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MEASUREMENTS OF EIGHT EARLY-TYPE STARS ANGULAR DIAMETERS USING VEGA/CHARA INTERFEROMETER

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Abstract. The surface brightness color (SBC) relation is an important tool to derive the distance of extragalatic eclipsing binaries. We determined the uniform disc angular diameter of the eight following early-type stars using VEGA/CHARA interferometric observations: $\theta_{\rm UD}[\delta$ Cyg$]$ = 0.766 ± 0.047 mas, $\theta_{\rm UD}[\gamma$ Lyr$]$ = 0.742 ± 0.010 mas, $\theta_{\rm UD}[\gamma$ Ori$]$ = 0.701 ± 0.005 mas, $\theta_{\rm UD}[\zeta$ Peg$]$ = 0.539 ± 0.009 mas, $\theta_{\rm UD}[\lambda$ Aql$]$ = 0.529 ± 0.003 mas, $\theta_{\rm UD}[\zeta$ Per$]$ = 0.531 ± 0.007 mas, $\theta_{\rm UD}[\iota$ Her$]$ = 0.304 ± 0.010 mas and $\theta_{\rm UD}[8$ Cyg$]$ = 0.229 ± 0.011 mas (by extending V-K range from -0.76 to 0.02) with typical precision of about 1.5%. By combining these data with previous angular diameter determinations available in the literature, Challouf et al. (2014) provide for the very first time a SBC relation for early-type stars ($-1 \leq$V-K≤ 0) with a precision of about 0.16 magnitude or 7% in term of angular diameter (when using this SBC relation to derive the angular diameter of early-type stars).

Keywords: Stars: early-type, methods: data analysis, instrumentation: interferometers, techniques: medium spectral resolution

1 Introduction

The Optical Gravitational Lensing Experiment (OGLE) has been monitoring around 35 million stars in the LMC for more than 16 years. Using this unique data set, Pietrzyński et al. (2013) have detected a dozen of very long-period (60-772d) eclipsing binary systems composed of intermediate-mass, late-type giants located in a quiet evolutionary phase on the helium-burning loop. By observing spectroscopically eight of these systems intensively over the past 8 yr, the team could accurately measure the linear sizes of their components, while the angular sizes have been derived from the surface-brightness color relation (SBC relation). The LMC distance that was derived from these systems is accurate to 2.2% and provides a base for a 3% determination of the Hubble constant. The error budget on the LMC distance is as follows: photometry (15%), spectroscopy (5%), reddening (10%), uncertainty on the derived absolute radii (15%), and the remaining (about 55%) is due to the surface brightness color relation. Thus, the systematic uncertainty in the distance measurement comes mainly from the calibration of the SBC relation. The root mean squared scatter in the current SBC is 0.03 mag (Di Benedetto 2005), which translates to an accuracy of 2% in the respective angular diameters of the component stars. Conversely, early-type eclipsing binaries are very bright systems that are very easily detected in the LMC and even in M33. Even if these objects are promising for the distance scale calibration, the largest limitation when using these systems comes again from the surface brightness relation. In this context we have performed observations of a sample of 8 stars composed by 6 low rotators (λ Aql, γ Ori, γ Lyr, ζ Per, ι Her and 8 Cyg) and by 2 fast rotating stars (δ Cyg and ζ Peg). In our study we include two rotators in order to understanding the effect of rotation on the SBC relation. A theoretical study which aims at quantifying the impact of the fast rotation on the SBC relation for early-type stars is currently under progress and will appear in another paper. To observe this sample we used the resolving power of the Visible spEctroGraph and polArimeter (VEGA) beam combiner (Mourard et al. 2009, 2011) operating at the focus of the CHARA (The Center for High Angular Resolution Astronomy) Array (ten Brummelaar et al. 2005) located at Mount Wilson Observatory (California, USA). The CHARA array consists of six telescopes of 1 meter in diameter, configured in a Y shape, which offers 15 different baselines from 34 meters to 331 meters. These baselines can achieve a spatial resolution up to 0.3 mas in the visible which is necessary in order to resolve early-type stars.

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2 Deriving the angular diameters

The observations of our sample were performed during most 2 years. We started the first observation on July 23, 2011 and we ended our observation program on August 29, 2013. After calculate the raw visibilities of observations, the first step is to calibrate the visibility measurements of our targets using observations of reference stars. The need of transfer function analysis is useful to test the consistency of the reference stars, and to define a good strategy of calibration. The transfer function T calculated from the observations on the reference stars Cal using the following formula:

$$T^2 = \frac{\mu_{cal}^2}{V_{cal}^2} \tag{2.1}$$

where μ_{cal} is the measured squared visibility on a given calibrator, while V_{cal} is the expected squared visibility on the calibrator that we could calculate with the following relation:

$$V_{cal}^2 = 4\left(\frac{J_1(z)}{z} \right)^2 \tag{2.2}$$

with $J_1(z)$ is the first-order Bessel function and $z = \pi\theta_{\mathrm{UD}}B/\lambda$, where B is the projected basline, λ the wavelenght. θ_{UD} is given for example by the SearchCal (`http://www.jmmc.fr/searchcal`) developed by the JMMC (Bonneau et al. 2006). We know that, under correct seeing conditions, the transfer function of VEGA/CHARA is stable at the level of 2% for more than one hour (Mourard et al. 2009). The estimate visibility on each bloc of observation is measured in a given spectral band using the estimator defined by Roddier & Lena (1984) (see also Mourard et al. 2009, 2011). The squared calibrated visibility (V_{target}^2) obtained from our VEGA observations are fitted with a model of uniform disc (see Fig. 1) using for instance LITpro (`http://www.jmmc.fr/litpro`) software developed by the JMMC (Tallon-Bosc et al. 2008). The fitting engine is based on a modified Levenberg-Marquardt algorithm combined with the trust regions method. The equivalent uniform disc angular diameter θ_{UD} is then converted into a limb-darkened disc. The following formula of Hanbury Brown et al. (1974b):

$$\theta_{LD}(\lambda) = \theta_{UD}(\lambda)\left[\frac{(1-U_\lambda/3)}{(1-7U_\lambda/15)}\right]^{1/2}, \tag{2.3}$$

provides an efficient way to perform the conversion using linear limb-darkening coefficients U_λ.

3 Results for the stars in our sample

Using the uniform disc model we can find the best fit of angular diameters (θ_{UD}) and by combination of these diameters with the limb-darkening coefficients (U_λ) we derived the limb-darkened angular diameters (θ_{LD}). All these parameters are listed in Table 1 for each star in our sample. We obtained θ_{LD} ranges from 0.31 to 0.79 mas, with a relative precision from 0.5% to 3.5% (average of 1.5%). The reduced χ^2_{red} is from 0.4 to 2.9 depending on the quality of the fit (Fig. 1).

Table 1. Angular diameters obtained with VEGA/CHARA and the corresponding surface brightness. The systematical uncertainties for the two fast rotating stars, ζ Peg and δ Cyg, are of 0.039 mas and 0.047 mas.

Star	$(V-K)_0$	$\theta_{\mathrm{UD}}[mas]$	χ^2	U_R	θ_{LD} [mas]	$S_{\mathrm{v}}[mag]$
λ Aql	-0.265 ± 0.055	0.529 ± 0.003	1.0	0.301	0.544 ± 0.003	2.079 ± 0.030
γ Lyr	-0.102 ± 0.072	0.742 ± 0.010	2.9	0.402	0.766 ± 0.010	2.544 ± 0.059
γ Ori	-0.703 ± 0.097	0.701 ± 0.005	0.4	0.269	0.715 ± 0.005	0.909 ± 0.081
8 Cyg	-0.492 ± 0.147	0.229 ± 0.011	1.3	0.299	0.234 ± 0.011	1.456 ± 0.177
ι Her	-0.459 ± 0.076	0.304 ± 0.010	1.2	0.280	0.310 ± 0.010	1.225 ± 0.082
ζ Per	-0.592 ± 0.092	0.531 ± 0.007	1.2	0.343	0.542 ± 0.007	0.652 ± 0.081
ζ Peg	-0.204 ± 0.055	0.539 ± 0.009	1.7	0.442	0.555 ± 0.009	2.076 ± 0.152
δ Cyg	$+0.021 \pm 0.055$	0.766 ± 0.004	1.3	0.408	0.791 ± 0.004	2.318 ± 0.129

For the two rotators ζ Peg and δ Cyg in order to calculate the systematic error on the diameter determined by VEGA we derived the oblateness using the relation of van Belle et al. (2006), we found 1.07 and 1.06

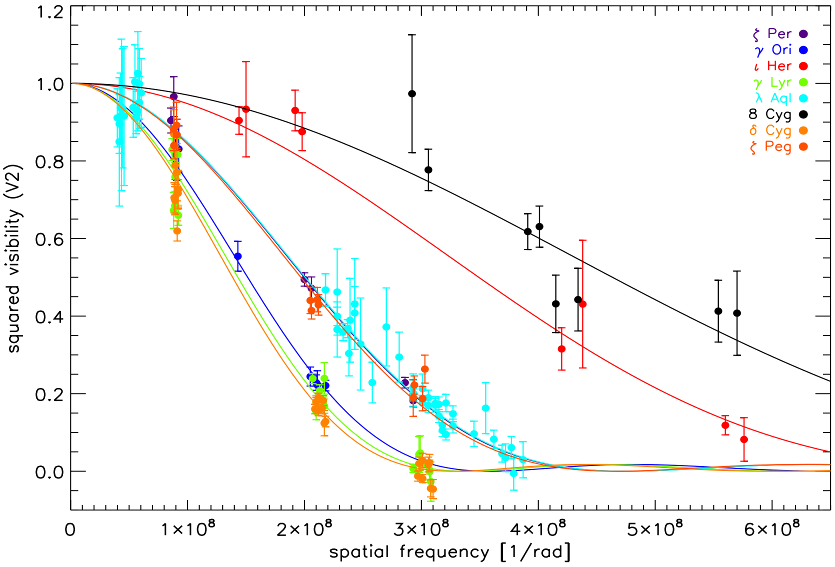

Fig. 1. Squared visibility for VEGA measurements of stars in our sample with their corresponding statistical uncertainties as function spatial frequency [1/rad]. The solid line is the model of the uniform disc angular diameter provided by the LITpro software.

respectively. Based on these two values we estimated the systematic error of about 0.039 mas for ζ Peg and 0.047 mas for δ Cyg.

The surface brightness S_V of a star is linked to its visual intrinsic dereddened magnitude m_{V_0} and its limb-darkened angular diameter θ_{LD}. In order to calibrate the SBC relation, we combine the eight limb-darkened angular diameters derived from the VEGA observations with different sets of diameters already available in the literature. We consider the angular diameter determination from Hanbury Brown et al. (1974a) (26 stars), Boyajian et al. (2012) (44 stars), Maestro et al. (2013) (9 stars) and Di Benedetto (2005) (45 stars). All the apparent magnitudes in V and K bands that we have collected from the literature are in the Johnson system (Johnson et al. 1966). For the dereddening of these magnitudes we need to calculate the extinction in the V band. We adopt the following strategy: For stars lying closer than 75 pc we using the simple relation $A_V = \frac{0.8}{\pi}$, where π is the parallax of the stars [in mas]. For distant stars we derive the absorption using the (B-V) extinction, $A_V = 3.1E(B-V)$ (Laney & Stobie 1993). We recalculate the intrinsic colors $(V-K)_0 = (V-K) - E(V-K)$ for all stars from the derived E(B-V) value using E(V-K)=2.7397E(B-V) (see Challouf et al. (2014)). Finally we find the relation:

$$S_{\rm v} = \sum_{n=0}^{n=5} C_n (V-K)_0^n \tag{3.1}$$

with, $C_0 = 2.624 \pm 0.009$, $C_1 = 1.798 \pm 0.020$, $C_2 = -0.776 \pm 0.034$, $C_3 = 0.517 \pm 0.036$, $C_4 = -0.150 \pm 0.015$, and $C_5 = 0.015 \pm 0.002$. This relation can be used consistently in the range $-0.9 \leq V-K \leq 3.7$ with $\sigma_{S_{\rm v}}$=0.10 mag.

4 Conclusions

In the present work, we determined the angular diameters of eight B- and A-type stars in the visible. We measured the visibilities calibrated for these stars with a good accuracy with typical precision of about 1.5% using the VEGA/CHARA instrument. These interferometric results are combined with other data and used by Challouf et al. (2014) to calibrate the surface brightness-color relation. They are found for the first time a relation with an accuracy of about 0.16 magnitude or 7% in term of angular diameter for -1≤V-K≤0 and a precision of 0.10 mag or 5% in term of angular diameter for V-K between -1 and 4. Further work is now in progress for quantifying the impact of rotation, in order to improve the accuracy of this relationship Sv, then applied to determine the distance of M31 and M33.

This research has made use of the SIMBAD and VIZIER (`http://cdsweb.u-strasbg.fr/`) databases at CDS, Strasbourg (France), and of the Jean-Marie Mariotti Center `Aspro` service (`http://www.jmmc.fr/aspro`) service and of electronic bibliography maintained by the NASA/ADS system. The research leading to these results has received funding from the European Community's Seventh Framework Programme under Grant Agreement 312430. The CHARA Array is funded by the National Science Foundation through NSF grants AST-0606958 and AST-0908253 and by Georgia State University through the College of Arts and Sciences, as well as the W. M. Keck Foundation. This research has largely benefited from the support, suggestions, advice of our colleague Olivier Chesneau, who passed away this spring. The whole team wish to pay homage to him.

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