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REVIEW AND LATEST NEWS FROM THE VEGA/CHARA FACILITY

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Abstract.
The VEGA instrument located at the focus of the Center for High Angular Resolution Astronomy (CHARA) array in California is a collaborating project between the Lagrange laboratory in Nice, where it has been developed (Mourard et al. 2009, 2011), the IPAG (Grenoble) and CRAL (Lyon) laboratories, and the CHARA group at Mount Wilson Observatory*. The outcome from this international collaboration is to provide to the community a visible spectro-interferometer with an unprecedented angular resolution of 0.3 milli-second of arc (mas) together with a spectral resolution of 5000 or 30000. With such an instrument it becomes possible to determine simultaneously the size and the kinematic of the photosphere and/or of the circumstellar environment of the star as a function of the wavelength, which basically means for each spectral channel in the continuum and/or within spectral lines (in Hα for instance). The only limitation is to get enough signal to noise ratio in each spectral channel. We can currently reach a limiting magnitude of 8 in visible in medium spectral resolution (5000) and 4.5 in high resolution (30000). In this proceeding, we illustrate the two main subjects studied with the VEGA instrument, namely (1) how angular diameters are useful to accurately derive the fundamental parameters of stars, (2) how the spectral resolution can allow to study the kinematical structure of stars or even to derive chromatic images of stellar objects.

Keywords: instrumentation: high angular resolution instrumentation: interferometers

1 The VEGA instrument on CHARA interferometer

After the pioneering work at visible wavelengths on the GI2T interferometer (Mourard et al. 1994), a team led by D. Mourard decided, in 2005, to install the VEGA instrument on the Center for High Angular Resolution Astronomy (CHARA) array in California (ten Brummelaar et al. 2005) and the first light was obtained at fall 2007. CHARA consists of six one meter telescopes placed in pairs along the arms of a Y-shaped array. It yields 15 baselines ranging from 34m to 331m. Since summer 2009, the VEGA/CHARA instrument is routinely operating for almost 60 nights per year, with an increasing fraction done remotely from Nice observatory. The instrument is labeled as a French national observing service (SO2) since 2013 and is opened to the community through a collaboration with the VEGA team. We published in December 2009 (Mourard et al. 2009) the principle of this instrument as well as its measured performance and we also demonstrated the performance of the simultaneous combination of 3 and 4 telescopes (Mourard et al. 2011). More recently, we describe in Ligi et al. (2013) the different steps from the raw data to the final products, and how the Virtual Observatory principles have been implemented to allow an interoperability between several softwares developed by the Jean-Marie Mariotti Center (`http://www.jmmc.fr/`).

VEGA addresses today two main classes of scientific programs: fundamental stellar parameters thanks to the unique angular resolution given by the short wavelengths and the long baselines of CHARA (Sect. 1), and morphological and kinematical studies in circumstellar environments thanks to the unique spectral resolution we achieved (Sect. 2).

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*The instrument is opened to the community throughout a collaboration with the VEGA and CHARA teams, and all information about the instrument can be found here: `http://www-n.oca.eu/vega/en/publications/index.htm`.

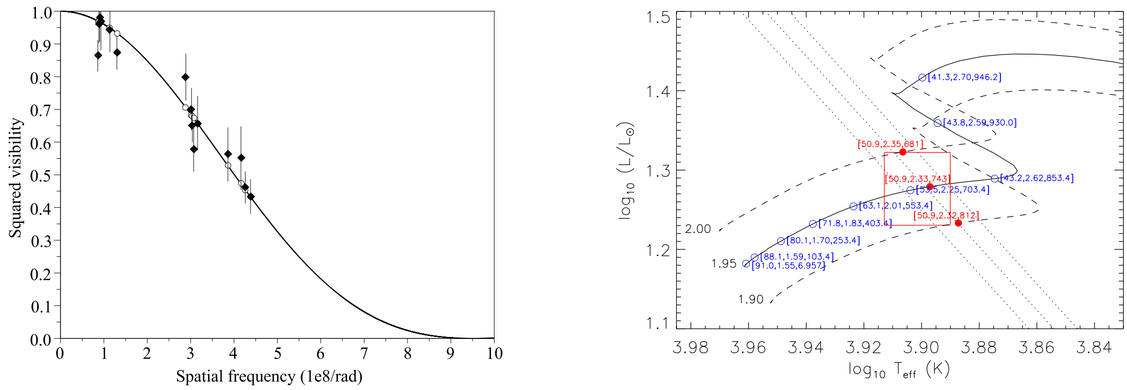

Fig. 1. Left. Squared visibility versus spatial frequency for 10 Aql obtained with the VEGA observations (diamonds). The solid line and the open circles represent the uniform-disk best model provided by LITpro model fitting tool (Tallon-Bosc et al. 2008). After a conversion, we obtain a very small and precise limb-darkened angular of $\theta_{\rm LD} = 0.275 \pm 0.009$ mas, which is at the limit of angular resolution of VEGA. Right. Evolutionary tracks with the observational 1-σ error box ($\log T_{\rm eff}$, $\log L$) in red and the diagonal dotted lines for R. The mass (in solar units) is indicated at the beginning of the evolutionary tracks. The best model is shown as full line, whereas the two extreme models are shown as dashed lines. For the best model, we show in brackets for several time steps (open circles) the evolution of the seismic mean large separation (μHz), the radius ($R_{\rm sun}$), and the age (My). The full circles represent the time at which the large separation equals the observed one, i.e. 50.95 μHz. This study from Perraut et al. (2013) is typical of what is currently done from optical interferometry.

2 The fundamental parameters

Any interferometer provides measurements of angular sizes of an object , like for instance an angular diameter. Such an observable, combined with the trigonometric parallax, provides the stellar radius in a geometric way that is as independent as possible of models. This becomes even more important in the context of Gaia launched last year. Such an approach has been successfully applied with VEGA/CHARA for several kinds of physical objects of interest.

First, the abnormal surface layers of rapidly oscillating Ap star may generate systematic errors in the determination of stellar luminosities and effective temperatures by spectrometric and/or photometric techniques (Matthews et al. 1999). Within this context, optical long-baseline interferometry allows a direct (and unbiased) measurement of the angular diameter of these apparent tiny stars which helps at determining their pulsation modes together with their temperature scale (Perraut et al. 2011, 2013). The way this is usually done is presented in Figure 1 in the case of 10 Aql. Another kind of approach is to use a direct interferometric determination of the angular diameter and advanced three-dimensional modeling, to derive the radius of seismic CoRoT targets in order to reduce the global stellar parameter space compatible with seismic data. This method has been applied to the HD49933 CoRoT target using VEGA/CHARA data (Bigot et al. 2011). This kind of analysis, is also extremely precious when studying metal poor stars, which indeed provides a wealth of chemical information about various stages of the chemical evolution of the Galaxy (Frebel 2010). The VEGA measurements of the benchmark Gaia star HD140283 are presented in Creevey et al. 2014 (in preparation). Third, the angular diameters as derived from stellar interferometry are of a tremendous importance for exoplanet host stars characterization. The precise radius of the star is indeed required to model the exoplanetary systems. This field of research is currently extremely active and one of the first contribution from the VEGA group can be found in Ligi et al. (2012) and in another paper in preparation. Another historical contribution from interferometric angular diameters is to study the surface brightness of stars, which are actually used in many fields of researches. One of the most recent application comes from the use of late-type eclipsing binaries to derive the distance of LMC (Pietrzyński et al. 2013). In order to extent the method and use bright early-type eclipsing binaries to derive the distance of distant galaxies in the local group like M31 and M33, one need a precise determination of the surface-brightness of hot stars. Such relation has been recently established by Challouf et al. (2014) as a function of the V-K color index with a precision of 0.16 magnitude.

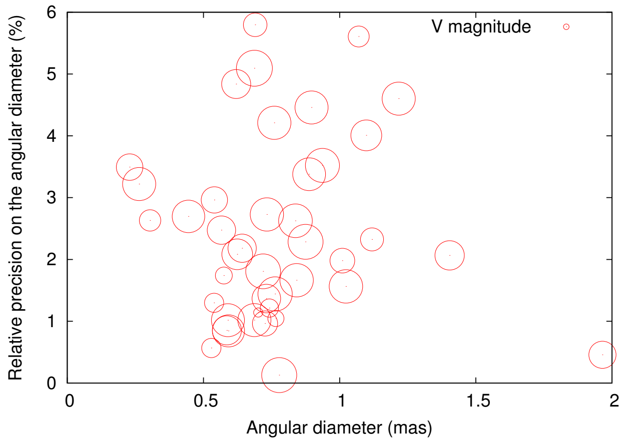

Fig. 2. Diagram showing all the angular diameter obtained with the VEGA/CHARA instrument up to now with their respective relative precision in %. The size of the dot provides the magnitude in V of the star, the larger the circle, the larger the magnitude.

To conclude this small review on fundamental parameters, we present in Fig. 2 most of the angular diameters that have been derived from VEGA instrument since 2009. The relative precision obtained is plotted as a function of the angular diameter while the size of the circles gives an indication about the m_V of the object. The fainter stars in this plot have a m_V magnitude of 6.5. The relative precision obtained is also related of course to the number of visibility measurements secured with the instrument. The average relative precision on our angular diameter is of about 2.5%, while for 15 stars we reach a precision of better than 1.5% (with magnitude from 1.5 to 6). A rough conclusion is that about 15 visibility measurements at least (or 5 observations with a CHARA triplet) are necessary to reach the 1.5% precision on a star of magnitude 6.

3 The kinematic of stars, their environment and imaging

By combining angular resolution to spectral resolution with VEGA/CHARA, it becomes possible to probe the kinematic of the close environment of a star. This is usually done by deriving the size of the material emitting within the Hα line. One can study for instance the mass transfer around young stellar objects (Perraut et al. 2010; Benisty et al. 2013), Be stars (Meilland et al. 2011) or, one of the most famous star in interferometry which is the interactive binary β Lyrae (Bonneau et al. 2011). But even for a star without environment, there is still the possibility to probe the differential rotation of the star within the photosphere, using for instance the Hα line in absorption. An attempt was made by Delaa et al. (2013) on the bright fast rotating star α Cep.

One interesting approach also with CHARA is to use the MIRC instrument (Monnier et al. 2008) as a imager in the K-band, and VEGA to probe the kinematical structure of the environment within the Hα line. This was done for the atypical star ϵ Aur. A disk is eclipsing the central star, the image of which has been restored by MIRC (Kloppenborg et al. 2010), while the structure of the Hα line emission was given by VEGA (Mourard et al. 2012). Similarly, several large campaigns have been organized recently by combining several interferometric instruments together with photometry and spectroscopy ones. This concerns mainly the prototype interactive binary β Lyrae, which is a very complex object (a second paper is in preparation) and the expanding Nova Delphini 2013 (Schaefer et al. 2014, in press Nature).

However, the main goal of spectro-interferometry is eventually to provide polychromatic images of an object. This would provide the image of the material with a given approaching or receding velocity (iso-velocity maps). Such an approach is currently applied to a fast rotating star ϕ Per (Mourard et al., in preparation).

4 Conclusion

The VEGA/CHARA instrument is currently providing geometrical and kinematical views for many objects in the solar neighbourhoods as well as robust constrains in term of stellar fundamental parameters. This is mainly due to this unique capability of combining high angular and high spectral resolution in the visible. These results require also the development of new models related to the structure, evolution and environment of stars (radiative transfer in gas and/or dust).

In order to push the sensitivity even further (and reach 10th magnitude), we are developing a prototype of new instrument in the visible using fibers and latest technologies of fast and sensitive analogic cameras (see Berio et al. 2014, SPIE, in press). This instrument would also take benefit from upcoming adaptive optics on the CHARA interferometer. Such specifications are opening new areas in term of stellar physics. The very high precision of such instrument would also create new synergies with Gaia and PLATO space missions.

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