Fundamental stellar parameters

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Abstract: I present a discussion of fundamental stellar parameters and their observational determination in the context of interferometric measurements with current and future optical/infrared interferometric facilities. Stellar parameters and the importance of their determination for stellar physics are discussed. One of the primary uses of interferometry in the field of stellar physics is the measurement of the intensity profile across the stellar disk, both as a function of position angle and of wavelength. High-precision fundamental stellar parameters are also derived by characterizations of binary and multiple system using interferometric observations. This topic is discussed in detail elsewhere in these proceedings. Comparison of observed spectrally dispersed center-to-limb intensity variations with models of stellar atmospheres and stellar evolution may result in an improved understanding of key phenomena in stellar astrophysics such as the precise evolutionary effects on the main sequence, the evolution of metal-poor stars, stellar pulsation, mass-loss from high-mass main-sequence stars as well as from evolved stars, circumstellar environments, stellar magnetic activity, stellar rotation, and convection and turbulent mixing. Examples of already achieved results with existing interferometric facilities and anticipated improvements during the VLTI era are described. A science case for a next-generation optical/infrared interferometric facilities is presented, and the required specifications to achieve it are given. Finally, important synergy effects with external facilities in order to reach a more complete picture are discussed.

1   Introduction

High-spatial-resolution studies across the electro-magnetic spectrum directly revealing the intensity distribution, and not only the integrated flux density, of astrophysical objects are an essential tool to further our understanding in all parts of astrophysics.

For a complete description of a star, a number of parameters are important, such as mass, luminosity, radius, age, pulsation period, chemical composition, angular momentum, magnetic field, mass-loss rate, and the circumstellar environment. The observational determination of several of these parameters requires a high spectral resolution. Furthermore, while some of these parameters are integrated quantities, several of them vary across the stellar disk and its environment, leading to the need for spatially resolved observations. For example, the radius of a star is not a well-defined quantity since stars are gaseous spheres and do not have a well-defined edge. Observable is in fact the center-to-limb intensity profile across the stellar disk

and its environment. For more detailed reviews on this aspects, see for instance Scholz (1998, 2001, 2003).

Optical and infrared interferometry has already proven to be a powerful tool for stellar astrophysics, in particular by providing fundamental stellar parameters such as CLVs (i.e., the stellar radius in first order) and masses, which are compared to predictions by models of stellar evolution and stellar atmospheres.

More detailed interferometric observations with current and future facilities, coupled with a high spectral resolution, promise to lead to a new level of accuracy of measured fundamental stellar parameters, and hence to a significantly improved understanding of stellar atmospheres and stellar evolution.

In this article, I discuss fundamental stellar parameters and the importance of their measurement for stellar physics in the context of measurements with current and future interferometric facilities. In Section 2, I discuss fundamental parameters and their relation to directly observable parameters. In Sect. 3, I remind of a few examples of interferometric observations already achieved in this field. A discussion of the anticipated progress of interferometric measurements making use of the facilities in the VLTI era is provided in Sect. 4. In Sect. 5, I present a science case for a next-generation optical/infrared interferometric facility that can not already be reached with the facilities of the VLTI era. Specifications for such a facility are derived. Finally, since optical/infrared interferometry alone is not able to provide the complete set of parameters that fully describe a star and its environment, important synergies with external facilities in order to reach a more complete picture are discussed in Sect. 6.

Interferometric observations of binaries and multiple systems provide as well fundamental stellar parameters, most importantly precise stellar masses. This aspect is in detail discussed by F. Verbunt (these proceedings), and therefore mostly left out in this article.

This article is not meant as a review of the field. In particular, the mentioned theoretical models, and the presented observations are just meant as examples. Many more interesting results have been achieved. For recent reviews of the topics of interferometric techniques, including their application to fundamental stellar parameters, see for instance, Quirrenbach (2001) and Monnier (2003). For a review on "Accurate masses and radii of normal stars", see Andersen (1991). Also, various lecture notes from Michelson Summer Schools on interferometry include presentations of fundamental stellar parameters in the context of optical/infrared interferometry, for example those by John Davis, Michael Scholz, Mel Dyck, Christian Hummel (2000); John Davis, Jason Aufdenberg (2003).

2   Fundamental Stellar Parameters

2.1   Fundamental parameters in stellar physics

Models of stellar evolution and stellar atmospheres are based on a set of fundamental parameters that describe the (model) star.

First-order fundamental parameters   The mass M, the luminosity L, and the radius R are fundamental parameters of any star. In addition, the chemical composition is needed to describe a star. These quantities evolve as a function of time, where the zero-point is usually defined when the star appears first on the main sequence, i.e. the so so-called zero age main sequence (ZAMS). For comparisons of observations to theoretical models, the current age of the observed star with respect to the time grid of the model is thus an additional a priori unknown parameter.

The effective temperature $T_{\text{eff}} = L/4\pi R^2\sigma$, the surface gravity $g = GM/R^2$, and the mean density $\bar{\rho} = 3M/4\pi R^3$ are dependent parameters of the set $\{M, L, R\}$, that are sometimes used to replace one or more of the set of parameters $\{M, L, \text{ or } R\}$ for reasons of convenience and in order to use a parameter set that may be closer to directly observed quantities.

Theoretical evolutionary calculations are often shown as mass-dependent tracks or isochrones in a (theoretical) Hertzsprung-Russel diagram ($\log L - \log T_{\text{eff}}$ diagram). Mass-luminosity- ($L - M$) and mass-radius- ($M - R$) relations are also used for comparisons with observations.

Recent grids of stellar evolutionary calculations were made available, for instance, by Girardi (2000) or Yi et al. (2003). These works include figures of mass tracks and isochrones in theoretical Hertzsprung-Russel diagrams. Theoretical mass tracks are for instance used to estimate the mass of a star based on measured effective temperature and luminosity. Isochrones are for instance used to estimate the age of a globular cluster. Girardi (2000) present as well a discussion on the precise effects on the main sequence as a function of stellar metallicity. Such small effects are so far not well constrained by observations due to their insufficient precision. This is for instance a field where a next-generation optical/infrared interferometric facility could have a significant impact on evolutionary calculations.

Additional fundamental parameters   The first-order set of fundamental parameters discussed above may not be sufficient for more detailed studies of stellar physics, especially if stars in certain evolutionary stages are considered. The following parameters can be of fundamental importance for a complete description of a star as well. These parameters include the (initial) angular momentum I, the magnetic field B, the mass loss rate $\dot{M}$, the pulsation period P, and also the characteristics of the circumstellar environment.

Examples of the non-negligible effects of rotation and magnetic fields on evolutionary tracks, for instance in a $\log L - \log T_{\text{eff}}$ diagram, were recently presented by Maeder & Meynet (2003, 2004). Effects of the time-dependent mass loss rate on the evolutionary tracks, together with comparison to observations, are shown in Girardi et al. (2000).

Purpose of measured fundamental stellar parameters   A next generation optical/infrared interferometric facility can provide measurements of fundamental parameters with a precision beyond the capabilities of current facilities and of the "VLTI era". Also, a more complete set of measured fundamental parameters can then be reached. There are several purposes for which an improved knowledge of fundamental stellar parameters is required in order to improve our knowledge of stellar physics.

Complete tests of stellar evolution theory and as well as of stellar atmosphere theory require high-precision measured fundamental parameters for stars in all evolutionary stages across the HR-diagram. In particular for small stars with low apparent magnitude, there are so far not many observational constraints. For all stars, the accuracy of obtained fundamental parameters depend also on observational constraints of additional effects on the stellar surface. For instance close circumstellar matter or surface spots may easily bias measurements of stellar radii if those effects are not simultaneously probed by the observations.

Constraints of the precise effects on the main sequence, as mentioned above need very high-precision effective temperatures, luminosities, and chemical compositions. Furthermore, main sequence stars have usually small angular diameters that require long baselines for precise measurements of their radii.

Different available material tables such as opacity tables, nuclear reaction rates, etc. can be tested only with higher accuracy measurements than currently available.

The physical description of key phenomena such as convection, mass loss, turbulent mixing, rotation, magnetic activity, can be significantly improved with more detailed interferometric measurements than currently available .

2.2   Relation of fundamental parameters to observables

Many of the (theoretical) parameters mentioned above, which are important quantities for theoretical calculations, can not easily be measured directly as such, but are deferred from measurements of other observational quantities.

Moreover, some of the (theoretically defined) parameters mentioned above are not well-defined parameters when additional effects for observed stars are considered. The radius R, for instance, is not well defined for observations. Stars are gaseous spheres, and do not have a well-defined "edge". Observable is the center-to-limb intensity variation (CLV) across the stellar disk (and its circumstellar environment), which depends on the star's atmospheric structure (for detailed reviews on this aspect, see e.g., Scholz 1999, 2001, 2003). The CLV is a measure of the vertical temperature profile of the stellar atmosphere. It may be superimposed by horizontal surface inhomogeneities. Also, quantities such as magnetic fields and chemical composition may not be constant, but may vary across the surface of the star. It is, thus, much more accurate to compare observed and model-predicted CLVs rather than just radii.

The mass M and luminosity L are well-defined integrated physical parameters. Since these are integrated quantities, their measurement does not necessarily require a very high angular resolution. A spatial resolution below the order of the angular size of the stellar disk is usually sufficient.

Mass M   Binary stars are the main source of measurements of high-precision masses. One can distinguish between double-lined astrometric-spectroscopic binaries (measurement of the radial velocities of both components and of the relative orbit), absolute astrometry (measurement of the absolute orbits for both stars), and single-lined spectroscopic binaries (measurement of the radial velocity of one component) together with a measurement of the relative orbit and the distance. Interferometry can surely improve high-precision mass estimates by measurements of high-accuracy astrometric orbits. The topic of binary and multiple systems is in detail presented by F. Verbunt (these proceedings), it will not be covered further in this article.

In addition, the surface gravity and effective temperature can indirectly be measured by means of spectroscopic observations. Coupling interferometric and spectroscopic techniques, these quantities can be derived with higher precision by comparing observed and model-predicted CLVs in the continuum and certain (narrow) lines. This approach makes use of the effect of stellar mass and (surface) temperature on the atmospheric structure. Together with a measurement of the stellar radius (from measured angular diameter and distance), the surface gravity gives the stellar mass. This mass estimate is, thus, not a direct measurement. However, this is a very interesting check of the consistency of observations with stellar evolution theory and stellar atmosphere theory.

Luminosity L   The luminosity can be derived from observations of the apparent bolometric flux and a distance estimate, such as the Hipparcos parallax. Accuracies of luminosities are currently often limited by the accuracies of the distances.

For improved observations of this parameter, higher accuracy distances (parallaxes) are required, as well as a high-precision bolometric photometry. For variable stars, the bolometric flux has to be obtained at the same time as other parameters such as the radius. This is, for

instance, an important aspect where carefully planned synergies with external facilities may be highly valuable.

Radius R The radius is often measured by means of optical interferometry. As mentioned above, the radius is not a well defined quantity. The direct observable is the CLV, which may be described by a parametrization. One resolution element across the stellar disk allows us usually to constrain only one parameter. In other words, one resolution element gives usually only the angular diameter for a a-priori adopted CLV model. Two resolution elements, usually including measurements of the visibility function in the second lobe, result in an estimate of the angular diameter and one additional parameter that described the shape of the CLV. Different radius definitions as for instance the Rosseland mean diameter, the continuum diameter, or an equivalent UD diameter do not necessarily coincide. Often, uniform disk angular diameters in a particular bandpass are measured and transformed into Rosseland mean diameters or continuum diameters using atmosphere models. For compact atmospheres, for instance for regular main sequence stars, different radius definitions may agree within the precision of current observations. For extended atmospheres, for instance for giant stars, these radii differ already within the precision of current observations (see, for instance, Wittkowski et al. (2001, 2003); or the reviews by Scholz (1999, 2001, 2003). CLV measurements at various narrow wavelength intervals will give the best characterization of the stellar radius by comparison with model-predicted CLVs. With improved observational accuracy, this approach may even result in a direct determination of the vertical and horizontal temperature profile. The observations by Perrin et al. (2004) demonstrate the importance of radius observations in narrow wavelength bands.

Chemical composition   At the given evolutionary stage of an observed star, the chemical composition on its surface is observable, for instance by using high-spectral-resolution observations. However, if one wants to measure abundance surface inhomogeneities, which may for instance be caused by magnetic fields, the chemical composition needs to be determined for several resolution elements across the stellar disk. In this respect, one future objective might be to discriminate stellar tracks with different initial chemical composition, and another to probe abundance inhomogeneities across the stellar surface.

Age   The age of a star is extremely difficult to be measured directly. It is usually obtained by comparing stellar evolutionary tracks with observational estimates of mass, luminosity, and radius. A test of the time dependence of evolutionary tracks would require an independent age determination. One approach to reach this is to identify stars with identical age, such as binary and multiple systems. An absolute age determination of a globular cluster was recently obtained by observations of Berillium spectral lines by Pasquini et al. (2004).

Angular momentum   For rotating stars, the (initial) angular momentum is an important fundamental parameter for the stellar model. Observable is the surface rotational velocity at the evolutionary stage of the observed star, by means of spectroscopic observations. Again, spatially resolved observations are needed to constrain the rotational parameters in more detail.

Magnetic fields   The magnetic field at the surface can be measured by observations of line splittings. The field strength may vary across the disk, again requiring a coupling of high spatial and high spectral resolution.

Mass-loss rate The mass-loss rate can for instance be derived from outflow velocities.

Pulsation period The pulsation period is an important parameter for variable stars, such as Cepheid or Mira variables. The variability of the luminosity, derived from monitoring of the bolometric flux, and the variability of the radius may differ in phase and even period. Different radius definitions, such as continuum and Rosseland-mean radius can as well lead to different observed phases and periods. See, for instance, the recent model studies by Ireland et al. (2004a,b). Luminosity-period relationships (of Cepheids) are of essential importance as distance indicator.

2.3 Required Precision

Referring to Andersen (1991), the precision needed for constraining theoretical models varies for the different parameters. For the mass and the radius an accuracy of 1% to 2% is currently required, whereas for the luminosity a precision of 5%-10% is sufficient. Higher accuracies are currently not needed since other effects would then limit the computations, such as effects of the metallicity. However, as our understanding of these limiting factors increases, a more sophisticated analysis of these stellar parameters becomes necessary again. Thus, it seems worth to carry out specific model investigations in parallel to the planning of a next generation interferometric facility in order to investigate the precision of the various parameters that will then be needed.

2.4 Specifications I

Resulting from this Section, a number of specifications for a next generation interferometric facility can already be summarized.

- Radius measurements, i.e. measurements of the CLV and comparison with model-predicted CLVs with sufficient accuracy require at least 2–3 resolution elements across the stellar disk.

- CLV observations in narrow spectral bands (spectral resolution larger than 100 000) are needed to constrain spatially resolved metallicity and magnetic fields.

- In order to distinguish the CLV caused by the vertical temperature profile and additional horizontal surface inhomogeneities, an even higher number of resolution elements (5–10) may be necessary. The aspect of imaging of stellar surfaces is discussed in detail by von der Lühe (these proceedings). Measurements of phases are essential to constrain asymmetric intensity profiles.

- For a complete understanding of stellar physics, high-precision measurements of various stars across the Hertzsprung-Russell diagram are needed, including stars with small angular diameters and low luminosity. The next generation interferometer should provide baselines and collecting areas that allow us to perform such observations.

- In addition to interferometric measurements, additional observational information is needed, such as high-precision distances and bolometric fluxes. Carefully planned synergies with other facilities may be very interesting in order to reach this.

3   Examples of interferometric results in stellar physics

A few examples of interferometric observations in the field of stellar physics are discussed below, in order to illustrate the capabilities of current interferometric facilities. Note that this discussion is not intended to have the character of a review. Many more exciting results have been obtained, see for instance the reviews by Quirrenbach (2001) and Monnier (2003), as well as the regularly updated newsletter OLBIN (olbin.jpl.nasa.gov), edited by Peter Lawson.

Fundamental parameters of very low mass stars   Low mass stars are characterized by a low effective temperatures and high surface gravities. Because of the rather small angular sizes, these objects are difficult for interferometric observations. However, first measurements of diameters of M dwarfs succeeded already (Lane et al. 2001, Segransan et al. 2003). These observations provide an empirical mass-radius relation, which is compared to theoretical stellar evolution calculation. These observations provide also observational constraints for atmosphere models.

Effects of stellar rotation   Interferometric measurements can also derive asymmetric shapes of stellar surfaces if baselines of different orientation are used. Van Belle (2001) presented recently the detection of an oblate photosphere of a fast rotator, the main sequence star Altair. Domiciano de Souza et al. (2003) reported on VLTI measurements of the asymmetric shape of the rotating Be star Achernar, and found that it is much flatter than theoretically expected.

Intensity profiles and limb-darkening   Optical/infrared interferometry has proved its capability to reach beyond the measurement of diameters, and to measure additional surface structure parameters. Through the direct measurement of stellar limb-darkening, interferometry tests the wavelength-dependent intensity profile across the stellar disk. However, the required direct measurements of stellar intensity profiles are among the most challenging programs in current optical interferometry. Since more than one resolution element across the stellar disk is needed to determine surface structure parameters beyond diameters, the long baselines needed to obtain this resolution also produce very low visibility amplitudes corresponding to vanishing fringe contrasts. Consequently, direct interferometric limb-darkening observations of stars with compact atmospheres, i.e. visibility measurements in the 2nd lobe, have so far been limited to a small number of stars (including Hanbury Brown et al. 1974; Di Benedetto & Foy 1986; Quirrenbach et al. 1996; Burns et al. 1997; Hajian et al. 1998; Wittkowski et al. 2001, 2004). For stars with extended atmospheres, described by for instance Gaussian-type or two-component-type CLVs, measurements of high to medium spatial frequencies of the 1st lobe of the visibility function may lead to CLV constraints as well (see, e.g. Haniff et al. 1995; Perrin et al. 1999; Woodruff et al. 2004; Fedele et al. 2005).

Fig. 1 shows an example of limb-darkening observations of the cool giant γ Sge obtained with the NPOI (Wittkowski et al. 2001). These observations include squared visibility amplitudes, triple products, and closure phases for 10 spectral channels. They succeeded not only in directly detecting the limb-darkening effect, but also in constraining ATLAS 9 model atmosphere parameters.

Fig. 2 shows an example of a limb-darkening observation of the cool giant ψ Phe, obtained with the VLTI (Wittkowski et al. 2004). These observations were compared to PHOENIX and ATLAS model atmospheres, which were also created by comparison to stellar spectra (right panel of the Fig.). Fig. 3 shows for illustration the monochromatic and filter-averaged CLV of the
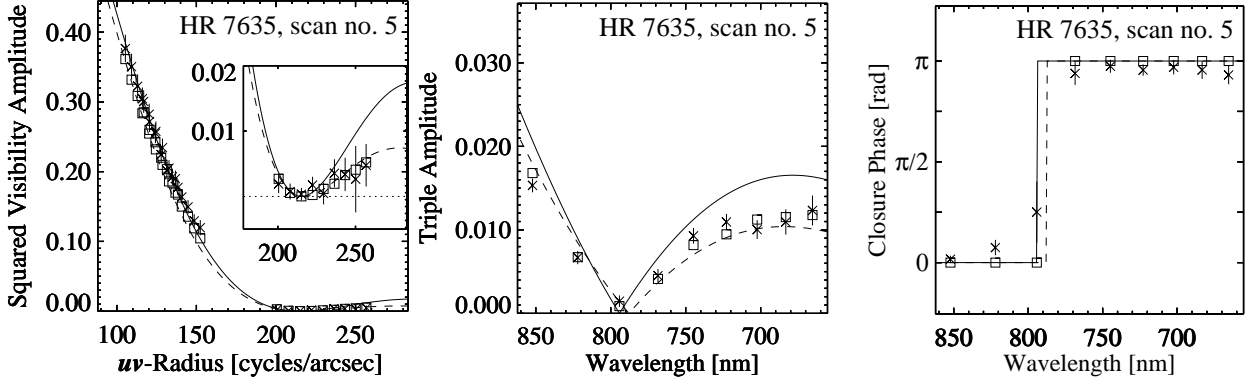
Figure 1: NPOI limb-darkening observations of the cool giant γ Sge (Wittkowski et al. 2001).
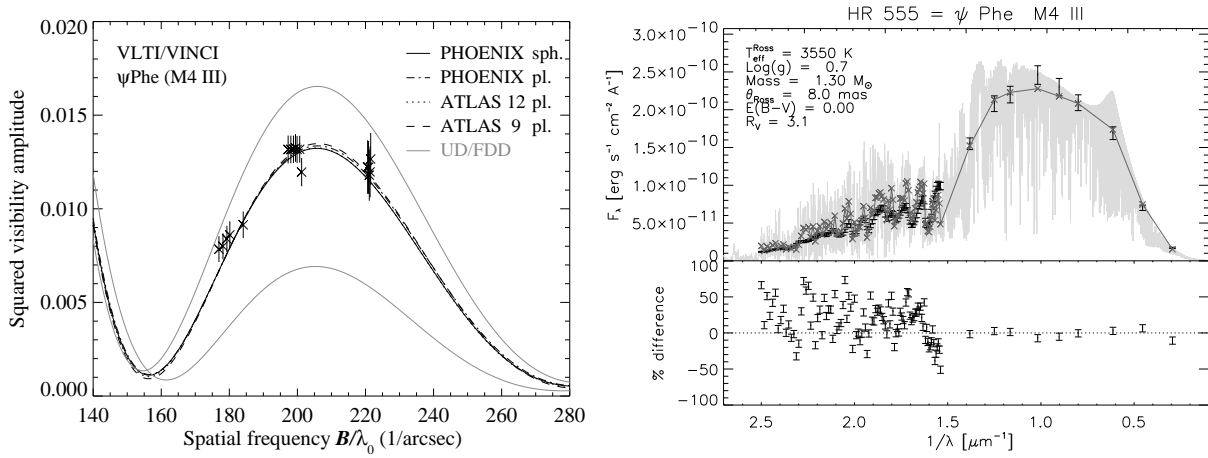

Figure 2: VLTI limb-darkening observations of the M4 giant ψ Phe (Wittkowski et al. 2004).

well fitting PHOENIX model atmosphere. These limb-darkening observations also result in a very precise and accurate radius estimate because of the precise description of the CLV.

For cool pulsating Mira stars, the CLVs are expected to be more complex, which can be described as maybe Gaussian-shaped and more-component CLVs, and to be highly variable as a function of stellar variability phase. Fig. 4 shows model predictions for Mira star CLVs at four different variability phases from the hydrodynamic model atmospheres by Hofmann et al. (1998), Tej et al. (2001), Ireland et al. (2004a,b). The model files are from Scholz & Wood (2004, private communication). These complex shapes of the CLV make it even more difficult to define an appropriate stellar radius. Fig. 4 shows as well the location of different radius definitions, the Rosseland mean radius, the continuum radius, and the radius at which the filter-averaged intensity drops by 50%. For complex CLVs at certain variability phases these definitions can result in differences of up to about 20%. Fig. 5 shows VLTI observations of the Mira star R Leo compared to the dynamic model atmospheres described above (Fedele et al. 2005). The direct comparison of measured intensity *profiles* with the model CLVs allow us to clearly relate certain points of the model CLVs to observable angular scales. With other words, a well-defined measurement of angular stellar sizes, and hence tests of model atmospheres and model evolutionary calculations, becomes possible when observed CLVs are compared to model-predicted CLVs, despite the general uncertainty of radius definitions. This, however, requires
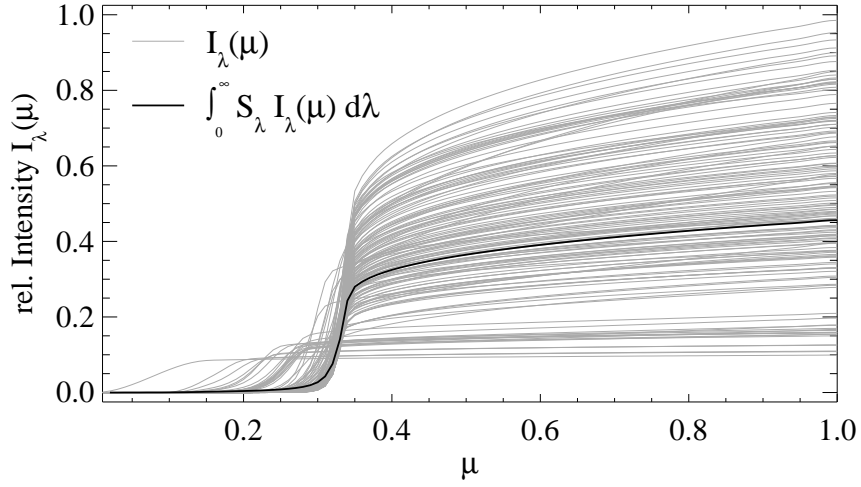
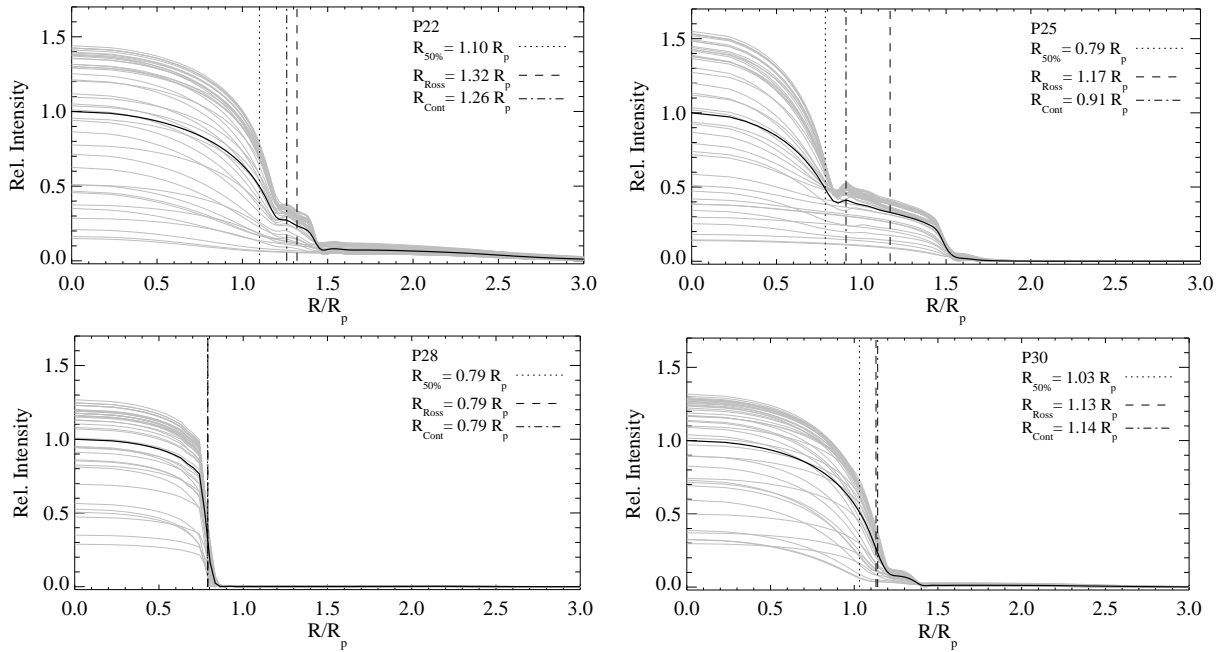Figure 3: Monochromatic and filter-averaged model CLV for the M4 giant ψ Phe (Wittkowski et al. 2004).

Figure 4: Monochromatic and filter-averaged model CLVs of Mira stars as a function of stellar phase, predicted by dynamic model atmospheres (P series) described in Hofmann et al. (1998), Tej et al. (2001), Ireland et al. (2004a,b). The model files used are from Scholz & Wood (2004, private communication).
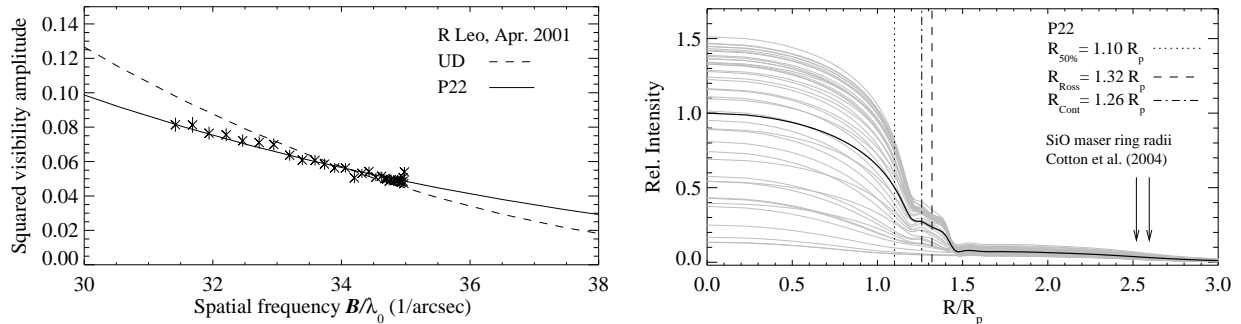
Figure 5: VLTI/VINCI observations of the intensity profile of the Mira variable R Leo and comparison to dynamic model atmosphere predictions (P series) by Hofmann et al. (1998), Tej et al. (2001), Ireland et al. (2004a,b). The left panel shows a comparison of the visibility values to a well-fitting model (P22), and the right panel shows the CLV prediction by this model atmosphere. Also shown are the mean positions of the SiO maser shells observed by Cotton et al. (2004). From Fedele et al. (2005).

usually several resolution elements across the stellar disk.

4   The VLTI era

The completed VLTI will provide the astronomical community with additional observational capabilities which are not yet available. Furthermore, other interferometric facilities will as well reach an increased level of observational possibilities during the same period of time. With increased observational capabilities, also the state-of-the-art of astrophysical interpretation will improve during the next years. The expected instrumental level during the "VLTI era" includes

- Baselines between 8 m to 200 m for the VLTI, and maybe up to the order of 1 km with other facilities during this era.

- A maximum collecting area corresponding to 8–10 m telescopes.

- A wavelength coverage from about 1μm to 10–20μm for the VLTI, and optical wavelengths with other facilities during this era.

- Three-way beam combination with first-generation instrumentation, up to 6–8-way beam combination with second generation (VLTI).

- A dual feed phase referencing system (PRIMA at VLTI).

5   The science case

A strong general science case to justify the construction of a next generation interferometric facility is presented below. This science case is based on the discussion in Sect. 2. It is challenging, and clearly reaches beyond the observational capabilities of the VLTI era as outlined in Sect. 3. However, it appears realistic for the next generation facility. The presentation of the general approach is followed by more specialized limiting cases that better allows us to specify the characteristics needed for the next generation interferometric facility, which are listed at the end of this section.

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5.1 Discussion of the general science case for the next generation optical/infrared interferometric facility

Based on the discussion in Sect. 2, it appears essential for the furthering of our understanding of stellar astrophysics that the complete set of fundamental stellar parameters is measured with a high precision for all types of stars across the Hertzsprung Russel diagram. Interferometric techniques have already proven their ability to derive high-precision fundamental stellar parameters, as outlined in Sect. 3. These parameters measured so far mostly include the first orders of intensity profiles or CLVs, i.e. precise radii, the strength of the limb-darkening effect, and asymmetric shapes of stellar surfaces. These measurements are already augmented with additional observational information and compared to theoretical models of stellar atmospheres and stellar evolution at a level that challenges or confirms theory. However, these measurements are so far mostly limited to the apparently largest and brightest stars, and do not provide a good sample of the whole Hertzsprung-Russel diagram, i.e. of the complete evolutionary tracks. Also, as discussed in Sect. 2, not only the basic set of fundamental parameters $\{M, L, R\}$ are of fundamental importance for stars in certain evolutionary phases. Also parameters such as I, B, $\dot{M}$ may be essential (see Sect. 2), and could be characterized (spatially resolved) with the new facility.

The science case for the next generation optical/infrared interferometric facility can thus be summarized as follows:

"High accuracy measurements of the full set of fundamental parameters of stars in all evolutionary stages across the Hertzsprung-Russel diagram."

Within this general framework, the following topics may be of particular importance for stellar astrophysics.

- Observational constraints of the precise effects on the main sequence.

- A detailed analysis of metal-poor stars and their evolution.

- A characterization of low-mass stars.

- An improved description of high-mass stars, in particular concerning their mass-loss on the main sequence.

- A better understanding of the mass-loss process from evolved stars, including characteristics of the circumstellar environment and the formation of asymmetric envelopes (see also Sect. 6).

- Measurements of magnetically active stars including surface features.

- Investigations of the effects of stellar rotation on stellar evolution and stellar atmospheres.

- An improved description of convection and turbulent mixing.

Observational constraints related to these topics require high-precision interferometric measurements of stars, including stars with small angular diameters and low apparent brightness. They require as well the coupling of interferometric techniques with high spectral resolution. In order to estimate the specifications for the interferometric facility needed, we consider below some limiting cases.

5.2 Limiting cases

The general science case presented above includes the measurement of many different stars at all evolutionary phases. The different aspects discussed imply different specifications for the next-generation interferometric facility.

The limiting case with respect to baseline length and collecting area may be the case of a very low mass star at the bottom of the main sequence.

According to recent evolutionary calculations (Chabrier et al. 2000), a star at the limit to a brown dwarf (mass $0.08\,\mathrm{M_\odot}$) with a typical age of $5\,\mathrm{Gyr}$ has a radius of $0.1\,\mathrm{R_\odot}$, and a luminosity of $\log L = $ -3.6 $\mathrm{L_\odot}$. The absolute magnitudes are $M_V \sim 19$, $M_K \sim 11$, and $M_M \sim 10$. For a close star at a distance of $10\,\mathrm{pc}$, this corresponds to an angular diameter of $0.1\,\mathrm{mas}$. For visibility measurements down to 1% (without the use of bootstrapping), the limiting magnitudes for this star correspond to $m_V \sim 24$, $m_K \sim 16$, and $M_m \sim 15$. The need to sample the CLV with at least 3–5 resolution elements (see above) at a typical wavelength of $1\,\mu\mathrm{m}$ implies a maximum baseline of 6–10 km.

The shortest baseline needed and the required field of view is maybe determined by apparently large evolved stars including their circumstellar envelope. In order to simultaneously characterize the stellar surface and the circumstellar environment, scales up to $1000\,\mathrm{R_\odot}$, corresponding at $10\,\mathrm{pc}$ to $\sim 1\,\mathrm{arcsec}$ should ideally be sampled. However, such studies may also be reached by combination of interferometry with high spatial resolution observations at single telescopes.

The required spectral resolution is determined by the need to characterize magnetic field strengths and abundance ratios for several resolution elements across the stellar disk. The spectral resolution should at least reach up to the values currently reached with single-telescope instruments, i.e. about 100 000.

5.3 Specifications and requirements for future interferometers

Based on the science case presented above, and taking into account the general aspects discussed in Sect. 2 (in particular the specifications in Sect. 2.4), the specifications and requirements for our next-generation optical/infrared interferometric facility can be given as follows.

Sensitivity: The sensitivity is set by low-mass stars at the bottom of the main sequence to $m_V \sim 24$, $m_K \sim 16$, and $m_M \sim 15$ for a star at $10\,\mathrm{pc}$ distance and visibility values down to 1%.

Observing mode: The requirement for high-precision estimates of the transfer function in order to measure high-precision fundamental stellar parameters would benefit from the use of multi fields, one on the scientific star, and one on the calibrator.

Spatial resolution: The longest baselines are determined by observations with 3–5 resolution elements on a $0.1\,\mathrm{mas}$ star, corresponding to a maximum baseline of 6–10 km at a typical wavelength of $1\,\mu\mathrm{m}$. Required are a minimum coverage of 1–2 radial points per resolution element, i.e. 3–10 uv radii up to the longest baseline. The azimuth angle should be sufficiently covered as well by 2–3 samples (plus the use of earth rotation). This results in 6–30 stations. In order to use them for stars of different angular diameter, they should ideally be re-locatable from shortest scales of up to $100\,\mathrm{m}$ to largest scales of up to $10\,\mathrm{km}$.

Wavelength range: The comparison to model atmospheres in order to derive high-precision CLV measurements, and thus accurate radii determinations, implies the need for a broad wavelength coverage from the optical to the infrared, i.e. about $0.4\,\mu$m to $10\,\mu$m.

Spectral resolution and polarimetric capability: The measurement of several of the fundamental parameters such as surface gravity, metallicity requires a high spectral resolution of $> 100\,000$.

Field of view: The field of view would ideally include the circumstellar environment. This would imply a value of about 1 arcsec.

Astrometric precision A high astrometric precision is required for determinations of astrometric orbits of binary and multiple systems, which could greatly improve mass estimates (see the presentation by F. Verbunt, these proceedings). Also, the correlation of the astrometric position of the stellar surface with respect to additional observational information of the circumstellar environment, as probed for instance by radio interferometry (see Sect. 6), would be of great value. A precision of a fraction of the stellar angular diameter would be needed, i.e. up to the order of 10-100 μarcsec.

6 Synergy effects with external projects

Interferometric observations with specifications outlined in Sect. 5 alone will be able to provide important measurements of fundamental stellar parameters, and will enlarge our view of stellar physics. However, the observational determination of the complete set of fundamental stellar parameters discussed in Sect. 2 will require additional observational information. As a result, carefully planned synergies with other instrumentation projects appear valuable. A few options are outlined in the following.

6.1 Bolometric fluxes

The primary measurement of effective temperatures of stars obtaine by combination of measured angular diameters and bolometric fluxes. Hence, it would be valuable to combine the next generation interferometric facility with a facility that allows us to obtain high-precision bolometric fluxes of the same sources, and ideally at the same time. The latter is particularly important for variable stars. Also, the measurement of high-precision lightcurves of variable stars which are targets of the interferometer would be valuable. A carefully planned synergy with such a facility appears important, so that the bolometric fluxes of the same sources can easily be obtained. Currently, measured effective temperatures are often limited by the measurement of the flux rather than by the measurement of the angular diameter, in spite of the fact that the former is in principle easier to obtain.

6.2 Distances/parallaxes

For comparison with theoretical stellar models, absolute stellar radii are needed rather than angular radii. Hence, the knowledge of precise distances is required, in particular when higher precision angular diameters are obtained. Often, these distances are currently not available with the required precision. Synergies with projects such as GAIA or SIM appear interesting.
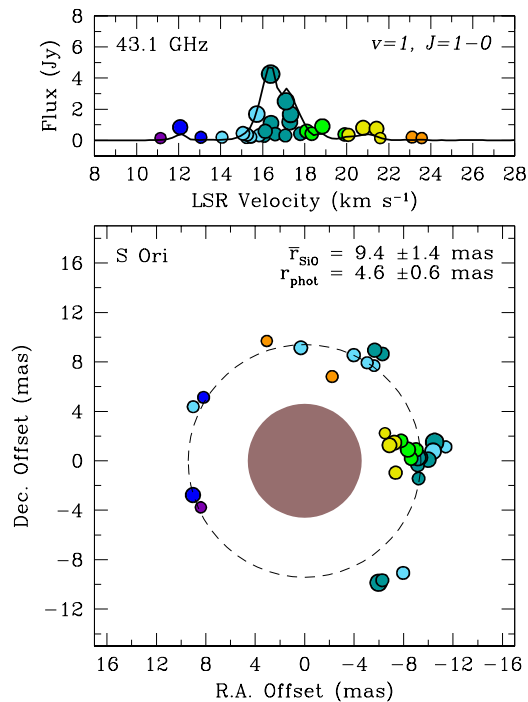
Figure 6: VLBA observation of the 43.1 GHz maser emission toward S Ori (color-coded in bins of radial velocity) concurrent with VLTI observations of the stellar photosphere at near-infrared wavelengths (represented by the disk in the center of the distribution). From Boboltz & Wittkowski (2005).

6.3 VLBA and ALMA

Investigations of the mass-loss and the circumstellar environment of evolved stars benefit from synergies of optical/infrared interferometry and radio interferometry. These different techniques at different wavelengths probe different regions of the star itself and its circumstellar environment, and thus provide us with a more complete picture of the stellar parameters, and in particular of the mass-loss process. For instance, infrared observations of the stellar photosphere or circumstellar dust have already been compared to radio observations of circumstellar masers and vice versa (e.g., Danchi 1994; Greenhill et al. 1995; Cotton et al. 2004; Monnier et al. 2004; Boboltz & Wittkowski 2005). Such approaches are still rare, and furthermore some of these studies suffer from combinations of observations of variable stars widely spaced in time, thus limiting the accuracy of the comparison. Boboltz & Wittkowski (2005) conducted concurrent observations of the Mira variable S Ori as part of a program designed to use the power of long baseline interferometry at infrared and radio wavelengths to study the photospheres and nearby circumstellar envelopes of evolved stars. Figure 6 shows the results of the first ever coordinated observations between NRAO's VLBA (Very Long Baseline Array) and ESO's VLTI (Very Large Telescope Interferometer) facilities. The VLBA was used to observe the 43-GHz SiO maser emission (represented by the circles color-coded in bins of radial velocity) concurrent with VLTI observations of the stellar photosphere at near-infrared wavelengths (represented by the red disk in the center of the distribution). The SiO masers were found to lie at a distance of roughly 1.7 stellar radii or 1.5 AU. With concurrent observations such as these can parameters of the circumstellar gas, as traced by the SiO masers, be related to the star itself at a particular
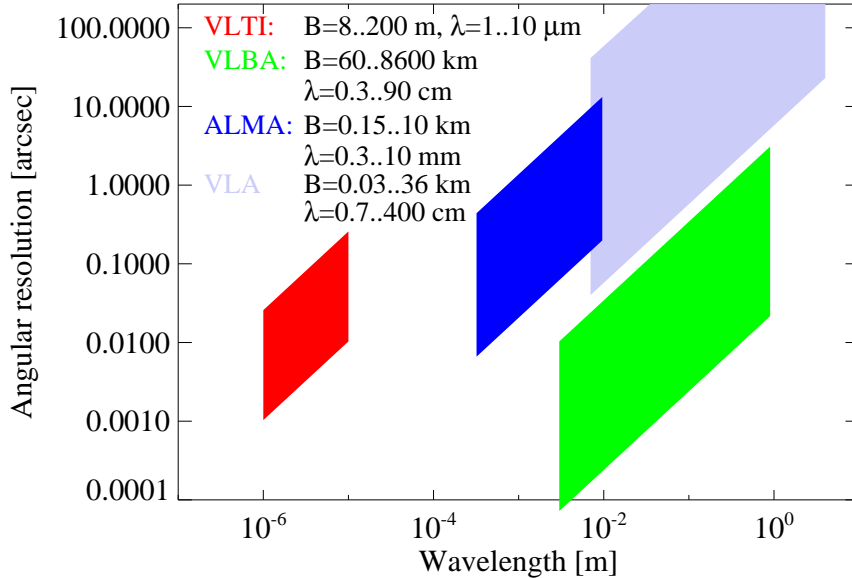
Figure 7: Comparison of resolution and wavelength ranges of the infrared, millimeter, and radio interferometric facilities VLTI, ALMA, VLBA, and VLA. Radio interferometry with the VLBA reaches currently an angular resolution which is about a factor of 10 above that of the VLTI. Transcontinental radio VLBI reaches even better angular resolutions. ALMA is restricted to lower angular resolution, but also typically probes cool dust, that is usually distributed at larger scales. Coordinated interferometric observations at infrared and radio wavelengths, using for instance the VLTI and the VLBA (Boboltz & Wittkowski 2005) in the field of stellar surfaces and circumstellar environment, have already started. More detailed multi-wavelength studies, also including mm interferometry with ALMA, are upcoming. A next-generation optical interferometric facility with baselines of 1-10 km would clearly enhance the possibilities of such approaches in stellar astrophysics. The maximum angular resolution would be comparable to that of current radio interferometry, and also the image fidelity could better match that of the 10-station VLBA or even the 64-station ALMA.

phase in its pulsation cycle. Such measurements can be used to constrain models of stellar pulsation, envelope chemistry, maser generation, and stellar evolution.

Synergies of a next-generation optical/infrared interferometer with VLBA appear interesting as well. Current VLTI observations can not match the maximum angular resolution of radio long-baseline interferometry. Fig. 7 shows a comparison of VLTI, ALMA, VLBA, and VLA in terms of wavelengths and angular resolution. Radio interferometry with the VLBA reaches currently an angular resolution which is about a factor of 10 above that of the VLTI. Transcontinental radio VLBI reaches even better angular resolutions. A next-generation optical/infrared interferometer could reach the maximum angular resolution currently provided by the VLBA, and thus allow us to compare VLBA and infrared interferometric results in more detail. Also, the image fidelity that is currently provided by the 10-station VLBA will not easily be reached by VLTI, but can be reached with the next generation optical/infrared interferometer.

Similar synergies with ALMA, the upcoming millimeter interferometer, are interesting as well. ALMA is restricted to lower angular resolution, but also typically probes cool dust, that is usually distributed at larger scales.

Synergies of infrared and radio interferometry may not only be interesting for evolved stars as outlined above, but also for other aspects of stellar physics, such as star formation.

6.4 Coordination with theoretical efforts

Finally, it seems appealing to coordinate observational and theoretical efforts in the field of stellar astrophysics in a more coordinated and closer way. With increasing observational capabilities and improved measurements of fundamental stellar parameters, also their interpretation and their comparison to model prediction will need to become more extensive and more sophisticated. Furthermore, the planning of observations will benefit more and more from simulations using theoretical models. Model studies to investigate the observational precisions needed and identifying the most interesting measurements in terms of, for instance, targets and wavelength ranges, can ideally be conducted already in parallel to the planning of a next-generation observational facility.

Acknowledgements

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