Annuaire de l'Universite de Sofia "St. Kliment Ohridski", Faculte de Physique v. 105, 2012

CYG OB2 ASSOCIATION – STELLAR POPULATION AND EXTINCTION

ANTONIYA VALCHEVA, EVGENI OVCHAROV, TOSHO KARADZHOV, PETKO NEDIALKOV

Department of Astronomy
Faculty of Physics, St. Kliment Ohridski University of Sofia

Антония Вълчева, Евгени Овчаров, Тошо Караджов, Петко Недялков. АСОЦИАЦИЯТА CYG OB2 – ЗВЕЗДНО НАСЕЛЕНИЕ И ЕКСТИНКЦИЯ

Изследвана е галактичната OB асоциация Cyg OB2 чрез UBV CCD фотометрия, получена с 50/70 cm Щмид-телескоп на НАО Рожен, България. Получени са UBV звездните величини на 2930 звезди, като 105 са с определен спектрален клас [1], [2]. Използвана е диаграмата (*U-B*)–(*B-V*), за да бъдат отделени най-младите членове на Cyg OB2 – 389 звезди от O+ранен B спектрален клас. За да се определят индивидуалните екстинкции към всяка от тях е използвана крива на почервеняване по зрителния лъч към Лебед [3], а получените *E*(*B–V*) варират от 1 до 3.3 mag. Построена е карта на екстинкцията, която показва повишена екстинкция към центъра на асоциацията.

Antoniya Valcheva, Evgeni Ovcharov, Tosho Karadzhov, Petko Nedialkov. CYG OB2 ASSOCIATION – STELLAR POPULATION AND EXTINCTION

We studied the galactic OB association Cyg OB2 using UBV CCD photometry carried out with the 50/70 cm Schmidt telescope at the NAO Rozhen, Bulgaria. UBV magnitudes of 2930 stars are obtained as 105 of them have spectral type [1], [2]. We used the diagram (*U-B*) vs. (*B–V*) to separate the youngest stars, candidates for association membership – 389 O+early B stars. We determined individual extinctions towards them using reddening curve along the Cygnus sight line [3] and derived *E*(*B–V*) vary from 1 to 3.3 mag. Constructed extinction map in the region of Cyg OB2 shows higher extinction towards the center of the association.

Keywords: OB associations individual: Cygnus OB2, photometry, extinction
PACS numbers: 97.10.-q; 97.10.Ri; 97.20.Ec

For contact: Antoniya Valcheva, Department of Astronomy, St. Kliment Ohridski University of Sofia, 5 J. Bourchier Blvd, Sofia 1164, Phone: +359 2 8161 716, E-mail: valcheva@phys.uni-sofia.bg.

1. INTRODUCTION

The galactic OB association Cyg OB2 contains one of the hottest and most luminous stars known. It is characterized with very high values of the extinction because of the congestion of molecular and dust clouds along its line of sight. A member of Cyg OB2 is one of the brightest and highly reddened star in the Galaxy – VI Cyg No.12 with $Av \sim 10.31$ mag [1]. The association was first noticed by [4], who called attention to this “probable clustering of blue giants.” The photometry of [5] reveals 14 members of spectral type B1 and earlier. These stars were found to be highly reddened, with values of *E(B-V)* ranging from 1.4 mag to 2.3 mag. Detailed photographic *UBV* study by [6] and [7] identified several hundred OB stars as possible members based upon their location in a two-color plot. Recently, the stellar content of Cyg OB2 have been investigated by [1] using *UBV* CCD photometry and spectroscopy. In the field of 4 overlapping fields of 19.5×19.5 arcmin^2, they found 108 stars with $Q < -0.70$, corresponding to B1.5 and $V < 15$ mag, 76 of them with spectroscopy.

The morphology and stellar content of Cygnus OB2 association has been also determined by [8] using 2MASS JHK bands. The analysis reveals a spherically symmetric association of 2º in diameter with a half-light radius of 13’. The interstellar extinction for member stars ranges from $Av \sim 5$ mag to 20 mag, which led to a considerable underestimation of the association size in optical studies. From the infrared color-magnitude diagram, the number of OB member stars is estimated to 2600 ± 400, while the number of O stars amounts to 120 ± 20. Spectroscopic observations in the optic indicate that Cyg OB2 is poorer of O stars [9] than it is considered before. However, only 37 O stars in this association [2] were confirmed spectroscopically.

2. OBSERVATIONS AND PHOTOMETRY

The observations were carried out on 2010 September 14, 15 and 16 with the 50/70 cm Schmidt telescope at the NAO Rozhen, Bulgaria. The telescope is equipped with FLI PL 16803 CCD camera with 4096×4096 pixels. The scale is 1.1 arcsec/pixel and the frame covers 74×74 arcmin^2 field. Observations were made with the standard Johnson *UBV* pass-bands. Dark frames are used to remove the amount of dark current produced by heat and accumulated in the pixels during an exposure and images of twilight sky are used to remove pixel-to-pixel and larger scale gain variations.

We obtained 19×300 sec exposures in U filter, 17×300 sec in B and 13×300 sec in V filter, centered on the optical center of Cyg OB2 (RA(J2000) = 20:32:45 DEC(J2000) = +41:28:26.6). The seeing of the images typically had a full width at half maximum (FWHM) of 2.5–3.0 pixels (~ 3”). Exposures in every filter were calibrated and sum to obtain the final images.

It turned out that the PSF is varying across the image and this necessitates the performance of aperture photometry. The Cyg OB2 images are not all that crowded and this will give satisfying results. Aperture photometry was performed using standard IRAF routines and aperture radius on each pass-band equals to its average FWHM. As a result, we obtained in our field 2930 stars with simultaneously *UBV* photometry and limiting magnitude of ~17.2 mag in *V* pass-band. Photometric conditions during all observing nights did not allow us to obtain standard stars fields and we used photometry of [1] for absolute calibration of our photometry. Calibration was obtained using 587 stars in *U*, *B* and *V* pass-bands as 105 stars have known spectral type [1], [2]. The resulting calibration equations were:

$$B = b + 0.178(\pm 0.009)\times(b\text{-}v) - 2.041(\pm 0.008)$$
$$(U\text{-}B) = 0.898(\pm 0.011)\times(u\text{-}b) - 1.535(\pm 0.023)$$
$$(B\text{-}V) = 1.288(\pm 0.012)\times(b\text{-}v) - 0.161(\pm 0.009)$$

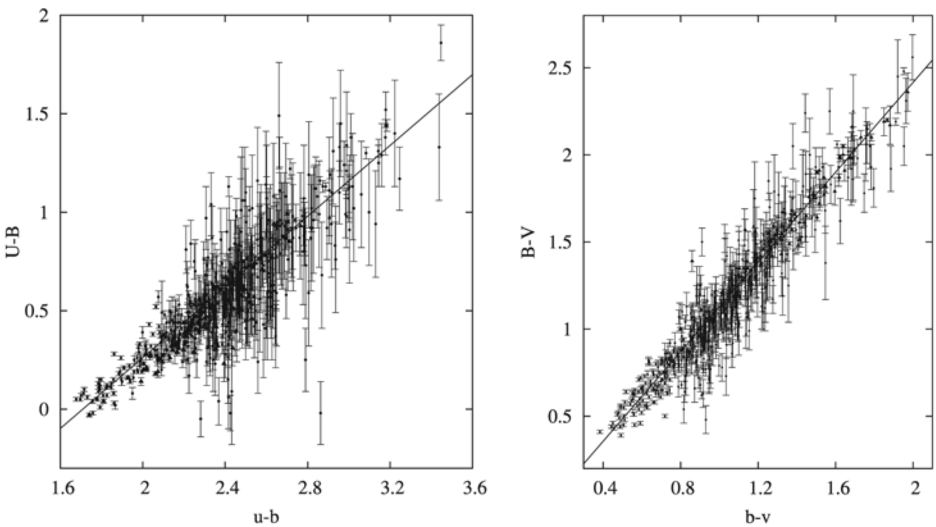

Fig. 1. Standard (*U–B*), (*B–V*) versus instrumental colors (*u–b*), (*b–v*). The fit lines have form *a+b*x*. The calibration equations are given in the text.

The stars with instrumental magnitude brighter than ~14.2 mag in filter *V* are not saturated but fall in the non-linear dynamical range of the CCD camera. This requires application of an aperture correction for all the stars with instrumental magnitudes brighter than 14.2 in *V*-band. It amounts to 0.42 mag for brightest detected non-saturated stars at standard *V* = 11.5 mag. As we are interested mostly in colors of the stars it is appropriate to calibrate them directly. Calibration diagrams for the colors (*U–B*) and (*B–V*) are shown in Fig. 1. *UBV* represents the magnitudes in standard system from [1] and *ubv* represents our instrumental magnitudes.

The instrumental error produced by the aperture photometry is an estimation of the Poisson statistics of the number of counts in the digital aperture, the read noise of the CCD, and the actual variation in the sky annulus. Adding the fitting errors, the distributions of final photometric errors with the standard magnitude are shown in Fig. 2 for the three pass-bands.

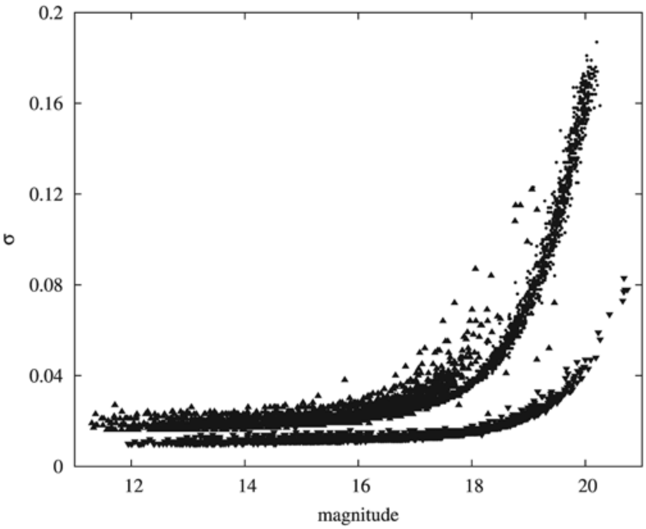

Fig. 2. Photometric 1 sigma errors as a function of the standard magnitude. Dots, reverse triangles and triangles represent the data in *U*, *B* and *V* pass-bands, respectively.

3. STELLAR POPULATION AND EXTINCTION

3.1. COLOR-MAGNITUDE DIAGRAM

We used the photometry of the 2930 stars with *UBV* magnitudes to construct a color-magnitude diagram for Cyg OB2 (see Fig 3). We cross-identified 105 stars from the list of [1] and [2] which have determined spectral types. Their positions are indicated with filled triangles in Fig. 3. These are the brightest and earliest type members of Cyg OB2.

The crucial point here is the separation of association members from foreground stars. Diagrams are strongly contaminated of F and G foreground stars as we expect from the small galactic latitude of the association (b~1°). The main sequence of Cyg OB2 can be clearly seen on *V* vs. (*B–V*) diagram (Fig. 3, left) but there are large number of heavily reddened bright stars. Unfortunately, this diagram can not be used to distinguish between foreground red stars and reddened cluster members. [1] showed that condition $E(B–V) > 1.2$ may be imposed for a star to be taken as an association member. The reddening-free index Q (Fig. 3, right), which shows good separation between younger members of the association ($Q < –0.4$ for B5 and earlier spectral class) and contaminating stars is also not enough to separate foreground and heavily reddened members, as the foreground F and G dwarfs will be found to have Q's ($Q = (U-B)-0.8 \times(B-V)$) similar to that of mid-B stars. Q index separates the stars only at the bright end on the diagram.

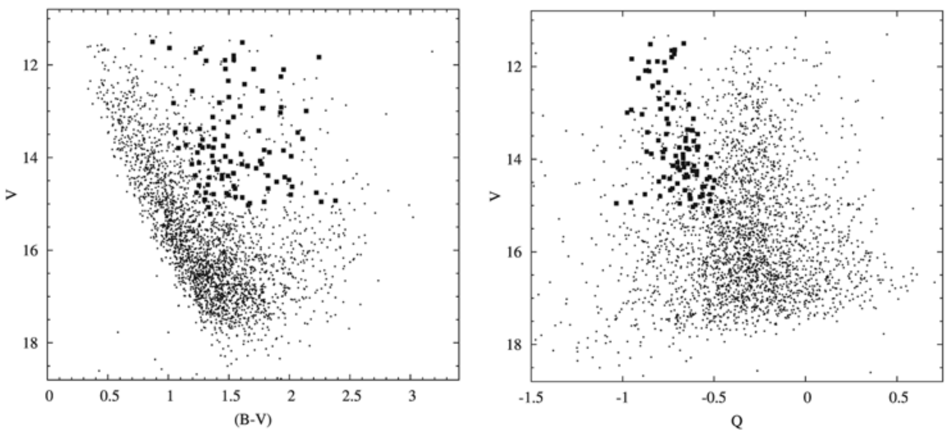

Fig. 3. *Left*: color-magnitude diagram V vs. $(B–V)$ for all 2930 stars (dots) with *UBV* photometry and 105 stars with known spectral types (filled squares) [1], [2] in the field of Cyg OB2. *Right*: diagram V vs. reddening-free parameter Q ($Q = (U–B) – 0.8\times(B–V)$) (see Section 3.1). Designations are the same as in the left.

The crucial point here is the separation of association members from foreground stars. Diagrams are strongly contaminated of F and G foreground stars as we expect from the small galactic latitude of the association (b~1°). The main sequence of Cyg OB2 can be clearly seen on V vs. $(B–V)$ diagram (Fig. 3, left) but there are large number of heavily reddened bright stars. Unfortunately, this diagram can not be used to distinguish between foreground red stars and reddened cluster members. [1] showed that condition $E(B–V) > 1.2$ may be imposed for a star to be taken as an association member. The reddening-free index Q (Fig. 3, right), which shows good separation between younger members of the association ($Q < –0.4$ for B5 and earlier spectral class) and contaminating stars is also not enough to separate foreground and heavily reddened members, as the foreground F and G dwarfs will be found to have Q's ($Q = (U-B)-0.8 \times(B-V)$) similar to that of mid-B stars. Q index separates the stars only at the bright end on the diagram.

The only reliable way to separate the candidate-members of the association is to select only the most massive and young (O+earlier B) stars on the two-color (*U–B*) vs. (*B–V*) diagram.

3.2. TWO-COLOR DIAGRAM

When a good *UBV* photometry for a large number of stars is available it is possible to derive a proper correction for interstellar extinction on two-color plot. Thus, the only reliable extinction information can be related to O+early B stars. We show in Fig. 4 (left) the two-color diagram for all 2930 stars with *UBV* photometry and 105 spectroscopically confirmed OB stars (59 of them are earlier than B1.5) of Cyg OB2. As a first approximation reddening will move stars along the straight solid line with a slope of $E(U–B)/E(B–V) = 0.8$ [1].

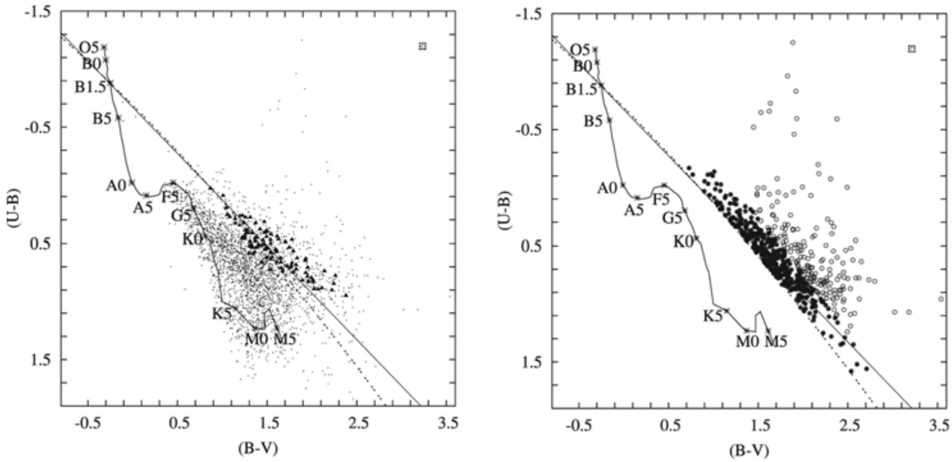

Fig. 4. *Left*: Two-color diagram for all 2930 stars with *UBV* photometry (dots) and 105 OB stars with known spectral class (filled triangles) in the field of Cyg OB2. The curve shows the relation of intrinsic colors for main-sequence stars (some spectral types are indicated), taken from [3]. The straight solid line with a slope of 0.8 [1] is the reddening line for a B1.5V star. When curvature $\beta = 0.05$ of shallower slope of 0.75 is taken into account the reddening will move stars along a parabola (shown with dashed line for B1.5V star). *Right*: two-color diagram for 576 O+early B star-candidates. Filled circles present 389 successfully dereddened stars and open circles are 187 stars which apparent colors do not allow proper dereddening with the adopted parameters. Typical error of colors is shown in the right upper corner.

When curvature $\beta = 0.05$ and shallower slope 0.75 [3] is taken into account the reddening will move stars along a parabola. We used this parabola to move every star to the sequence of intrinsic colors and derive its spectral type and respectively its intrinsic color. Only for B1.5 and earlier spectral types, this operation has one solution. In such way we distinguish between O+early B candidates (lay above the parabola) and other stars in the association. Two-color diagram for the candidate-stars is presented in Fig. 4 (right).

For 187 stars (open circles), the apparent colors do not allow proper dereddening with the adopted parameters and they are excluded. However, for 389 (filled circles) O+early B candidate-stars an extinction estimation can be made.

3.3. CYG OB2 MASSIVE STARS AND EXTINCTION

389 O+early B stars could be successfully dereddened as their colors allow proper estimation of the extinction with the adopted reddening line slope and curvature from [3]. Fig 5 shows the position of these stars on *V* vs. (*B–V*) diagram (left) and *V* vs. *Q* diagram (right).

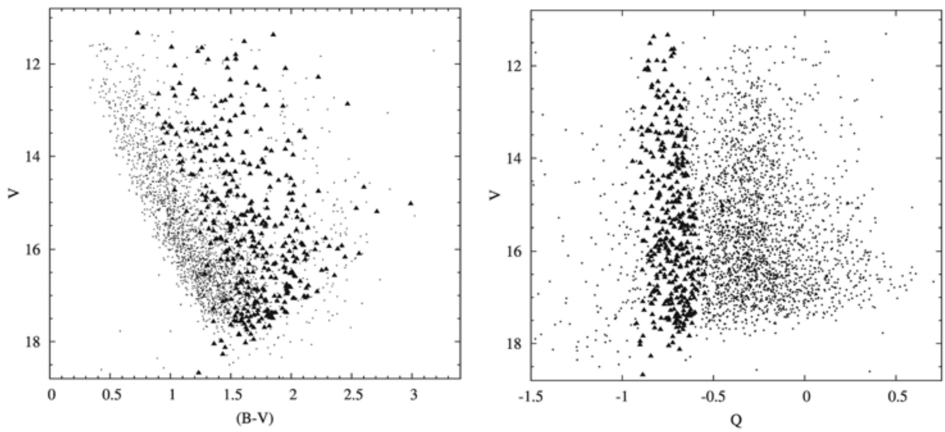

Fig. 5. *Left*: color-magnitude diagram *V* vs. (*B–V*) for all 2930 stars with UBV photometry (dots) and 389 selected candidates of O+early B spectral class (filled triangles) in the field of Cyg OB2. *Right*: diagram V vs. reddening-free parameter *Q* ($Q = (U–B) – 0.8×(B–V)$). Designations are the same as in the left.

In Fig. 6 (left) we compared the spatial distribution of all 2930 stars with *UBV* photometry and 389 successfully dereddened O+early B star-candidates. We roughly indicate there the position of Cyg OB2 as determined by [7] and [8] in optic and IR, respectively. The stellar density is highest in the regions, previously defined as Cyg OB2.

Derived individual extinctions *E*(*B–V*) vary between 1 mag and 3.3 mag. Using these estimations, an extinction map in the field of Cyg OB2 was constructed (Fig. 6, right). The mean extinction values were smoothed additionally with a boxcar filter of 20×20 arcmin^2. The isolines are at *E*(*B–V*) levels: 0.25 mag to 2.2 mag with a step of 0.25 mag. According to the obtained extinction map the mean color excess increases toward the center of the Cyg OB2, which is possibly the reason the true shape of the association to be hidden in the optical, as already pointed out by [8] on the base of IR photometry. Due to the fact that our photometry went 2 mag deeper than the photometry of [1] we were able to detect more heavily obscured stars.

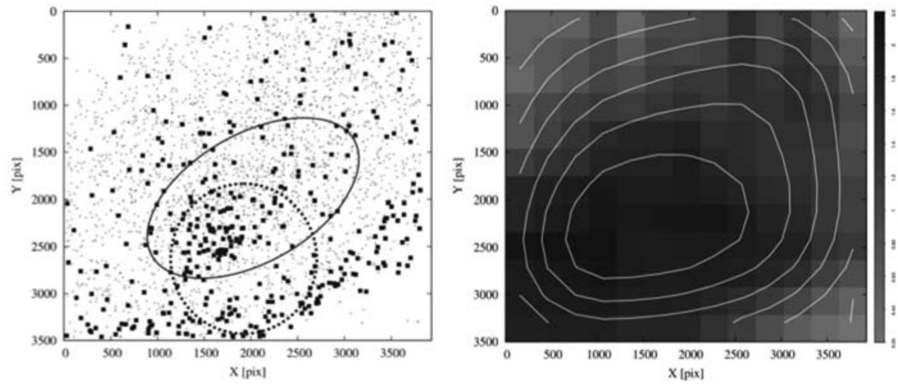

Fig. 6. *Left*: spatial distribution of all 2930 stars (dots) with *UBV* photometry and 389 successfully dereddened O+early B star-candidates (filled squares). The ellipsoid roughly indicates the size and position of Cyg OB2 as determined by [7] and the dashed circle indicates the center and the half light radius as derived by [8] on the base of *JHK* photometry. *Right*: extinction map in the field of Cyg OB2 based on successful dereddenings along 389 sight lines towards O+early B star-candidates. The mean extinction estimates were smoothed additionally with a boxcar filter of 20×20 arcmin^2 . The isolines are at $E(B–V)$ levels: 0.25 mag to 2.2 mag with a step of 0.25 mag. On both panels North is to the top and East is to the left.

4. CONCLUSION

We studied 71.5×64.2 arcmin^2 in the field of the galactic OB association Cygnus OB2. Our *UBV* photometry leaded to 2930 stars with *UBV* photometry in the field. 389 O+early B star-candidates, members of Cyg OB2, were selected on the two-color diagram ($U–B$) vs. ($B–V$) applying reddening curves technique. 389 individual extinction estimates $E(B–V)$ were made and they vary from 1 to 3.3 mag. Extinction map in the field of Cyg OB2 association based on successful dereddenings along 389 sight lines towards O+early B star-candidates was constructed and shows that the place of highest extinction on the map coincides with the place of highest early star's density.

Acknowledgements. This work was supported by the grant: SU-157/2010 of St. Kliment Ohridski University of Sofia.

REFERENCES

[1] Massey, Ph., and A. B. Thompson. *AJ*, 1991, **101**, 1408.
[2] Kiminki, D. C. et al. *AJ*, 2007, **664**, 1102.
[3] FitzGerald, M. P. *A&A*, 1970, **4**, 234.
[4] Munch, L., and W. W. Morgan. *ApJ*, 1953, **118**, 161.
[5] Johnson, H. L., and W. W. Morgan. *ApJ*, 1954, **119**, 344.
[6] Lawrence, L. C., and V. C. Reddish. *Publ. R. Obs. Edinburgh*, 1965, **3,** 275.
[7] Reddish, V., L. Lawrence, and N. Pratt. *Publ. R. Obser. Edinburgh*, 1967, **5**, 111.
[8] Knödlseder, J. *A&A*, 2000, **360**, 539.
[9] Hanson, M. *ApJ*, 2003, **597**, 957.