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Asteroseismology and interferometry

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Abstract. Asteroseismology aims at constraining the stellar evolution theory, and allows to determine the age of stars together with other fundamental parameters. We present recent results obtained by interferometry, and prospects for the future.

Key words. Stars: abundances – Stars: – Stars: –

1. Introduction

The angular diameter of a star, when combined with an accurate parallax, gives its linear diameter. This quantity combined with the luminosity is a link between the observations and the results of theoretical calculation of stellar interior codes with the predicted emergent flux of the atmosphere. In particular diameters can constrain the relatively inaccurate estimate of the effective temperature of the star. These quantities are also needed for the calibration of the Barnes-Evans (1976) relation between the effective temperature or the radii and the color indexes. These empirical relations can predict stellar radius to be used for stellar calibration when deriving information like the age of the star. Many diameters have been measured by interferometric techniques, including lunar occultation and speckle interferometry, but it is only recently that a relatively large number of dwarf star diameters have been measured with a mean accuracy of 1% thank to the Mark III and VLTI interferometers.

Focusing only on variable stars, we note that little work was done on Cepheides during the 90's, and it is one of the successes of the VLTI to have help to better constrain stars as asteroseismic targets. The challenge is important because, for these targets the effective temperature is poorly constrained and it prevents a high accuracy in the determination of the age of the star even when adding the asteroseismic frequency constraints.

Among the numerous challenges of asteroseismology constrained by interferometric diameters are the improvement of the following modeling tools: 1D convection theory approximation (and its mixing parameter), overshooting, diffusion of heavy elements in the interiors. One should also make a better use of the boundary conditions, i.e. the atmospheres. These new constraints on the theories implemented in the stellar codes are of a great importance for future works on Galactic evolution (age of stars or enrichment of the abundance of

Send offprint requests to: F. Thévenin helium with time: this abundance is not measurable in late-type stars).

2. Diameters to help asteroseismology constraints

After two years of operation, the commissioning instrument VINCI of the VLTI helped in several papers: Ségransan et al. (2003), Kervella et al. (2003a), (2003b), Kervella et al. (Kervella 2004), Di Folco et al. (2003), Thévenin et al. (2005), when measured diameters with asteroseismic constraints for dwarf and subgiant stars to obtain important results on their evolutionary status and on their masses. They revealed for example that several solutions for the calibration of stars are not acceptable anymore and helped to choose among different models with or without convective core. When combined with the large mean frequency spacing, an accurate radius can constrain the mass of the asteroseismic target. This has lead us to adopt lower masses for the stars α Cen B and Procyon.

For subgiant stars and giants at the beginning of the RGB, which are rapid stellar life phases, the use of the radius has helped to decrease by a factor of three the uncertainty on the age determination for a given input physics in the models and for a given age and helium content.

3. On the calibrated Barnes-Evans relations

The availability of a number of new interferometric measurements of Main Sequence and subgiant stars makes it possible to calibrate the surface brightness relations of these stars using exclusively direct angular diameter measurements. These empirical laws make it possible to predict the limb darkened angular diameters $\theta_{\rm LD}$ of dwarfs and subgiants using their de-reddened Johnson magnitudes, or their effective temperature. The smallest intrinsic dispersions of $\sigma \leq 1\%$ in $\theta_{\rm LD}$ are obtained for the relations based on the K and L magnitudes. These calibrations are valid between the spectral types A0 and M2 for dwarf stars (with a possible extension to later types when using the effective temperature), and between A0 and K0 for subgiants. Such relations are particularly useful for estimating the angular sizes of calibrators for long-baseline interferometry from readily available broadband photometry.

As an example of diameter predictions we selected in the list of MOST and COROT targets several stars and in Table 1 we give radii computed using these empirical relations (Kervella 2004). It appears that most of these targets are beyond the capabilities of existing interferometers to estimate their radius with enough accuracy to be useful for asteroseismology studies. The predictions with the Barnes-Evans relations have good uncertainties of by mean 1.5%, uncertainties dominated by the error on the parallaxes.

4. 3D RHD models vs Interferometry

The modern interferometric instruments reach nowadays a good enough precision on the measurement of stellar limb darkening that it is possible to use them as diagnostics on the stellar outer layers, in particular the temperature profiles. During the last decade much effort has been dedicated to the improvement of instrumental techniques, resulting in a considerable improvement of the angular diameter measurement precision (now routinely in the 1% range). If one wants to take advantage of this instrumental precision, a similar effort in numerical modelling of stellar atmosphere has to be done. In this respect, the use of standard atmospheric models like ATLAS (Kurucz 1992) or Phoenix (Hauschildt 1999) have to be overcome. Indeed, these models are based on very drastic assumptions: hydrostatic, radiative equilibrium, unidimensional. The explosion of computer capacities in the last 10-15 years allows nowadays the use of much more realistic 3D radiative hydrodynamical (RHD) models.

4.1. 3D hydrodynamical models

These models have been initiated two decades ago by Åke Nordlund, R. Stein and coworkers to model the solar convective surface (Nordlund 1982; Stein & Nordlund 1989,

Table 1. Diameters of selected asteroseismic targets

MOST targets	V	K	θ_{LD}(mas)	R/R$_\odot$	π(mas)
HD 10700	3.49	1.794	1.935 ± 0.031	0.758 ± 0.016	274.18 ± 0.80
HD 22049	3.72	1.776	2.037 ± 0.033	0.704 ± 0.014	310.74 ± 0.85
HD 38529	5.95	4.211	0.641 ± 0.010	2.919 ± 0.132	23.57 ± 0.92
HD 76932	5.80	4.362	0.567 ± 0.009	1.299 ± 0.038	46.90 ± 0.97
HD 99028	4.00	2.790	1.124 ± 0.018	2.928 ± 0.103	41.26 ± 1.16
HD 102870	3.59	2.269	2.438 ± 0.039	1.706 ± 0.037	91.74 ± 0.77
HD 114710	4.23	2.923	1.075 ± 0.017	1.058 ± 0.023	109.23 ± 0.72
HD 120136	4.50	3.507	0.778 ± 0.013	1.304 ± 0.030	64.12 ± 0.70
HD 142860	3.85	2.703	1.158 ± 0.019	1.383 ± 0.030	89.92 ± 0.72
HD 224930	5.80	4.068	0.683 ± 0.011	0.910 ± 0.040	80.63 ± 3.03
51 Peg	5.49	3.970	0.689 ± 0.011	1.137 ± 0.060	65.10 ± 0.76
COROT targets					
HD 43587	5.71	4.205	0.617 ± 0.010	1.280 ± 0.032	51.76 ± 0.78
HD 49933	5.78	4.715	0.452 ± 0.007	0.673 ± 0.022	33.45 ± 0.84
μ Ara	5.15	3.683	0.779 ± 0.013	1.279 ± 0.030	65.46 ± 0.80

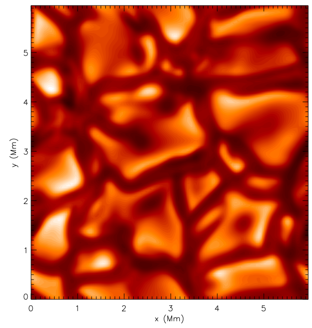

Fig. 1. Snapshot of the disk-center (μ = 1) intensity emerging at the stellar surface at a representative time.

1998). The fundamental equations of physics (mass, momentum, energy conservation) are solved onto a cartesian staggered mesh. The size of the domain of simulation is a few mega-meters in each direction. These equations are coupled with radiative transfer solved along several inclined rays. Significant updates have been brought since then concerning both the numerical and physical aspects (equation of states and/or opacities). A more detailed description can be found in Stein & Nordlund (1998). The realism of these simulations is now such that they can reproduce almost perfectly solar and stellar lines (for both shifts and asymmetries), solar acoustic oscillation frequencies and granulation dynamics. Recently, new 3D RHD codes appeared, such as CO5BOLD initiated by Freytag, Steffen, Wedemeyer (http://www.astro.uu.se/ bf/) and PENCIL initiated by Brandenburg and Dobbler (http://www.nordita.dk/data/brandenb/pencil-code/).

The use of 3D RHD codes in the context of interferometry has been proposed recently by Aufdenberg et al. (2004) for Procyon and by Bigot et al. (2005) for the diagnostic of the VINCI/VLTI measurements of the K-dwarf α Cen B (see below). They are more attractive than the 1D standard codes in mainly two respects. First, the absence of free-parameters, like the so-called mixing length, makes the diagnostic much more realistic since the result of the analysis does not depend on the input.

The second advantage is the great realism of the 3D simulations. Indeed, even if the temperature structure in 1D code can always be calibrated by a judicious choice in the free parameters, it cannot reproduce the temperature profile in the transition (surface) region since the coupling between radiation and gas dynamics is essential.

The monochromatic limb darkening $I_\lambda(\mu)$ is obtained by solving the radiative transfer with the 3D RHD code along different ray inclinations. The squared visibility as observed by the instrument is calculated using an Hankel transform of this center-to-limb variation of its intensity.

4.2. Application to a nearby K-dwarf, α Cen B

The application was made to the K-dwarf α Cen B (HD 128621) for which new visibility measurements were obtained, especially in the second lobe of the visibility function (see Bigot et al. 2005, and Fig 2). The amplitude and position of the second lobe of visibility is very sensitive to the limb darkening and therefore the temperature structure of the atmosphere. These extra points thus provide strong constraints to test our modelling of the external layers. Another interesting aspect of this star is the presence of solar-like acoustic oscillations which brings additional constraints on the modelling, especially an independent estimate of the linear radius of the star (see below). Finally, this nearby star is also very interesting because of its proximity (1.3 pc): it can be easily resolved by interferometry. This is mostly not the case for dwarf stars more than 20 pc away.

The result of the analysis of the VINCI/VLTI interferometric observations is shown in Fig. 2. For this analysis, a 3D RHD simulation of the surface layers of the star was performed. A representation of its emerging intensity is shown on Fig. 1. This 3D model fits well the fundamental parameters of the star, $T_{\rm eff}$ = 5200 K, $\log g$ = 4.5 and [Fe/H] = +0.2. The fit of the visibility data obtained at the VINCI/VLTI is performed using a standard χ^2 minimizing procedure.

Several models of the stellar surface are considered in the fitting process: uniform disk (UD, no limb darkening), and two limb darkened (LD) models: 1D ATLAS and 3D RHD. The different results are shown on Fig. 2. The best fit of the data is obtained for the 3D model with an angular diameter of θ_{LD} = 6.000 mas. The 1D and UD models produce larger diameters than the 3D one. Using the parallax from Söderhjelm (1999), π = 747.1 ± 1.2 mas, the derived linear radius is $0.863 \pm 0.003\,R_\odot$ which agrees well with the value obtained from asteroseismically constrained modeling (Thévenin et al. 2002). It should be emphasized that the improvement brought by 3D compared with 1D model is small for this type of star: its low effective temperature limits the importance of convection in energy transport. Therefore, the improvement brought by 3D modeling is smaller than in hotter A, F-stars (e.g. Allende-Prieto et al. 2004). However, even this small correction is significant since the difference between 3D and 1D models reaches $1\,\sigma$. This precision in the modelling will be even more appreciable when models will be based on AMBER data.

4.3. Other stars

The 3D modelling in a numerical box described previously applies only if the convective envelope does not extend too much. For more evolved giant stars the combined low effective temperature and low surface gravity makes the size of the convective structures (granules) huge enough to cover a significant part of the entire stellar surface. In those cases, the approach presented above, i.e. solving RHD equations locally does not apply. The simulations must include the entire volume, i.e. a "star-in-the-box" simulation. Such numerical codes already exist like the CO5BOLD and PENCIL codes which have been used to model for example Betelgeuse (Freytag et al. 2002, Dorch 2004) Of course, these "star-in-the-box" simulations are much more CPU demanding, and so far it is not possible to reach the same fine resolution as in the local simulations.

A huge amount of effort will be done in the future on metal-poor stars like μ Cas or Gmb

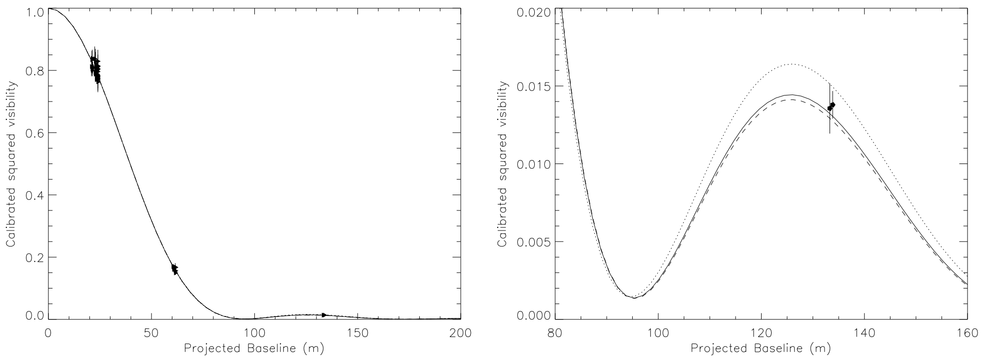

Fig. 2. (Left panel) Overview of α Cen B squared visibilities. The continuous line represents the broadband, limb darkened disk visibility model derived from the 3D RHD, with θ_{3D} = 6.000 mas. (right panel) Close up views of the squared visibilities of α Cen B in the lower part of the first lobe (left panel) and the second lobe (right panel). The continuous line represents the broadband, limb darkened disk visibility model derived from the 3D RHD, with θ_{3D} = 6.000 mas. The dashed lines correspond to results obtained from 1D ATLAS model with θ_{1D} = 6.017 mas. The upper dotted curve is a UD model with θ_{UD} = 5.881 mas. From Bigot et al. (2005).

1830 among others in order to get their asteroseismic constraints with their diameter measurements. Metal-poor stars are an important challenge because they represent other laboratory conditions for testing internal structure codes, but they are also an important challenge for deriving ages and helium content in the first phases of the Galaxy.

5. Some pharaonic projects: interferometers devoted to asteroseismology

At present day, asteroseismology is developed with space photometric missions like MOST and COROT and radial velocimetry from ground spectrographs like HARPS/3.6m. There is only one star for which the photosphere is known in detail: the Sun. As a comparative basis, a solar-like star at 1 pc has a surface disk of $\approx$10 mas which requests a baseline telescope of 1km giving a resolution angle of 0.2 mas if one wants to observe oscillation modes of degree 50.

5.1. 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 on the spectrum, as they introduce spurious peaks (aliases) which interfere with real modes and disturb their measurements.

Then, if one wants to characterize the surface of solar-like stars for asteroseismic studies, one needs to imagine future projects in space or on the ground as stellar imagers with baselines of a few kilometers. Such projects are under study like the one foreseen for Antartica which is a stellar imager using a central beam combiner: KEOPS (Schmider et al. 2004).

In first approximation, the number of telescopes necessary to observe all modes up to a degree l is of the order of l ($2l$ to fully resolve the modes). The largest baseline should also be of the order of the inverse of the smallest structure, i.e. $\frac{l\lambda}{\Phi}$. Whether these telescopes are to be co-phased is an open question. If the answer is yes, this would be a challenging task, 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 in the blue or UV as possible, in order to get a large number of spectral lines, and the best possible spatial resolution.

An imaging interferometer of about 40 telescopes of 30 cm on 2 km baselines provides a resolution of about 20 on solar-type stars at 10 pc, and the equivalent collecting surface of a 2 m telescope. With the efficiency of a Fourier Transform Spectrometer like SIAMOIS (Mosser et al. 2003), it would be possible to reach a level of photon noise lower than 1 cm/s in 10 days of continuous observations on a 5th magnitude star (the Sun at 10 pc). It has already been shown 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, some of the environment constraints for operating such an interferometer are relaxed. The seeing is such that 30 cm telescopes will be diffraction limited 90 % of the time, making adaptative optics useless.

6. Conclusions

The improvement of the angular diameter estimates in the future will further tighten the uncertainty domain in the HR diagram, especially as detailed modeling of the atmosphere will be required. This improvement will naturally require a higher precision on the parallax value to derive the linear diameters. Some progress in the asteroseismic observations is also required to better constrain the evolutionary state of stars for which the frequency spacings are still relatively imprecise. Both MOST and COROT satellites are essential observatories to complement spectro-velocimetry technique done from the ground. A huge amount of effort on the accuracy of parallaxes is also requested to get smallest error bars on the linear diameter estimates.

References

Allende Prieto, C. et al. 2004, A&A, 423, 1109
Aufdenberg et al. 2005, A&A, in press
Barnes, T. G. et al. 1976, MNRAS, 174, 503
Bigot, L. et al. 2005, A&A, in press
Di Folco E. et al. 2004, A&A, 426, 601
Dorch, S. B. F. 2004, A&A, 423, 1101
Freytag, B., 2002, Astronom. Nachrichten, 323, 213
Hauschildt, P. H. 1999, ApJ, 512, 377
Kervella P. et al. 2003a, A&A, 404, 1087
Kervella P. et al. 2003b, A&A, 408, 681
Kervella P. et al. 2004, A&A, 426, 297
Kurucz, R. L. 1992, IAU Symp. 149: The Stellar Populations of
Mosser et al. 2003, PASP, **115**, Issue 810, 990-1001
Nordlund Å., A&A 1982, 107, 1
Schmider et al. 2004, Coll. Liège, in press
Ségransan D. et al. 2003, A&A, 397, L5
Stein R.F., Nordlund Å. 1989, ApJL, 342, 95
Stein R.F., Nordlund Å. 1998, ApJ, 499, 914
Söderhjelm, S. 1999, A&A, 341, 121
Thévenin, F. et al. 2002, A&A, 392, L9
Thévenin F. et al. 2005, A&A, 426, 253