astronomical instruments are designed to reach new frontiers. This often means being able to examine extremely faint objects at the edges of our Galaxy or the universe. But there is also an inward-facing frontier to be breached, a frontier in the quality of data for bright objects. Astronomical spectroscopy has traditionally used (and still does) photographic plates to record stellar spectra. Photographic emulsions are inefficient (only 1 in 1,000 photons gets recorded), and even for the best cases the data are mediocre. The quality of a spectrogram is measured by its signal-to-noise (S/N) ratio. An exposure with S/N = 100 means that there are random fluctuations of ± 1 % in the data. Such fluctuations prevent the detection of very weak absorption lines, and stronger lines do not get defined well enough to detect subtle but interesting phenomena. Photographic spectra rarely exceed a S/N of 100.

Technological advances in the last decade have produced the Reticon and the CCD. The Reticon is particularly well suited for high S/N spectroscopy of bright stars. It is better than 90 % efficient at many wavelengths – hardly any photons are wasted! A Reticon is capable of producing data with S/N $\gtrsim 10^4$. Obtaining such data is time consuming and difficult, but the efforts are rewarded by spectra of unprecedented detail.

Such a Reticon is in use on ESO's Coudé Echelle Spectrometer (CES), a high resolution stellar spectrograph that is fed by the Coudé Auxiliary Telescope (CAT). The CES is the best instrument of its kind in the southern hemisphere – no other can deliver the same combination of high S/N and high spectral resolution. Because it is unique, ESO has granted time on the CAT/CES to North American astronomers; indeed, one such person was involved with the design and testing of the instrument. Further, our National Science Foundation provides travel funds to use such instruments if they do not duplicate US facilities.

I therefore found myself on La Silla in April 1983, using the CAT/CES to observe α Centauri A and B. My objective was to compare these stars to the Sun in order to learn about several age-related properties of solar-type stars. All of these properties relate to the presence of a convective envelope. Convection mixes the surface material deep down into the star. One manifestation of this mixing is that lithium atoms are gradually destroyed because they undergo nuclear reactions at a temperature of about two millions degrees. Although the exact process is poorly understood, the convective envelopes of solar-type stars must reach such a temperature because we can see that their lithium is depleted. For example, meteoritic material contains about 200 times the lithium that is now present on the solar surface, and very young stars also have lots of lithium. Old stars have little or no lithium. Because of this gradual lithium depletion, a star's lithium abundance can be used to estimate its age.

Determining a star's lithium abundance is difficult. If one wished to observe, say, iron in a star, there are hundreds of absorption lines to measure, and so some of the errors of measurement cancel out. But there is only one lithium feature available, at 6708 Å wavelength. To make matters worse, no element in the Sun is less abundant than lithium (except for the heavy, radioactive elements). The only positive factor is that this lithium feature is well out in the red, where modern detectors like the Reticon are especially sensitive, and where other spectral lines are less of a problem.

The solar lithium feature is extremely weak, and because of this some observers have claimed that it is not even there at all. However, some observations of extraordinary quality, made about ten years ago at Kitt Peak, provide an accurate solar lithium abundance. The Sun is the only old star for which a good lithium abundance exists, and is therefore crucial for calibrating the lithium abundance-age relation. Therefore α Cen A provides a good test of whether or not the Sun has a lithium abundance that is typical for a star of its mass and age.

To see why this is so, we need to consider the age of the Sun and α Cen. We know the Sun's age by radioactive dating of solar system material. We can also use stellar structure theory to calculate what the present properties of the Sun *ought* to be, and then compare those to the real Sun. As the Sun has grown older, it has converted hydrogen into helium in its core – this produces the solar luminosity. The very center of the Sun