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Spectroscopy and $BVI_{\rm C}$ photometry of the young open cluster NGC 6604⋆

R. Barbon[1], **G. Carraro**[1], **U. Munari**[2], **T. Zwitter**[3], **and L. Tomasella**[2]

[1] Osservatorio Astrofisico del Dipartimento di Astronomia, Università di Padova, I-36012 Asiago (VI), Italy
[2] Osservatorio Astronomico di Padova, Sede di Asiago, I-36012 Asiago (VI), Italy
[3] University of Ljubljana, Department of Physics, Jadranska 19, 1000 Ljubljana, Slovenia

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Abstract. $BVI_{\rm C}$ photometry and classification spectroscopy is presented for the young open cluster NGC 6604. Additional Echelle spectroscopy of the brightest members is used to check the reddening against the interstellar NaI and KI absorption lines, to measure the cluster radial velocity and to derive the individual rotational velocities. We obtain 1.7 kpc as the cluster distance, an age of $\sim 5\ 10^6$ years and a reddening E_{B-V}= 1.02 ($\pm$0.01 from three independent methods). Pre-ZAMS objects are apparently not detected over the $\triangle m$ = 8.5 mag explored range. The cluster radial velocity is in agreement with the Hron (1987) model for the Galaxy disk rotation.

Key words: open clusters: general — open clusters: individual (NGC 6604)

1. Introduction

NGC 6604 ($\alpha_{2000} = 18^{\rm h}\ 18\overset{\rm m}{.}1$, $\delta_{2000} = -12^\circ\ 14'$, $l\ =\ 18\overset{\circ}{.}3$, $b\ =\ +1\overset{\circ}{.}7$) is a fairly compact open cluster belonging to class I3p (Ruprecht 1966) and lies at the core of the HII region S54 (Georgelin et al. 1973). The fairly large extinction to the cluster ($A_V \sim 3$) is surely linked to the partnership with an HII region. The cluster contains several OB type stars (Stephenson & Sanduleak 1971), which suggest the cluster to be fairly young (Forbes & Dupuy 1978). Its distance is rather uncertain, with estimates ranging from 0.7 to 4.4 kpc (Alter et al. 1970). Moffat & Vogt (1975, hereafter MV) presented photoelectric photometry for a dozen stars in the cluster field, deriving a 1.6 kpc distance and a E_{B-V}=1.01 reddening. Forbes and DuPuy (1978, hereafter FD) performed photoelectric and photographic photometry, which yielded a 2.1 kpc distance, a E_{B-V} = 0.96 reddening and a $4\ 10^6$ years age. They pointed out the possible presence of pre-ZAMS members which demanded confirmation.

In this paper we report about our CCD $BVI_{\rm C}$ photometry of the cluster central area, medium resolution spectroscopy of a field larger than the cluster and high resolution Echelle spectroscopy of the brightest cluster members.

2. Photometry

Observations of NGC 6604 have been carried out with the CCD camera mounted on the 1.0 m telescope of the South Africa Astronomical Observatory (SAAO) at Sutherland on July 2, 1992. The journal of observations is given in Table 1 and a finding chart is presented in Fig. 1. The surveyed area corresponds to 2.1×3.3 arcmin centered on the Of star HD 167971. The reader is referred to Munari & Carraro (1995) for the observing technique employed. As usual, we observed several E-regions standard stars to determine the extinction coefficients ($K_B = 0.77 \pm 0.04$, $K_V = 0.52 \pm 0.01$ and $K_I = 0.42 \pm 0.02$) and the color equations:

$$B - b = -0.002(B-V) - 4.204 \quad (1)$$
$$V - v = -0.025(B-V) - 4.387 \quad (2)$$
$$I - i = -0.055(V-I) - 4.954 \quad (3)$$
$$B - V = +1.024(b-v) + 0.187 \quad (4)$$
$$V - I = +1.019(v-i) + 0.584. \quad (5)$$

The resulting $BVI_{\rm C}$ magnitudes are listed in Table 2 together with their internal errors. These ones average at $\sigma \sim 0.0015$ mag and increase only for stars fainter than

Send offprint requests to: R. Barbon,
e-mail: barbon@pd.astro.it

⋆ Based on observations secured with the telescopes of the South African Astronomical Observatory (SAAO) and those of the Padova and Asiago Astronomical Observatories.

Table 1. Journal of observations. The last column is the FWHM of stellar images as measured on the CCD frames

Date	Filter	Exp. time (sec)	Seeing ($''$)
July 9, 1992	V	30	2.1
	V	180	2.2
	B	300	2.4
	B	60	2.3
	I	3	2.1
	I	30	1.9

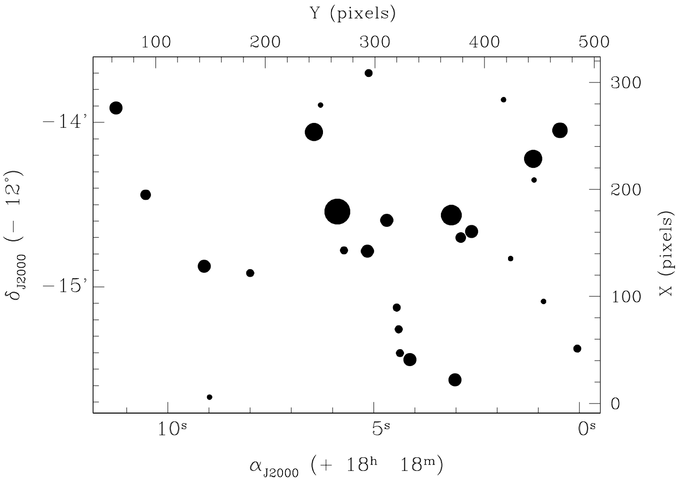

Fig. 1. Identification map for the stars with $BVI_{\rm C}$ photometry in Table 2. The imaged field covers 2.1 × 3.3 arcmin. North is up, East to the left

$V = 14$ mag for which photon statistics becomes the dominant source of noise.

Comparison between our CCD profile photometry (DAOPHOT) and the photoelectric observations of MV yields for the seven stars in common:

$$V \; - \; V_{\rm MV} \; = \; 0.034 \;\; (\sigma = 0.055) \qquad (6)$$

$$(B-V) \; - \; (B-V)_{\rm MV} \; = \; 0.033 \;\; (\sigma = 0.020). \qquad (7)$$

The comparison with the photoelectric observations of FD gives for the seven stars in common:

$$V \; - \; V_{\rm FD} \; = \; 0.039 \;\; (\sigma = 0.047) \qquad (8)$$

$$(B-V) \; - \; (B-V)_{\rm FD} \; = \; 0.092 \;\; (\sigma = 0.028). \qquad (9)$$

Our CCD profile photometry appears slightly fainter and redder than older aperture photometry. It is our opinion that fainter and therefore generally redder stars (quite abundant in a crowded field like that of NGC 6604) have entered and contaminated the older aperture photometry, performed with fixed diaphragms. The different standard stars used (Landolt' equatorial stars for older photometric works, Cousin's E-regions for us) may add a little to the differences in the photometry. The excellent agreement in the interstellar reddening found below via three independent methods gives some support to such arguments.

3. Low resolution spectroscopy

Slitless spectroscopic observations of a circular area of ~ 13 arcmin diameter centered on the cluster have been obtained with the AFOSC spectrograph at the Asiago 1.8-m telescope on July 29 1998 between 20:00 and 22:30 UT (see Fig. 2). We used grism No. 7 (100 Å/ mm), resulting in a dispersion of ~ 2 Å/pix and a resolution (seeing/guide dominated) of ~ 7 Å. The night was photometric with a seeing better than 1.5 arcsec. Altogether 10 spectral frames bracketed by 17 V-band images were obtained at different orientations (0°, 45° and 90° position angles) and with different placements on the spectrograph focal plane. This way the spectral overlap of stars near the clusters center can be disentangled. All spectral frames have been exposed for 60 s, except for a 300 s one.

The observations were reduced using IRAF 2.11 running on a laptop PC under Linux operating system. One dimensional spectral tracings were wavelength calibrated using the positions of the stars in the adjacent V-band images as a reference. Once the spectral lines have been identified, their centroids have been used for refinement of wavelength calibration. Spectral information could be extracted for 32 stars, most of them observed in multiple exposures. The wavelength calibration was generally good to 2 Å. The covered wavelength range for most stars was $\lambda\lambda 3700-6500$ Å. The flux calibration was obtained using standard stars observed during the same night. Inter comparison of tracings of the same star observed at different placements in the field and at different spectrograph orientations shows that the relative flux calibration (colours) are accurate to within 5% redwards of 4500 Å. The resolution and the sometime low S/N ratio of the spectra has prevented in most cases the determination of the luminosity class. Our spectral types, V magnitudes (from Table 2 when appropriate, or from the AFOSC V band frames in the other cases), $B-V$ colors (from Table 2 when appropriate, and in the other cases from convolution with the appropriate photometric band profile on the flux calibrated spectra) and other derived data are listed in Table 3, where comparison with the scarce spectral classification from literature is also provided (Stephenson & Sanduleak 1971; Fitzgerald et al. 1979).

4. Echelle spectroscopy

High resolution spectral observations of the four brightest stars in NGC 6604 have been carried out on Oct. 10, 1998 with the Echelle spectrograph mounted at the Cassegrain focus of the 1.82 m telescope operated by Osservatorio Astronomico di Padova on top of Mt.Ekar in Asiago (Italy). The detector has been a THX31156 Thomson CCD 1024×1024 pixels, 19 μm each and the slit was set to 2.2 arcsec. The whole λ range 4550 − 8750 Å

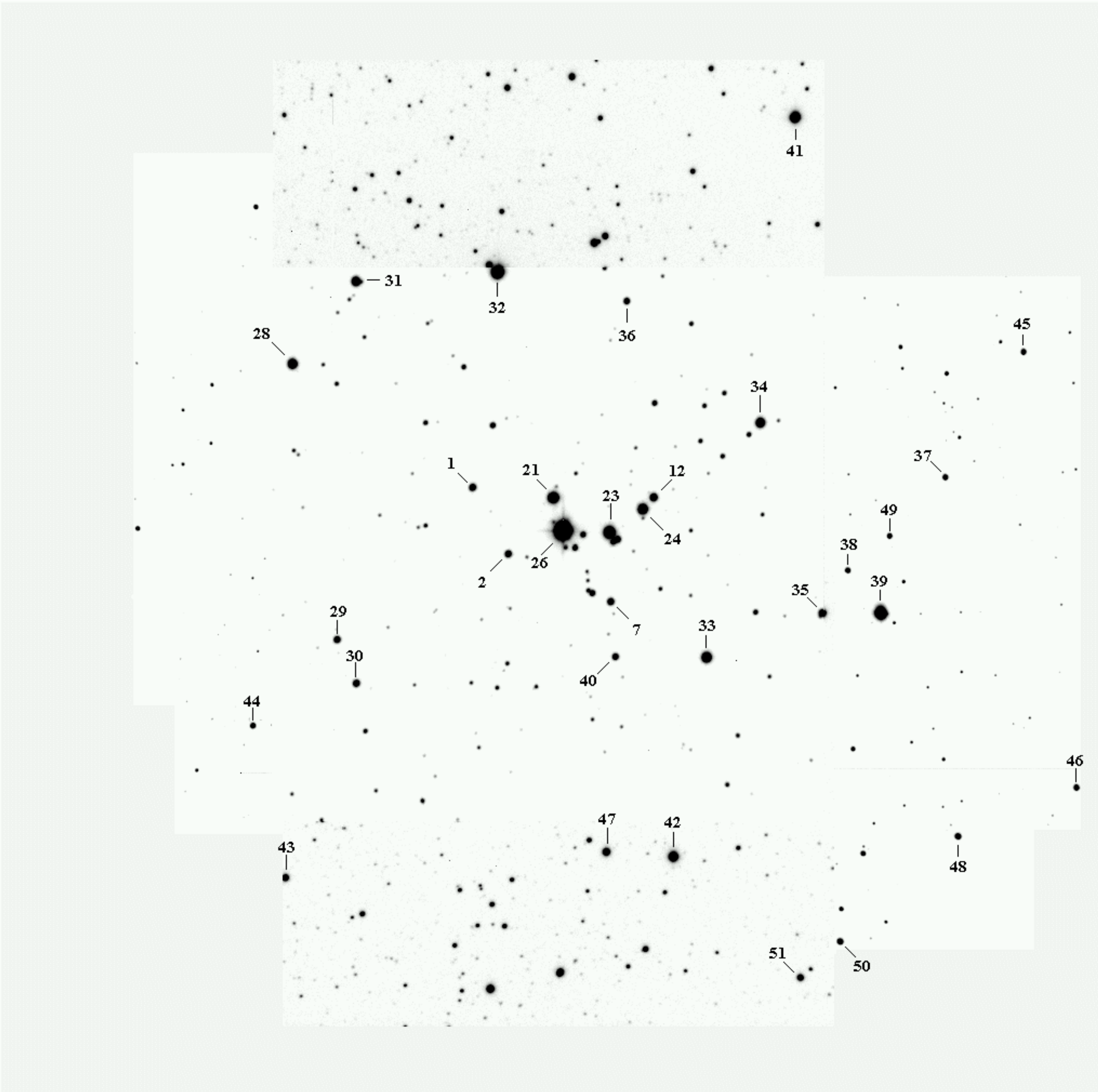

Fig. 2. Identification map for low resolution slitless spectroscopy. North is at the top, East to the left. The identification map for the BVI_C photometry in Fig. 1 covers the central part of this collage of V band frames obtained in parallel with the slitless spectroscopic observations

was recorded on each frame, with a average dispersion of 0.173 Å/pix at NaI D. Stars #21 and #32 have been observed with a 2×2 binning. The spectra have been extracted and calibrated in a standard fashion with IRAF running under Linux on a desk-top Pentium. The spectra are part of a long term investigation of the kinematics of young open clusters conducted in Asiago (see Munari & Tomasella 1999 for details).

The profiles of the Na I D (5890, 5896 Å) and KI (7699 Å) interstellar lines are presented in Fig. 4 and their equivalent widths are given in Table 4 together with the E_{B-V} derived from the Munari & Zwitter (1997) calibration.

The radial velocities of the same four cluster members are given in Table 5, together with their rotational velocities.

Table 2. BVI_C photometry of NGC 6604. Columns gives our identification number and those used by MV and FD, the X and Y positions on the chip, the corresponding J2000.0 equatorial coordinates (linked to the GSC I system), and the BVI magnitudes and colours with associated internal errors as provided by the DAOPHOT package

ID	MV	FD	X	Y	α_{J2000}	δ_{J2000}	V	σ_V	$B–V$	σ_{B-V}	$V–I$	σ_{V-I}
1		D	276.51	63.89	18 18 11.26	–12 13 54.71	12.101	0.001	0.763	0.001	1.025	0.002
2		M	128.33	144.03	18 18 09.12	–12 14 52.47	12.201	0.001	0.800	0.001	1.065	0.002
3	11		142.21	293.03	18 18 05.15	–12 14 46.96	12.993	0.001	0.840	0.002	1.271	0.013
4	10		171.07	310.88	18 18 04.68	–12 14 35.69	12.996	0.002	0.807	0.003	1.108	0.004
5		51	69.04	321.60	18 18 04.39	–12 15 15.48	14.683	0.005	0.943	0.009	1.175	0.004
6			40.66	331.84	18 18 04.12	–12 15 26.55	12.873	0.001	0.839	0.002	1.138	0.003
7		J	21.64	373.07	18 18 03.02	–12 15 33.94	12.227	0.001	0.807	0.001	1.094	0.002
8			154.74	378.57	18 18 02.88	–12 14 42.02	13.025	0.002	0.767	0.003	1.051	0.004
9			160.40	388.27	18 18 02.62	–12 14 39.80	12.411	0.001	0.751	0.001	1.052	0.003
10		2	283.59	417.69	18 18 01.84	–12 13 51.72	15.894	0.013	1.020	0.026	2.586	0.025
11		72	94.91	453.76	18 18 00.87	–12 15 05.31	15.987	0.013	1.026	0.026	1.394	0.035
12	9	Z	254.86	469.18	18 18 00.47	–12 14 02.90	11.658	0.001	0.772	0.001	1.057	0.001
13		52	5.97	148.61	18 18 08.99	–12 15 40.20	15.187	0.008	0.943	0.014	1.236	0.026
14		49	121.83	185.94	18 18 08.00	–12 14 54.98	14.971	0.006	1.176	0.013	1.505	0.014
15		31	308.73	294.42	18 18 05.12	–12 13 42.00	14.478	0.004	0.989	0.007	1.185	0.011
16		71	135.02	424.02	18 18 01.67	–12 14 49.68	15.282	0.007	0.909	0.013	1.200	0.021
17		76	50.75	484.57	18 18 00.05	–12 15 22.52	14.259	0.003	0.872	0.005	1.239	0.009
18			46.77	322.57	18 18 04.36	–12 15 24.17	14.083	0.003	0.869	0.006	1.185	0.009
19			143.02	271.89	18 18 05.72	–12 14 46.66	14.265	0.006	0.892	0.008	1.271	0.013
20		50	89.39	319.79	18 18 04.44	–12 15 07.55	14.790	0.009	0.963	0.013	1.240	0.016
21	2	H	253.65	244.38	18 18 06.45	–12 14 03.52	10.127	0.001	0.707	0.001	0.921	0.001
22			278.91	250.70	18 18 06.29	–12 13 53.66	15.454	0.011	1.037	0.019	1.238	0.027
23	3		175.74	369.74	18 18 03.11	–12 14 33.83	9.681	0.001	0.729	0.001	0.972	0.001
24	4	Y	228.36	444.68	18 18 01.12	–12 14 13.25	10.426	0.001	0.735	0.001	0.984	0.001
25			208.44	445.42	18 18 01.10	–12 14 21.02	15.112	0.010	0.853	0.016	1.233	0.019
26	1	X	179.19	265.92	18 18 05.88	–12 14 32.55	7.524	0.001	0.812	0.001	1.116	0.001
27			195.26	90.86	18 18 10.54	–12 14 26.39	13.716	0.017			2.890	0.017

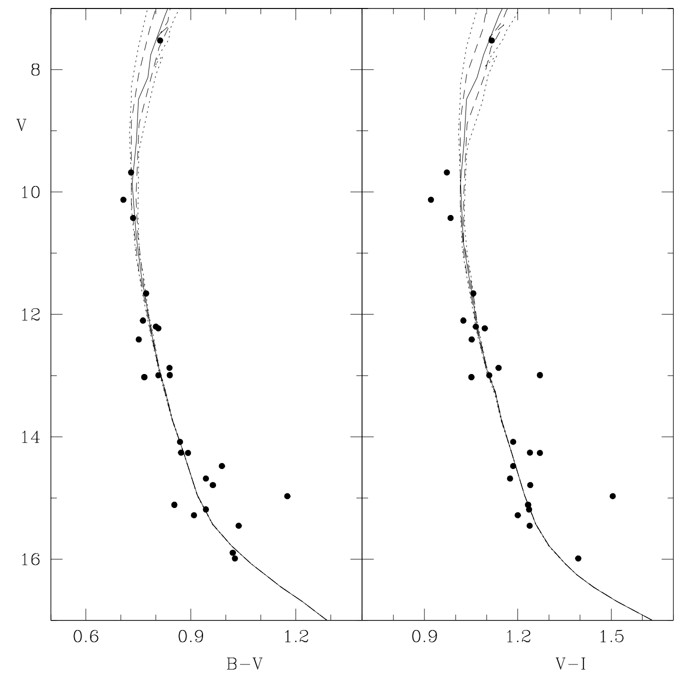

Fig. 3. Colour-magnitude diagrams for the stars in Table 2. Solar abundance isochrones for 3, 4, 5, 6 and 7 10^6 yr are overimposed

5. Results

The V, $(B-V)$ and V, $(V-I)$ diagrams for the stars in Table 2 are shown in Fig. 3. Stars # 10 and 27, which have very red $V-I$ colors laying well outside the diagram borders are not plotted. The situation for these two stars looks confuse (and need additional observations to be settled), because # 10 has a $B-V$ color that places it exactly on the ZAMS, and # 27 (which is too faint for a reliable measure on the B frames) appears too bright in V to be a pre-ZAMS cluster member.

We started with a fit of the observed V, $(B-V)$ diagram to the Zero Age Main Sequence (Schmidt-Kaler 1982) obtaining an apparent distance modulus $m-M=14.28$ and a mean reddening $E_{B-V}=1.02$. Then, the age was determined through trial fits to the observed main sequence with theoretical isochrones of the Padova group (Bertelli et al. 1994) characterized by a standard [He/H] ratio and solar metallicity and scaled to the distance modulus and reddening found before. The best fit, shown in Fig. 3, is obtained for the isochrone corresponding to the age of 5 10^6 years, slightly older than the value reported by FD. The resulting age is sensitive to the position in the color-magnitude diagram of star #26 (the brightest one) and to a lesser extent of #23. Both stars lie very close to

Table 3. Our and literature spectroscopic classifications. Stars with identification numbers greater than 27 lie outside the area covered by Fig. 1 and are identified in Fig. 3

star	V	$B-V$	spectral type		E_{B-V}	$V-M_V$
			ours	liter.		
1	12.101	0.763	early B			
2	12.201	0.800	B2V		1.04	14.65
7	12.227	0.807	mid B			
12	11.658	0.772	late B			
21	10.127	0.707	B0	B0V	1.01	14.13
23	9.681	0.729	O9.5	B1IV	1.04	13.93
24	10.426	0.735	B1V		1.00	13.63
26	7.524	0.812	O7	O8f	1.10	14.32
28	10.73	0.7	B3			
29	12.27	0.7	late B			
30	12.12	1.0	G4			
31	11.06	1.0	M4III			
32	9.26	0.7	O9.5	B1Ib		
33	10.43	0.9	B4:	OB		
34	10.82	0.9	B0.5	OB		
35	12.06	1.1	early B			
36	12.63	0.8	early F			
37	12.72	0.9	K5:			
38	12.77	1.6	late K			
39	8.96	1.7	early G			
40	12.41		K3			
41	10.65		late B			
42	10.90		early B			
43	12.60		K3			
44	12.66		A			
45	12.83		early F			
46	12.65		late A			
47	12.04		A			
48	12.24		K4			
49	12.94		A			
50	12.22		early G			
51	12.90		F:			

the cluster center, their spectro-photometric parallax and reddening agree with the cluster distance and extinction, and furthermore the wide field spectroscopy of Fig. 2 and Table 3 shows a marked drop of O-B stars outside the region covered by Fig. 1. Thus, it is quite safe to assume both stars as validated members of the cluster. The radial velocity of #26 is $\sim 2.5\sigma$ off the mean of the other three cluster members in Table 5, which could suggest a binary nature. The contribution to the #26 brightness by the possible companion cannot be directly determined by the data at hand; however it is worth noticing that (a) the companion is not severly affecting the star colour, and (b) its spectral features does not show up in our Echelle spectra. Thus the position of star #26 in Fig. 3 should not be affected by a possible companion by more than a few tenths of a magnitude. Dimming star #26 by 0.25 mag would change by no more than 1 million year the age estimate, for which we can therefore assume a safe 5(±2) 10^6 years. It may be of interest to note that Feinstein et al. (1986) have suggested

Table 4. Equivalent width and corresponding E_{B-V} (from the Munari & Zwitter 1997 calibration) of the interstellar NaI and KI lines in the Asiago Echelle+CCD spectra of some NGC 6604 stars

star	V	NaI (5890, 5896 Å)		KI (7699 Å)	E_{B-V}
		EW (Å)	EW (Å)	EW (Å)	
21	10.13	0.67	0.64	0.20	1.0
23	9.68	0.66	0.64	0.25	1.0
26	7.52	0.72	0.67	0.25	1.1
32	9.26	0.65	0.63	0.19	0.9

Table 5. Radial and rotational velocity for some NGC 6604 stars derived from Asiago Echelle+CCD spectra. EW, HIW = equivalent width and half intensity width of He I λ 5876 Å; $V_{\rm rot} \sin i$ = projected rotational velocities derived from the HIW of the He I λ 5876 Å line and the Munari & Tomasella (1999) calibration

star	JD$_\odot$	$RV_\odot$ (km s^{-1})	σ (km s^{-1})	EW (Å)	HIW (Å)	$V_{\rm rot} \sin i$ (km s^{-1})
21	2451097.277	+21	2	1.35	8.81	354 ± 6
23	2451097.253	+25	6	0.67	2.80	90 ± 5
26	2451097.234	+15	3	0.64	3.10	104 ± 5
32	2451097.291	+21	2	1.41	3.36	115 ± 6

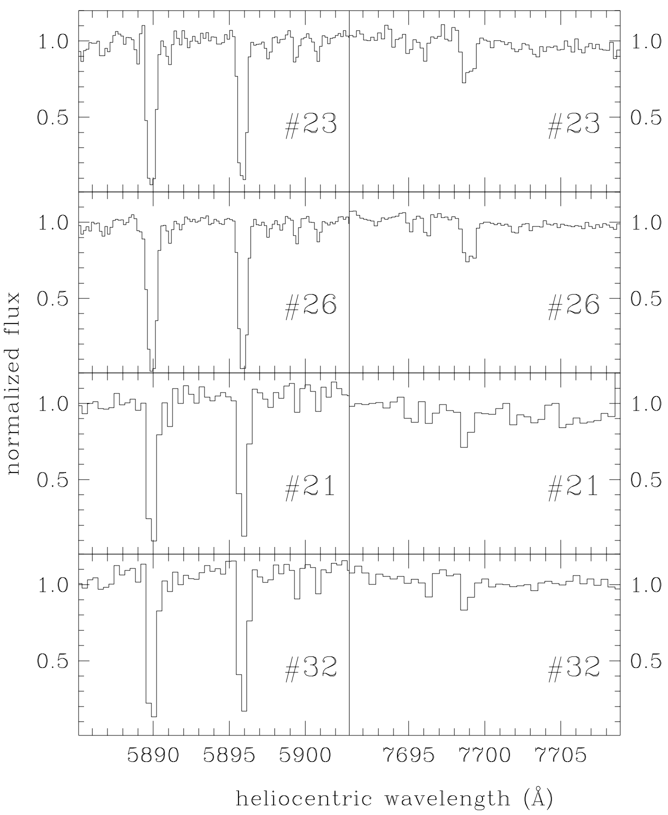

Fig. 4. Interstellar NaI (5889.951, 5895.924 Å) and KI (7698.979 Å) lines from Asiago Echelle+CCD spectra of four NGC 6604 stars

that open clusters having stars with Of characteristics like star #26 should not be older than 5 10^6 years.

The distance to NGC 6604 is $d = 1.7$ kpc, for a $R_V = 3.1$ standard reddening law. Such a distance is 25% smaller than found by FD, which is mainly based on photographic photometry, but quite in agreement to the value derived by MV and places the cluster at a galactocentric distance 6.9 kpc, on the outer boundary of the Carina-Sagittarius arm. Adopting the ZAMS in the $(B-V)$, $(V-I)$ as tabulated by Munari & Carraro (1996), a ratio

$$\frac{E_{B-V}}{E_{V-I}} = 0.77 \quad (10)$$

is found for the reddening affecting NGC 6604, in agreement with the value for the $R_V = 3.1$ standard reddening law. The fitting to isochrones in the V, $V{-}I$ plane is shown in Fig. 3, with $V - M_V = 14.28$ mag and $E_{V-I} = 1.32$ as scaling factors, in agreement with the values from the V, $B-V$ diagram. In view of the larger uncertainities affecting the transformations from the theoretical plane (log L, log T) to the observational one when red photometric bands are involved, the resulting isochrone fitting to the observational data seems satisfactory.

The spectroscopic data of Table 3 for the four stars with detailed spectral classification (# 2, 21, 23, 24) give a mean reddening of $E_{B-V} = 1.02 \pm 0.01$, the same determined from photometry (the star #26 has not been considered because of its emission line nature). The mean reddening from interstellar lines from Table 4 is $E_{B-V} = 1.00 \pm 0.04$. It seems noteworthy that three independent methods converge within 0.01 mag to the same $E_{B-V} = 1.02 \pm 0.01$ value for the reddening affecting NGC 6604.

The mean spectroscopic apparent modulus $V - M_V = 14.13 \pm 0.17$ mag for the cluster members in Table 3 is in good agreement with the $V - M_V = 14.28$ derived from ZAMS fitting.

Finally, the data listed in Table 5 give a cluster heliocentric radial velocity $RV_\odot = +20.5 \pm 2.1$ km s^{-1}, in agreement with the $RV_\odot = +19.0 \pm 3.5$ km s^{-1} of Liu et al. (1991). The Hron's (1987) rotation curve gives a heliocentric radial velocity of $+8.2 \pm 2.5$ km s^{-1} at the galactic location of NGC 6604. Bearing in mind that the effect of the galactic rotation, as seen from the Sun, nearly vanishes toward the Galaxy center direction (close to which NGC 6604 lies) the resulting difference between model and observational velocities (12 km s^{-1}) is within the dispersion of the galactocentric radial velocities for extreme Pop I objects (12.5 km s^{-1}, Binney & Merrified 1998). Therefore the cluster distance and position, its radial velocity and the Hron's model for the Galaxy disk rotation appear in good mutual agreement.

6. Conclusions

Our determination for the cluster distance and reddening confirm earlier studies. From the small dispersion around the cluster main sequence in Fig. 3 we may conclude that most of the stars in Fig. 1 and Table 2 are physical members of NGC 6604. From the spatial concentration of early spectral types in Table 3, the diameter of NGC 6604 is of the order of ∼10 arcmin. The $E_{B-V} = 1.02 \pm 0.01$ reddening follows the standard $R_V = 3.1$ reddening law, with no evidence for a marked differential reddening over this cluster. The cluster age is estimated as 5 10^6 years. Our observations do not go faint enough to address the reality of the pre-ZAMS objects suspected by FD. Extrapolating from the turn-on tracks by Stauffer et al. (2000), pre-ZAMS objects in NGC 6604 should have $V \geq 16$, corresponding to a ZAMS spectral type somewhat later than A0. Thus, star #14 (which is ∼2 mag off the ZAMS) looks too bright both for a pre-ZAMS object and for an equal-mass binary, and therefore it should be a field star.

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