

Proper motions and CCD-photometry of stars in the region of the open cluster Trumpler 2[★]

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ABSTRACT

The results of a complex study of the galactic open cluster Trumpler 2 are presented. In order to obtain the proper motions, the positions of approximately 3000 stars up to the limit magnitude $B \sim 16.25$ mag in the area $80' \times 80'$ around the cluster were measured on 6 plates with a maximal epoch difference of 63 years. The root-mean error of the relative proper motions is 4.2 mas yr^{-1} . The catalogue of BV magnitudes of all the stars in the investigated area was compiled. The selection of the cluster members within the region of $R < 16'$ from the center of the cluster was made. Altogether, 148 stars were considered to be cluster members by both astrometrical and photometrical criteria. We present the estimated age (8.91×10^7 yr) and physical parameters of the cluster and append the catalogues of the proper motions and of the photometry of the stars.

Key words. open clusters and associations: individual: Trumpler 2

1. Introduction

The open cluster Trumpler 2 is located near the famous rich clusters h and χ in the Perseus constellation. Its equatorial and galactic coordinates are: $\alpha = 2^{\text{h}}37^{\text{m}}15^{\text{s}}$, $\delta = +55^{\circ}59'$; $l = 137^{\circ}.4$, $b = -3^{\circ}.89$ (2000.0). In the Trümpler (1930) catalogue it is classified as II 2p (a pure cluster with little central concentration). All that was known about the cluster to the present day is based on the data from the Washington catalogue “Photometry of stars in Galactic cluster fields” (Hoag et al. 1961, HJ). For Trumpler 2 it included the UBV photoelectrical photometry of 28 stars in the $15' \times 15'$ area and photographic photometry of 133 stars in the circle $R < 22'$ around the supposed cluster center. All the contemporary determinations of the cluster parameter are based on that data (Figs. 1a, b present the color–magnitude diagram (CMD) and the two-color diagram of the cluster from that study). The existence of the cluster itself was not confirmed by any other original papers. This area has never been investigated kinematically on the basis of proper motions. Our paper tries to fill this gap.

2. Astrometry

2.1. Proper motions

The observational material belongs to the Normal astrograph collection of the Pulkovo observatory and dates from 1937 to 2000 (Table 1). The scale of the Normal astrograph plates is $60'' \text{ mm}^{-1}$. The cluster-region star positions from the USNO-A 2.0 catalogue were used as an additional plate (epoch 1954.8).

* Tables 2, 3A, 3B and 5 are only available in electronic form at the CDS via anonymous ftp to

cdsarc.u-strasbg.fr (130.79.128.5) or via
<http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/451/901>

★★ Deceased.

All of the plates were scanned by means of the automated measuring complex “Fantasy” of the Pulkovo observatory. The description of the complex was presented in Frolov et al. (2002, FJA). The positions of the 2362 stars in the area $80' \times 80'$ centered on the cluster Trumpler 2 were measured up to the limit magnitude $B = 16.25$ mag. Positions of some faint stars were not measured on all plates because of the poor quality of their images, so from three to seven stellar positions were used to derive proper motions (PM), which were determined by the line-method. The details of this method were presented in Jilinski et al. (2000). The deepest plate K376 with the faintest images was considered to be the central plate. It was orientated by means of the stars’ positions from the “Tycho-2” catalogue. Then all the other plates were reduced to this central one.

For that reduction 72 reference stars were selected in the interval between 13.5 and 14.5 mag. The rms errors of derived PM are: $\sigma_x = \pm 4.1 \text{ mas yr}^{-1}$, $\sigma_y = \pm 4.2 \text{ mas yr}^{-1}$. The analysis of error distributions demonstrates that they increased from 3.9 to 4.2 mas yr^{-1} with the increase in distance from the area center and from 3.1 mas yr^{-1} for stars with the magnitude $B < 10.5$ mag to 4.4 for $B > 16$ mag stars. The astrometrical results are given in Table 2 with columns containing: 1 – the star number; 2 – the star number from the USNO-A 2.0 catalogue; 3, 4 – its rectangular coordinates X and Y on the plate K376; 5 – radius-vector; 6–9 – X and Y relative proper motions and their errors; 10 – the number of used plates; 11 – photographic B -magnitude, resulting from the “Fantasy” measurements; 12 – notes (bl marks blends, bad – bad measurement, abs – absence of the star on the plates, BD and AG – star identification).

2.2. Members segregation

The selection of cluster members was made for stars located in the circle with $R < 16'$ around the cluster center. That region

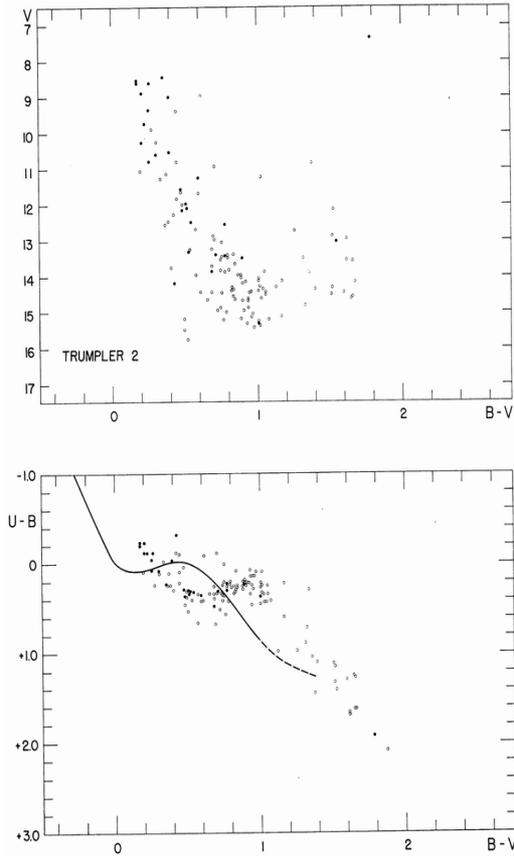


Fig. 1. Color–magnitude and two-color diagrams of Trumpler 2 from the Washington catalogue.

Table 1. Astrometric plates.

Plate	Exposure (min)	Epoch	Quality
Early epoch			
K 376	25	1937 Sep. 12	high
D 80	30	1949 Mar. 31	good
D 135	30	1949 May 5	poor
Recent epoch			
18160	25	1999 Dec. 12	poor
18171	30	2000 Feb. 4	good
18175	25	2000 Feb. 6	good

contains 313 stars with determined proper motions. Blended images and stars measured only on two or less plates were expelled. The size of this circle was selected according to two criteria: first, it should be large enough not to miss the cluster members from the corona; second, not be too large to litter the vector point diagram (VPD) with a large amount of the field stars.

We used the method in which membership probabilities, magnitude equations (ME), and parameters of the star distributions on the vector point diagram (VPD) were determined step by step in an iterative process. The details of this procedure are described in FJA. The starting selection was realized in the circle with $R < 10'$ centered on the Trumpler 2. As a first approximation, stars with the photoelectric BV magnitudes from the HJ were considered to be the cluster members. Based on the proper motions and magnitudes of these stars the magnitude equation (ME) was studied and the proper motions of all stars were corrected for it. Then at each step that was characterized by

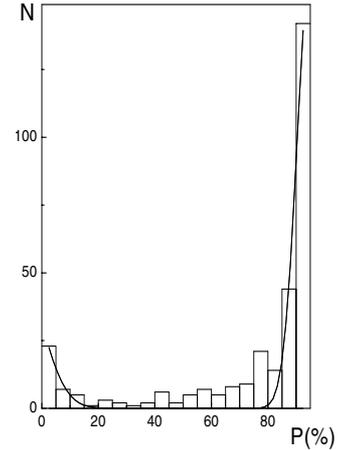


Fig. 2. Final histogram of star membership probabilities.

increasing value of R ($+2'$), the parameters of the bivariate Gaussian distributions of proper motions, circular for the cluster and elliptical for the field, were computed by the Sanders method (1971). The preliminary selection of the cluster members was made in each iteration step. Then the proper motions were tested for the ME. If it turned up, then all the PM in the catalogue were refreshed. The last step was made for the stars in the circle with radius $R < 16'$.

It is important to note that it is impossible to visually divide stars of the cluster and of the field on the VPD because of the proximity of the centers of their distributions. This fact is frequently registered for the far clusters (for example see Sanner et al. 1999, 2000, 2001). Nevertheless it takes only 8 iterations to reach the stable solution numerically with relative precision: $E = 0.001$. The following initial values of the parameters were accepted: $N_c/N = 0.5$, centers of the distributions: the field $-1, 1$, the cluster: $1, -1$, the dispersion: the field $12, 8$, the cluster 4 . Calculations resulted in the following values: the relative number of cluster members and all stars $N_c/N = 0.74$; centers of distributions: the field $\mu_{x_f} = 0.98, \mu_{y_f} = -2.11$; the cluster $\mu_{x_c} = 0.33, \mu_{y_c} = -0.53$; standard deviations: the field $\Sigma_x = 14.62, \Sigma_y = 9.28$, the cluster $\sigma_c = 4.78$. All the values are in mas yr^{-1} . They were used to calculate the individual membership probabilities of the stars in the area by the formulae:

$$P(\mu_x, \mu_y) = \frac{N_c \Phi_c(\mu_x, \mu_y)}{N_c \Phi_c(\mu_x, \mu_y) + N_f \Phi_f(\mu_x, \mu_y)},$$

where N_c is the normalized number of cluster stars, N_f the normalized number of field stars, μ_{x_i} and μ_{y_i} the proper motion in x and y for the i th star.

The resulting histogram shows that the stars with the probabilities $P > 85\%$ can be considered as cluster members (Fig. 2). The whole amount of such stars is 192, and the final VPD is presented in Fig. 3a. Cluster members are plotted by the solid dots, and field stars by the crosses.

3. Photometry

The final conclusion about star membership was based on two criteria: its proper motion and its position on the CMD. Only a small part situated in the central circle stars has got the initial UBV -photometry (HJ). The B and V magnitudes of the rest of the stars were determined partly as a by-product of astrometric

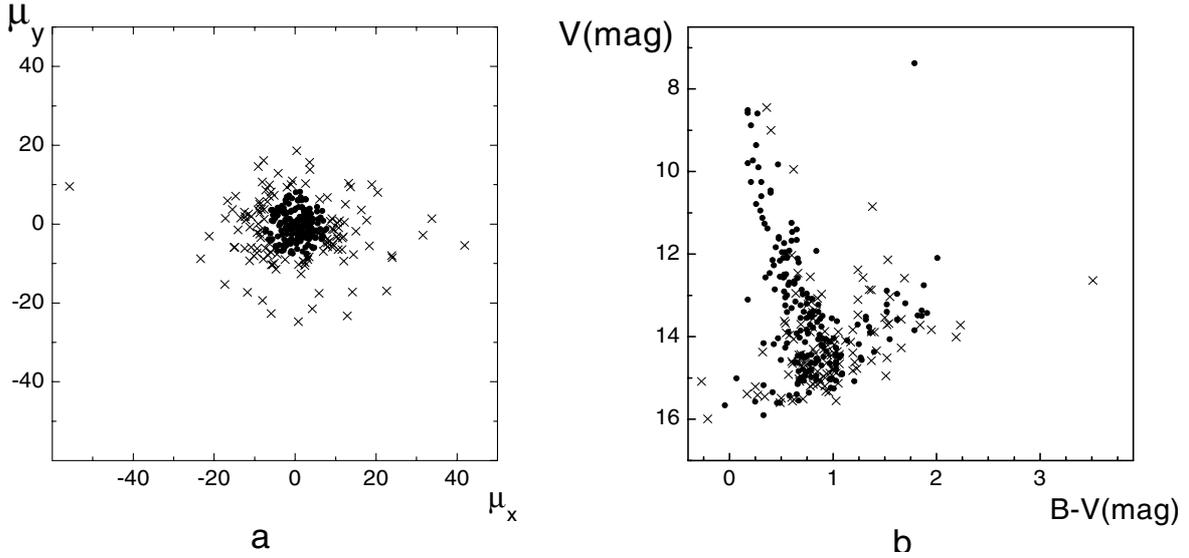


Fig. 3. a) VPD and b) CMD of the central part ($R < 16'$) of Trumpler 2. Astrometrical cluster members are plotted by solid dots, field stars by crosses.

plate measurements (image diameters) or by our original CCD-observations and were partly calculated from the infrared J , H , K magnitudes from the 2MASS catalogue by the derived transformation formulae. Unfortunately, for technical reasons, we were only able to obtain CCD -magnitudes in the area of $17' \times 24'$. The identification map of the central part of the cluster is presented in Fig. 4. The star number from the Washington catalogue is indicated in front of the authors' number. Data available from all the different sources of the broadband photometry for each star are presented in Table 3A, where columns contain: 1 – the star number according to Table 2; 2 – the radius-vector; 3 – the specific numbers from 1 to 10 corresponding to photometry data; 3, 4 – B and V magnitude; 5 – $B - V$; 6 – notes. The description and corresponding comments of the specific numbers that mark the sources of photometry are given in Table 4, whose columns contain: 1 – the specific number (S/N); 2 – photometry band; 3 – source of the material; 4 – the area dimensions in arcmin; 5 – the photometric errors in magnitudes.

Notes for specific numbers:

- 1, 2. While plotting the characteristic curve V , the systematic difference between the photoelectric and photographic values ($V_{pe} - V_{pg}$) = 0.01 in the HJ catalogue was detected, and was taken into account. The same difference was detected for the colors $B - V$.
3. The real precision of the photometric data given in the Tycho-2 catalogue for stars $V_T > 9$ mag is much lower than claimed. That's why we preferred alternative sources for these stars.
- 4–6. B -photographic values of the majority of the stars in the studied region were determined by measuring their diameters by means of the "Fantazy" complex. It is well known that B magnitudes obtained with the Pulkovo Normal astrograph are infected by the color equation (CE), which is why characteristic curves $B \sim F(D)$ were plotted separately for "red" ($B - V \geq 1.0$) and "blue" ($B - V < 1.0$) stars. The B magnitudes of the "blue" stars were not corrected for CE as its value was non-significant (smaller than the mean error). At the same time as the original observations made of the "red" stars, the value of the correction was 0.35 mag per magnitude and was taken into account in all cases.

4. V -magnitudes were obtained from original the observations made with the 320-mm mirror astrograph ZA-320 of the Pulkovo Observatory equipped with the CCD-receiver ST-6 with a fixed TC241 matrix (Bekyashev et al. 1998).
5. V -magnitudes were calculated with the J , H , K magnitudes from the infrared 2MASS catalogue by the derived transformation formula:

$$V = 0.02528 + 1.04259J - 0.83847(J - H) + 3.16435(J - K) + 2.39154(J - H)^2 - 1.34984(J - K)^2.$$

7. B -magnitudes from the USNO-2A catalogue were treated only as control values.
8. B , V magnitudes were obtained from original observations with the 320 mm mirror astrograph ZA-320 of the Pulkovo Observatory equipped with the CCD-receiver ST-6 with a fixed TC241 matrix (Bekyashev et al. 1998).
- 9, 10. B -magnitudes were calculated with the J , H , K magnitudes from the infrared 2MASS catalogue by the derived transformation formulae:

$$B = 1.0621J + 1.0732(J - H) + 2.9973(J - K) + 0.3785(J - H)^2 + 0.4259(J - K)^2$$

$$B - V = -0.21236 + 0.04164J - 2.51276(J - H) + 2.43958(J - K) + 2.27583(J - H)^2 - 0.14797(J - K)^2.$$

Table 3B contains the additional magnitudes B and V obtained by means of the CCD -photometry for stars whose brightnesses are less than the limit sensitivity of the astrometric plates. Their numbers begin with the 3 on the identification map of the central part of the cluster (Fig. 4). Columns in Table 3B contain: 1 – the star number; 2–4 – B -magnitude, its error and the number of observations; 5–7 – V -magnitude, its error and the number of observations. As the standards for these observations we took the Washington photoelectric and partly (for the faint stars) photographic photometry. Errors of the magnitude determination were defined as external relative to the standards. Photometric data from Table 3A were used to construct the CMD for 313 stars in the circle $R < 16'$. As was mentioned in the process of membership determination, the positions of stars on the CMD were used as a second parameter. Because of the unequal accuracy of the material, the following application priority order of the specific

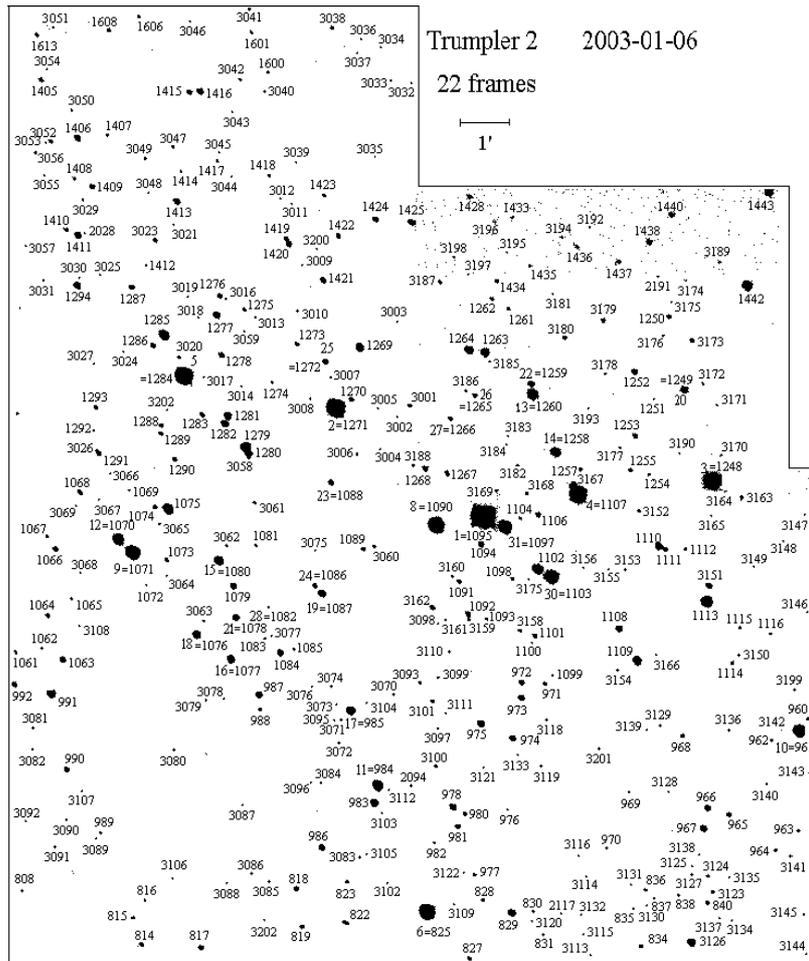


Fig. 4. CCD map of the central part of the cluster Trumpler 2. The numbers of stars are given according to the photometric study.

numbers (S/N) was set: 1(photoelectric HJ) – 28 stars; 2(photo-graphic HJ) – 56 stars; 3 (Ticho) – 6 stars, 8 (CCD) – 95 stars, 4(the combination of authors' photographic and CCD) – 1 star, 5 – (the combination of authors' photographic and 2MASS) – 127 stars. The CMD of all these stars is shown in Fig. 3b.

4. Analysis and conclusion

Stars of the IV and V luminosity classes falling on the CMD into the $\pm 3\sigma_{B-V}$ interval from the cluster main sequence are considered to be the photometric cluster members. As the average error of the color index determination rises from the bright to faint stars, the width of the MS band increases approximately from 0.02 mag to 0.11 mag.

In order to determine the mean absorption in the region of the cluster, the two-color diagram $(U - B) \sim (B - V)$ was plotted using the HJ UBV photometry only for the 44 astrometric cluster members with $P \geq 85\%$ falling on the MS. For the inclination $E(U - B)/E(B - V) = 0.72$, the best coincidence of the line of normal colors with the two-color sequence of the cluster was achieved at the value of the color excess $E(B - V) = 0.40 \pm 0.06$ mag (Fig. 5) that differs from what is accepted in existing compiled catalogues values: 0.30 (Hoag 1966) and 0.34 (Electronic Database WEBDA, 2001¹). The superposition of the MS of the cluster with the ZAMS (Schmidt-Kaler 1965) was made with this fixed value of color excess. During

this procedure, special attention was paid to the stars with photoelectric photometry. The best coincidence was achieved at the value of the apparent distance module $(V - M_V) = 10.50 \pm 0.35$, which corresponds to the true module $(V - M_V)_0 = 9.30$ and the distance $r = 725$ pc ($610 < r < 851$). The CMD diagram for probable cluster members (according to both photometric and astrometric criteria) is presented in Fig. 6. Solid circles mark the stars supplied by photoelectric photometric data, and hollow circles all the others.

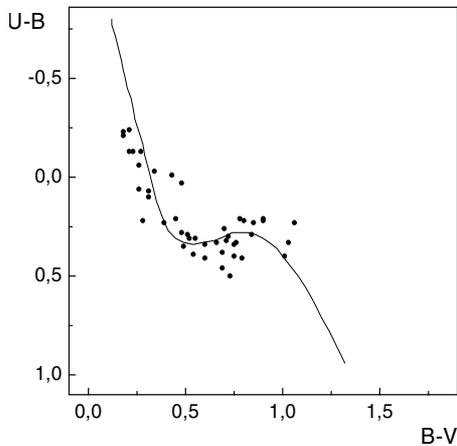
The catalogue of the stars in the central circle ($R < 16'$) is presented in Table 5. Its columns contain 1 – the author's number; 2 – sign of membership; 3, 4 – the rectangular coordinates of star (arcmin); 5 – the distance from the center (arcmin); 6–9 – the proper motions and their root-mean-square errors (mas yr^{-1}); 10 – the number of the astrometric plates; 11 – the membership probability; 12 – the photometry specific author's number (see Table 4); 13, 14 – the star magnitude and color.

Located in the cluster's center, the red giant (st. N 1095) has high individual membership probability. Large dispersion in its photometric data may be evidence of its variability. Although it does not fall in the $16'$ circle where the individual membership probabilities were determined, another red giant (st. N 1748) relates to the third class of Eibighausen (1942) classification. This means that this star lies within the circle of the $R = 2\sqrt{2}\sigma$ on the VPD where 98% of all cluster members are situated (Kadla 1966). The same refers to st. N 1941, which must have travelled far from the cluster center but is gravitationally linked to it.

¹ <http://obswww.unige.ch/webda>

Table 4. Cross-references for the photometry.

S/N	Bands	Sources	Area	Errors
1	B, V	HJ, photoelectric magnitudes	$17' \times 17'$	$\sigma_V = \pm 0.021$ mag, $\sigma_{B-V} = \pm 0.018$ mag
2	B, V	HJ, photographic magnitudes	$30' \times 12'$	$\sigma_V = \pm 0.041$ mag, $\sigma_{B-V} = \pm 0.050$ mag
3	B_T, V_T	Tycho catalogue		$\sigma_V = \pm 0.060$ mag, $\sigma_{B-V} = \pm 0.100$ mag (all stars), $\sigma_V = \pm 0.012$ mag, $\sigma_{B-V} = \pm 0.019$ mag ($V_T < 9$ mag)
4	B	Author's photographic magnitudes catalogue	$120' \times 120'$	$\sigma_B = \pm 0.09$ mag for "red" stars $\sigma_B = \pm 0.03$ mag for "blue" stars
	V	Author's CCD magnitudes catalogue	$19' \times 24'$	$\sigma_V = \pm 0.06$ mag
5	B	Author's photographic magnitudes catalogue	$120' \times 120'$	$\sigma_B = \pm 0.09$ mag for "red" stars $\sigma_B = \pm 0.03$ mag for "blue" stars
	V	2MASS catalogue calculated from the J, H, K magnitudes		$\sigma_V = \pm 0.11$ mag
6	B	Author's photographic magnitudes catalogue	$120' \times 120'$	$\sigma_B = \pm 0.09$ mag for "red" stars $\sigma_B = \pm 0.03$ mag for "blue" stars
	V	No data		
7	B	USNO 2A catalogue		
	V	No data		
8	B	Author's CCD magnitudes catalogue	$19' \times 24'$	$\sigma_B = 0.08$ mag
	V	Author's CCD magnitudes catalogue	$19' \times 24'$	$\sigma_V = 0.05$ mag
9	B	calculated from the values of $B - V$ derived from the 2MASS catalogue		
	V	Author's CCD magnitudes catalogue	$19' \times 24'$	$\sigma_V = \pm 0.06$ mag
10	B	derived from the 2MASS catalogue		
	V	Author's CCD magnitudes catalogue	$19' \times 24'$	$\sigma_V = \pm 0.05$ mag

**Fig. 5.** Two-color diagram of the cluster Trumpler 2.

These possible cluster members are marked by "prob". In Fig. 6 they are plotted by Δ .

The estimation of the age of the cluster is based on the grid of isochrones published by the Padua research group² and described in the paper Girardi et al. (2000). The superposition of various isochrones on the CMD shows the perfect coincidence of the 8.913×10^7 yr isochrone for $Z = 0.019$ with the cluster diagram. The accuracy of determining age depends on the grid step ($\pm 0.05 \log A$). Corresponding to this isochrone, the turn-off point of the MS is $(B - V)_0 = -0.16$ mag.

N	Radius-vector (arcmin)	M_V mag	$(B - V)_0$ mag	P %
1095*	1.15	-3.12	1.39	94
1748	17.35	-2.94	1.48	prob
1941	36.70	-3.19	0.51	prob

* Suspected variable star.

The cluster luminosity function is plotted for 148 cluster members (Fig. 7a). The cluster mass function was plotted using only stars of the cluster MS located lower than the turn-off point $M_V = -0.41$ mag (Fig. 7b). Star masses were calculated using the data from the work of Girardi et al. (2000). The straight line drawn by the least-squares-fit with the 95% confidence level has the slope $\Gamma = -1.90 \pm 0.22$. That is in good agreement with the numerical results of Scalo (1998) in his three-segment power law of the initial mass function for star clusters and associations of the Milky Way and LMC. The Trumpler 2 mass function shows the lack of stars with the mass about $2.8 M_\odot$. This feature is also observed on the CMD for the $M_V \sim +0.7$.

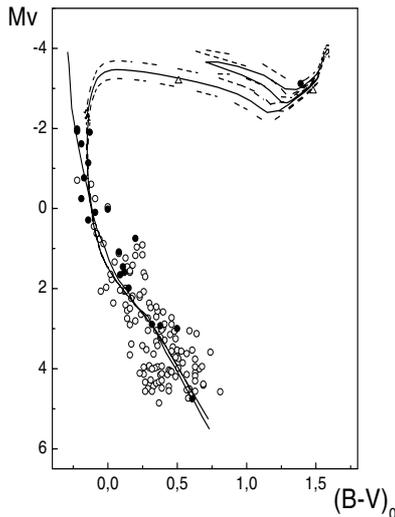
5. Variable stars

In this study of the $80' \times 80'$ area where star proper motions were obtained, seven variable stars from the General catalogue (GCVS) of Kholopov (1998) were found. All of them are situated far from the center of the cluster ($R > 15'$) and hardly belong to it, in spite of the fact that they lie in a $2\sqrt{2}\sigma$ circle on the VPD. Their data are given in part A of Table 6. Its rows contain 1 – the GCVS star indication; 2 – the authors' number; 3, 4 – the right ascension and the declination of the star; 5 – variability type; 6 – the distance from the center;

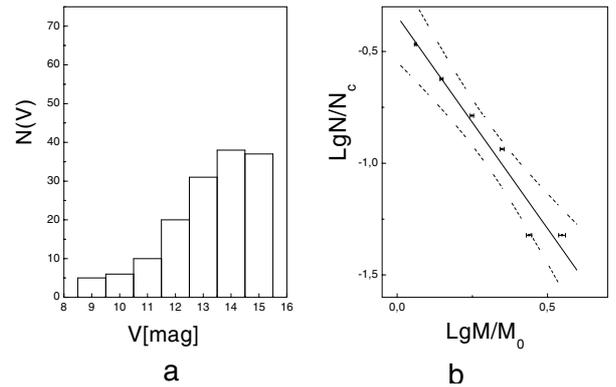
² <http://www.pleadi.astro.pd.it>

Table 6. Variable stars in the region of the open cluster Trumpler 2.

A											
Symbol	LR Per	DX Per	DZ Per	VZ Per	EI Per	EK Per	EM Per				
The author's number	2355	1856	1571	996	1042	1381	513				
$\alpha(1950.0)$	02 29 14	02 31 14	02 32 22	02 35 07	02 36 15	02 36 35	02 37 52				
$\delta(1950.0)$	+56 16.1	+56 05.0	+55 55.9	+55 33.1	+55 40.8	+55 57	+55 18.5				
Variability type	SR:	EA/SD:	EB/KE	LB	M	L	L				
$R(\text{arcmin})$	52.06	29.03	15.51	16.79	23.95	28.86	44.21				
Membership	prob	prob	93	prob	prob	prob	prob				
$B(\text{mag})$	15.39	15.49	14.11	14.20	14.35	15.34	15.51				
$V(\text{mag})$	14.16	14.92	12.10	8.94	13.21	14.70	10.40				
B											
ID	The author's number	MaScat	MedMag	MedEr	Ng	Quality	R	Membership	$B(\text{mag})$	$V(\text{mag})$	S/N
1803249	1137	0.155	12.38	0.056	49	poor	17.98	prob	12.80	12.23	5
1803292	1139	0.147	12.145	0.044	44	poor	17.37	prob	13.47	12.69	5
1803346	1143	0.2	12.654	0.068	42	poor	18.13	prob	13.27	12.65	5
1803553	1241	0.153	10.693	0.016	31	poor	12.79	94	10.57	10.26	2
									10.45	10.16	3
									10.51	10.28	5
1803662	1127	0.145	11.985	0.036	27	poor	11.68	93	12.11	11.63	2
									11.81	11.75	3
									11.95	11.71	5
1803669	954	0.232	12.667	0.067	22	poor	15.05	94	13.30	12.86	5
1803717	1442	0.146	11.787	0.031	22	poor	9.62	93	12.27	11.67	3
									12.26	11.47	4
									12.26	11.45	5
1803741	961	0.123	10.767	0.016	21	poor	10.13	94	10.47	10.26	1
									10.50	10.37	3
									10.42	10.27	4
									10.42	10.32	5
1921137	721	1.324	11.546	0.025	101	good	17.96	prob	12.79	12.19	3
									13.21	12.18	5
1921548	1294	0.937	12.792	0.059	199	good	10.55	93	13.35	12.66	4
									13.35	12.67	5
1922164	1393	0.62	13.622	0.115	205	high	16.76	prob	14.41	13.82	5
1922260	1049	1.217	12.091	0.04	227	high	17.66	prob	14.41	12.12	5

**Fig. 6.** CMD diagram of all cluster members. ZAMS – Schmidt-Kaler (1965). Isochrones: $z = 0.0019$, solid line – age = 8.913×10^7 yr; dot lines – adjacent ones, \bullet – stars supplied by photoelectric photometric data, \circ – all the other.

7, 8 – B, V magnitudes from authors photometry catalogue (Table 3); 9 – membership.

**Fig. 7.** a) Luminosity function and b) mass function of the Trumpler 2.

The search for variable stars was carried out in the recently published database SKYDOT³ (SD; Woźniak 2004) relied on the Northern Sky Variability Survey (NSVS). From the list of all the objects presented in the SD we selected only those whose amplitude exceeds more than 3 times the mean error. Twelve of them could be the cluster members. The list of selected objects is given in part B of Table 6. Its columns contain 1 – the SD star indication; 2 – the authors' number; 3 – the maximum

³ <http://skydot.lanl.gov>

brightness amplitude; 4 – the mean magnitude; 5 – the mean error of the magnitude determination; 6 – the number of the reliable observations during the whole period; 7 – quality of observations; 8 – the distance from the cluster center; 9 – membership; 10, 11 – B , V magnitudes; 12 – the photometry specific number from Table 3. Star magnitudes in the SD were determined in the natural system that was close to the V band. Curves of the brightness variation do not permit determination of the types of the variability because of the low quality of most of the observations. Unfortunately the technical reasons did not permit the investigators to observe the bright stars, which made it impossible to compare their results with the work of the other researchers. This obstacle in particular prevented us from verifying our supposition about the variability of the probable cluster member star N 1045 (the red giant).

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