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HIGH ANGULAR RESOLUTION IN MODERN ASTRONOMY: NEW INSIGHTS INTO THE STELLAR PHYSICS

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Abstract. The new generation of ground-based instruments for high angular resolution from optical interferometry provides a qualitatively new information for improving our understanding of the physics, structure and evolution of stars through the comparison of observational results with the predictions of theoretical models of stellar interiors and atmospheres. Traditionally, the optical interferometry has been considered as a tool for determination of the fundamental properties of stars, namely their effective temperatures, radii, luminosities and masses, by the combination of angular diameters, with complementary photometric, spectrophotometric and spectroscopic measurements, made with conventional telescopes. However, the influence of stellar interferometry extends beyond classical regimes of stellar diameters and binary orbits. In this contribution we review a selection of outstanding problems in stellar physics showing the potential of new methods which combine the classical techniques (as photometry and spectroscopy) and long baseline interferometry, providing informations that cannot be obtained otherwise with each of these techniques taken at once.

1. INTRODUCTION

An optical long-baseline interferometer is a device that allows astronomers to achieve a higher angular resolution than is possible with conventional telescopes. It is composed of an array of at least two telescopes, which sample the wavefronts of light emitted by a source at separate locations and redirect starlight to a central location in order to recombine the sampled wavefronts. The contrast of interference fringes, or visibility, varies according to the characteristics of the light source (for example, the size of a star or the separation between two stars in a binary system) and according to the length and orientation of the interferometer's baseline, the line connecting the two mirrors. It is possible to take measurements from many different baselines, most easily by waiting while Earth rotates. In addition, most of the new interferometers have more than two mirrors in the array and can move the mirrors along tracks.

Although the first measurement of a stellar angular diameter was made of the supergiant star α Orionis with Michelson's stellar interferometer in 1920 (Michelson and Pease, 1921), the optical interferometry was slowly evolving from a difficult laboratory experiment to a mainstream observational technique. The real difficulty is to combine the beams in phase with each other after they have traversed exactly the same optical path from the source through the atmosphere, each telescope and down to the beam recombination point. This has to be done to an accuracy of a few tenths of the wavelength, which in the case of visible light is not an obvious task particularly because of atmospheric turbulence which makes the apparent position of a star on the sky jitter irregularly. This jitter often causes the beams in different arms of the interferometer to overlap imperfectly or not at all at any given moment. For this reasons, the optical interferometry requires extreme mechanical stability, sensitive detectors with good time resolution, and ideally an adaptive optical system to reduce the effects of atmospheric turbulence. The development of the required technology allowed to built modern interferometers which are currently operating:

- CHARA Center for High Angular Resolution Astronomy
  Georgia State University Mt Wilson, CA, USA
- COAST Cambridge Optical Aperture Synthesis Telescope
  Cambridge University Cambridge, England
- GI2T Grand Interféromètre à 2 Télescopes
  Observatoire Côte D'Azur Plateau de Calern, France
- IOTA Infrared Optical Telescope Array
  Smithsonian Astrophysical Observatory, Mt Hopkins, AZ, USA University of Massachusetts (Amherst)
- ISI Infrared Spatial Interferometer
  University of California at Berkeley Mt Wilson, CA, USA
- KI Keck Interferometer
  NASA JPL Mauna Kea, HI, USA
- MIRA I Mitake Infrared Array
  National Astronomical Observatory, Japan Mitaka Campus, Tokyo, Japan
- NPOI Navy Prototype Optical Interferometer
  Naval Research Laboratory, Flagstaff, AZ, USA US Naval Observatory
- PTI Palomar Testbed Interferometer
  NASA JPL Mt Palomar, CA, USA
- SUSI Sydney University Stellar Interferometer
  Sydney University Narrabri, Australia

- VLTI VLT Interferometer
  European Southern Observatory Paranal, Chile

2. APPLICATIONS OF STELLAR INTERFEROMETRY

2.1. REVIEW OF SOME OUTSTANDING PROBLEMS

The classical primary goal of interferometry has been the determination of fundamental astrophysical parameters characterizing stars through angular diameter measurements. With the advent of accurate parallaxes from the Hipparcos astrometry satellite *linear radii* can be determined precisely as well as *emergent fluxes* and *effective temperatures* (in conjunction with photometry). Additionally, interferometry can provide a very precise determination of stellar *masses* from binary star orbital motion studies through the application of Kepler's Third Law.

However, stellar interferometry is not limited only to these classical applications. For example, the exact behavior of photospheric limb darkening leads to better insight into the *stellar atmospheres theory* through wavelength dependence of the uniform disk diameter (e.g. Quirrenbach et al., 1996; Wittkowski et al., 2001). Other applications, as well as interferometric techniques, have been reviewed by Quirrenbach (2001), and here we give a non-exhaustive list updated with some more recent developments in the field.

Red giants and *Supergiants* have so far been one of the prime targets for interferometric observations because of their large sizes and brightness. Surface features have been detected on the surfaces of the apparently largest supergiants α Orionis, α Scorpii and α Herculi (e.g. Buscher et al., 1990; Tuthill et al., 1997; Young et al., 2000). For the same reason Optical interferometry has already been successfully used to study *Be star circumstellar environments and winds* (Thom et al., 1986; Quirrenbach et al., 1993; Vakili et al., 1994; Stee et al., 1995).

Spatial resolution in the far infrared is the most promising approach in looking for the complex structures that are expected to be associated with *star forming regions.* Structures associated with *Pre main sequence objects* are of great interest, and require imaging at infrared wavelengths. The study of *Young stellar objects* (YSOs) is one of the exciting topics that can be undertaken now. Different aspects can be tackled by interferometry: circumstellar disks, multiplicity, jets.

The process of *mass-loss* is essential for our understanding of late stages of stellar evolution. Optical and infrared interferometry can provide important observational constraints to the evolution of late-type stars along the *Asymptotic Giant Branch* (AGB) and variability in *Mira* and other variable stars as *P Cygni, R Corona Borealis, Flare stars, Herbig-Haro Objects, Cataclysmic variables, RR Lyrae, Ap and Be stars etc.*. Particularly the *Calibration of Cepheid Period-Luminosity relation* (with progressively increasing accuracy in the mean angular diameter) will improve our knowledge on *Distance scale in the Universe* (e.g. Kervella et al., 2004).

The technique of Interferometric-Doppler Imaging, using the relative phase of the interferometric signal along a spectral line with respect to the continuum (Petrov, 1988), has been developed by Jankov et al. (2001) who treated explicitly (see also Jankov et al., 2002) the case of *non-radial stellar pulsations*, for which the cancellation of opposite sign temperature or velocity fields introduces difficulties, and showed that interferometric constraint introduces the crucial improvement. The effects of *differential rotation* and *gravity darkening* on interferometric observables have been studied by Domiciano de Souza et al. (2004) and Domiciano de Souza (2002) respectively.

2.2. RAPID ROTATION AND STELLAR PHYSICS

In order to perform the following scientific goals:

- Detailed mapping of the star in order to deduce the geometrical deformation due to rapid rotation,
- Gravity darkening
- Accurate determination of equatorial diameter, critical velocity and effective temperature,

Domiciano de Souza et al. (2003) carried out dedicated observations of α Eridani (Achernar) from 11 September to 21 December 2002, with quasi-uniform time coverage, on the VLT Interferometer (VLTI) equipped with the VINCI beam combiner (Kervella et al., 2003). This instrument recombines the light from two telescopes in the astronomical K band centered at 2.2 μm. An array of 35cm siderostats with two interferometric baselines (66m and 140m) was used. The baseline orientations are almost perpendicular to each other giving an excellent configuration for the detection of stellar asymmetries. Moreover, Earth rotation has produced an efficient synthesis effect. The final product of data processing were 60 squared visibility measurements of the object for each baseline projected on the sky, which are directly related to the Fourier transform of the brightness distribution of the object via the Zernike-Van Cittert theorem.

Achernar's pronounced apparent asymmetry (Fig. 1) together with the fact that it is a Be star, raised the question of whether they observed the stellar photosphere with or without an additional contribution from a Circum-Stellar Envelope (CSE). Arguing that the observed asymmetry of Achernar reflects its true photospheric distortion with a negligible CSE contribution, they concluded that the usual Roche approximation does not apply to Achernar, where deviations from gravitational potential and differential rotation must be closely regarded with respect to the internal momentum distribution. One possible scenario is that of the shellular rotation law (Zahn, 1992), in which the angular velocity increases toward the stellar center, implies the oblateness larger than that of a uniformly rotating star (Maeder, 1999). In this context their result on Achernar's surface distortion should also impact other internal mechanisms like meridional circulation, turbulence, transport and diffusion of the chemical elements and angular momentum, increase of mass loss with rotation as well as anisotropies in the mass ejection and wind density from rotating stars.

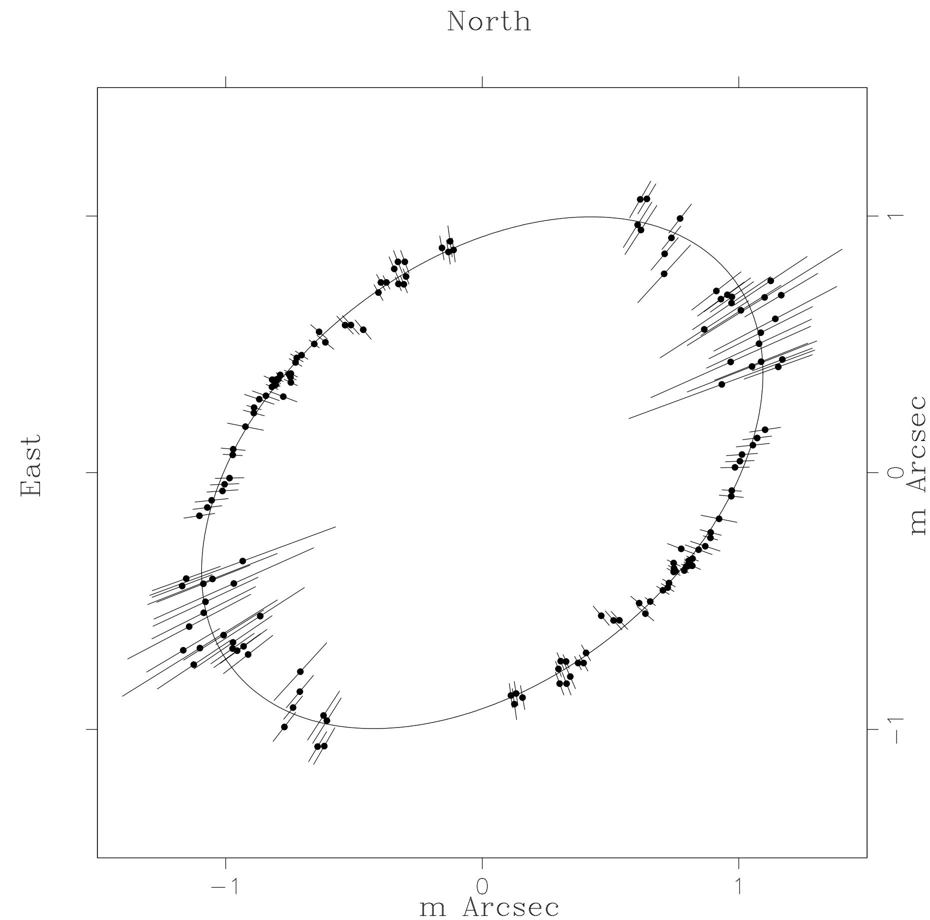

Figure 1: VLTI/VINCI measurements revealing the spectacular oblateness of Achernar.

The highly distorted photosphere of Achernar poses the question of Be stars rotation rate. The formation of out-flowing discs from Be stars remains their central puzzle, where rapid rotation is the crucial piece. Under the Roche approximation the observed oblateness indicates that Achernar should rotate close to its critical velocity since the model solution which implies 96% of the critical velocity is more consistent with the data. Original vision of a critically rotating Roche star, ejecting material from its equator, has been discarded in the past by observing that Be stars rotate at most at 70% to 80% of their critical velocity. However, this statistically observed limit may be biased by the fact that close to or beyond such velocities the diagnosis of Doppler-broadened spectral lines fails to determine the rotation value due to gravity darkening. We believe that only direct measures of Be star photospheres by interferometry can overcome the challenge to prove whether these objects rotate close, to a few percent, of their critical velocity or not. This will have a profound impact on the dynamical models of Be stars disc formation from rapid rotation combined to mechanisms like pulsation, radiation pressure of photospheric hot spots or expelled plasma by magnetic flares.

2.3. STELLAR SURFACE INHOMOGENEITIES

The study of starspots using classical interferometric techniques requires a very high spatial resolution which, even for RS CVn stars, should be better than 0.2 mas. In parallel to the development of interferometric techniques, the method of Doppler Imaging (Rice, 1996 and references therein) allowed access to the spatial structure of non-resolved stars through observation and interpretation of temporal spectroscopic variability along the stellar rotational phase. Similarly to classical spectroscopy, the differential interferometry (Beckers, 1982) makes it possible to measure the shift of the stellar photometric barycenter (photocenter) of an unresolved star as a function of wavelength. The photocenter is the angular vectorial function and it provides the first order moment of the spatial brightness distribution, in addition to the zero order moment spectroscopic information, allowing better spatial resolution of stellar atmospheres when compared to the classical Doppler Imaging (Jankov et al., 2001).

Doppler Imaging has also been applied to magnetic Ap (CP2) stars, because many of these stars show strong changes of their spectral line profiles due to surface abundance inhomogeneities. The most accepted mechanism in explaining the chemical peculiarities of these stars involves the radiatively driven diffusion of chemical elements in the atmosphere which is influenced by the orientation and strength of a magnetic field, yielding a separation of elements in different layers at the surface of magnetic stars. Observationally, this theory can be verified by comparing the geometry and strength of the magnetic field derived from polarization observations with the structure of "abundance spots" on the stellar surface. Thus, the Doppler Imaging of chemically peculiar stars is an excellent tool for testing theories of elemental diffusion and the origin of magnetic fields in stars with radiative envelopes since the question of the prevalence of magnetic fields among such stars is still open.

However, due to the intrinsic limitations of the Doppler Imaging technique (e.g. Rice et al., 1989) and particularly what concerns the reconstruction of features in the hemisphere in which the rotational pole is hidden, the reliable Doppler maps, which allow to draw physical conclusions, can be obtained only in the narrow range of stellar inclinations. For stars tilted at low inclinations only a small part of the southern hemisphere can be observed and even this small part cannot be reliably reconstructed since it is observed only at the stellar limb. When the inclination of a star approaches 90° the southern hemisphere becomes progressively more visible but for an equator-on star the Doppler Imaging solution is intrinsically non-unique and practically the artifacts due to mirroring effect prevents the mapping for stars with high inclinations.

In order to study this subject Jankov et al. (2003) conducted numerical experiments using an artificial star with a known surface structure. A test pattern for the surface of the star was constructed to reproduce the main pattern of surface maps of the distribution of Chromium (Cr) for ϵ UMa (Rice and Wehlau, 1990). The map of the surface of the star shows a ring feature about an axis of symmetry where the axis is presumed to represent the magnetic axis of the star. The relative depletion of Chromium by about three orders of magnitude in a belt around the magnetic equator has been found. Fig. 2 displays the artificial star at four rotational phases. The stellar image corresponds to the surface abundance distribution of Chromium on a star with [Cr/H] = -4 and an underabundant ([Cr/H] = -7) ring along the magnetic equator tilted by 30° to the stellar rotation equator. In this example, the artificial star has a rotation axis tilted by $i = 60°$ to the line of sight and rotates with a projected equatorial velocity $V_e \sin i$ of 35 $\mathrm{km\,s^{-1}}$. Using only the normalized flux spectra with the Gaussian noise $1/\sigma = 1000$ added, the input image (Fig. 3 left) was reconstructed (Fig. 3 right).

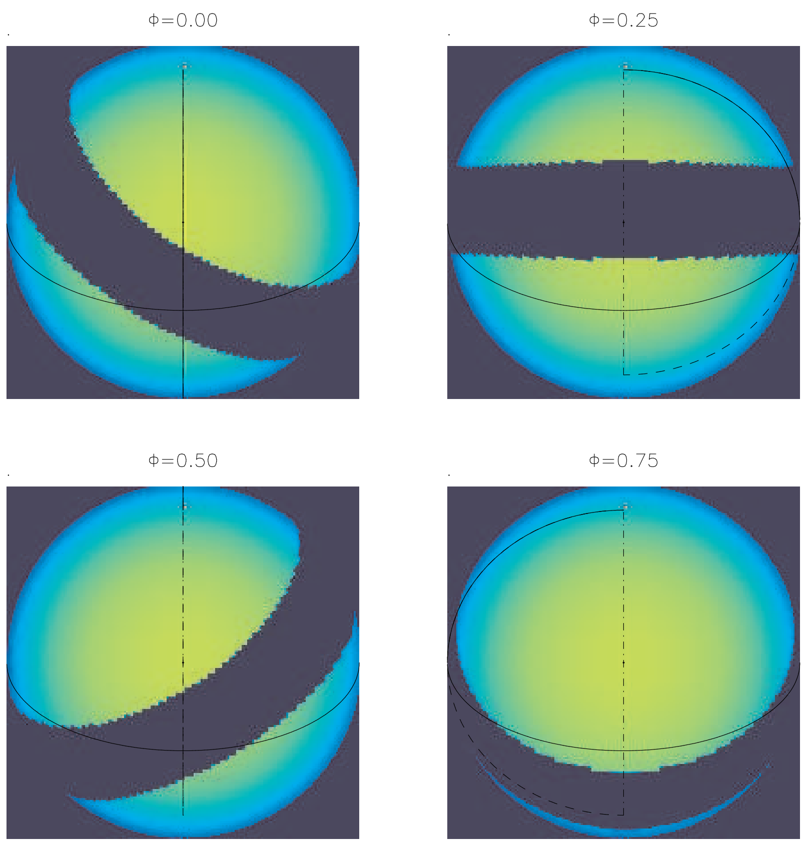

Figure 2: Spherical projections of the inhomogeneous stellar surface for a star tilted at i=60°, and Chromium abundance distribution, in the belt around the magnetic equator tilted by 30° to the stellar rotation equator. The abundance of Chromium in the belt is three order of magnitude less than the abundance in the surrounding regions as observed on the Ap star ϵ UMa (Rice and Wehlau, 1990).

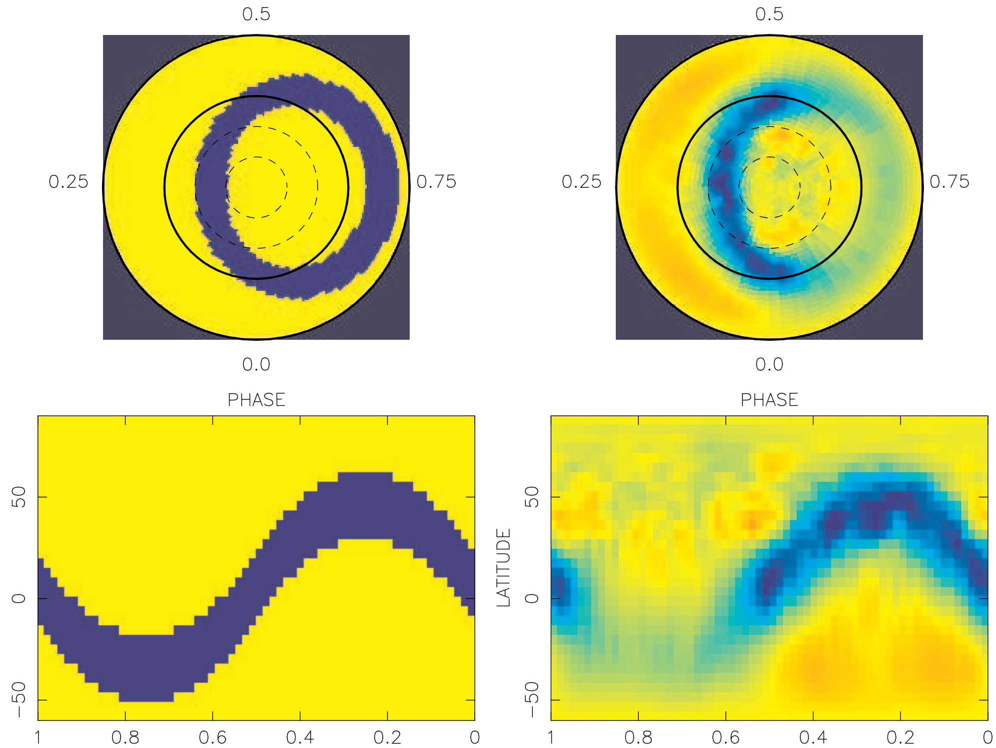

Figure 3: Pole-on (Top) and Mercator (Bottom) projections of the visible surface on a star tilted at $i = 60°$. Left: The input image of the surface temperature distribution as shown in Fig. 2. Right: Maximum Entropy reconstructions from normalized flux spectra alone (Doppler Imaging). Thirty spectra evenly spread throughout the rotational cycle were used as input, with a wavelength step corresponding to a spectral resolution of $\lambda/\Delta\lambda = 15\,000$, Gaussian noise and signal-to-noise ratio ($1/\sigma = 1000$).

This reconstruction shows the loss of contrast of features in the hemisphere bellow the stellar equator (which is the basic limitation of the Doppler Imaging technique). The reasons for this are clear: the contribution to the line profiles in such areas is significantly reduced due to foreshortening and limb darkening effects (see Fig. 2). Moreover, features are visible only briefly, so they contribute to the observed profiles for only a few rotational phases.

The degradation of restored maps is much less present in the reconstructions performed using the moments parallel to rotation in conjunction with normalized flux spectra (Fig. 4 left and right) where Gaussian noise and signal-to-noise ratios ($1/\sigma = 1000$) and ($1/\sigma = 330$) respectively were added.

The recovered maps should be compared to the original one (Fig. 3 left) as well as to the map obtained from flux spectra alone (Fig. 3 right). One can notice a significant improvement since the features in the hemisphere in which the rotational

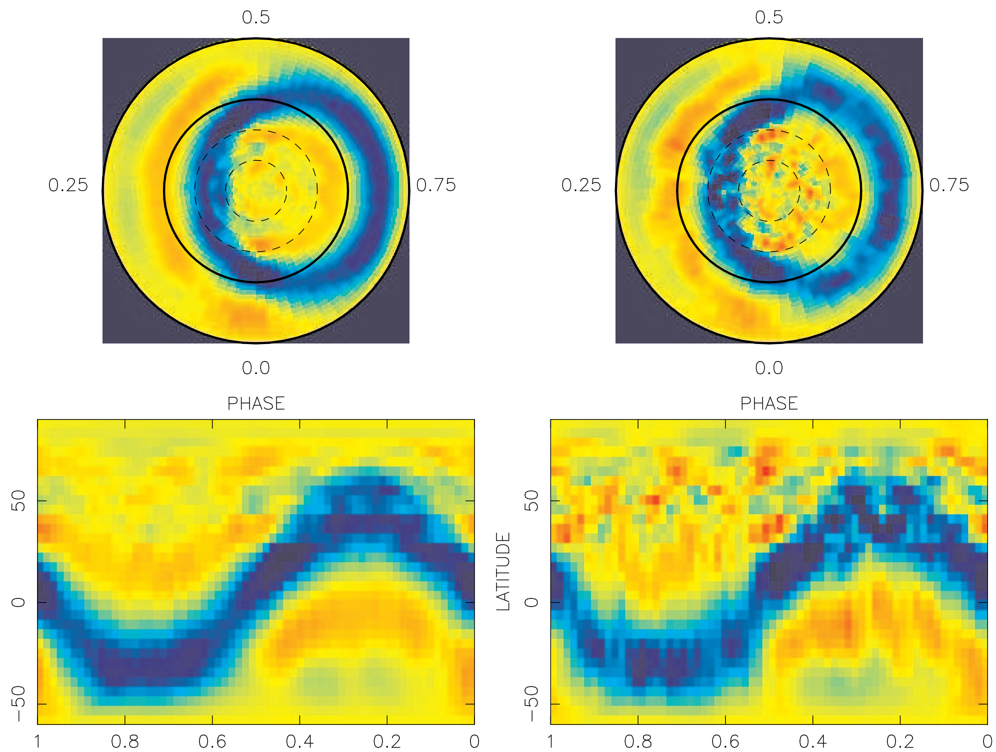

Figure 4: Pole-on (Top) and Mercator (Bottom) projections of reconstructed images from flux spectra and photocenter projection parallel to rotation. Left: Gaussian noise and signal-to-noise ratio ($1/\sigma = 1000$). Right: Signal-to-noise ratio ($1/\sigma = 330$).

pole is hidden are enhanced. When using the moments parallel to rotation, the corresponding stellar regions are reinforced by weighting with coordinate parallel to the stellar rotation axis (as can be seen in Fig. 2), and consequently reproduced in the reconstructed map.

Previous examples show clearly that the interferometric constraint introduces the crucial improvement, making the mapping of stellar surface chemical abundances much more reliable and informative than Doppler imaging alone. *Consequently, the interferometry provides a qualitatively new informations that cannot be extracted from classical spectroscopy alone.*

3. WHAT IS COMING IN THE NEAR FUTURE?

In the following years interferometers of ever increasing sophistication will be operational. Some will develop from current facilities, for example VLTI will introduce the moderate spectral resolution (up to $\lambda/\Delta\lambda = 15\,000$) with AMBER (Petrov et al., 2003) and phase-referenced imaging with PRIMA (Paresce et al., 2003). The future of optical interferometry can be foreseen to evolve in the direction of more capable arrays boasting significantly larger and more numerous telescope apertures and baselines. The CHARA and NPOI interferometers incorporated six telescopes spread over hundreds of meters, to allow imaging capabilities at milliarcsecond resolution. The VLTI and Keck Interferometer will be extended with auxiliary telescope arrays, allowing many new kinds of science to be pursued.

The Large Binocular Telescope and Interferometer (Mnt Graham, Arizona) is under construction and is in an advanced stage now. Its configuration will allow essentially complete sampling of all spatial frequencies in the image up to 22.8 meters using interferometric imaging between the two 8.4 m apertures. When combined with adaptive optics, the LBT interferometric mode will offer high signal-to-noise imaging on the faint objects, over a relatively wide field.

OHANA (Optical Hawaiian Array for Nanoradian Astronomy) project has carried out initial experiments to couple light from Mauna Kea telescopes into single mode fibers, the first step in a plan to link the existing giant telescopes with optical fiber and to create a powerful optical interferometer with a unique combination of sensitivity and angular resolution. The largest baseline of OHANA (Subaru-Gemini) has a length of 800 meters yielding resolutions of 0.25 and 0.5 milliarcseconds at 1 and 2 microns respectively, thus the sources as small as 30 microarcseconds will be partially resolved (characterized in size). For example, these are typical likely apparent dimensions of accretion disks in a variety of environments

MRO (Magdalena Ridge Observatory) project is shaping up and site (Magdalena mountains, New Mexico) work is expected to begin soon. The 2.4-meter-diameter single telescope will be completed first, followed by the interferometeric array composed of ten telescopes, each approximately 1.4 meters in diameter. The optical/infrared telescopes will be spaced by distances of up to 400 meters and, as a result of the large number of telescopes in the array, the interferometer will be able to make accurate images of complex astronomical objects in optical and infrared domains.

Concerning the near future of space interferometry we can expect, in the next 10 to 20 years, more progress in stellar physics to be possible from the ground. Darwin and TPF (Terrestrial Planet Finder) are respectively ESA and NASA projects dedicated to the search for extra-solar planets, but very probably they will also contribute to the stellar physics. The SIM (Space Interferometry Mission) is in advanced planning stages and is being designed to measure accurate positions of stars with microarcsecond resolution. It will be the first mission to attempt space interferometry, opening the new windows for astronomy. The emergence of future space interferometry facilities, which will benefit from the absence of atmospheric turbulence and much larger baselines, promise to revolutionize the impact of high resolution observations in many areas of astrophysics and particularly in stellar physics.

References

Beckers J.M.: 1982, *Optica Acta*, **29**, 361.

Buscher, D.F., Baldwin, J.E., Warner, P.J., Haniff, C.A.: 1990, *Mon. Not. R. Astron. Soc.*, **245**, 7.

Domiciano, A., Vakili, F., Jankov, S., Janot-Pacheco, E., Abe, L.: 2002, *Astron. Astrophys.*, **393**, 345.

Domiciano de Souza, A., Kervella, P., Jankov, S., Abe, L., Vakili, F., di Folco, E., Paresce, F.: 2003, *Astron. Astrophys.*, **407**, L47.

Domiciano de Souza, A., Zorec, J., Jankov, S., Vakili, F., Abe., L., Janot-Pacheco, E.: 2004, *Astron. Astrophys.*, **418**, 781.

Jankov, S., Vakili, F., Dominiciano de Souza, Jr., Janot-Pacheco, E.: 2001, *Astron. Astrophys.*, **377**, 721.

Jankov, S., Vakili, F., Domiciano de Souza Jr., A., Janot-Pacheco, E.: 2002, *Astronomical Society of Pacific Conference Series*, **259**, eds. C. Aerts, T.R. Bedding and J. Christensen-Dalsgaard, 172.

Jankov, S., Domiciano de Souza, A., Stehle, C., Vakili, F., Perraut-Rousselet, K., Chesneau, O.: 2003, Interferometry for Optical Astronomy II. Edited by Wesley A. Traub. *Proceedings of the SPIE*, **4838**, 587.

Kervella, P. et al.: 2003, Interferometry for Optical Astronomy II. Edited by Wesley A. Traub. *Proceedings of the SPIE*, **4838**, 858.

Kervella, P., Bersier, D., Mourard, D., Nardetto, N., Coudé du Foresto, V.: 2004, *Astron. Astrophys.*, **423**, 327.

Maeder, A.: 1999, *Astron. Astrophys.* **347**, 185.

Michelson, A.A. and Pease, F.G.: 1921 *Astrophys. J.*, **53**, 249.

Paresce, F., Delplancke, F., Derie, F., Glindemann, A., Richichi, A., Tarenghi, M.: 2003, Interferometry for Optical Astronomy II. Edited by Wesley A. Traub. *Proceedings of the SPIE*, Volume **4838**, 486.

Petrov, R.G.: 1988, *Diffraction-Limited Imaging with Very Large Telescopes*, eds. D.M. Alloin, J.M. Mariotti, Kluwer, 249.

Petrov, R.G., Malbet, F., Weigelt, G., Lisi, F., Puget, P., Antonelli, P., Beckmann, U., Lagarde, S., Lecoarer, E., Robbe-Dubois, S. et al.: 2003, Interferometry for Optical Astronomy II. Edited by Wesley A. Traub. *Proceedings of the SPIE*, **4838**, 924.

Quirrenbach, A., Hummel, C.A., Buscher, D.F. et al.: 1993, *Astrophys. J.*, **416**, L25.

Quirrenbach, A., Mozurkewich, D., Buscher, D.F. et al.: 1996, *Astron. Astrophys.*, **312**, 160.

Quirrenbach, A.: 2001, *Ann. Rev. Astron. Astroph.*, **39**, 353.

Rice, J.B.: 1996, In: Strassmeier K.G., Linsky J.L. (eds.) Stellar Surface Structure. *Proceedings of the IAU Symp.* **176**, Kluwer, 305.

Rice, J.B.: 1989, *Astron. Astrophys.*, **245**, 561.

Rice, J.B., Wehlau, W.H.: 1990, *Astron. Astrophys.*, **233**, 503.

Stee, P., de Araujo, F.X., Vakili, F. et al.: 1995, *Astron. Astrophys.*, **300**, 219.

Thom, C., Granes, P., Vakili, F.: 1986, *Astron. Astrophys.*, **165**, L13.

Tuthill, P.G., Haniff, C.A., Baldwin, J.E.: 1997, *Mon. Not. R. Astron. Soc.*, **285**, 529.

Vakili, F., Mourard, D., Stee, P.: 1994, *Proceedings of the IAU Symp.* **162** p. 435.

Wittkowski, M., Hummel, C.A., Johnston, K.J. et al.: 2001, *Astron. Astrophys.*, **377**, 981.

Young, J.S., Baldwin, J.E., Boysen, R.C. et al.: 2000, *Mon. Not. R. Astron. Soc.*, **315**, 635.

Zahn, J.-P.: 1992, *Astron. Astrophys.*, **265**, 115.