Performances and first science results with the VEGA/CHARA visible instrument

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ABSTRACT

This paper presents the current status of the VEGA (Visible spEctroGraph and polArimeter) instrument installed at the coherent focus of the CHARA Array, Mount Wilson CA. Installed in september 2007, the first science programs have started during summer 2008 and first science results are now published. Dedicated to high angular (0.3mas) and high spectral (R=30000) astrophysical studies, VEGA main objectives are the study of circumstellar environments of hot active stars or interactive binary systems and a large palette of new programs dedicated to fundamental stellar parameters. We will present successively the main characteristics of the instrument and its current performances in the CHARA environment, a short summary of two science programs and finally we will develop some studies showing the potential and difficulties of the 3 telescopes mode of VEGA/CHARA.

Keywords: VEGA/CHARA, visible wavelengths, AB Aur, Deneb, Rigel

1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) of the Georgia State University operates an optical interferometric array[1] located at Mount Wilson Observatory. It is formed by six telescopes placed in pairs on the arms of a Y-shaped configuration. It yields 15 baselines ranging from 34 to 331 m. The distribution of length and orientation of these baselines allows a good coverage of the spatial frequency plane and permits the instrument to reach very high angular resolution.

The VEGA[2] instrument works in the visible domain [0.45μm;0.85μm] and benefits from three spectral resolutions. The medium (6000) and high (30000) spectral resolutions are well suited to perform kinematic analysis of the interferometric signal, providing resolution of 60 and 10km.s^{-1} respectively. These spectral resolutions are best dedicated to the extraction of differential spectral information. Radiative winds and fast rotating photospheres of hot stars can be probed efficiently with the medium spectral resolution. The low (1700) and medium resolutions are well suited to absolute visibility studies and are also well adapted for the study of binaries or multiple systems.

This paper presents in section 2 the principle of VEGA and its performance. In section 3 we present a short summary of two recent science papers. Section 4 is dedicated to a general overview of the main science programs accessible to VEGA/CHARA and finally section 5 deals with the main characteristics of the VEGA program using the new 3 telescopes mode.

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2. VEGA: PRINCIPLE AND PERFORMANCE

The spectrograph is designed to sample the visible band from 0.45 to 0.85 μm. It is equipped with two photon counting detectors[3] looking at two different spectral bands. The main characteristics of the spectrograph are summarized in Table 1. The simultaneous operation of the two detectors is only possible in high and medium spectral resolutions. The optical design allows simultaneous recording of data, in medium spectral resolution, of the spectral region around $H\alpha$ with the red detector and around $H\beta$ with the blue detector. Observing in the blue requires good seeing conditions but increases by 30% the limit of spatial resolution of the instrument with respect to its operation around 700nm.

Grating	**R**	$\Delta\lambda$ **(Blue)**	$\Delta\lambda$ **(Red)**	$\lambda_R - \lambda_B$
R1: 1800gr/mm	30000	5 nm	8 nm	25 nm
R2: 300gr/mm	5000	30 nm	45 nm	170 nm
R3: 100gr/mm	1700	100 nm	150 nm	not possible

Table 1. Spectral resolution (R) and bandwidth ($\Delta\lambda$) of the VEGA spectrograph, as well as the spectral separation between the two detectors.

The VEGA control system[4] conforms to the CHARA control system and can now observe via remote operation. The first step of the process is the software to prepare the observations. It aims at generating ASCII files containing the parameters of observing blocks. These blocks contain all the necessary information regarding the configuration of CHARA and VEGA. They serve as input for the observation control software and are also used for the scheduling of each program as well as for the whole night scheduling. This preparation tool also uses the SearchCal[5] software developed by the Jean-Marie Mariotti center (JMMC). The second step is the observation itself. After selecting an observing block, the operator checks the steps of the automatic sequence: initialization, control of pupil alignment, control of the science detectors, flux optimization, fringe tracking, data recording and calibration recording. Contextual information such as configuration, dark file, pupils and images files, operator comments, etc... are collected with the raw data. This entire operation can be made remotely from France with a limited network bandwidth. At the end of the night an automatic archiving system stores all the data files and performs a quality control of the data. These quick-look results are now stored automatically in the VEGA database.

While the observing software is based on a preferred setup (baseline, spectrograph capability, etc), the data reduction pipeline is based on predefined sequences: V^2 mode, $Ve^{i\phi}$ differential visibility mode or $SPIN$ mode for spectro-polarimetric interferometry. During the data reduction process, intermediate or final results are stored in files and linked to entries in the VEGA database. The details of the data reduction pipeline can be found in our reference publication.[2]

The VEGA/CHARA interface table can accept up to four beams as does the spectrograph itself. The 4 output pupils are reconfigured in a linear and fully redundant way (2 diameters between two successive centers) and the fringe signals are separated thanks to the combination of spatial and spectral encoding. We already perform observations in 3 telescopes mode and the full characterization will be described soon in a forthcoming publication.

Up to now science programs have been performed using the two telescopes mode only. We have dedicated some times in the early operation of the instrument to correctly establish its performances. Typical calibrated V^2 measurements with an accuracy of about 2% are obtained in the medium resolution mode. Concerning the differential measurements, a phase noise of 1 to 2° is reached even for the highest spectral resolution. Fig. 1 presents the results of simulation performed to reproduce the measurements in terms of signal to noise ratio and extrapolated then in terms of limiting magnitudes. When considering interferometry in the speckle regime, we usually consider two domains for the signal to noise ratio, depending on the number of photons per speckle and per single exposure. If this number is larger than 1, then the signal to noise ratio increases as the square root of the number of photons, whereas if it is smaller than 1, the signal to noise ratio[6] increases with the number of photons. As a consequence, we define the limiting magnitude as the magnitude giving a signal to noise ratio of 10 for an unresolved source ($V^2 = 1$) in 10s. It is clear however that the signal to noise ratio could reach

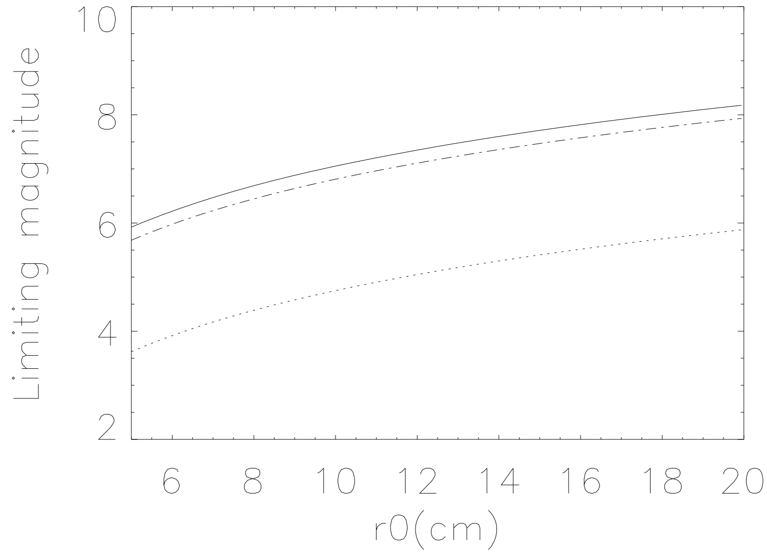

Figure 1. VEGA limiting magnitude for a 10s integration time. The dotted line is for the high spectral resolution mode ($\Delta\lambda = 6$nm), the dash-dotted one for the medium resolution mode ($\Delta\lambda = 40$nm) and the solid line for the low resolution mode limited to a band of $\Delta\lambda = 50$nm to correctly take into account the limited spectral coherence of the atmosphere. The central wavelength used for the simulation is 650nm.

high values at this limit, since one can integrate a large number of single exposures containing a large number of speckles. This high signal to noise ratio is usually used in our case for measurements in narrow spectral channels. In the next section we will present two recent science results using these characteristics in terms of sensitivity and in terms of high spectral resolution capabilities.

3. TWO RECENT SCIENCE RESULTS

3.1 Hα line forming region of AB Aur

In a recent publication[7] Perraut et al. have presented the very first observations of a young stellar object by long baseline interferometry at visible wavelengths. To derive key constraints on the launching point of the jets and on the geometry of the winds of young stars, VEGA is an unique and efficient means to probe the structure and the kinematics of the hot circumstellar gas at sub-AU scales around intermediate-mass young stars. These Ae/Be Herbig stars are commonly studied by near-infrared interferometry which has allowed the dusty and gaseous environment of such objects at scales of about 0.5-1 AU to be resolved while spectroscopy has enabled to derive global constraints on the stellar and circumstellar activity of these objects (variability of line profiles, variation of radial velocity). Performing spatially and spectrally resolved observations of such targets in the visible range enables a higher angular resolution to be reached and bring the very first spatial constraints on the accretion/ejection scenario at scales as small as 0.1 AU.

AB Aurigae (AB Aur; A0Ve; d=144 pc) is the brightest Herbig Ae star in the northern hemisphere, and is often considered as the prototype of the HAeBe class. Its photometric and spectral properties are well studied over a wide wavelength range[8–10] and there is evidence of both accretion and outflows[11,12]. The Hα line exhibits a P-Cygni profile, which is a common probe of stellar wind, and is known to be variable, especially in the blue wing of the line. AB Aur is surrounded by a complex combination of gas-rich and dust-dominated structures probed on large scales by imaging. Spatially resolved observations at high angular resolution at near-infrared, thermal infrared, and millimetric wavelengths have shown the presence of a circumstellar disk rotating at non-Keplerian velocities.

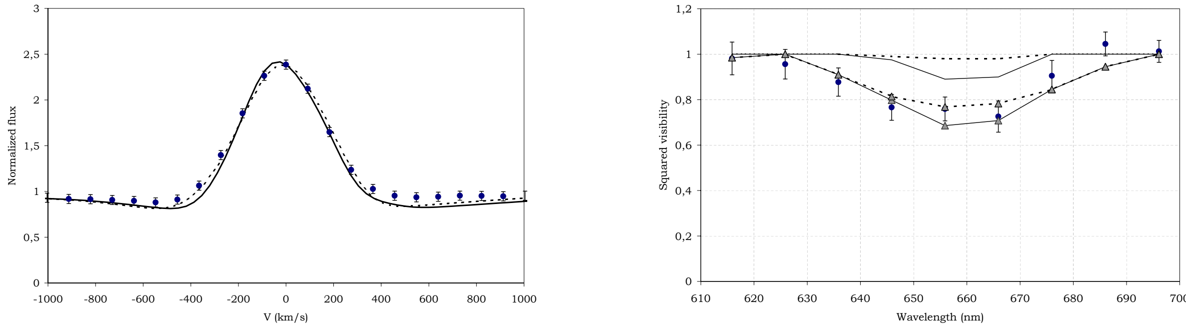

Figure 2. Best model predictions compared to the VEGA spectrum (left) and spectral visibilities (right), both in full circles with error bars. Dashed lines correspond to the X-wind model and full lines to the disk-wind one. For the squared visibilities, triangles denote the model prediction including both the wind and the contribution of the asymmetric reflection nebula.

Data were collected at the CHARA Array with the VEGA spectrometer in October 2008. Observations with the S1S2 (34 m ground length) were performed between 610 and 700 nm, at the lowest spectral resolution of VEGA (R=1700). Observations of AB Aur were sandwiched between those of a nearby calibration star (HD 29646) that was chosen to be bright enough (mV= 5.7) and to have a similar spectral type (A2). The VEGA spectrum of AB Aur exhibits an Hα emission line with a clear P-Cygni profile (Fig. 1-left). The line to continuum ratio is at most about 2.5, the line FWHM is 6 , and its emission peak is slightly red-shifted. In addition, the line (see Fig. **??**) presents a very broad absorption from 640 nm until 665 nm, probably due to Stark broadening in the absorption of the radiation by nearly hydrostatic cold layers located just above the stars photosphere. Due to the spectral width of the processing window, the squared visibilities (see Fig. **??**) at 646 nm, 656 nm, and 666 nm include all or part of the Hα emission, and the values of the squared visibility are between 0.72 and 0.75. Although they are relative to continuum emission alone, the squared visibilities at 636 nm and 676 nm are below unity, while those farther away from Hα are consistent with 1. AB Aur is thus clearly resolved by the S1S2 baseline both in the Hα line and in a part of the visible continuum.

We used the radiative transfer code RAMIDUS (Rajabi, 2010, PhD) to test various configurations of wind (stellar wind, disk wind, X-wind) and try to simultaneously fit the line profile and the inferred visibilities (Figure 2). A spherical wind model originating on the star itself could be also ruled out because it will introduce a larger blue-shifted absorption in the Hα line than the one that has been observed. Our data are compatible with a magneto-centrifugal mechanism for the production of the wind. It was difficult, however, to determine the exact morphology of the wind and disentangle the X-wind (that originates from the reconnection point at the basis of the inner disk) and the disk wind because of the extended nebulosity. To correctly reproduce the V^2 measurements, we have to consider an additional component producing an extended continuum emission (Figure 2 right, plots with triangles). A point-like source contributing for 7% of the flux located at about 38 millisecond of arc (i.e. 5.5 AU) is able to correctly reproduce the decrease of visibility which could come from the extended reflection nebulosity around the system.

3.2 Mass-loss in the supergiants Deneb and Rigel

BA-type supergiants are amongst the most optically-bright stars, observable in extragalactic environments, and potential accurate distance indicators. Extensive record of emission activity in the Hα line of the BA supergiants α Orionis (Rigel, B8Ia) and α Cygni (Deneb, A2Ia) suggests the presence of localized time-dependent mass ejections. However, little is known about the spatial distribution of these structures. In 2008 and 2009 observing campaigns, we have used VEGA to study the Hα line-formation region in these stellar environments. High spectral (R=30000) resolution observations of Hα were obtained using the S1S2 array-baseline (34m). Six independent observations were done on Deneb over the years 2008 and 2009, and two on Rigel in 2009. We

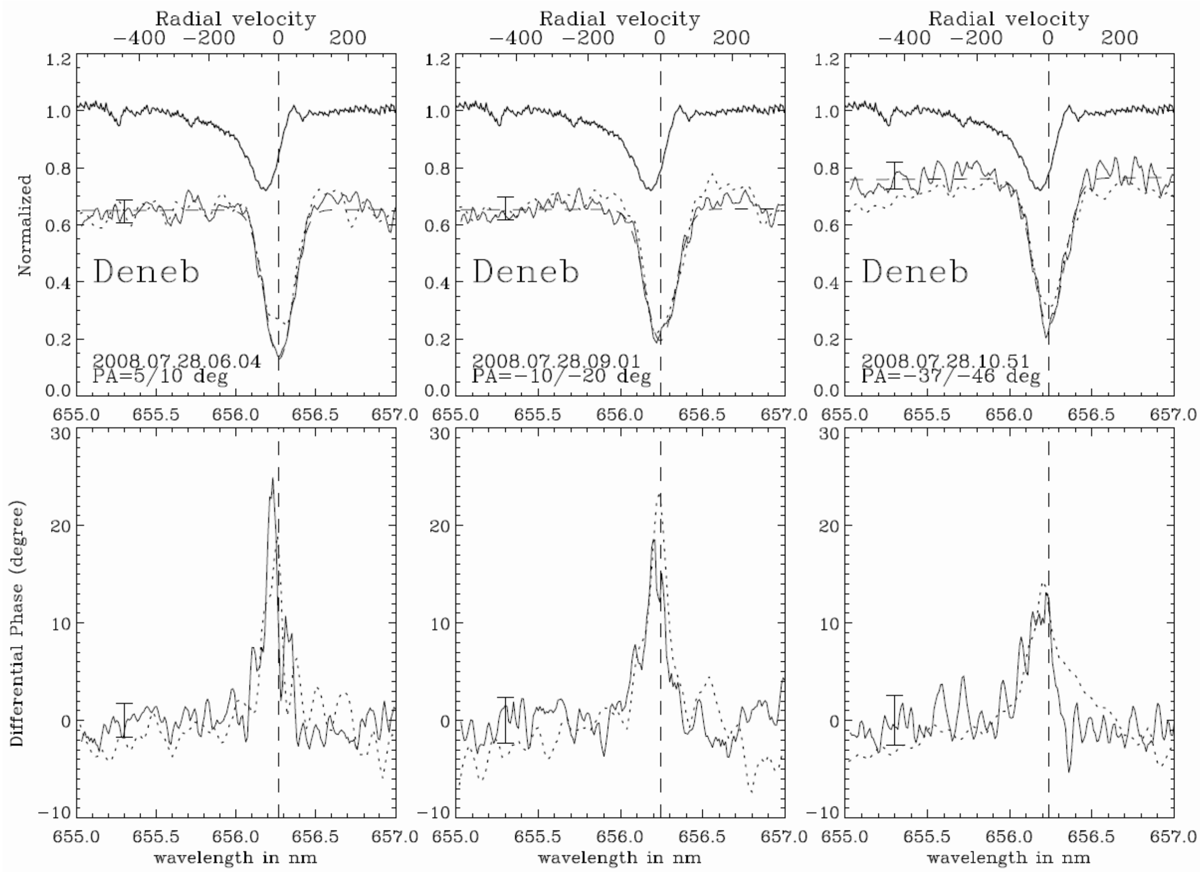

Figure 3. Top row: normalized flux and spectrally resolved differential visibility for deneb around Hα. Bottom row: spectrally resolved differential phase. A strong signal changing with the baseline direction is observed, indicating a significant asymmetry of the line formation region at this time.

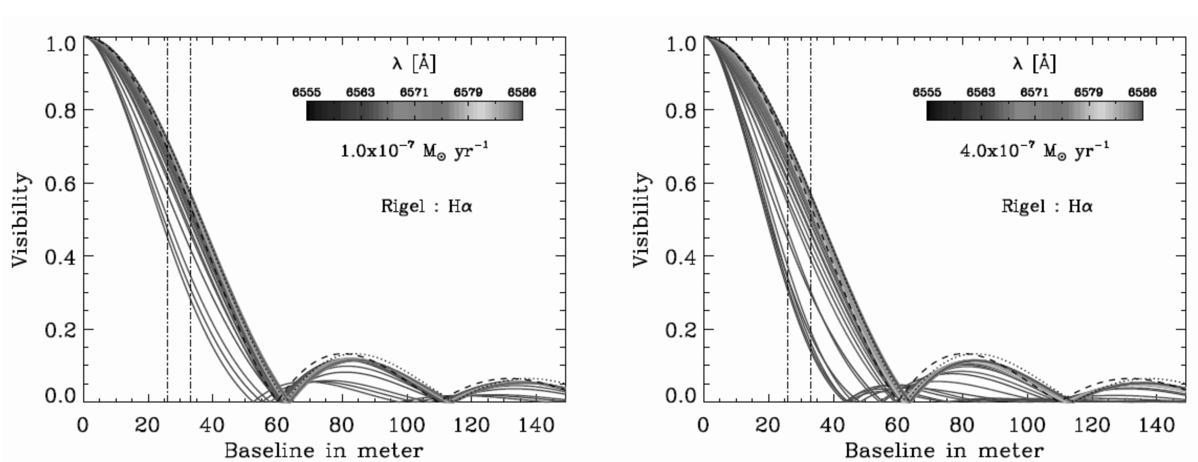

Figure 4. Theoretical visibility curves for Deneb, computed at select wavelengths through the Hα line and for two different values of the mass-loss rate. The range of baselines used in these observations are indicated by two vertical dash-dotted lines.

analyze this dataset with the 1D non-LTE radiative-transfer code CMFGEN, and assess the impact of the wind on the visible and near-IR interferometric signatures, using both Balmer-line and continuum photons. We observe a pronounced visibility decrease in Hα (see Fig. 3). We witness time variations of the differential phase for Deneb, implying an in-homogeneous and unsteady circumstellar environment, while no such variability is seen in differential visibilities. Radiative-transfer modeling of Deneb, with allowance for stellar-wind mass loss, accounts fairly well for the observed decrease in the Hα visibility. Based on the observed differential visibilities, we estimate that the mass-loss rate of Deneb changed by less than 5%. Same observations have been pursued on Rigel and we present in Fig. 4 the theoretical visibility curves through the Hα line generated by the model for two different mass-loss rates. These results have been accepted for publication in Astron.&Astrophys. and will be published very soon (Chesneau et al. A&A 2010).

4. MAIN SCIENCE PROGRAMS

The most promising science drivers of VEGA are within the fields of fundamental stellar parameters, stellar activity (rotation, surface structures, polarization, pulsation) and circumstellar environment studies.

4.1 Fundamental stellar parameters

Physical processes working in the stellar interiors as well as the evolution of stars are based on some fundamental measurements (mass, radius, luminosity or abundances). The effective temperature, the surface gravity and the mean density are useful parameters defined from these fundamental values. Some other physical parameters like mass loss rate, pulsation period, rotation period or magnetic fields are interesting for the study of peculiar evolutionary stages. A classical way to test stellar interior models is to compare the predicted and observed location of a star on theoretical evolutionary tracks in an H-R diagram. This can be done only for stars for which the mass, radius, luminosity and abundances are well known. To obtain significant results, an accuracy of 1%-2% for the mass and the radius and an error in the effective temperature better than 50K is necessary. Then a precision of about 5% - 10% luminosity is sufficient. Next section will be devoted to the study of the VEGA observing possibilities in this field.

We are also interested in the measurement of the equatorial vs polar angular diameter ratio of Bn stellar photospheres (Bn are Be stars without a circumstellar disk at the epoch of the observations) in order to directly measure this parameter as it was originally done for the Be star Achernar.[13] This ratio R_{eq}/R_{pole} is strongly dependent on the internal stellar structure of these fast rotating stars and thus is able to directly put strong constraints on various theoretical scenarios which try to reproduce the observed flattening. It is also a way to directly estimate the rotational velocity of the stellar photosphere since it is strongly model dependent when estimated by spectroscopic technics only. VEGA seems really well suited for putting strong constraints on the physical properties of the photosphere of these stars (Zorec et al. 2010 in preparation).

4.2 Variable stars

Our team has a long history in cepheids observations using optical long baseline interferometry.[14] In complement to the application of the classical Interferometric Baade Wesselink method, our main concern with VEGA is to take benefit from the high spectral resolution to study more deeply the atmosphere dynamics in metallic lines,[15,16] as well as the signatures of their envelopes in hydrogen lines.[17,18]

Although binaries and more generally multiple systems are complex objects both from observational and modeling points of view, their study can provide fundamental data to refine the theory of single-star formation and constrain possible scenarios of double star formation. The angular diameters can be combined with the distance to obtain the stellar radii. On the other hand, combining interferometric and spectroscopic orbits leads to direct determination of distances. The specific case of eclipsing binaries allows a complete resolution of the system's parameters. Finally, combining all these data using classical methods allows the masses to be determined. The geometrical structure of more evolved and interacting binaries involves not only the stellar disks but also various components of circumstellar matter: the accretion disk, the scattering envelope and jet-like structures outside the orbital plane and also the gaseous stream between the components.

Visible interferometry can contribute to the study of stellar activity by detecting and mapping star spots. A limited number of stars have features large enough to allow interferometric imaging. The gain in resolution by the use of visible light will substantially increase the number of targets. Sunspots are relatively small (1% of the solar radius), they are usually formed in the equatorial region, and tend to move to the largest latitude. It seems that no solar spots have been observed close to the poles. Doppler imaging has a number of drawbacks so the uniqueness and the accuracy of many images may be questionable.

4.3 Circumstellar environments

The envelopes of Be stars are a popular topic for visible interferometric observation. However, the mechanisms causing the mass loss and shaping the resulting circumstellar envelopes remain unclear, as well as the mechanisms of the formation and the disappearance of the circumstellar disk as a function of time. One important parameter is the typical size of the envelope for a given wavelength. We have observed two Be stars with VEGA/CHARA, namely 48 Per and ψ Per using the medium spectrograph resolution. We were able to estimate the disk extension in the continuum and in the Hα line for both stars, as well as the kinematics within the disks thanks to spectrally resolved visibility modulus and phases. We found that both stars are nearly critical rotators but the disk of 48 Per seems to be in Keplerian rotation (β=0.5), whereas ψ Per's disk is rotating faster. A paper about these results is in preparation (Delaa et al. 2010).
Interacting massive binaries are also interesting targets. The main observational characteristics of these systems are dominated by the presence of a dense, optically thick disk and/or by jet-like features. Mass loss and mass transfer in these systems as well as the nature of some of the observed variations are open problems[19] which must be solved to a better understanding of the past and future evolution of these objects. Beta Lyr and upsilon Sgr are among the rare massive binaries that can be caught in the rapid phase of large mass exchange. Spectro-interferometric observations can bring a new insight into these complicated binary systems permitting at least to obtain some constraints on the circumstellar structures and orbital elements.

5. FUNDAMENTAL STELLAR PARAMETERS AND VEGA-3T MODE

We now concentrate our analysis on the possibility for VEGA to measuring accurate angular diameters over a large range of main sequence stars. As already said, an accuracy on the angular diameter measurement of 1 to 2% is mandatory. Taking into account the 2% accuracy on the calibrated squared visibility, we computed, for the range of baselines accessible to VEGA/CHARA, the smallest angular diameter accessible and allowing to reach an accuracy of 1 and 2% on the angular diameter determination. The results are presented in Fig. 5.

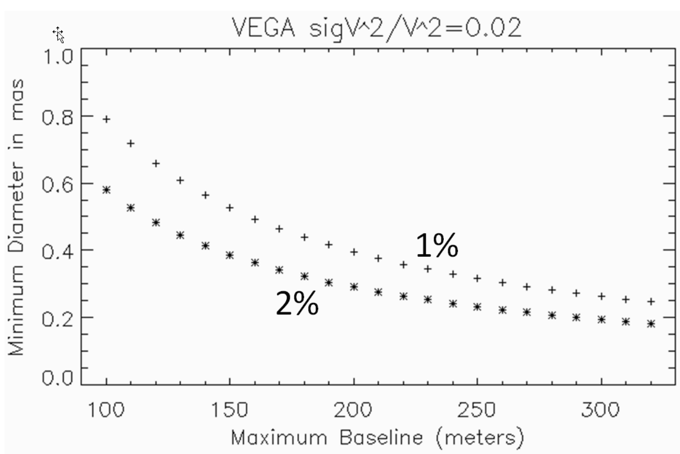

Figure 5. Smallest accessible angular diameter as a function of the maximum baseline for two different accuracies on the angular diameter determination.

This figure shows that angular diameters in the range from 0.4 to 1.0 milliseconds of arc are the most favorable targets for this study. We estimated that almost 4000 stars brighter than V magnitude 6.5 can be studied by VEGA. However, this figure also indicates that long baselines (larger than 100 meters) are mandatory and thus this program will automatically leads to low visibility measurements. These long baselines could be reached by using the classical baseline bootstrapping method with observations in 3 telescopes mode with tracking fringes

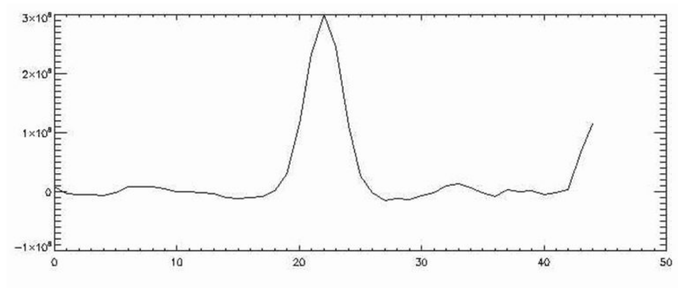

Figure 6. Long integration of the VEGA fringe signal with CLIMB used as group delay tracker. The vertical axis has just arbitrary units whereas the horizontal axis is a quantity proportional to the optical path difference.

on the two shortest ones and getting data at the longest ones. However, 3 telescopes operation with CHARA immediately leads to long baselines, even for the tracking baselines. The more compact triangle (S1S2W2) has already a baseline of 170 meters which leads to the same issue of low visibility measurements. Up to now the internal VEGA fringe tracker, which is based on real time processing of the science data, is not able to track fringes at the needed rate of 0.1Hz for visibility below than 0.3. We thus decided to consider the possibility of using an external infrared fringe tracker. Preliminary and successful attempts have been made during the may and june 2010 observing runs with the new infrared instrument called CLIMB (ten Brummelaar et al., 2010, these proceedings). In Fig. 6 we present a long integration (20 minutes) of spectral densities of short exposures VEGA images with the new infrared instrument CLIMB used a group delay tracker. We measured a typical residual jitter on the optical path difference of the order of 7 μm, well in coherence with our need in high and medium spectral resolution. An accuracy twice better is needed in low spectral resolution mode and progresses are foreseen through the use of faster scan rates on CLIMB.

During these tests we encounter one main difficulty which is related to the current limiting magnitude of the CLIMB instrument with respect to our need of ”faint” stars as calibrators. We thus made a study of the number of potential calibrators for this kind of observations. We identified the stars brighter than magV 6.5, magK 4.5 (or 5.0) and having an estimated angular diameter smaller than 0.4mas. With the limit of 4.5 on magK, we found 46 stars and for 5.0 this number increases to almost 210 stars. Results are shown in Fig. 7. One can see thatIhe sky coverage with a limiting magnitudn K of 4.5 is very poor whereas it becomes decent (except near the galactic pole) as soon as the K limiting magnitude reaches at least 5.

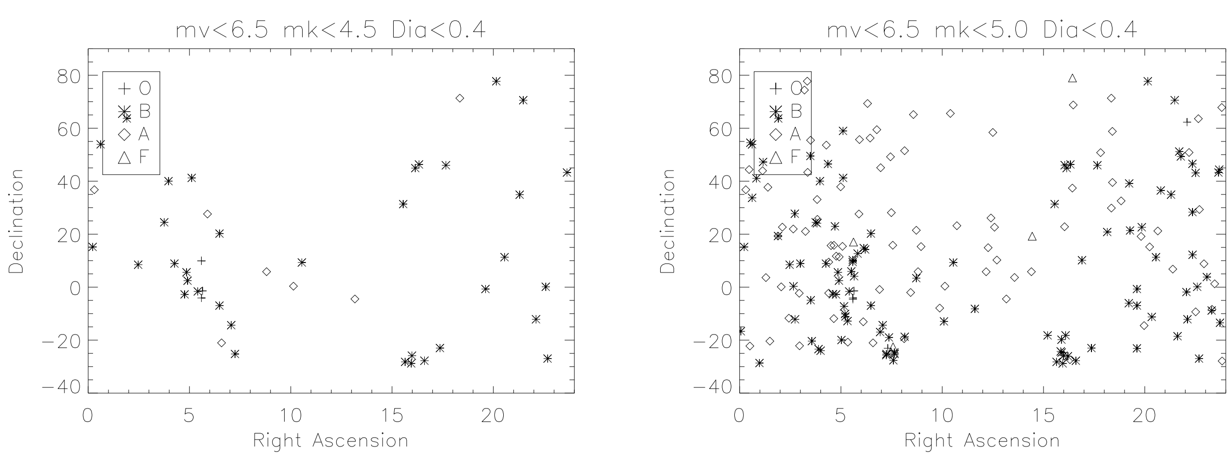

Figure 7. Distribution of calibrators on the sky for two different limiting magnitudes in the infrared K band

With these numbers in hands, we have been able to estimate the repartition of stars that could be observed with these limitations in V (≤ 6.5) and K magnitude (≤ 4.5 or ≤ 5.0) as well as in angular diameter ($0.4 \leq \theta \leq 1.0$). The numbers are presented in Tab. 2. 8 stars of spectral type ranging from O6 to 09 are identified and a

Spectral Type	mK≤4.5	mK≤5.0
O	8	8
B	77	89
A	169	233
F	243	483
G	481	558
K	501	504
M	-	2

Table 2. Number of stars as a function of their spectral type with angular diameters smaller than 1 mas, a V magnitude brighter than 6.5 and a K magnitude brighter than 4.5 (second column) or 5.0 (third column).

small hundred of B stars are also accessible. From spectral type A to K a good statistics of sources could be find and a dedicated program will be establish on a long-term plan with VEGA/CHARA.

6. CONCLUSION

After a successful and rapid installation of the VEGA instrument on the CHARA array in september 2007 (3 weeks from packaging to fringes on the sky), the science programs have really started during summer 2008. The first priority has then been put to correctly qualify the control system, the data reduction software and to establish quantitatively the performances on the sky. As usual for interferometric instruments, this step of a project is iterative and fine tuning of observing strategies is usually necessary. The experience gained all over the world on interferometric facilities is now very rich and this has contributed to the rapid progresses on VEGA. In july 2009, the first remote operation of VEGA from our observatory in France was possible and routine operations are now regularly scheduled. With the publication of the two first science papers of VEGA in first semester of 2010 and 5 to 6 other results almost ready for publications, VEGA has proven to be fully operational and benefits now from a unique science niche well adapted to the CHARA capabilities.

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