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Impact of next generation interferometers on asteroseismology

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Abstract: Asteroseismology aims to study the internal structure and dynamic of stars with a high precision, thanks to the measurement of their oscillation frequencies. It constraints the stellar evolution theory, and permits to determine the age of the stars. In order to get this information, a good knowledge of several other parameters is required. We will study how the current interferometers help to determines this fundamental parameters, and what would be the requirements for next generation optical interferometers in order to get the full benefit of the coming projects in asteroseismology.
Keywords:asteroseismology, stellar oscillations, interferometry, fundamental parameters, stellar evolution

1 Introduction

During the year 1990, several authors considered the measurement of stellar oscillations through interferometry. It mainly concerns the possibility to detect diameter variations in Cepheids stars, as a direct measurement of stellar distances, and evolved stars like Miras. Nevertheless, the possibilities of combining asteroseismology and HAR remains marginal in these years. Since 2000, it has changed drastically, and the recent literature shows an important increase of the number of publication considering simultaneously asteroseismology and interferometry and the trend is exponential. In 2004, the number of papers having both this keywords is already higher than the sum of the two previous years. This can be explained by two facts: first, the unambiguous detection of solar-like oscillations from the ground, and the incoming of new space instruments have contributed to a large increase of the activity in this field, both on the interpretation and on the possibility of observations, and second, the new interferometric capabilities offered to the community by the instrument of the VLTI allow to consider new programs in stellar physics.

Clearly, the two techniques are complementary for the determination of stellar parameters. Presently, HARPS and VINCI, tomorrow AMBER and COROT, will be used together. In the future, other space or ground based projects will provides much more precise fundamental parameters (GAIA) and much

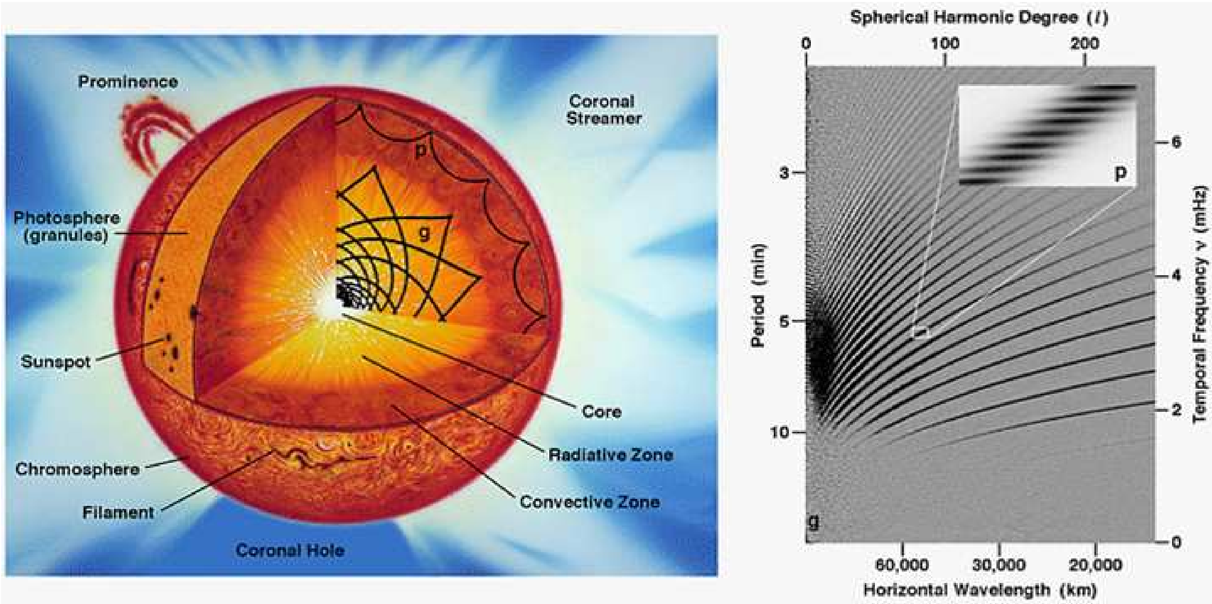

Figure 1: The two different types of oscillations occurring in a star produces p-modes (acoustic waves) and g modes (driven by buoyancy). Only the former have been detected on the Sun, as the latter are exponentially damped in the convective zone. The diagram on the right shows how the p modes organise themselves in ridges in a $k - \omega$ diagram, where the vertical axis is the temporal frequency, and the spatial frequency is displayed in the abscissa.

more frequencies on a large number of stars (Eddington). It is worth to explore the potential of using simultaneously both techniques with the present capacities and to extrapolate what should be the performances required in interferometry to follow this evolution.

2 Sounding the stars

Thanks to the HR diagram, the stars have been the main tool of investigation of the Universe. The stellar evolution theory, based on this diagram, provides the most important parameters to understand the universe: the age and the distance of the observed stars. It also provides an explanation for its chemical evolution since the Big Bang until the apparition of life.

However, the evolution models are rather simple, and do not reflect the complexity of the physics which take place in stars. There is a lot more to learn about and from the stars: physical processes, like convection, dynamo effects, fundamental physics with the equation of state, opacities, astronomical processes like stellar winds, mass loss, evolution of angular momentum, and so on.

The limiting factors for precise modeling are insufficient observable parameters, and our incapacity to produce models including accurate physical processes, in particular transport processes.

The present models of evolution of stars which are used to interpret the observed luminosity-temperature diagrams take 5 parameters as an input: the mass M, the age θ, the initial chemical composition in helium Y and heavy elements Z. It also needs a free parameter $\alpha = L/H_p$ to scale the phenomenological description of the convection, known as the "mixing length" theory.

On the observing point of view, the measured quantities, all coming from the stellar surface, are the luminosity L, the effective temperature T_{eff}, and the gravity and quantity of heavy elements at the surface g and z. The first two parameters suffer from calibration problems and are generally not known with precision better than 10 % in the best cases, and it is even worst for g and z. Therefore,

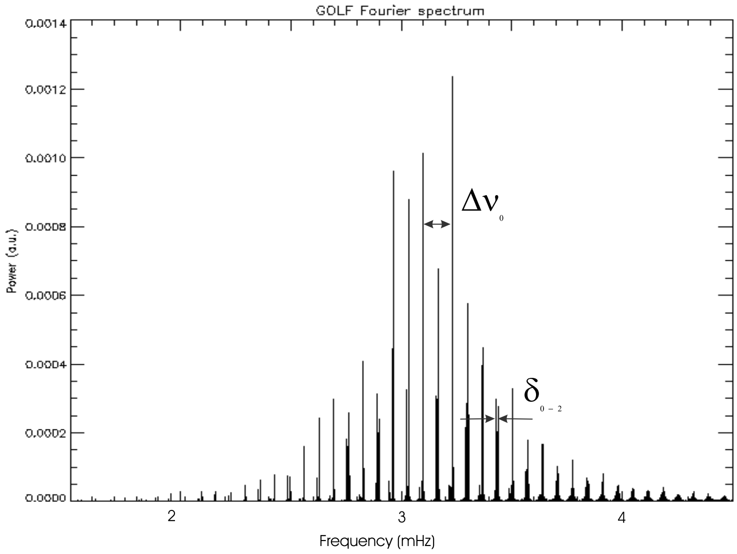

Figure 2: Spectrum of the Sun, as seen as a star, by the instrument GOLF on board of SOHO after 6 months of observations.

the new constraints offered by asteroseismology, which provides several independent measurements, like the main frequency separation $\Delta\nu_0$ and the small separation δ_{0-2}, will in principle improve a lot the situation. In particular, the first parameter is a good measurement of the stellar mass, if the radius is known, when the second one provides the density in the core, and therefore is good indication of its age.

The detection of stellar oscillations is presently the only way for investigation of the internal structure of the stars. The success of helioseismology since 30 years proved the capability of such a technique. On the Sun, million of modes have been observed continuously during years, first from ground based networks (IRIS, BiSON, GONG), than from space, with the SOHO satellite. One of the most spectacular results of this study is the internal rotation of the Sun at any radius and any latitude.

The peculiar interest of measuring stellar oscillations stands on the fact that their frequencies can be measured with very high precision, easily 10^{-4} or better, something which is uncommon in astronomy, and that generally a lot of such frequencies are measured simultaneously. Taken together, all these modes are like a grid of measurement along the radius and latitude to determine the internal structure.

However, the requirements for such a technique are quite severe: detection of very small amplitude variations, and necessity of continuous observations during many weeks.

That is the reason why the progresses have been much slower in asteroseismology than in helioseismology. After several attempts, (EVRIS lost with Mars96, several other projets unselected), asteroseismolgy is now successful, with both ground-based and space instrument: MOST has been launched in July 2003, and is fully operational since January 2004. COROT is expected to be launched in early 2006. At the same time, after several announcements of first detection, not confirmed later, the first clear evidence of oscillation on a solar-type star was obtained on αCen by Bouchy et al. in 2001. 25 years after the beginning of helioseismology, asteroseismology enters in its golden age. Therefore, it is of particular interest to thing about the complementary work to be done, both in modelisation and in observation, which could help to take a maximum scientific reward for the asteroseismic programs. One of the way to be explored is the new observational capability offered by present and future interferometers: this will be the subject of the next section. But before, it is necessary to precise the state of art in asteroseismic observations.

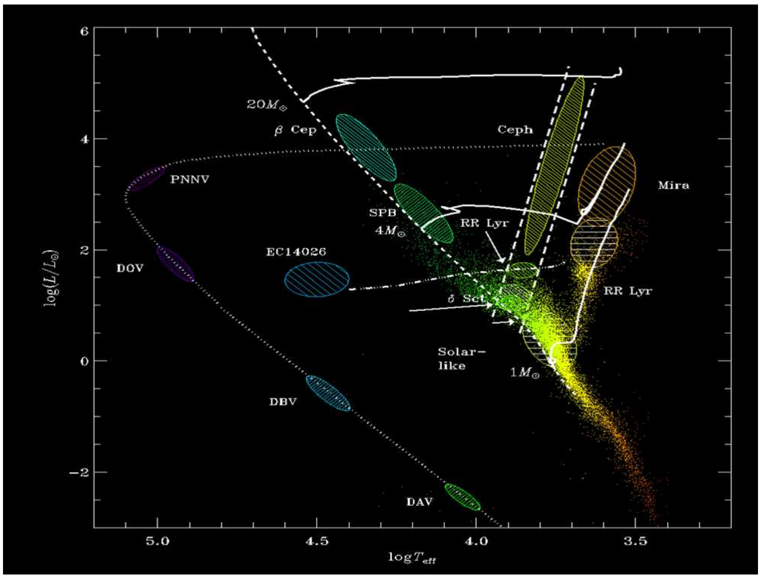

Figure 3: HR diagram showing the presence of oscillating stars. Stars of the Cepheid instability strip, and βCepheids have only a few modes excited with large amplitudes. In solar-like stars, all possible radial and non-radial modes are excited, with small amplitudes, in a given range of frequencies.

2.1 Observation techniques in asteroseismology

As can be seen on the figure 3, the whole HR diagram is covered by stars oscillating at different frequencies, and with different amplitudes. The periods of oscillations range from minutes to weeks. Mira variables have even longer periods.

The excitation mechanism of the oscillations is not the same for the different type of stars. In the instability strips, opacity variations drive an amplification of the oscillations for some peculiar modes, either radial or non-radial. The amplitudes of the oscillations detectable in photometry vary from several millimagnitudes to one or two magnitudes. In the case of solar-type stars, the oscillations are damped and excited permanently, by coupling with the convection. A lot of modes can be excited in that way, but with amplitudes limited to a few μmag.

The detection and measurement of the oscillations frequencies is then a very challenging task. Two techniques have been mainly used from the ground, following the amplitudes of the modes: photometry and spectroscopy.

- Photometric measurements have been used for a long time to detect stellar variations. With modern CCD camera, the relative photometric precision, generally limited by atmospheric scintillation, can be better than a fraction of mmag. Several photometric networks exists, each one dedicated to a specific type of stars, like STEPHI for δScuti and WET for white dwarfs.

- Spectroscopic measurements allow the detection of much smaller amplitude on solar-type oscillators. In that case, radial velocity variations are measured through the use of Doppler shift of many spectral lines. New spectrographs, particularly stable and efficient, like HARPS, have been designed for that goal.

It has to be noticed that the sensitivity of such an instrument is quite good, as it would give a noise level of 10 cm/s in 1 hours on a 6th magnitude star with a 2 m telescope. But this sensitivity is reduced for fast rotators because of the lines broadening. This limitation could be avoided with

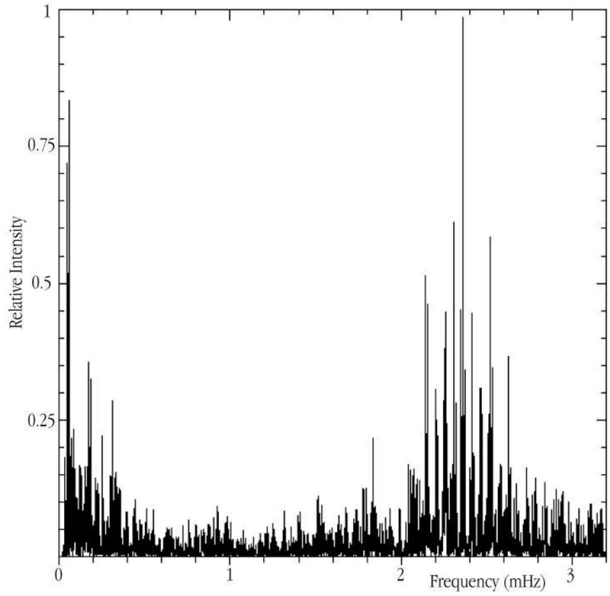

Figure 4: Power density spectrum of αCen A, observed during 10 nights at La Silla observatory, with the spectrograph Coralie on 1.2 m telescope, by F. Bouchy. The spectrum clearly exhibits a serie of regularly spaced modes, in the frequency range between 2 and 3 mHz. This spectrum is comparable with the first detection of global solar oscillations from the South Pole by Fossat and Grec in 1981.

adapted interferometers providing the necessary spatial resolution along the equator, so the spectral lines will not be broaden by rotation.

2.2 Need for continuity

Asteroseismic measurements are worth lasting for a long period. The precision of frequency measurement improves as the integration time for stable modes, and as the square root of integration time T for damped modes, when T is larger than the damping time τ. It is therefore interesting to integrate during a time greater than τ to take the maximum benefit with the shortest integration. Another reason is to separate all the components. It has been seen that the separation of multiplets split by rotation is of the order of the rotation period, which could be as long as several months for solar-type stars. The daily interruptions in the data series due to day-night alternance have devastating effects upon the spectrum, by introducing spare peaks (alias) which could interfere with real modes and disturb their measurements.

Long period of uninterrupted observation are needed. Historically, the global oscillations of the Sun have been first detected from the South Pole, where continuous observations could be obtained. On other stars, networks of telescopes well distributed around the Earth have permitted to obtain series of observations during several weeks with a duty-cycle up to 60%. The efforts to organise these observing campaigns are considerable, and limits the total amount of observing time. That is why the space projects have been set-up. COROT will be able to observe several stars continuously during 6 months, without interruption. The precision on the measured frequencies will improve by a factor of about 10 with respect with the best ground-based observations.

Eddington was another space project, originally selected by ESA, and finally canceled, due to financial reason. But its scientific objective remains a good goal to meet in a close future. Like COROT, the Eddington project is based on a photometer, but with a larger field, specially designed to observe all stars in several close open clusters. Young open clusters are very exciting objectives for asteroseismology: all stars of the cluster having almost the same age, same initial chemical composition, and same distance, it reduces the number of free parameters for evolution model to only individual masses. It is important to have cluster young enough, so that massive stars are still present. The main targets of Eddington were the Hyades and the Pleiades. Praeseppe is also an interesting cluster to consider, as it contains several δScuti stars. In a sphere of 500 pcs, there are about 30 open clusters, which are potential good objectives for asteroseismology. That is also the distance that we will consider for exploring the possibilities of interferometry.

3 Why to observe stars with an interferometer?

In the year 90's the possibility to apply High Angular Resolution technique to stellar activity and stellar seismology has been contemplated by different authors (Petrov, Vakili, Schmider).

There are two classes of observations at higher angular resolution than the theoretical limit of the classical telescopes, that could improve our knowledge of the internal structure and evolution of stars, together with asteroseismic techniques. For one side, there are the measurements of fundamental stellar parameters, like diameter and rotation, which will provide an a-priori better evolutionary model of the star, and help to take the maximum benefit from the oscillations frequency measurements. On the other side, there are the observations of the oscillation modes themselves, which could be improved by interferometric techniques, in particular with the possibility of detection of modes of higher degree that would remain invisible with classical observations.

We will try to review all the possible observations, in order of increasing difficulties, more or less.

3.1 Diameter

Diameters are fundamental parameters of stellar models. They play more or less the same role that absolute luminosity, but they can be determined mode precisely, as they depend only on the distance, and not on its square, and can be measured without the problem of calibration which affects luminosity measurements. On the other hand, the observed angular diameter depends on limb-darkening models.

It has been shown recently [Kervella, 2004C], that its knowledge helps a lot in determining the correct evolutionary model. Figure 5 shows how the error box is reduced. On the temperature-luminosity diagram, a given diameter gives a line with a slope of 4, as $L = 4\pi R^2 \sigma T^4$. The number of possible evolutionary stages fitting the new error box is largely reduced, and only a fine adjustment of the parameters is needed. Moreover, the main frequency separation is given by $\Delta\nu_0 = kM^{\frac{1}{2}}R^{-\frac{3}{2}}$, so that the combination of the diameter and the main frequency directly provides the mass, for single stars or badly known binaries. This limits drastically the range of models to be computed, and permits to explore much more precise physical processes like diffusion and rotational effects.

Independently of intrinsic measurement errors, diameter precision is limited by visibility calibration, and Limb-Darkening models. In the case of far solar type stars, the use of stellar calibrator in order to remove the instrumental visibility is somewhat silly, as a calibrator smaller than the target would be much fainter and therefore requires much more telescope time. It is much more interesting to seek a combination of aligned telescopes and to constraint the stellar model with ratios of visibilities at different bases, avoiding the calibration time. This requires at least three aligned telescopes, and preferably more, to constraint also the limb-darkening. A beam switching, like offered at AMBER (BCD), could be of great help to eliminate individual beam effects. This solution has been already proposed for the measurement of the diameters of the man targets of the COROT asteroseismology program. Using the AT with AMBER, it is probably feasible to achieve a precision of a few percent on solar-type stars up to 50 pcs.

In order to get the best possible precision, angular diameters should be measured with better precision than the parallax, so that the precision of the linear diameter will only be limited by the former measurement. Although such precision is very likely feasible with the VLTI for solar type stars

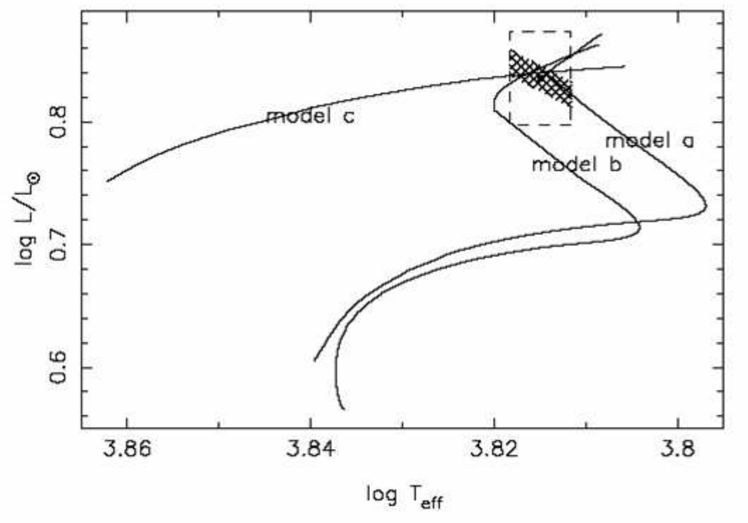

Figure 5: The figure shows the possible evolutionary stages of Procyon fitting with the error box. It can be seen that the uncertainty on the diameter (the gray parallelogram) reduces dramatically the error box, as compared to the luminosity error (the vertical rectangle). The frequencies computed for the possible models can be compared to the detected oscillations. (Kervella *et al*, 2004C)

up to 50 pcs, like the main targets of the COROT helioseismology program, it is not true anymore for secondary targets, and certainly not for future projects like Eddington, which will be seeking for oscillations on stars up to 1000 pcs . The precision on diameters measured by visibility decreased as the square of the ratio of Φ by the interferometer resolution λ/B, when the precision on the distance deduces from the Hipparcos parallax only decreases proportionally to the distance - at least for stars brighter than the 9th magnitude. In the future, GAIA will improve the precision on the parallaxes by one or two orders of magnitude. In order to maintain the corresponding precision in angular diameter measurement, an increase of 5 magnitude in the targets (up to 12 for solar-type stars) will suppose an increase of a factor of 10 on the baseline of the necessary interferometer. A 2km baseline interferometer would provide the necessary resolution.

Alternatively, diameter measurements obtained by the mean of differential phase measurements are limited by rotational velocity and suffer from biases due to line shapes, but their precision only decrease proportionally to the inverse of the angular diameter. An improvement of the spectral resolution, with the same interferometer base, could in principle be more precise than visibility measurement of distant stars, when they have a sufficient rotational velocity. A more complete study, including atmospheric modelling, should be achieved, in order to asses what would be the better compromise between realisable base length and acceptable precision.

We could not conclude this paragraph without mentioning the recent measurement of direct diameter variation on Cepheid stars by interferometry. Other similar programs exist for Mira stars and SPB. Although not oriented to the study of the internal structure, these measurement are important for the determination of the distance scale (Cepheids), and for the comprehension of the pulsation in stellar envelopes.

3.2 Rotation

Rotation and differential rotation are fundamental parameters, both for evolution of stars and for interpretation of asteroseismic measurements. Rotation is related to activity and winds. Through the

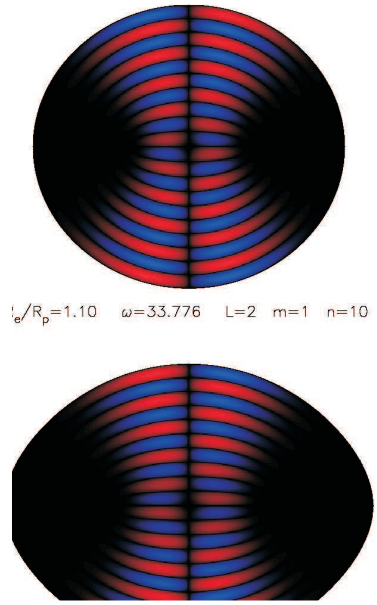

Figure 6: This figure shows the effect of the oblateness on the shape and the frequency of a given oscillation mode (from Roxburgh, 2004)

meridian circulation, it produces mixing, and contributes to the evolution of the star. The history of the rotation in a star is also related to the mass loss, and breaking mechanism, which could be either magnetic field, or internal oscillations (g modes). It is therefore important to measure it, simultaneously with the study of the internal structure.

Rotation has also important effects on the frequency of the modes. When it is small, it just removes the degeneracy of frequency of the m components, by adding a constant frequency $\nu_m = \nu_0 + m\Omega_r$, where Ω_r is the rotation frequency, in case of a rigid rotator. In case of differential rotation, the frequency splittings are obtained from an integral equation

$$\nu_{l,m} - \nu_{l,0} = \int K_{n,l,m}\Omega_r(r,\theta)drd\theta \quad (1)$$

The inversion of this formula permits to recover the rotation law inside the star.

3.2.1 Oblateness

In case of fast rotator, the situation is more complicated. It has been shown that the departure for geometrical spherical symmetry is the main perturbation for theoretical oscillations models. As a result, the central frequency of the mode (not split) is displaced by a quantity depending on the oblateness. A good determination of this geometrical factor would be necessary to correct the central frequency measurement, for the 1D models.

A sub product of diameter measurement are oblateness. Obviously, oblateness require precise diameter measurement as they are generally small, but as a ratio, the absolute precision is not not required. Simultaneous measurement of visibilities in different directions will provide an accurate shape profile, independently of absolute diameter. Again, the targets are solar type stars up to a few hundreds of pcs, and a good objective would be the determination of oblateness of about 1%, with a precision of 10%.

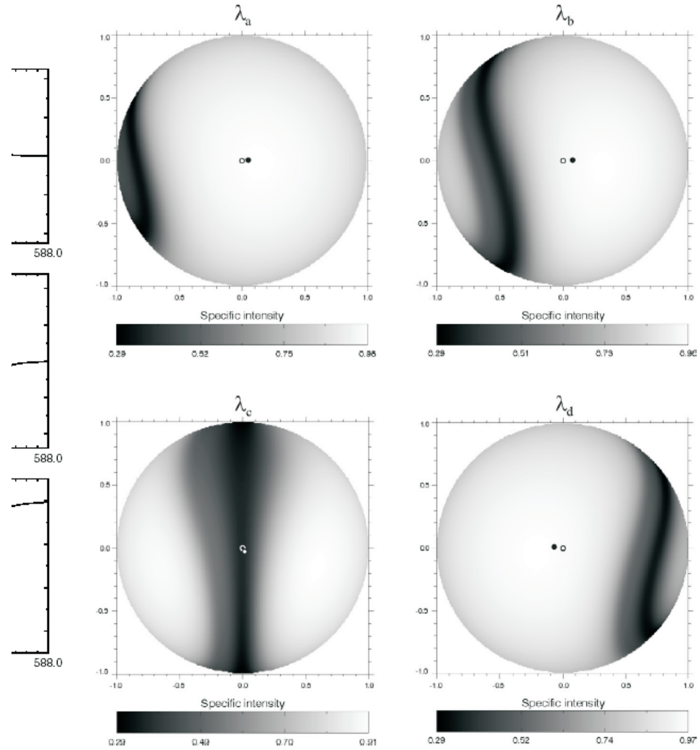

Figure 7: Left: photocenter components, ϵ_z(top) and ϵ_y (middle), and the normalized spectral flux (bottom) across the asymmetric He I 5876$\AA$ line. Photocenter components are given in units of angular stellar radius ρ. Right: intensity maps associated to the DI observables on the left side at the four selected wavelengths. The curved dark patterns correspond to Doppler shifts of the local line profile caused by differential rotation. These non-symmetrical intensity maps result in a displacement of the stellar photometric barycenter, i.e., the photocenter (filled circles), relative to the geometrical center (opened circles). (Domiciano *et al*, 2003)

The recent measurement of the oblateness of Archenar by Domiciano et al (2003) have proven the possibility of such measurement with the VLTI. It has shown also that the limb-darkening on such rotator depends on the direction. A good model of the atmosphere is required. More measurements are also necessary, simultaneously on two perpendicular directions, and with different bases. A large wavelength range and a redundant configuration, allowing boot-strapping analysis, would be useful.

3.2.2 Inclination of rotation axis

As already mentioned, the phase differences obtained along a spectral line for the interference pattern is a measurement of the photocenter displacement. The photocenter displacement provides the product $\Phi V \sin i$, from which it is possible to remove the diameter which have be determined independently. It provides also the direction of the rotation axis, but not the inclination [Petrov 1989]. More recently, Domiciano and Jankov show that in case of differential rotation, the same technique also allows the determination of the inclination of the rotation axis [Domiciano *et al*, 2004].

With the knowledge of the inclination of the rotation axis, the rotation frequency and the visibility of the different m components will be known. The identification of degree and the fit of multiplets in the frequency spectrum will be much easier. A precision of a few percents on the inclination angle is required.

The precision which could be achieved for such a measurement depends on the angular diameter

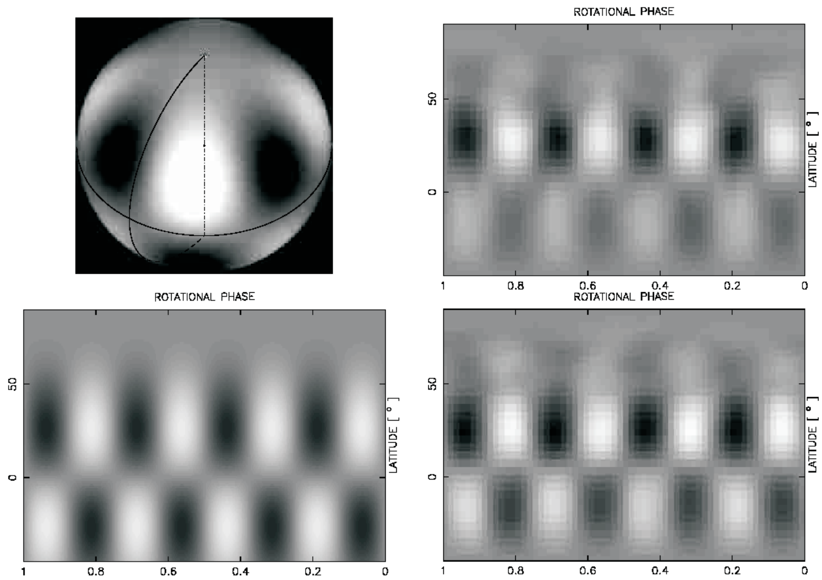

Figure 8: Simulation of reconstruction of a non-radial mode on a star (left) with only the spectrum (right top) and with the photocenter displacement obtained by interferometry (right bottom) [Jankov *et al*, 2001]

of the star, with respect to resolution of the interferometer. As previously, it is important to have the best possible spatial resolution. The spectral resolution required here suppose to have access to the second zero of the Fourier transform of the spectrum, which means to have at least 4 points of resolution within the rotation velocity. For a solar-type star rotating at 10 km/s, this suppose a spectral resolution of about 120000. On star rotating slower than the intrinsic line width, the signal decrease rapidly, so there is no interest in increasing much more the spectral resolution. At the contrary, there is an interest to have access to as many lines as possible. Although not all lines will have exactly the same response to differential rotation, because of the other effects that could affect the line shape, in principle, it is possible to consider that the gain in precision will increase as the square root of the number of spectral lines measured simultaneously.

Considering several hundredth of available lines that could be monitored simultaneously (this is easily achieved with an echelle spectrograph in the visible domain), the precision which could be reached on the inclination angle would be better than 1° on a solar-type star with 10 km/s rotation speed and 10% differential rotation, if the spatial resolution of the interferomer would be sufficient.

3.3 Mode identification

Spectroscopic measurements also permit the detection and identification of modes through the deformation of the line profiles. Different techniques could be used for this study, like the method of moments or Doppler imaging. With the MUSICOS network, several stars have proved to oscillate with non-radial modes, and it has been possible to identify more or less exactly the degree and azimuthal order of the detected modes [Mathias *et al*, 2004].

Imaging of stellar surface has been a probe for High Angular Resolution since a long time, with a first detection of spots on Betelgeuse [Roddier & Roddier, 1983] by pupil rotation interferometry, but this is limited to close giant stars which are resolved with individual telescopes. However, another technique has been used successfully: Doppler imaging. In the case of fast, rigid, rotating star, the rotation profile acts as revelator of the angular dimension. Indeed, projected on the line-of-sight, the radial velocity is proportional to the distance at the rotation axis. It is then quite easy to extract a structure $I(x, y)$ from the line profile in the spectrum [Vogt & Penrod, 1985], as it can be written as

$$S(\lambda) = \int\int I(x,y)P(\lambda(1+\frac{v(x,y)}{c}))dxdy \quad (2)$$

with

$$v(x,y) = V_{rot}\frac{x}{R}$$

Although quite successful, that technique is intrinsically limited to fast rotators, excluding most solar type stars. It also suffers of the limited information on the direction parallel to the rotation axis. In the case of asteroseismology for instance, the detected modes are generally not identified precisely in term of degree and azimuthal order. Jankov (2001) has shown that interferometry provides a good improvement of the situation.

Mode identification could be problematic in the case of complicated internal structure (mixed modes) or when not all the modes are excited and just a few of them are detected. This is generally the case for stars of the instability strip. In that case, the benefit of precise measurement of frequencies could be wasted by the impossibility to find an unique identification of the observed modes. Different solutions have been investigated for this purpose, like phase difference in color photometry (the effects are very tiny, and strongly model dependant), spectroscopic simultaneous measurement (method of the moments, Doppler imaging). These methods suffer from the lack of spatial information. In Doppler imaging, in particular, the absence of information in the direction parallel to the rotation axis conducts to an ambiguity in the determination of the mode degree. This is also illustrated by the detection of polar spot on several stars, very difficult to explain, and which could arise very easily from a wrong modelling of the mean line profile. Other explanation could come from the presence of the differential rotation. The capability of super resolution offered by differential phase measurement helps to solve this difficulty.

In term of signal/noise ratio, it can be seen that differential phase measurement is similar to Doppler measurement SNR multiplied by the super angular resolution factor $\Phi\frac{B}{\lambda}$ [Jankov *et al*, 2001], but with two main advantages:

- differential phase measurement provides information along the rotational axis. Figure 8 illustrates how interferometry in the direction of the rotation axis allows the reconstruction of the mode geometry, in particular at negative latitudes.
- differential phase measurements are insensible to instrumental PSF, and to their temporal variations, and much less sensible than Doppler measurement to the model of the spectral line

The capability of interferometry for identification of modes has been proved theoretically , and this will be confirmed by future observations with AMBER.

3.4 Intermediate modes

Measurement of oscillations on unresolved stars, either in photometry or Doppler shift measurements are limited to degree less than 3. Although very important, as there are the only one to reach the stellar core, only thus modes are insufficient to allow frequency inversion, to produce a sound velocity profile. Moreover, following the inclination of the rotation axis, the visibility of some of these low degree modes could be null, limiting the number of accessible modes.

It has been shown [Schmider *et al*, 1997] that the photocenter displacement gives access to several more modes, depending of the rotation velocity. In fact, it gives the same modes as Doppler imaging do (and with more or less the same visibility), but with the advantage that the effects of both instrumental instabilities and unknown line profile are reduced. On the other hand, in order to be competitive in term of signal to noise ratio, photocenter displacement measurements implies that the object diameter is of the order of the angular resolution of the telescope or interferometer. This determines the base to be used.

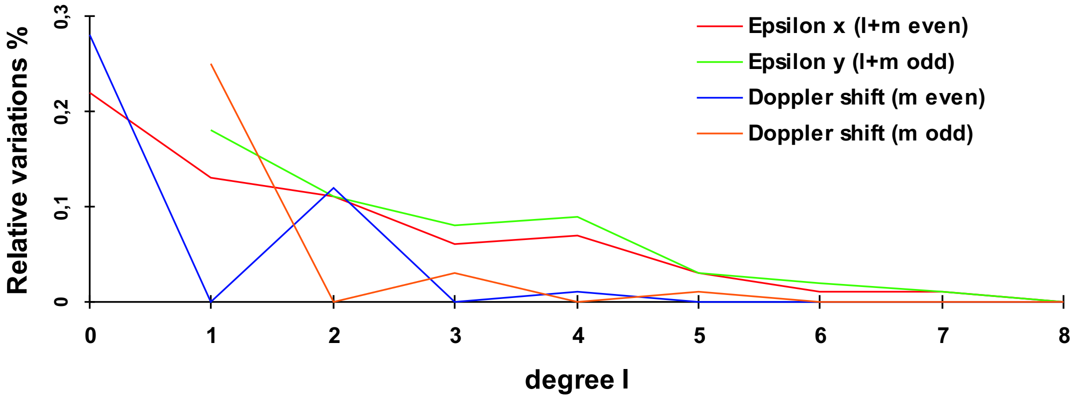

Figure 9: Relative visibilities of non-radial modes as they will be detected by different techniques: Doppler shift measurements, and Differential Phase measurement, as a function of the degree of the modes. The parameters here are a rotation of 10 km/s and an inclination of the rotation axis of 90° . It can be seen that DP is more sensible to intermediate degree modes $3 \leq l \leq 5$ than Doppler shift. It also provides an identification of the detected modes that Doppler shift does not give.

In some case, it will be very interesting to have access to this intermediate degree modes, and to dedicate the necessary observing time for this goal. When a physical model of the star could be obtained, an inversion of the frequencies is possible, if a sufficient set of data exists. As for any asteroseismic program, we talk here of weeks of uninterrupt observations. This possibility will be discussed in the next paragraph.

3.5 High degree modes: the stars as the Sun

On the Sun, several millions of modes are measured, as the resolution achievable reach easily 1000 x 1000, even from the ground. This is probably not feasible on other stars, even the closest. However, the spatial resolution offered by a deca-kilometric baseline interferometer would allow the detection of modes with degree of $l = 100$ on stars at 10 parsecs. With such a degree, it would be possible to fit directly the ridges on the $k - \omega$ diagram, like the one of the figure 1, opening new windows on stars, like inversion of rotation profile in 2D, and even local seismology (i.e. just beneath the surface).

The physical problems which could be addressed then includes study the convection and the diffusion, the shape of the external/internal convective zone, and their effects on dynamo and stellar activity, the physics of the atmosphere, the origin and effects of magnetic fields, precise rotation profiles, necessary to understand the evolution of angular momentum and stellar winds, and so on. But such a task appears difficult, and requires a dedicated strategy.

4 An interferometer devoted to asteroseismology ?

4.1 Position of the problem

The requisite for stellar activity and stellar seismology are almost the same: continuous observations during long periods (months, or even years in the case of AGB stars), completeness of the spatial observations in order to identify unambiguously the modes or the structures observed. It has to be noticed that this second condition is never fulfilled, even in the case of the Sun, because no information is available from one side of the star, until a satellite will look to the other face of the Sun. This lack of information conducts to the so-called "mode leakage". It results in the presence of several contiguous modes in the signal of a given degree mode, and it increases the difficulty of mode-identification. In interferometry, the empty structure of the optical pupil will make it worst. It has to be noticed here that the aperture synthesis proposed to complete the pupil plane thanks to the Earth rotation is not applicable here because of the necessity of a complete time coverage. Several authors considered that a mode selection through the interferometer pupil configuration is possible. This solution is mainly applicable in space, where the pupil configuration could be maintained with respect to the object field, and it would not be very interesting for solar-type stars, because of the geometrical leakage.

These conditions, continuity of observations and completeness of the pupil plane, conduct to the definition of an interferometer dedicated to asteroseismology and stellar imaging. This supposes a particular strategy.

Since 1996, several space projects have been envisioned. In 2000, the EPICURE project was submitted in response of the flexi-mission proposal. It included an hyper-telescope recombination for snapshot imaging. Recently, a project dedicated to asteroseismology has been proposed in the frame of ESA Cosmic Vision by Catala and Roxburgh, but this cannot be envisioned before 2030, at least. A program combining long term observations of a star for asteroseismology, and characterization of a surrounding planet is feasible by combining large base interferometry and high spectral resolution. For that purpose, an Imaging Fourier Transform Spectrometer associated with a snapshot interferometer would probably be the best solution.

Are there any closer opportunities for ground based instruments ? Clearly the problem is a very challenging one. On ground, the diurnal movement of the pupil projected on the sky impose a higher coverage of the Fourier space domain. Moreover, the need for long period of observations implies that the instrument would be cheap, automatic and easy to maintain. This sounds somehow contradictory with the present status of interferometers and even more for future projects.

Despite this difficulties, an positive answer has to be found in Antarctica. The possibilities offered by the Concordia station at Dome C, opens a window for such a project. Continuous observations of circumpolar objects can be obtaines during several months, solving one of the major problems for asteroseismology. Moreover, the incredible quality of the atmosphere makes interferometry much easier. Adaptative optics is not necessary for telescope smaller than one meter and the coherence time allows longer individual exposures.

4.2 Requirement for the interferometer

In first approximation, the number of the telescopes necessary to observe all modes up to a degree l is of the order of l ($2l$ if only resolved modes are seek). The largest base should also be of the order of the inverse of the smallest structure seek, i.e. $\frac{l\lambda}{\Phi}$. Wether these telescopes are to be co-phased is an open question. If the answer is yes, this would be a very challenging task, requiring R&D in order to keep a large number of sub-wavelength delay lines working together. On the other hand, R&D in the domain of the detectors and the capability of photon counting without loss of quantum efficiency would probably allow to work in the coherent domain, a much cheaper solution for an imaging interferometer. The best spectral range to look for small velocity variations is obviously the visible domain, as far to the UV as possible, in order to get the highest number of spectral lines, and the better spatial resolution. As already seen, a spectral resolution of 60000 is the minimum, and 120000 is preferable, in order to get super spatial resolution through differential phase measurement.

As seen before, the duration of continuous observations is a fundamental limitation of asteroseismic measurements. Although it could be reduced for higher degree modes (as it is possible to fit over several m components in order to extract frequencies and rotational splittings), a observation run of 10 to 30 days is a minimum for solar-like stars, and even more for some AGB stars. It is clear therefore that only space or Antarctic offers such a possibility. If the former is probably excluded from the present exercise, the latter is not, and the development of a large interferometric facility in Antarctica has necessarily to be explored for the close future.

distance pc	stellar disc mas	baseline km	angular resolution mas	degree
1	9	1	0.2	50
		10	0.02	500
10	0.9	10	0.02	50
		40	0.005	200
45	0.2	10	0.02	10
		40	0.005	40
180	0.05	40	0.005	10
180	0.5	40	0.005	100

Table 1: In this table, presented in the proposal for ESA Cosmic Vision by Catala and Roxburg (2004), the accessible degree for a given interferometer for different type of stars at different distance. Although oriented for spatial interferometer, this table gives an idea of what would be accessible from the ground with interferometer between 1 and 5 km baseline

In any case, atmospheric conditions play a crucial role in interferometric capabilities, particularly in the visible domain. The incredible qualities of the site of Dome C, on the Antarctic plateau, will certainly offer new solutions, not foreseen before.

4.3 Proposed solution

A first idea here would be to combine an imaging interferometer, with densified image recombination for instance [Vakili *et al*, 2004], with high spectral resolution. It is also clear from what has been said before that the spectrometer should give access to both angular dimension. It is also required to use a large number of spectral lines, preferentially in the visible domain. Imaging Fourier Transform Spectrometry (IFTS) is probably the best solution to that problem. It can easily be combined to a stellar imaging interferometer.

Another solution would require to distribute the different pupil in lines, like in AMBER, at the entrance slit of a classical spectrograph. This solution is certainly interesting for a small number of telescopes, but it starts to be complicated when the number of telescopes increases.

An imaging interferometer of about 40 telescopes of 30 cm on a base of 2 km offers a resolution of about 20 on solar-type stars at 10 pcs, and provides a equivalent surface of a 2 m telescope. With the efficiency of an Fourier Transform Spectrometer like SIAMOIS [Mosser *et al*, 2003], it would be possible to reach a level of photon lower than 1 cm/s in 10 days of continuous observations on a 5th magnitude star, as would be the Sun at that distance. It is been already seen that with such an interferometer, the sensitivity of the spectrograph is not any more reduced by stellar rotation, as the spatial resolution avoid the broadening of the spectral lines.

At Dome C, such an interferometer is probably feasible quite easily. The seeing is such that 30 cm telescopes will be diffraction limited 90 % of the time, making adaptative optics useless.

The possibility of following the oscillations photometrically should also be considered. If we are only seeking modes of degree higher than $l = 2$, transparency fluctuations (which are expected to be low in Antarctica) could be disregarded. On the Sun, photometric measurement of high degree solar modes are easily obtained, like instance in the TON experiment. This could be extended to stars with sufficient spatial resolution. It has to be noticed that the amplitudes at higher degree are larger as they include the sum of several m order simultaneously.

The advantage for photometric imaging is to simplify the focal instrument, but the stability should be studied. On the other hand, the spectral resolution offered by the spectrometer has the advantage to increase drastically the coherence length, making the acquisition of fringes much easier. A complete study has to be undertaken in order to find the best concept, for the type of recombination and for the focal instrument. Both observing modes are probably interesting, and complementary. Indeed, velocity and intensity variations observed simultaneously provide important information about the physics of the stellar atmosphere.

5 Conclusion

As seen previously, interferometric measurement are very useful, and complementary with asteroseismic technics, for investigation of stellar internal structure and evolution. Next generation optical interferometer will improve these capacities. However, we have to distinguish between the different programs of observations. Indeed, they require quite different capabilities.

Some of them could be realised with multi-purpose interferometers. Obviously, several characteristics are expected to be improved with respect to present instruments. In particular, higher spectral resolution and an extension of the spectral range to the visible domain, as far as possible to the blue, in order to get the largest number of spectral lines, would be necessary for detection of differential rotation and single mode identification.

Other programs however, require mostly a large number of bases and long integration time. This means a dedicated interferometer. Therefore, strategic consideration should be taken into account. As it seems quite difficult to build a dedicated interferometer only for this projects, is it possible to combine several observing programs having the same constraints ? Is it possible to build a "cheap" imaging interferometer, with several tens of small telescopes ? These questions should be studied in details, and imaginative solutions for the recombination, delay lines, system control, detection and signal processing are to be investigated.

Table 2: The requirements for a new generation interferometer are summarised here for different observing program

	Differential Visibilities	Differential Phase	Imaging
	Radius Oblateness	Differential rotation Mode identification Intermediate degree $2 < l < 6$	High degree imaging $2 < l < 100$
Baseline	1-2 km		1-10 km
Telescopes	> 3 (boot-strapping)	3	$> 36 (\approx l)$
Wavelength		420-840nm	
Resolution		120000	IFTS
Magnitude	$M_V = 13$	$M_V = 10$	$M_V = 7$
Precision	$\sigma_V = 10^{-3} - 10^{-4}$	$\sigma_\varphi = 10^{-5} rd$	

In any case, all these programs require much better spatial resolution that what already exists: kilometric baselines at shorter wavelength are to be considered as soon as possible. The precision is also a critical parameter. This is clearly a problem of calibration. Configurations allowing auto-calibrated measurements should be explored. One possibility is to use redundant array and beam commuting device, in order to eliminate most of instrumental visibility. Differential phase measurements are also interesting for that goal.

Finally, the potential for interferometry offered by the Antarctic station at Dome C should be explored. First, new measurements are necessary to assess the real capabilities of the site for interferometry. In particular, several parameters should be monitored during the full winter season, not only r_0, but also the isoplanetic angle θ_0, the coherence time τ_0, which is unknown up to now, and also the external scale L_0. Simultaneously, a phase A study for the installation of an interferometer should start as soon as possible. Obviously, the requirements of asteroseismology are to be taken into account for that study. Thanks to the exceptional quality of the site, the old dream to see the stars as the Sun might not be so far in the future.

References

[Aristidi *et al*, 2004] E. Aristidi, A. Agabi, E. Fossat, T. Travouillon, M. Azouit, J. Vernin, A. Ziad, F. Martin, Robuchon G., 2004, *in Proc. Dome C Astronomy/Astrophysics meeting*, Toulouse 2004, in press

[Bouchy *et al*, 2004] Bouchy, F.; Carrier, F., 2002, The acoustic spectrum of alpha Cen A,*Astron. Astroph.*, **390** , 205

[Domiciano *et al, 2003]* Domiciano de Souza A., Kervella P., Jankov S., Abe L., Vakili F., di Folco E., Paresce F., 2003, The spinning-top Be star Achernar from VLTI-VINCI,*Astron. Astrophys.*, **407**, L47-L50

[Chelli & Petrov, 1995] Chelli A., Petrov R.G., 1995, Model fitting and error analysis for differential interferometry. II. Application to rotating stars and binary systems, *A&AS*, **109**, 401

[Domiciano *et al*, 2004] A. Domiciano de Souza, J. Zorec, S. Jankov, F. Vakili, L. Abe, E. Janot-Pacheco, 2004, Stellar differential rotation and inclination angle from spectro-interferometry, *Astron. Astrophys.*, **418** , 781

[Domiciano *et al*, 2003] Domiciano de Souza, A.; Kervella, P.; Jankov, S.; Abe, L.; Vakili, F.; di Folco, E.; Paresce, F., 2003, The spinning-top Be star Achernar from VLTI-VINCI,*Astron. Astrophys.*,**407**, 47D

[Domiciano *et al*, 2002] Domiciano de Souza, A., Jr.; Vakili, F.; Jankov, S.; Janot-Pacheco, E. , 2002, Tuning Pulsation Modes with Stellar Interferometry, *in Radial and Nonradial Pulsations as Probes of Stellar Physics, ASP Conference Proceedings* Vol. 259. Edited by Conny Aerts, Timothy R. Bedding, and Jrgen Christensen-Dalsgaard, p.170

[Duvall *et al*, 1988] Duvall, T. L., Jr.; Harvey, J. W.; Libbrecht, K. G.; Popp, B. D.; Pomerantz, M. A., 1988, Frequencies of solar p-mode oscillations, *ApJ*,**324**, 1158

[Eggenberger *et al*, 2004] Eggenberger, P. Charbonnel, C. Talon, S. Meynet, G. Maeder, A. Carrier, F. Bourban, G., 2004, Analysis of α Centauri AB including seismic constraints, *Astron. Astroph.*, **417**, 235-246

[Fossat *et al*, 1981] Fossat, E.; Grec, G.; Pomerantz, M., 1981, Solar pulsations observed from the geographic South Pole - Initial results, *Solar Phys.*, **74**, 59

[Jankov *et al*, 2001] S. Jankov, F. Vakili, A. Domiciano de Souza, E. Janot-Pacheco, 2001, Interferometric-Doppler imaging of stellar surface structure, *Astron. Astrophys.*, **377** , 721

[Kervella, 2004A] Kervella, P., Fouqué, P., Storm, J., Gieren, W. P., Bersier, D., Mourard, D.,Nardetto, N., Coudé du Foresto, V., 2004, The Angular Size of the Cepheid l Carinae: A Comparison of the Interferometric and Surface Brightness Techniques", *Ap. J. Letters*, **604**, L113-L116

[Kervella, 2004B] Kervella, P. Nardetto, N. Bersier, D. Mourard, D., Coudé du Foresto, V.,2004, Cepheid distances from infrared long-baseline interferometry. I. VINCI/VLTI observations of seven Galactic Cepheids,*Astron. Astroph.*, **416**, 941-953

[Kervella, 2004C] Kervella, P. Thévenin, F. Morel, P. Berthomieu, G. Bordé, P. Provost, J., 2004, The diameter and evolutionary state of Procyon A. Multi-technique modeling using asteroseismic and interferometric constraints, *Astron. Astroph.*,**413**, 251-256

[Kervella, 2003] Kervella, P.; Thvenin, F.; Ségransan, D.; Berthomieu, G.; Lopez, B.; Morel, P.; Provost, J., 2003, The diameters of alpha Centauri A and B. A comparison of the asteroseismic and VINCI/VLTI views, *Astron. Astroph.*, **404**, 1087-1097

[Mathias *et al*, 2004] Mathias, P.; Le Contel, J.-M.; Chapellier, E.; Jankov, S.; Sareyan, J.-P.; Poretti, E.; Garrido, R.; Rodrguez, E.; Arellano Ferro, A.; Alvarez, M.; Parrao, L.; Peña, J.; Eyer, L.; Aerts, C.; De Cat, P.; Weiss, W. W.; Zhou, A. *Astronomy and Astrophysics*, **417**, 189-199

[Mosser *et al*, 2003] Mosser Benoît, Maillard Jean-Pierre, Bouchy François, 2003, Photon Noise-limited Doppler Asteroseismology with a Fourier Transform Seismometer. I. Fundamental Performances, *PASP*, **115**, Issue 810, 990-1001

[Petrov 1989] Petrov, R. G., 1989, Differential Interferometry, *in Diffraction-Limited Imaging with Very Large Telescopes, Proceedings of the NATO Advanced Study Institute*, Kluwer, D. Alloin and J. M. Mariotti eds, **274**, p.249

[Pijpers *et al*, 2003] Pijpers, F. P. Teixeira, T. C. Garcia, P. J. Cunha, M. S. Monteiro, M. J. P. F. G. Christensen-Dalsgaard J.,2003, Interferometry and asteroseismology: The radius of τ Cet, *Astron. Astroph.*,**406**, L15-L18

[Renaud *et al*, 1999] Renaud C., Grec G., Boumier P., Gabriel A. H., Robillot J. M., Roca Cortes T., Turck-Chièze S., Ulrich R. K., 1999, Solar oscillations: time analysis of the GOLF p-mode signal, *Astron. Astroph.*, **345**, p.1019-1026

[Roddier & Roddier, 1983] Roddier C., Roddier F., 1983, High angular resolution observations of alpha Orionis with a rotation shearing interferometer, *ApJ*, **270**, L23

[Schmider *et al*, 1997] Schmider F.-X., Petrov R., Chouchane M., 1997, Asteroseismology with differential interferometry, *in Sounding solar and stellar interiors, Proc. IAU 181*, J. Provost and F.-X. Schmider eds, Universit de Nice, Poster vol., 247

[Vakili *et al*, 2004] Vakili, F.; Aristidi, E.; Abe, L.; Lopez, B., 2004, *Astron. Astroph.*, **421**, 147-156

[Vakili & Percheron, 1990] Vakili F., Percheron I., 1991, On the Possibility to Detect NRP's by Optical Interferometry, in *Rapid Variability of OB-stars: Nature and Diagnostic Value, Proc. ESO Workshop*, Dietrich Baade ed, p.77

[Vogt & Penrod, 1985] Vogt S. S., Penrod G. D., 1983, Doppler Imaging of spotted stars Application to the RS Canum Venaticorum star HR 1099, *PASP*, **95**, 565