Spectroscopy and $BVIC$ photometry of the young open cluster NGC 6604

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Abstract. $BVIC$ 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 13.7×10^6 years and a reddening $E_{B-V}=1.02$ (±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 IRon (1987) model for the Galaxy disk rotation.

Key words: Open Clusters: general – Open Clusters: individual (NGC 6604)

1. Introduction

NGC 6604 ($\alpha_{2000} = 18^h 18^m 1.1, \delta_{2000} = -12^\circ 14\arcmin, l = 18^\circ 3, b = +1^\circ.7$) 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 and Sanduleak 1971), which suggest the cluster to be fairly young (Forbes and DuPuy 1978). Its distance is rather uncertain, with estimates ranging from 0.7 to 4.4 kpc (Alter et al. 1970). Moffat and Vogt (1975, hereafter MV) presented photometric and photographic 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 photometric and photographic photometry, which yielded a 2.1 kpc distance, a $E_{B-V}=0.96$ reddening and a 4×10^7 years of age. They pointed out the possible presence of pre-ZAMS members which demanded confirmation.

In this paper we report about our CCD $BVIC$ 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 African 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 Figure 1. The surveyed area corresponds to 2.1×3.3 arcmin centered on the Of star HD 167971. The reader is referred to Munari and 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:

\[ B - b = -0.002(B - V) - 4.204 \]  
\[ V - v = -0.025(B - V) - 4.387 \]  
\[ I - i = -0.055(V - I) - 4.954 \]  
\[ B - V = +1.024(b - v) + 0.187 \]  
\[ V - I = +1.019(v - i) + 0.584 \]

The resulting $BVIC$ 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 $V = 14$ 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:

$$V - V_{MV} = 0.034 \quad (\sigma = 0.055) \quad (6)$$

$$\langle B - V \rangle - \langle B - V \rangle_{MV} = 0.033 \quad (\sigma = 0.020) \quad (7)$$

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 (arcsec) |
|--------------|--------|-----------------|-----------------|
| 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             |

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

$$V - V_{FD} = 0.039 \quad (\sigma = 0.047) \quad (8)$$

$$\langle B - V \rangle - \langle B - V \rangle_{FD} = 0.092 \quad (\sigma = 0.028) \quad (9)$$

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 Figure 2). We used grism No. 7 (100˚A/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 sec, except for a 300 sec 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 λλ3700 – 6500Å. 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 and 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 Os-
Table 2. BVI<sub>C</sub> 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<sub>J2000</sub> | δ<sub>J2000</sub> | V   | σ<sub>V</sub> | B−V | σ<sub>B−V</sub> | V−I | σ<sub>V−I</sub> |
|----|----|----|-----|-----|-------------------|-------------------|-----|----------|-----|-------------|-----|------------|
| 1  | D  | 276.51 | 63.89 | 18  | 18  | 11.26 | -12  | 13  | 54.71 | 12.101 | 0.001 | 0.763 | 0.001 | 1.925 | 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 | 1.032 | 0.026 | 1.394 | 0.035 |
| 12 | 9  | 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. 2. Identification map for low resolution slitless spectroscopy. North is at the top, East to the left. The identification map for the $BVIC$ photometry in Figure 1 covers the central part of this collage of $V$-band frames obtained in parallel with the
Fig. 3. Colour-magnitude diagrams for the stars in Table 2. Solar abundance isochrones for 3, 4, 5, 6 and $7 \times 10^6$ yr are overimposed.

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

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 (5889, 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     |

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.
In Figure 3, with $V_{\lambda}$ law. The fitting to isochrones in the $V$, $V$ as scaling factors, in agreement with the values from the data at hand; however it is worth noticing that (#26 brightness by three cluster members in Table 5, which could suggest a binary nature. The contribution to the brightness by the companion is not severely affecting the star colour, and furthermore the wide field spectroscopy of Figure 2 and Table 5. Radial and rotational velocity for some NGC 6604 spectra. Thus the position of star #26 in Figure 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 age of 5(±2)×10⁶ years. It may be of interest to note that Feinstein et al. (1986) have suggested that open clusters having stars with O characteristics like star #26 should not be older than 5 × 10⁶ 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 and Carraro (1996), a ratio

$$\frac{E_{B-V}}{E_{V-I}} = 0.77$$

(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 $V$ plane is shown in Figure 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 uncertainties 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 5$E_{B-V} = 1.00 \pm 0.04$. 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 $R_V = +20.5 \pm 2.1$ km sec⁻¹, in agreement with the $R_V = +19.0 \pm 3.5$ km sec⁻¹ of Liu et al. (1991). The Hron’s (1987) rotation curve gives a heliocentric radial velocity of +8.2±2.5 km sec⁻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 sec⁻¹) is within the dispersion of the galactocentric radial velocities for extreme Pop I objects (12.5 km sec⁻¹, Binney and Merrifield 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 Figure 3 we may conclude that most of the stars in Figure 1 and Table 2 are physical members of NGC 6604. From the spatial concentration of early spectral types in Table 3, the diameter of NGC6604 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 × 10⁶ 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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