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CALIBRATION OF THE SURFACE-BRIGHTNESS RELATION OF B EARLY TYPE STARS: TOWARDS A VERY ACCURATE DISTANCE DETERMINATION OF LMC ECLIPSING BINARIES

M. Challouf[1,2], N. Nardetto[1], D. Mourard[1], H. Aroui[2] and O. Chesneau[1]

Abstract. The eclipsing binaries are currently used to determine the distance of the Magellanic clouds with an accuracy of 2%. Eclipsing binaries observable in the Magellanic clouds are generally composed of bright stars, with B spectral types. But there is no surface brightness relation available for stars earlier then A0, which is a limitation of the method. We propose to extent the surface brightness relation to B stars using VEGA/CHARA interferometric observations. In this paper, we present preliminary results on three stars: HD 186882, HD 176437 and HD 35468 (B2 to B9). Thirteen stars in total will be observed in a near future with VEGA/CHARA.

Keywords: angular diameters, surface brightness, distance, LMC, SMC, HD 186882, HD 176437, HD 35468

1 Introduction

The Large Magellanic Cloud (LMC) is an irregular dwarf galaxy and a companion to our own Milky Way Galaxy. Unlike spiral and elliptical galaxies, irregular galaxies lack any appearance of organized structure. Like its neighboring Small Magellanic Cloud (SMC), the LMC appears as a huge and diffuse cloud in the southern nighttime sky. The measurement of distances to the LMC in the century revolutionized our understanding of the distance scale of the Universe and provided the evidence for universal expansion. The distance to the LMC is a critical rung on the cosmic distance ladder, and numerous independent methods (utilizing, for example, RR Lyrae stars, Cepheids and red clump giant stars) have been employed to determine it. The use of eclipsing binaries in the LMC is a promising method (Pietrzyński et al. 2009; Graczyk et al. 2012). Recently, the LMC distance was determined with an accuracy of 2% using 8 eclipsing binaries (Pietrzyński et al. 2012, Nature, submitted). The method consists of combining the radii of the stars determined from spectro-photometric observations with their angular diameter derived from the surface brightness relation (hereafter SB relation). Currently, the largest limitation of the method is the uncertainty on the relationship SB. Increasing the accuracy of the SB relationship of FGK stars (by a factor 2) would allow a 1% precision on the distance of the LMC. Besides, constraining the SB relation for B stars would allow the use of brighter eclipsing binary systems, and thus helps to increase the number of distant objects detected. The aim of this work is to improve our understanding of the SB relationship (especially for B stars) using interferometry. For this, we use the interferometer VEGA on CHARA (Mourard et al. 2009). This instrument operates in the visible and benefits from bases CHARA interferometer (Ten Brummelaar et al. 2005). It has a spatial resolution of 0.3 mas, which makes it an ideal tool to determine diameters of stars. In Sect. 2, we describe the determination of angular diameter for 3 stars (δ Cyg, γ Ori, γ Lyr) and in Sect. 3, we show how these diameters are used to test the relationship of Di Benedetto (2005), which is currently widely used for the determination of the distances of eclipsing binaries in the LMC.

2 Angular diameter of δ Cyg, γ Ori and γ Lyr

Using VEGA/CHARA interferometer, we first determine the uniform disc angular diameter of the three stars in our sample.

[1] Laboratoire Lagrange, UMR 7293, UNS/CNRS/OCA, 06300 Nice, France.
[2] Laboratoire Dynamique Moléculaire et Matériaux Photoniques, UR11ES03, UT2/ESSTT, Tunis, Tunisia.

2.1 Uniform Disk (UD) angular diameter

δ Cygni (HD 186882) has a spectral type of B9.5III, a magnitude of 2.86 and its index color is 0.04. This star was observed with the VEGA instrument of the CHARA Array the 23rd and 27th of July, 2011 (refer to Table 1 for details). The visibilities have been calibrated using the procedure described in Mourard et al. (2009). We find an angular diameter of 0.764 ± 0.005 mas with a reduced χ^2 of 1.67 and an accuracy of about 0.7% (Figure 1).

Table 1. Journal of the observations of δ Cyg, γ Lyr an d γ Ori. The sequence of calibration are given with T for the target and C for the calibrators: C1=HD 185872 (0.198 ± 0.014 mas), C2=HD 184875 (0.291 ± 0.021 mas), C3=HD 178233 (0.393 ± 0.029 mas), C4=HD 34989 (0.129 ± 0.009 mas), C5=HD 37320 (0.152 ± 0.011 mas).

Star	Date	Telescope	Seq	λ [nm]	$\Delta\lambda$ [nm]	HA [h]	Base [m]	V^2 [mas]
δ Cyg	23/07/2011	E1E2W2	C1TC1	715	20	−0.160	66	$0.717_{\pm 0.035}$
						−0.262	155	$0.124_{\pm 0.032}$
						−0.262	220	–
				735	20	−0.153	66	–
							155	$0.190_{\pm 0.011}$
							220	$0.018_{\pm 0.010}$
	23/07/2011	E1E2W2	C1TC1	715	20	1.484	65	–
						1.460	154	$0.182_{\pm 0.012}$
						1.460	219	$0.022_{\pm 0.021}$
				735	20	1.491	65	$0.705_{\pm 0.038}$
						1.481	154	$0.179_{\pm 0.011}$
						1.500	219	$0.020_{\pm 0.017}$
	27/07/2011	E1E2W2	C1TC2	715	20	0.815	66	$0.726_{\pm 0.049}$
							156	$0.128_{\pm 0.013}$
							221	–
				735	20		66	$0.789_{\pm 0.049}$
							156	$0.157_{\pm 0.014}$
							221	$0.027_{\pm 0.018}$
	27/07/2011	E1E2W2	C2TC1	715	20	1.610	65	$0.771_{\pm 0.073}$
							154	$0.163_{\pm 0.014}$
							218	$0.017_{\pm 0.019}$
				735	20		65	–
							154	$0.160_{\pm 0.012}$
							218	$-0.012_{\pm 0.012}$
γ Lyr	27/07/2011	E1E2W2	C3TC3	715	20	−0.916	65	$0.796_{\pm 0.047}$
						−0.885	155	$0.181_{\pm 0.029}$
						−0.885	220	$0.022_{\pm 0.022}$
				735	20	−0.916	66	–
						−0.901	155	$0.227_{\pm 0.009}$
						−0.901	220	$-0.007_{\pm 0.070}$
	01/09/2011	E1E2W2	C3TC3	715	20	1.060	64	–
						1.065	152	$0.134_{\pm 0.018}$
						1.065	216	–
				735	20	1.060	65	$0.785_{\pm 0.047}$
						1.070	152	$0.181_{\pm 0.015}$
						1.070	216	$-0.010_{\pm 0.010}$
γ Ori	12/10/2011	E1E2W2	C4TC4	731.5	23	−2.150	150	$0.256_{\pm 0.008}$
						−2.150	214	$0.002_{\pm 0.013}$
	13/10/2011		C4TC5	731.5	23	−1.705	154	$0.221_{\pm 0.013}$
						−1.705	219	$0.019_{\pm 0.018}$

γ Lyr (HD 176437) is a giant star with a stellar classification of B9III and its index colour $V - K$ is 0.01. The measured angular diameter of this star is determined by two observations that were performed on 27th of July and 1st of September, 2011. The fit of the data are shown in Figure 1. The uniform-disk model diameter is 0.739 ± 0.007 mas with reduced χ^2 is 4.0 and with accuracy around 0.9%.

γ Ori (HD 35468) is B2III spectral type stars and its colour index is -0.70. We observed this star on 12th and 13th of October, 2011. The estimation of the angular diameter equal to 0.714 ± 0.006 mas with reduced χ^2 is 3.7 and with accuracy around 0.8%.

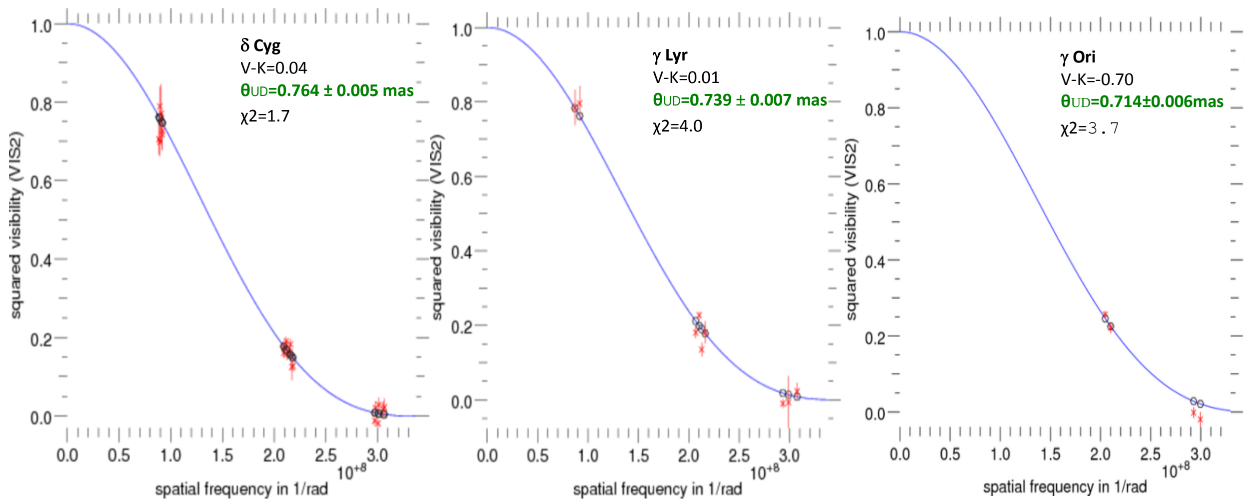

Fig. 1. The red points are the calibrated visibilities obtained with the VEGA interferometer and the solid blue line is the best model of uniform disk of the star (the angular diameter is the only parameter).

2.2 *Limb-darkened (LD) angular diameter*

The limb-darkening corrections (U_λ), for converting uniform-disc angular diameters to limb-darkened angular diameters, have been computed using stellar atmosphere models by Claret & Bloemen (2011), using the following stellar parameters: effective temperatures ($T_{\rm eff}$), surface gravities ($\log g$) and metallicity ($[Fe/H]$). The conversion factor between uniform and limb darkened diameters as defined by Hanbury Brown et al. (1974) is:

$$\theta_{LD}(\lambda) = \frac{\rho(\lambda)}{\theta_{UD}(\lambda)} \tag{2.1}$$

with

$$\rho(\lambda) = \left[\frac{(1 - \frac{U_\lambda}{3})}{(1 - 7\frac{U_\lambda}{15})} \right]^{1/2} \tag{2.2}$$

Table 2 summarises the stellar parameters of δ Cyg, γ Lyr and γ Ori found in the literature. We finally obtain $U_R = 0.3491$, 0.3434 and 0.2211 for our three stars, respectively.

Table 2. Stellar parameters used for δ Cyg, γ Lyr and γ Ori.

Star	$T_{\rm eff}$ [K]	log g	U_R	Reference
δ Cyg	9781	3.68	0.3491	Lanz (1987)
γ Lyr	9970	3.50	0.3434	Leggett et al. (1987)
γ Ori	21580	4.20	0.2211	Code (1976)

3 The surface-brightness relation

The surface brightness relationship is a very interesting relation for determining the extragalactic distance. It simply relies on the fact that the stars are good black bodies and that there is a relation of conservation between the surface flux in a given spectral band and the color of the star. According to the formula of Stefan, the bolometric flux L is connected to the effective temperature $T_{\rm eff}$ and the bolometric radius R of the star by:

$$L \propto R^2\, T_{\rm eff}^4 \tag{3.1}$$

So, the logarithm of the surface flux F defined by $F = \log(L/R^2)$ is directly related to the effective temperature of the star and thus to its colour. According to Barnes & Evans (1976), the surface flux in a given spectral band F_λ may be found from its absolute visual magnitude V_0 and true apparent angular diameter θ_{LD}:

$$S_v = V_0 + 5\log\theta_{LD} \tag{3.2}$$

Then, the interferometric measurements of angular diameters are used to calculate the surface brightness for each star. We are therefore able to calibrate the surface brightness relation. Conversely, once calibrated, this relationship allows an estimate of the photometric angular diameter of eclipsing binaries. Combined its angular diameter photmetric with its radius, it is possible to determine the distance of the star. Di Benedetto (2005) gives a fit of this relation using 44 stars over the color range $-1 \leq (V-K)_0 \leq 3.7$:

$$S_v = [2.565 \pm 0.016] + [1.483 \pm 0.015](V-K)_0 - [0.044 \pm 0.005](V-K)_0^2 \tag{3.3}$$

Figure 2 shows a fit of the surface brightness relation using 88 stars (points of Benedetto and Boyajian) in A, F, G and K spectral types. Using all these measurement, we find a revised relation of:

$$S_v = [2.669 \pm 0.009] + [1.340 \pm 0.011](V-K)_0 - [0.007 \pm 0.003](V-K)_0^2 \tag{3.4}$$

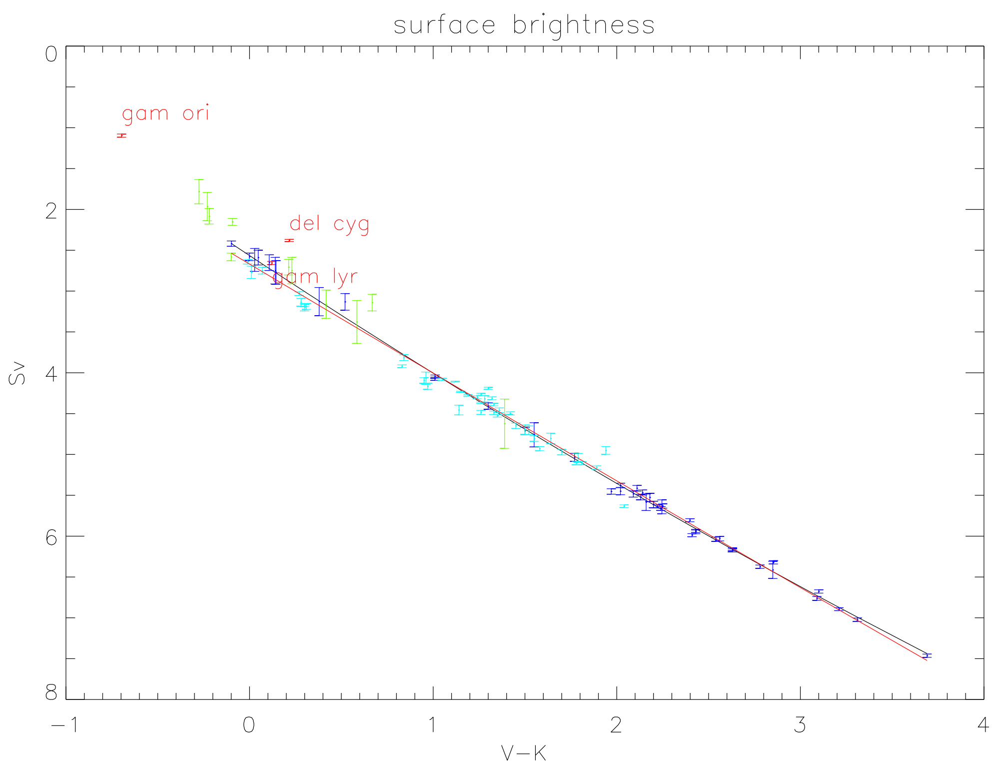

Fig. 2. The relation between visual surface-brightness parameter S_v as a function of the colour index $V-K$. The dark blue points represent the angular diameters of 44 stars that Di Benedetto (2005) established accurately. The light blue points indicate angular diameters of 44 stars determined meticulously by Boyajian et al. (2012). The black line is the fit of Di Benedetto and the red line is the fit using the points of Di Benedetto and Boyajian.

Fig. 2 also shows the VEGA measurements of Table 3 for the three stars: γ Ori, γ Lyr and δ Cyg. Eleven measurements by Hanbury Brown et al. (1974) (green dots) are shown. In the list of Hanbury Brown we removed stars in binary systems and fast rotating stars.

Table 3. VEGA/CHARA angular diameter obtained for δ Cyg, γ Lyr and γ Ori.

Star	$V-K$	θ_{UD}	θ_{LD}	S_v
δ Cyg	0.216	0.764 ± 0.005	0.785 ± 0.005	2.3682 ± 0.0013
γ Lyr	0.121	0.739 ± 0.007	0.759 ± 0.007	2.6439 ± 0.0020
γ Ori	-0.697	0.714 ± 0.006	0.728 ± 0.006	0.9552 ± 0.0020

4 Conclusion

We determined the interferometric angular diameters of three stars using the VEGA/CHARA interferometer. The capabilities of VEGA are shown with relative precision on the angular diameter of 1%. Including recent results by Boyajian et al. (2012) (44 stars), we find that the relation by Di Benedetto (2005) is slightly modified and the precision improved. However, more work is necessary to select the star carefullly depending on their class and fundamental characteristics in order to avoid any bias. In particular for B stars, the impact of a wind is not excluded and will be studied. Such study will be possible only with a larger sample of B stars. In total, we expect to observe 10 more stars with the VEGA/CHARA interferometer. Some observations are already on-going. This work, fully part of my PhD, is fundamental to improve the method of distance determination of eclipsing binaries in the LMC and SMC.

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