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UBVRI CCD photometry of the OB associations Bochum 1 and Bochum 6

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Abstract. We report the first deep *UBVRI* CCD photometry of 2460 stars in the field of two poorly studied OB associations Bochum 1 and Bochum 6. We selected 15 and 14 probable members in Bochum 1 and Bochum 6 respectively using photometric criteria and proper motion data of Tycho 2. Our analysis indicates variable reddening having mean value of $E(B-V) = 0.47\pm0.10$ and 0.71 ± 0.13 mag for Bochum 1 and Bochum 6 respectively. Using the zero-age main-sequence fitting method, we derive a distance of 2.8 ± 0.4 and 2.5 ± 0.4 Kpc for Bochum 1 and Bochum 6 respectively. We obtain an age of 10 ± 5 Myrs for both the associations from isochrone fitting. In both associations high and low mass stars have probably formed together. Within the observational uncertainties, mass spectrum of the both associations appears to be similar to the Salpeter's one.

Keywords : OB Associations: Bochum 1 and Bochum 6 - Star: Interstellar extinction, luminosity function, mass function - HR diagram.

1. Introduction

The study of young stellar systems in a galaxy provides useful information on its structure and formation history. Most of the stars are born as members of stellar groups of different types (Gomez et al. 1993; Massey et al. 1995). Stellar associations being typically loose stellar systems (Blaauw 1964) characterized by their bright blue stellar populations, are considered tracers of the distribution of the youngest population in a galaxy. Moffat

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Table 1. General information of the objects under study, taken from Dias et al. (2002).

Objects	α_{2000}	δ_{2000}	Radius (arc min)	Distance (Kpc)	$E(B-V)$ (mag)	log(age)
Bochum 1	$06^h25^m27^s$	$19^d46'15''$	-	2.8	0.50	6.7
Bochum 6	$07^h32^m00^s$	$-19^{\circ}26'27''$	5.0	3.9	0.70	7.0

and Vogt (1975) suggest that Bochum 1 is a group of 9 OB stars in which 8 stars show a sequence in the UBV colour-colour (CC) and colour-magnitude (CM) diagram and hence can be considered at the same distance of 4.06 Kpc from Sun. They derived a mean reddening of $E(B-V) = 0.45\pm0.06$ mag in the direction of the object. Recently Fitzsimmons (1993) presented the CCD Strömgren uvby photometry of 9 stars in the Bochum 1 region and found that Bochum 1 is 2×10^7 yrs old and located at a slightly larger distance of 4.8 Kpc. Moffat and Vogt (1975) also studied Bochum 6 for the first time and conclude that this is a group of 5 OB stars. They also indicated that the object appears to coincide with the HII region S 309 for which Georgelin et al. (1973) gives photometric distance of 6.30 Kpc and Kinematic distance of 2.24 ± 0.36 Kpc. Moffat & Vogt (1975) derived a mean value of reddening $E(B-V) = 0.70\pm0.10$ mag, and distance 4.0 Kpc which lies almost midway between Georgelin et al.'s two independent estimates. Other basic informations about both Bochum 1 and 6 are given in Table 1. For both the objects available photometric studies are limited to the stars brighter than $V \sim 12.5$ mag. We therefore obtained first deep $UBVRI$ CCD photometric data and used them in combination with the available kinematical data for better estimation of basic parameters, such as reddening, distance and age. Such parameters are valuable for understanding the disk sub-system which these associations belong to. Although, deep photometric data is not much useful in our study but it is valuable in modelling of the Galaxy. The next section presents the observations and data reduction while the membership, reddening, distance and age etc. of both the objects are determined in the remaining part of the paper.

2. $UBVRI$ CCD Observations and data reductions

The CCD broad band photometric UBV (Johnson), RI (Cousins) observations were carried out using 2K$\times$2K CCD system at the f/13 Cassegrain focus of the Sumpurnanand 104-cm telescope of the State observatory, Nainital. The read-out noise and gain of the CCD system are 5.3 e^- and 10 e^-/ADU respectively. The $0.''36$/pixel plate scale resulted in a field of view of $12'.3\times12'.3$. For the accurate photometric measurements of fainter stars, 2 to 3 deep exposures were taken in each passband in 2×2 pixel binning mode. Further details of the observations are listed in Table 2. The covered region is shown in Fig 1 where DSS images is presented for both Bochum 1 and Bochum 6.

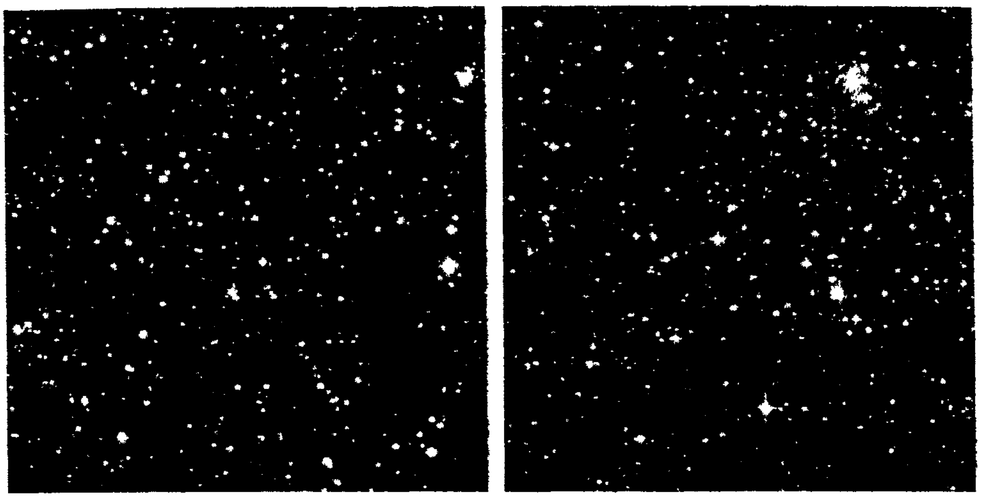

Figure 1. The 13′.0 × 13′.0 area of Bochum 1 and Bochum 6 taken from DSS. North is up and east is left.

The data have been reduced by using the IRAF, MIDAS and DAOPHOT software packages. The instrumental signatures were removed using bias and flats taken during the observing run by means of standard IRAF routines. Further reductions including profile magnitudes of the stars were performed using the DAOPHOT (Stetson 1987) in the MIDAS environment. To construct a point spread function (PSF) for the entire CCD frame on each exposure, we used typically 50 well isolated stars.

We observed SA 98 (Landolt 1992) standard field in *UBVRI* for calibrating the observations of Bochum 1 and 6. We used 7 standard stars for calibration purpose which are having 11–15 mag range in V and 0.1–2.0 mag range in $(V-I)$ colour. Thus the stars used for calibration cover a wide range in brightness as well as in colour. This standard field is also observed at different airmasses to obtain a reliable estimate of nightly atmospheric extinction coefficients.

The calibration equations obtained by observing standard field are :

$$u = U + 6.66 \pm 0.01 - (0.02 \pm 0.01)(U - B) + 0.45X$$
$$b = B + 4.62 \pm 0.01 - (0.04 \pm 0.01)(B - V) + 0.23X$$
$$v = V + 4.22 \pm 0.01 - (0.03 \pm 0.01)(B - V) + 0.13X$$
$$r = R + 4.15 \pm 0.01 - (0.04 \pm 0.01)(V - R) + 0.09X$$
$$i = I + 4.67 \pm 0.01 - (0.12 \pm 0.01)(R - I) + 0.05X$$

Table 2. Journal of *UBVRI* photometric observations of Bochum1 and Bochum 6. N is the number of stars measured in the filter.

Objects	Date	Exp. Time	Filters	N
Bochum 1	16 Jan 01	1800×3, 300	*U*	750
$\alpha_{2000} = 06^h25^m27^s$	"	1200×3, 240	*B*	993
$\delta_{2000} = +19^d46'15''$	"	900×3, 240	*V*	997
	"	900×3, 240	*R*	1000
	"	300×3, 60×2	*I*	1000
Bochum 6	03 Jan 00	1500×3, 900	*U*	270
$\alpha_{2000} = 07^h32^m00^s$	"	900×3, 180	*B*	1400
$\delta_{2000} = -19^d26'27''$	"	600×3, 120	*V*	1430
	"	240×3, 60	*R*	1430
	"	240×3, 60	*I*	1460

Table 3. Internal photometric errors as a function of brightness. σ is the standard deviation per observation in magnitude.

Magnitude range	σ_U	σ_B	σ_V	σ_R	σ_I
≤13.0	0.011	0.002	0.005	0.003	0.009
13.0 - 14.0	0.019	0.006	0.010	0.008	0.019
14.0 - 15.0	0.021	0.007	0.012	0.014	0.014
15.0 - 16.0	0.023	0.012	0.014	0.017	0.014
16.0 - 17.0	0.025	0.012	0.016	0.017	0.017
17.0 - 18.0	0.026	0.014	0.016	0.018	0.019
18.0 - 19.0	0.026	0.019	0.018	0.018	0.021
19.0 - 20.0	0.028	0.025	0.022	0.024	0.023

where U, B, V, R and I are standard magnitudes, u, b, v, r and i are the instrumental one corresponding to exposure time of 1 sec, and X is the airmass. The plots of colour equations are shown in Fig 2. The errors determined by least square fitting in zero points and colour coefficients are ~ 0.01. In Table 3, we list the internal errors as a function of brightness estimated on the S/N ratio of the stars as outputed by ALLSTAR programme of the DAOPHOT. There are 1000 and 1460 stars measured in the region of Bochum 1 and Bochum 6 respectively. The (X, Y) pixel coordinates and *UBVRI* magnitudes of the stars are available in electronic form from authors as well as from WEBDA site[1].

[1] http://obswww.unige.ch/webda/

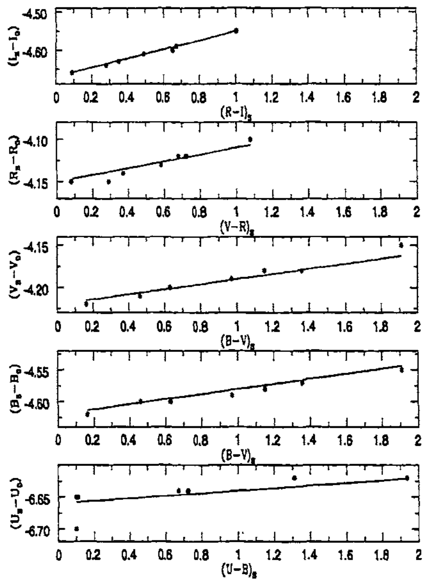

Figure 2. Plots of colour equations. Least square fitting is presented by the solid line.

3. The present study

3.1 Apparent colour-magnitude diagrams

The V vs $(U-B)$, $(B-V)$, $(V-R)$ and $(V-I)$ CM diagrams for all the stars detected in the region of Bochum 1 and Bochum 6 are shown in Fig 3. In V, $(U-B)$ and V, $(B-V)$ diagrams we have also plotted the brighter stars observed by Moffat & Vogt (1975) but not by us. In the CM diagram of Bochum 1, there is a poorly populated MS from $V = 8.5$ up to $V = 14$ mag. The stars on the red side of the MS appear to form a sequence parallel to the MS, that can be ascribed to Galactic disk field stars. Below $V \sim 14$ mag, MS if exists, can not be isolated from the strong field star contamination. In the case of Bochum 6, we have observed stars down to $V = 21$ mag and contribution of field stars is more after V ~14.5 mag. It is also well known that in OB associations only O and B type stars are found and hence probability of forming the fainter member is negligible. Therefore, we are interested only in brighter members of the associations. Separation of the members of these associations from the field stars is a difficult task in the absence of precise proper motion and/or radial velocity measurements for all the stars of the region. Proper motion measurement is available for 3 stars in Bochum 1 and 5 stars in Bochum 6 and has been used to separate the members of these associations. The detail description about the procedure is given in the next section. In addition to this we also adopted the photometric criteria in selection of probable members. According to this criteria a star is considered as a member which simultaneously having reconcilable position in colour-colour and colour-magnitude diagrams respectively. For this we defined the blue and red envelope of the MS in colour-magnitude diagrams. In this way 12 stars in Bochum 1 and 9 stars in Bochum 6 are separated as a probable members and they are listed in Table 4.

3.2 Evidence of clustering and membership

In the Tycho-2 catalogue (Høg et al. 2000), astrometric data is available for the region of Bochum 1 and Bochum 6. The accuracy (2 mas/yr) of Tycho-2 astrometric data is of the same order as of the Hipparcos data (Makarov et al. 2000). Because of the large number of stars down to $V = 12.5$ mag, the Tycho-2 catalogue may provide an opportunity for the separation of stars having similar motions as has been done earlier by Patat et al. (2001) for Bochum 9, 10 and 11 and by Carraro (2002) for NGC 133.

In the $30' \times 30'$ area centered on Bochum 1 and Bochum 6, Tycho-2 has provided the proper motion data for 30 and 50 bright ($V < 13$ mag) stars respectively. We present the vector point diagrams of these stars in Fig 4. The filled circles denote the probable members given by Moffat & Vogt (1975) and the horizontal and vertical bars represent the uncertainties in the proper motion components. A close inspection of vector point diagram of Bochum 1 indicates that a group (including 3 stars given by Moffat & Vogt (1975)) of stars are having approximately same proper motion component. Some stars are isolated and obviously are non-member of that group. In the case of Bochum 6, in spite of having large uncertainties in the proper motion component there seems to be a group of stars including those 5 stars which are observed by Moffat & Vogt (1975) having same motion within the error. In nutshell, we can say that there are indications that a small number of stars are clustered along the line of site of both Bochum 1 and Bochum 6. The average value of proper motion component of the group is $\mu_\delta = -0.33\pm1.15$ and $\mu_\alpha\cos(\delta) = 0.67\pm0.67$ for Bochum 1 and $\mu_\delta = 2.68\pm1.53$ and $\mu_\alpha\cos(\delta) = -5.02\pm2.24$ for Bochum 6. In this way we selected 3 stars in Bochum 1 and 5 stars in Bochum 6 having nearly same proper motion component and list them in Table 4. These stars are also selected as probable members using photometric method (see Sec 3.1). Finally, 15 and 14 stars in Bochum 1 and Bochum 6 respectively are selected as probable members using photometric as well as kinematical data and will be used in the further study.

3.3 Colour-Colour diagrams

To determine the reddening in the direction of the region Bochum 1 and Bochum 6, we plotted $(U - B)$ versus $(B - V)$ diagram of probable members in Fig 5. The reddening

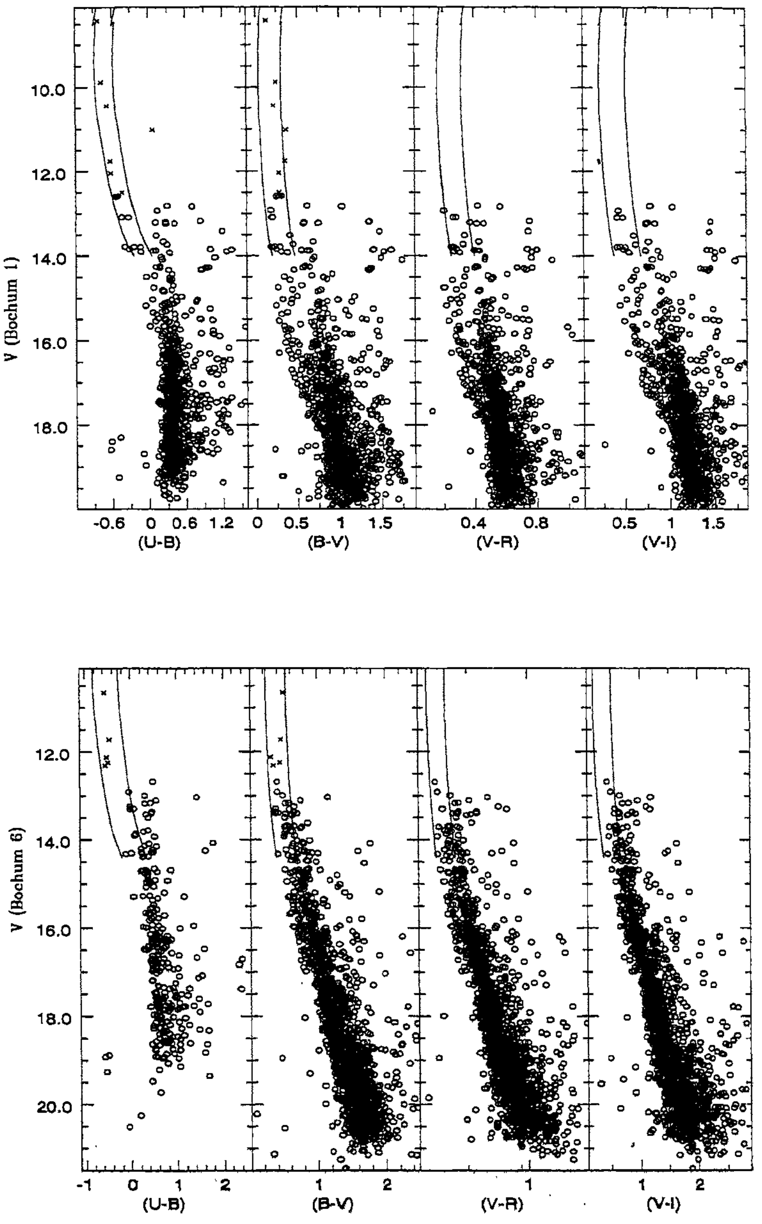

Figure 3. The colour-magnitude diagrams of all the measured stars in the regions of Bochum 1 and Bochum 6. Open circles and crosses represent the stars observed by us and stars taken from Moffat & Vogt (1975) for both associations respectively. Solid lines represent the blue and red envelope of the MS of the association.

Table 4. Photometry and proper motion data of likely member stars in the field of Bochum 1 and Bochum 6. In the first column the ID number 44, 46, 47, 51, 53, 54, 48 and 45 in Bochum 1 and 499, 501, 496, 503 and 498 in Bochum 6 represent the stars taken from Moffat & Vogt (1975). The ID number starting from 1 in both associations are observed by us.

ID	TYC No	$(U-B)$ (mag)	$(B-V)$ (mag)	$(V-R)$ (mag)	$(V-I)$ (mag)	V (mag)	$\mu_\alpha Cos(\delta)$ (mas/yr)	μ_δ (mas/yr)	$E(B-V)$ (mag)
				Bochum 1					
44	133601468	-0.83	0.13	*	*	8.42	-0.1	-0.1	0.45
46	133601813	-0.78	0.24	*	*	9.88	1.1	-1.9	0.56
47		-0.68	0.21	*	*	10.44			0.49
51	133601173	-0.63	0.35	*	*	11.75	1.0	1.0	0.65
53		-0.62	0.28	*	*	12.04			0.56
54		-0.44	0.28	*	*	12.50			0.52
48		-0.51	0.31	*	*	12.58			0.57
45		-0.54	0.24	*	*	12.59			0.48
1		-0.44	0.19	0.26	0.41	13.09			0.39
2		-0.33	0.20	0.28	0.48	13.09			0.36
3		-0.39	0.22	0.26	0.45	13.78			0.42
4		-0.24	0.29	0.27	0.51	13.79			0.49
5		-0.14	0.18	0.25	0.42	13.79			0.27
6		-0.32	0.25	0.29	0.48	13.84			0.41
7		-0.13	0.31	0.27	0.54	13.89			0.45
				Bochum 6					
499	598701023	-0.57	0.50	*	*	10.65	-2.0	3.7	0.82
501	598700524	-0.46	0.46	*	*	11.72	-6.6	0.5	0.74
496	598700891	-0.52	0.31	*	*	12.12	-7.6	1.9	0.57
503	598700657	-0.49	0.45	*	*	12.24	-5.2	2.9	0.73
498	598701067	-0.55	0.35	*	*	12.31	-3.7	4.4	0.63
1		-0.04	0.40	0.26	0.50	12.91			0.54
2		0.01	0.65	0.76	1.12	13.24			0.81
3		0.06	0.38	0.30	0.58	13.29			0.47
4		0.11	0.52	0.33	0.60	13.86			0.61
5		0.09	0.66	0.43	0.85	13.90			0.80
6		0.23	0.69	0.40	0.69	14.20			0.78
7		0.23	0.70	0.35	0.62	14.28			0.79
8		-0.11	0.71	0.47	0.94	14.32			0.95
9		0.25	0.62	0.36	0.61	14.38			0.71

seems to be non-uniform in the line of site of both associations. Using the ZAMS given by Schmidt-Kaler (1982) we found that the $E(B-V)$ value ranges from 0.40 to 0.60 mag in the direction of Bochum 1 and from 0.55 to 0.80 mag in the direction of Bochum 6. The cause of the variability in $E(B-V)$ in these associations needs to be investigated for understanding the star formation processes. As the stars are of early type, Q - method is used to determine the individual $E(B-V)$ values of the probable members and the same has been applied in generating the intrinsic CM diagrams discussed below. The mean

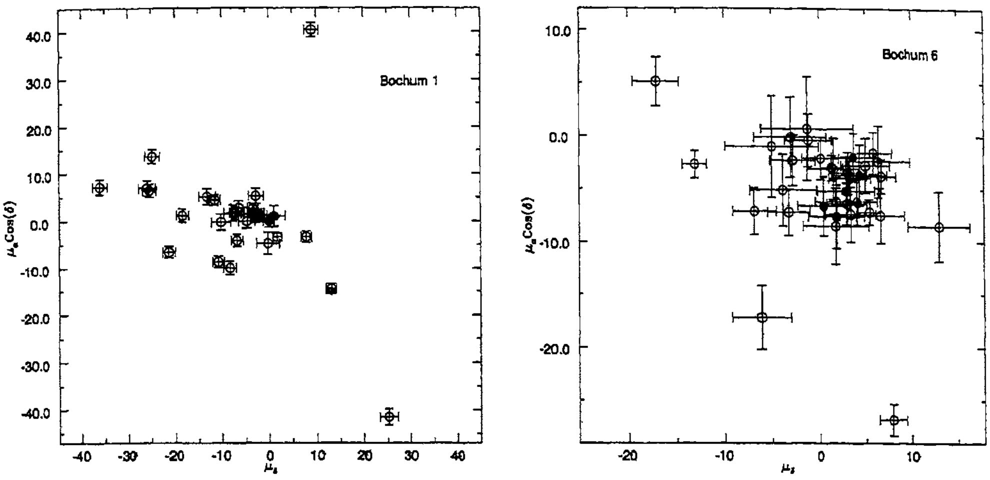

Figure 4. Vector point diagrams for Tycho-2 stars in the filed of Bochum 1 and Bochum 6. Filled circles indicate the member of Bochum 1 and Bochum 6 according to Moffat & Vogt (1975). The lengths of horizontal and vertical bars indicate the uncertainties in the proper motion in mas/yr.

values of the $E(B-V)$ are given in Table 5. They are in good agreement with the values given in the literature (see Table 1).

3.4 Distance and Age

In Fig 6, we plot the intrinsic CM diagrams in the plane of V_0 vs $(U-B)_0$ and V_0 vs $(B-V)_0$ for Bochum 1 and Bochum 6 to estimate their distances and ages. The probable members listed in Table 4, have been used in this analysis. All the stars have been corrected for the individual reddening using $E(B-V)$ values given in Table 4 and following the relation $E(U-B) = 0.72 \times E(B-V)$ and $A_v = 3.1 \times E(B-V)$. In Fig, we superimposed the ZAMS with dotted line given by Schmidt-Kaler (1982). The fitting of ZAMS to the member stars is satisfactory and gives the true distance modulus $(m-M)_0 =$ 12.2±0.2 and 12.0±0.2 mag for Bochum 1 and Bochum 6 respectively. The corresponding distances are 2.8±0.4 and 2.5±0.4 Kpc respectively. The estimated distances for both the associations should be considered reliable because they have been derived by fitting

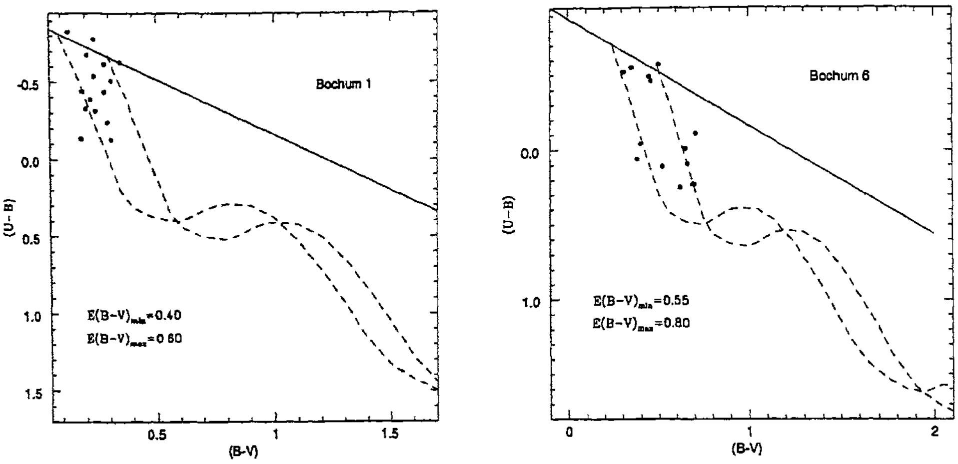

Figure 5. The $(U-B)$ versus $(B-V)$ diagrams of the stars in the region of Bochum 1 and Bochum 6. The continuous straight line and dotted curve represents the reddening vector and empirical Schmidt-Kaler (1982) ZAMS.

the ZAMS over a wide range of MS. This is possible due to CCD photometry of stars fainter than Moffat & Vogt (1975). The derived distance values for both Bochum 1 and Bochum 6 are lower than the corresponding values given by Moffat & Vogt (1975) while the value (2.5 Kpc) given by Dias et al. (2002) for Bochum 1 is in agreement.

To derive the ages for Bochum 1 and Bochum 6, we have plotted the isochrones of log(age) = 7.0 taken from Schaller et al. (1992) for Solar metallicity in the Fig 6. By fitting the isochrones we have estimated 10±5 Myr age for Bochum 1 and Bochum 6 which is in agreement with 10 Myr given by Moffat & Vogt (1975).

Table 5. Derived fundamental parameters of Bochum 1 and Bochum 6.

Name	Distance (Kpc)	$E(B-V)$ (mag)	log(age)
Bochum 1	2.8±0.4	0.47±0.10	7.0
Bochum 6	2.5±0.4	0.71±0.13	7.0

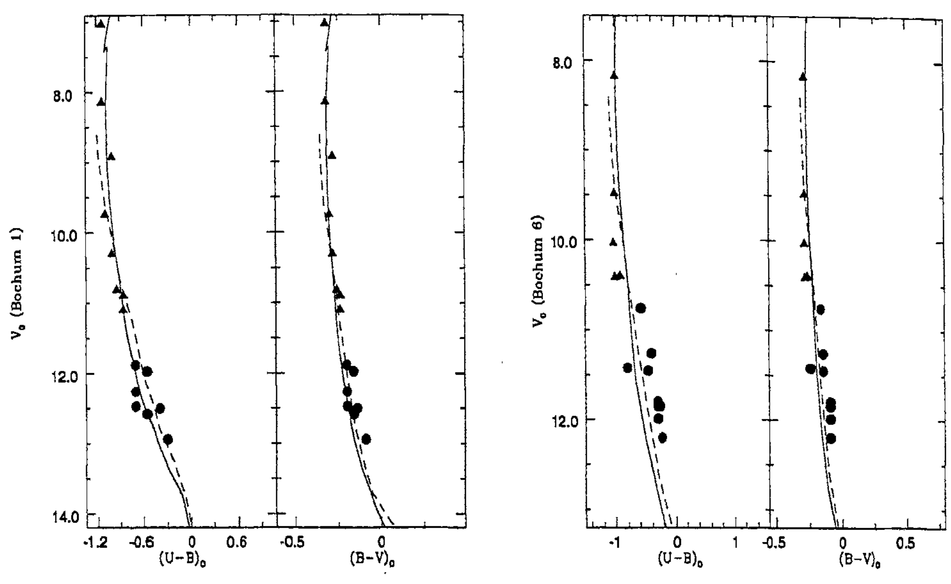

Figure 6. The intrinsic CM diagrams of the probable members of associations Bochum 1 and Bochum 6. Filled circles and filled triangles represent probable photometric and kinematic members . Solid lines represent the Solar metallicity isochrones given by Schaller et al. (1992) for log(age) = 7.00 while dotted lines represent the ZAMS given by Schmidt-Kaler (1982).

3.5 Stellar evolutionary aspects and star formation history

Using the parameters derived in the present study and stellar evolutionary tracks given by Schaller et al. (1992) for Solar metallicity we derived the masses of probable members of Bochum 1 and Bochum 6. The mass range of the members are 17.0–3.0 $M_\odot$ and 14.0–3.0 $M_\odot$ respectively. From the stellar evolution theory we know that 17.0 and 14.0 $M_\odot$ star will leave the MS after about 10 and 15 Myr respectively. On the other hand 3.0 $M_\odot$ star will take about 5 Myr to reach on MS. Hence the ages of brighter members are smaller than 10 and 15 Myr in the case of Bochum 1 and Bochum 6 respectively while the corresponding ages of fainter stars are larger than 5 Myr. We can therefore conclude that brighter and fainter members in both associations have almost similar ages and may probably have formed together about 10 Myr ago.

3.6 Mass Function

The mass function (MF) of a cluster is derived from its luminosity function (LF). For deriving the LF, it is essential to correct the data for field star contamination and data incompleteness. For separating the members, we used the kinematical as well as photometric data (see Sec. 3.1, 3.2). In this way all the selected probable members are brighter than 14.5 mag in both associations and at such brightness level data completeness is almost 100%. Using these probable members, we derived the LF of Bochum 1 and 6.

The MF, which denote the relative number of stars in unit range of mass centered on mass M. The MF slope has been derived from the mass distribution $\xi(M)$. If dN represents the number of stars in a mass bin dM with central mass M, then the value of slope x is determine from the linear relation

$$\log\frac{dN}{dM} = -(1+x)\times\log(M)+\text{constant}$$

using the least-squares solution. The Salpeter (1955) value for the slope of MF is x = 1.35.

Table 6. The mass function slope derived from Schaller et al. (1992) isochrone of Solar metallicity.

Objects	Mass range $M_\odot$	Mass Function slope (x)
Bochum 1	3.0 - 17.0	0.87±0.37
Bochum 6	3.0 - 14.0	1.35±0.16

To derive the MF from LF we need theoretical evolutionary tracks and accurate knowledge of physical parameters of Bochum 1 and 6. Using the parameters derived by us and stellar evolutionary tracks of Solar metallicity given by Schaller et al. (1992) we converted the observed LF to the MF. Fig 7 shows the plot of MFs of Bochum 1 and 6 while Table 6 lists the estimated MF slope. Our derived MF slope for both Bochum 1 and 6 are in agreement with Salpeter's (1955) value, however the estimated errors are large due to small number of members.

Massey et al. (1995) studied 11 OB associations of the Milky Way and conclude that there is no statistically significant difference in slope among these objects with mean value of slope x=1.1 for stars with masses > 7.0 $M_\odot$. They also compared the IMF study

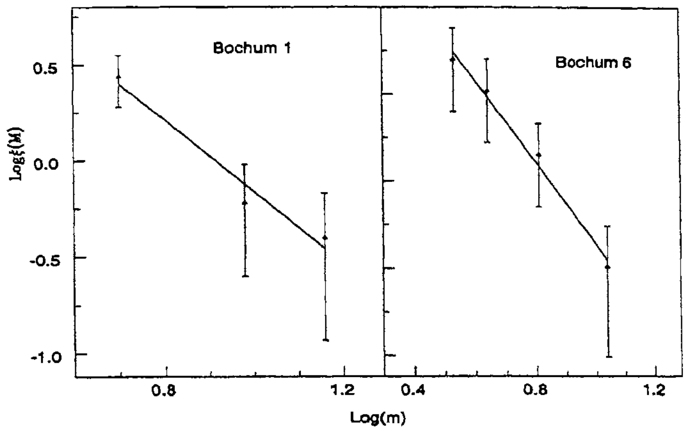

Figure 7. The plot shows the mass functions derived using isochrones of Solar metallicity given by Schaller et al. (1992).

of the Magellanic Cloud's OB associations and suggest that there is no difference in IMF slopes.

4. Conclusions

In this paper we have presented new CCD *UBVRI* photometry for the 2460 stars in the field of Bochum 1 and Bochum 6. We can summarized our findings as follows.

(i) In both associations variable reddening is present with mean value of $E(B-V)$ =0.47±0.10 and 0.71±0.13 for Bochum 1 and Bochum 6 respectively. The corresponding distance values are 2.8±0.4 and 2.5±0.4 Kpc respectively. The fitting of Schaller et al. (1992) isochrones of Solar metallicity to the intrinsic CM diagrams indicate an age of 10±5 Myrs for both OB associations.

(ii) Present analysis indicate that brighter and fainter members of both associations have almost similar ages and may probably have formed together.

(iii) Mass function study gives MF slope of 0.87±0.37 and 1.35±0.16 for Bochum 1 and Bochum 6 respectively. They are in agreement within uncertainty with the Salpeter's (1955) value.

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