Photometric and spectroscopic study of the intermediate age open cluster NGC 3960

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ABSTRACT
We present CCD $UBV_1$I photometry and high-resolution spectroscopy of the intermediate age open cluster NGC 3960. The colour - magnitude diagrams (CMDs) derived from the photometric data and interpreted with the synthetic CMD method allow us to estimate the cluster parameters. We derive: age $\tau = 0.9$ or 0.6 Gyr (depending on whether or not overshooting from convective regions is included in the adopted stellar models), distance $(m-M)_0 = 11.6 \pm 0.1$, reddening $E(B-V) = 0.29 \pm 0.02$, differential reddening $\Delta E(B-V) = 0.05$ and approximate metallicity between solar and half of solar. We obtained high resolution spectra of three clump stars, and derived an average $[\text{Fe/H}] = -0.12$ (rms 0.04 dex), in very good agreement with the photometric determination. We also obtained abundances of $\alpha$-elements, Fe-peak elements, and of Ba. The redenngs toward individual stars derived from the spectroscopic temperatures and the Alonso et al. calibrations give further support to the existence of significative variations across the cluster.

Key words: Hertzsprung-Russell (HR) diagram – open clusters and associations: general – open clusters and associations: individual: NGC 3960 – stars: abundances

1 INTRODUCTION
Open clusters (OCs) have been recognized since a long time to be among the best objects to study the Galactic disk (e.g., Janes & Phelps 1994, Friel 1995, Twarog, Ashman & Anthony-Twarog 1997). We have an ongoing project aimed at exploiting their ability to trace the present properties of the disk, its history and evolution by collecting photometric and spectroscopic data of a large sample of old OCs and deriving in a precise and homogeneous way their fundamental properties (age, distance, reddening, chemical abundance). An updated review of our general project, although mostly focussed on the photometric part, can be found in Bragaglia & Tosi (2005).

This paper is devoted to NGC 3960 (C 1148-554), an intermediate age open cluster located at RA(2000) = 11:50:40, DEC(2000) $=-55:40:28$, or $l = 294.41$, $b = 6.18$. We have acquired CCD photometry of two fields and high-resolution spectra of three stars, which have allowed us to derive the cluster age, distance, reddening and chemical abundances.

There are two main literature papers about this cluster based on photometry, Janes (1981, hereafter J81) first published its CMD, based on BV photographic photometry for 318 stars, 98 of which have also photoelectric measures. His estimate of the cluster parameters are: $(m-M)_0 = 11.1 \pm 0.2$, $E(B-V) = 0.29 \pm 0.02$, and age slightly older than the Hyades. More recently, Prisinzano et al. (2004, hereafter P04) used data obtained with the Wide Field Imager at the ESO-Max Planck 2.2m telescope in the $B, V, I$ bands to determine an age between 0.9 and 1.4 Gyr and $(m-M)_0 = 11.35$ using isochrones with $Z = 0.01$, the metallicity given by Friel et al. (2002). They also inferred the luminosity (and mass) function. They find strong indications of differential reddening, with $E(B-V)$ varying from 0.16 to 0.62 over the about $30 \times 30$ arcmin$^2$ field of view, with a value of 0.29 near the cluster centre.

The metallicity of NGC 3960 has been found to be subsolar by many studies, but the individual estimates range from $[\text{Fe/H}] = -0.68 \pm 0.06$. J81 obtained DDO data for six giants, and derived $[\text{Fe/H}] = -0.3 \pm 0.06$, while Flynn & Merrmilliod (1991) and Piatti, Clarià & Abadi (1992), using improved DDO abundance calibrations, derived $[\text{Fe/H}] = -0.19$, and $-0.06$, respectively, Friel & Janes (1993), using low resolution spectroscopy, found $[\text{Fe/H}] = -0.34 \pm 0.08$, and determined the membership status of 7 giants. Geisler, Clarià & Minniti (1992), using Washington photometry of the cluster giants, determined $[\text{Fe/H}] = -0.68 \pm 0.28$. Paunzen & Maitzen (2002) observed NGC 3960 among other clusters in their search for chemically peculiar stars using the $\Delta a$ system (a three filter photometric narrow band system), and found only one. Finally, Merrmilliod et al. (2001) determined precise radial velocities for 14 red giants, and UBV photoelectric magnitudes for 6 of them.

NGC 3960 has been included in two recent papers aimed at...
2 PHOTOMETRIC OBSERVATIONS AND DATA REDUCTION

NGC 3960 was observed with DFOSC (Danish Faint Object Spectrograph and Camera) at the 1.54m Danish telescope located in La Silla, Chile, on 2001 January 24, and 2001 May 16 and 17. DFOSC was equipped with the back-illuminated CCD EEV 42-80 (2048x4096 pixels, but only half of the CCD is actually used) with a scale of 0.39 arcsec/pix and a field of view of 13.3 × 13.3 arcmin². We used the Johnson-Bessel-Gunn B, V, i (ESO 450, 451, and 425) and U (ESO 632, in May only) filters; Table 1 gives a log of the observations. Two positions were observed, one centered on the cluster, and a second about 30 arcmin away, to be used as comparison for field stars contamination; Fig. 1 shows our pointings. All frames were trimmed and corrected for bias and flat fields (each one of 13.5 × 13.5 arcmin²). The three circles indicate the stars observed with FEROS.

2.1 Calibration to the standard system

The January 2001 night was photometric with good seeing conditions; the main observing program of that night was on RR Lyrae stars in the Large Magellanic Cloud, for which excellent calibrations and a precise determination of the night extinction were essential. Complete description of the procedure can be found in Clementini et al. (2003) and Di Fabrizio et al. (2005), from which we adopt the calibration. The extinction coefficients for the night were found to be $K_B = 0.240$, $K_V = 0.142$, and $K_i = 0.071$, which well agree with the average ones derived for La Silla. 27 stars in the Landolt (1992) - Stetson (2000) standard stars fields PG0918+029, PG0231+051, PG1047+003, and SA98 were used, with $-0.273 < B - V < 1.936$ and $-0.304 < V - I < 2.142$, and the following calibration equations were derived:

$$B - b = 0.1106 \times (b - v) - 0.472 \quad (r.m.s. = 0.032)$$
$$V - v = 0.0213 \times (b - v) - 0.175 \quad (r.m.s. = 0.017)$$
$$I - i = -0.0227 \times (v - i) - 1.507 \quad (r.m.s. = 0.025)$$

where $B, V, I$ are in the Johnson-Cousins system, while $b, v, i$ are the instrumental magnitudes. These equations, that will be used as a threshold of 4 $\sigma$ over the local sky value. Instrumental magnitudes were measured with a Moffat PSF. The resulting catalogues were selected in error ($\sigma_{DAO} \leq 0.1$ mag), in $\chi^2$ (only to eliminate the very bad cases, i.e. the almost saturated stars), and in sharpness (a shape defining parameter, useful to discriminate between stars and spurious or extended objects). The output catalogues were then aligned to a reference frame in each filter, for which aperture corrections (i.e., the difference between aperture and PSF magnitudes) and extinction corrections were derived. Finally, the instrumental $u, b, v, i$ magnitudes for each star were computed from a (weighted) average of the individual values. Using dedicated software by P. Montegriffo (private communication), all frames were aligned to the same coordinate system, then astrometrized to the GSC2.

analyzing open clusters properties in a homogeneous way: Twarog et al. (1997), on the basis of J81 data, found a Galactocentric distance $R_{GC} = 7.95$ kpc, a distance from the Sun of 1.73 kpc, and a metallicity $[\text{Fe/H}]=–0.17$; Carraro, Ng & Portinari (1998) applied the synthetic CMD method, using J81 photometry, Friel & Janes (1993) metal abundance, and the Padova tracks (Bertelli et al. 1997), on the basis of J81 data, found a Galactocentric distance $R_{GC} = 8$ kpc, and an age of 0.6 Gyr.

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Table 1. Observing log, with exposure times in seconds for each filter, and seeing excursions

| Field    | RA(2000) | DEC(2000) | UT Date     | U     | B     | V     | I     | seeing |
|----------|----------|-----------|-------------|-------|-------|-------|-------|--------|
| Central  | 11:50:42.5 | -55:40:33 | January 24 2001 | 480,80,20 | 240,40,10 | 240,40,10 | 0.94 - 1.2 |
|          |          |           | May 16, 17 2001 | 900,900,60 | 5     | 5     | 1     | 1.1 - 1.5 |
| External | 11:54:19.3 | -55:41:06 | May 17 2001    | 600,60,5  | 600,60,1 | 600,60,1 | 1.2 - 1.6 |

Figure 2. Comparison between our photometry and the photolectric one by J81 (for the B and V filters, 74 stars) or Mermilliod et al. (2001) for the U band (6 stars). The 2 panels on the right show the differences in B and V photolectric measures for the 6 stars in common.

'master calibrations' for our data, have been computed putting together standards observed in both nights of the run.

For the May 2001 run we derived new calibrations, since we also have U band data, and a second, separate, field. We computed aperture photometry for 9 stars in the two areas PG1323–086 and PG1657+078 (with $-0.149 < B - V < 1.069$ and $-0.127 < V - I < 1.113$), and used average extinction coefficients for La Silla ($K_U = 0.44$, $K_B = 0.21$, $K_V = 0.13$, and $K_i = 0.06$) to derive the following equations:

- $U - u = 0.0955 \times (u - b) - 2.9086 \ (r.m.s. = 0.028)$
- $B - b = 0.1108 \times (b - v) - 0.4674 \ (r.m.s. = 0.020)$
Table 2. Completeness ratios (cB, cV, ci) in the three bands for the central (cols. 2 to 4) and external (cols. 5-7) field.

| mag   | cB Centre | cV Centre | ci Centre | cB External | cV External | ci External |
|-------|-----------|-----------|-----------|-------------|-------------|-------------|
| <14.50 | 1.0       | 1.0       | 1.0       | 1.0         | 1.0         | 1.0         |
| 14.50  | 1.0       | 1.0       | 0.98      | 1.0         | 1.0         | 1.0         |
| 15.00  | 1.0       | 0.99      | 0.94      | 1.0         | 0.99        | 1.0         |
| 15.50  | 1.0       | 0.98      | 0.95      | 0.99        | 0.98        | 1.0         |
| 16.00  | 1.0       | 0.93      | 0.94      | 0.97        | 0.95        | 0.98        |
| 16.50  | 0.99      | 0.97      | 0.95      | 0.96        | 0.94        | 0.96        |
| 17.00  | 0.98      | 0.95      | 0.92      | 0.95        | 0.93        | 0.93        |
| 17.50  | 0.95      | 0.93      | 0.92      | 0.96        | 0.97        | 0.94        |
| 18.00  | 0.88      | 0.92      | 0.90      | 0.92        | 0.90        | 0.93        |
| 18.50  | 0.92      | 0.90      | 0.87      | 0.91        | 0.88        | 0.91        |
| 19.00  | 0.92      | 0.88      | 0.86      | 0.93        | 0.86        | 0.89        |
| 19.50  | 0.90      | 0.90      | 0.84      | 0.86        | 0.89        | 0.89        |
| 20.00  | 0.89      | 0.88      | 0.79      | 0.89        | 0.85        | 0.86        |
| 20.50  | 0.88      | 0.87      | 0.65      | 0.84        | 0.82        | 0.83        |
| 21.00  | 0.86      | 0.84      | 0.30      | 0.80        | 0.77        | 0.74        |
| 21.50  | 0.85      | 0.77      | 0.00      | 0.74        | 0.71        | 0.21        |
| 22.00  | 0.77      | 0.64      | 0.00      | 0.35        | 0.59        | 0.00        |
| 22.50  | 0.66      | 0.11      | 0.00      | 0.00        | 0.07        | 0.00        |
| 23.00  | 0.20      | 0.00      | 0.00      | 0.00        | 0.00        | 0.00        |
| 23.50  | 0.00      | 0.00      | 0.00      | 0.00        | 0.00        | 0.00        |

$V - v = 0.0103 \times (b-v) - 0.1673 \quad (r.m.s. = 0.011)$

$I - i = -0.0177 \times (v - i) - 1.5368 \quad (r.m.s. = 0.020)$

These equations give the same $B$ and $V$ of the previous ones (to about a few thousandths of magnitude), and a very similar $I$ (to about 0.02 mag). The ones involving $B$, $V$, $I$ will be used only to independently calibrate the external field. The transformation for the $U$ band can not be compared the same way.

We have further checked our transformations with the photoelectric measurements existing for some of our stars; we used J81 for the $B$ and $V$ filters, and Mermilliod et al. (2001) for the $U$ band. Stars were identified, and we found 74 and 6 objects in common, respectively. Differences between our photometry and the photoelectric measures are shown in Fig. 2: on average they are 0.035 and 0.025 mag in the $B$ and $V$ bands, respectively. Differences between our photometry and the photoelectric measures are shown in Fig. 2: on average they are $0.035, 0.025, 0.025$ mag in $B$, $V$, $I$ respectively, with a small trend with magnitude. The effect of these differences on the CMDs is negligible, as demonstrated by adding artificial stars (50000, at random positions and selected in magnitude according to the observed luminosity function) to the deepest $B$, $V$, and $I$ images and exactly repeating the procedure of extraction of objects and PSF fitting used for the original frame (see e.g. Bragaglia & Tosi 2003 for more details). The output catalogue of the added stars was selected exactly as the science one, using error, $\chi^2$ and sharpness. A star is considered recovered if its output coordinates coincide (within a fraction of pixel) with the input ones, and if the difference in magnitude is less than 0.75 mag. The completeness level of our photometry at each magnitude is given by the ratio of the number of recovered artificial stars to the number of added ones and is shown in Table 2.

3 THE COLOUR-MAGNITUDE DIAGRAMS

The final catalogue for the cluster contains 6019 stars with $B$, $V$, $I$ magnitudes; the resulting CMDs in $V$, $B-V$ and $V$, $V-I$ are shown in Fig. 3(a,b), while the ones for the external comparison field are in Fig. 3(c,d).

In spite of the relatively large distance ($\sim$30 arcmin) from the cluster centre of the observed external field, its CMD has a MS similar to that of the cluster, suggesting that stars formed in NGC 3960 are spread over a large area, as often found for open clusters having suffered strong evaporation. We have plotted the CMDs of regions with increasing distance from the cluster centre and found that beyond a radius of $\sim$4 arcmin the field contamination and the spread of the various evolutionary sequences increase significantly, while the number of probable cluster members (such as clump stars) re-

\[ \text{http://www.univie.ac.at/webda/new.html} \]
Figure 4. CMDs for the field centered on NGC 3960 (left-hand panels) and the external comparison one (right-hand panels).

mains roughly unchanged. We will thus restrict the analysis with synthetic CMDs to the central region of 4 arcmin radius.

The reddening maps by Schlegel et al. (1998) give a value of \( E(B-V) = 0.424 \text{ mag} \) for the cluster centre position, but this appears to be an overestimate. Literature determinations all converge to \( E(B-V) = 0.29 \), and our own analyses, both photometric (Section 4) and spectroscopic (Section 5), confirm it. Furthermore, as noted by the referee, NGC 3960 is at a distance about two thirds of that of the edge of the dust disc in its direction; in the not unreasonable assumption than the dust is approximately evenly distributed, only two thirds of the dust would be in front of the cluster and its reddening value would be justified.

Given this concordance, we have used the two-colours diagram to confirm the validity of our \( U \) magnitudes rather than to derive a reddening value. We have considered the location of stars of the well studied OC NGC 752, with \([\text{Fe/H}] = -0.09\) (i.e., very similar to the one we derive for NGC 3960, see Section 6), for which we adopted the photoelectric \( UBV \) data by Johnson (1953) and \( E(B-V) = 0.034 \) (data and information are taken from the BDA). With \( E(B-V) = 0.29 \), its sequence matches the one of NGC 3960 reasonably well, and the fit is even better if our \( U \) values are made 0.03 mag fainter, a confirmation that our \( U \) photometry is quite well - but not perfectly- calibrated. We may reasonably assume this as the residual uncertainty affecting our \( U \) data calibration.

4 DERIVATION OF THE CLUSTER PARAMETERS FROM THE PHOTOMETRY

We have derived age, reddening and distance modulus of NGC 3960 from the photometric data, using the synthetic CMD method (Tosi et al. 1991), as for all the clusters of our project (see Kalirai & Tosi 2004; Bragaglia & Tosi 2005). As usual, we have applied the method adopting three different sets of stellar evolution models, in order to estimate the theoretical uncertainty on the resulting values. The adopted evolutionary tracks are those computed by the Padova group (Bressan et al. 1993, Fagotto et al. 1994; hereafter BBC) considering overshooting from convective regions, the Full Spectrum Turbulence models computed by Ventura et al. (1998; hereafter FST), with and without overshooting, and the models with semiconvection and no overshooting computed by the Frascati group (Dominguez et al. 1999; hereafter FRA). More details on the method and a summary of the results obtained for all the clusters studied so far are provided by Bragaglia & Tosi (2005).

The synthetic CMDs have been created assuming a Salpeter Initial Mass Function, an (almost) instantaneous burst of star formation, the photometric errors and the completeness factors derived from the extensive artificial star tests on the data images described above. Theoretical luminosity and effective temperature of the synthetic stars have been transformed to magnitudes and colours using Bessel, Castelli & Pletz (1998) photometric conversions to the Johnson-Cousins system.

For the reasons presented in the previous Section, we have decided to consider only a region within a 4 arcmin radius of the cluster centre, that contains 1966 stars. Since equal area zones of the external field contain between 1750 and 1840 stars, if none of these...
were attributable to NGC 3960, the cluster members should be at most 216. However, synthetic CMDs with this total number of cluster objects grossly underproduce the number of stars on the upper MS and post-MS phases. We therefore believe that many low-mass stars have evaporated from the cluster. We have iteratively considered as representative of the original number of objects formed in the cluster only the number of existing stars brighter than a given magnitude (i.e. more massive than a given mass). It turns out a posteriori that only stars brighter than V=15 appear to be unaffected by evaporation. In fact, synthetic models with 90 stars\(^4\) brighter than V=15 reproduce very well the empirical luminosity function. Such models predict between 400 and 440 stars still alive in NGC 3960, about twice as many as the 216 obtained subtracting the number of stars observed in the control field. This indicates the high level of evaporation occurred during the cluster lifetime (much longer than the cluster relaxation time).

The synthetic CMDs allow for a fraction of unresolved binary systems from 0 to 50\%, assuming a random mass ratio between the primary and the secondary star of the system. Given the large colour spread in the sequences of the observational CMD of NGC 3960, varying amounts of differential reddening have also been considered. We have found that to simultaneously reproduce the shape of the TO and of the MS, their colour spread and distribution, on average we need to assume with all the stellar models a fraction of binaries of 50\% and a differential reddening \(\Delta E(B-V)\) of about 0.1. Models with smaller differential reddening have tighter MS and may be acceptable with the BBC tracks but not with the FRA ones. Models with less binaries and larger \(\Delta E(B-V)\) (or vice versa) do not reproduce equally well the observed features, since the two effects widen the MS toward the red in different ways.

For sake of homogeneity with the approach followed for the other clusters of the project for which no metallicity estimate from high-resolution spectroscopy is available, we have run the simulations for various metallicities as if we had not derived the cluster abundances from our own spectra. The comparison of the model metallicity leading to synthetic CMDs in better agreement with the photometric data with that derived from the spectroscopic ones is then a check of how well the theoretical abundances compare with the actual ones. The tested metallicities are: \(Z=0.004, Z=0.008\) and \(Z=0.02\) with the BBC models, and \(Z=0.006, Z=0.01\) and \(Z=0.02\) with the FRA and FST models. We find that the synthetic CMDs with \(Z=0.004, 0.006\) and 0.008 all lead to unsatisfactory results, because they do not reproduce either the shape of the MS or of the TO, or they overpopulate the clump. They all need reddenings \(E(B-V)\) of at least 0.40, larger than both the literature and the spectroscopic values.

Models with \(Z=0.01\) and 0.02, instead, reproduce quite well the observed features of both the V, B–V and the V, V–I diagrams. With the FST models, we find that to reproduce the observed features of NGC 3960, the evolutionary tracks assuming the maximum overshooting parameter \((\eta=0.03, \text{see Ventura et al.} 1998)\) are more appropriate. The best agreement with the data is reached with \(Z=0.01\) (with age 0.9 Gyr, \(E(B-V)=0.30 \pm \Delta E(B-V)\), and \((m-M)_0=11.5)\), although the \(Z=0.02\) model (with age 0.8 Gyr, \(E(B-V)=0.28 \pm \Delta E(B-V)\), and \((m-M)_0=12.0)\) is not bad either. With the FRA models the agreement is less good, because they all overpopulate the clump and have the TO shape more vertical than observed. It is difficult to choose between the \(Z=0.01\) models (with age 0.5 Gyr, \(E(B-V)=0.43 \pm \Delta E(B-V)\), and \((m-M)_0=11.3)\) and the \(Z=0.02\) ones (with age 0.6 Gyr, \(E(B-V)=0.31 \pm \Delta E(B-V)\), and \((m-M)_0=11.6)\), but the latter look slightly more adequate. BBC models are not available for metallicity values between 0.008 and 0.02, and the solar ones reproduce well the data (although not as well as the FST \(Z=0.01\) ones, because of a slight overpopulation of the clump) with age 0.9 Gyr, \(E(B-V)=0.27 \pm \Delta E(B-V)\), and \((m-M)_0=11.7). \Delta E(B-V)\) is equal to 0.05 for all these models; it indicates the differential reddening and not the error on the average reddening. Notice how small the spread on the three parameters resulting from the theoretical uncertainties is: for the best models, the average reddening is between 0.27 and 0.31, the distance modulus between 11.5 and 11.7, and the age is 0.9 Gyr with both the BBC and FST overshooting models and obviously less, 0.6 Gyr, with the FRA no-overshooting ones.

The synthetic CMDs in better agreement with the cluster data for each of the three types of stellar evolution models are shown in Figs 6 and 7. In these diagrams, to the synthetic stars we have superimposed the 1757 stars measured in an equal area zone of the exter-

\[^4\] 90 = 111 - 21 being the number of stars with \(V\leq15\) in the central region of 4 arcmin radius minus the corresponding number in the external field.

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**Table 3. Log of the spectroscopic observations and information on the three observed stars.**

| Id | BDA | Id | date-obs | exptime | Rat(2000) | Dec(2000) | B | V | I | 2MASS | K |
|----|-----|----|----------|---------|-----------|-----------|---|---|---|-------|---|
| 28 | 4358 | 2001-02-22 | 2×3600 | 177.611607 | -55.674498 | 14.190 | 12.999 | 11.774 | 10.815 | 10.254 |
| 2001-04-25 | 3600 | 2001-04-26 | 3600 |
| 41 | 4351 | 2001-04-26 | 3×3600 | 177.650183 | -55.701565 | 14.435 | 13.131 | 11.757 | 10.671 | 10.080 |
| 50 | 4324 | 2001-04-25 | 2×3600 | 177.656742 | -55.670876 | 14.337 | 13.128 | 11.810 | 10.820 | 10.295 |

**Table 4. Atmospheric parameters and iron abundances for the three clump stars.**

| Id | BDA | Id | T\(_{eff}\) | log g | [A/H] | \(v_2\) | nr | log \(\epsilon\) | \(\sigma\) | Fe I | Fe II | log \(\epsilon\) | \(\sigma\) |
|----|-----|----|----------|-------|-------|--------|----|----------|------|------|------|----------|------|
| 28 | 4358 | 4900 | 2.06 | -0.15 | 1.23 | 98 | 7.402 | 0.108 | 13 | 7.346 | 0.190 |
| 41 | 4351 | 4850 | 2.20 | -0.14 | 1.21 | 97 | 7.390 | 0.132 | 14 | 7.335 | 0.176 |
| 50 | 4324 | 5000 | 2.70 | -0.06 | 1.15 | 106 | 7.478 | 0.112 | 12 | 7.431 | 0.182 |
Figure 5. Synthetic CMDs in better agreement with the data of the cluster central region of 4 arcmin radius. The empirical CMD is in the top panel. The type of stellar models adopted for the synthetic CMDs and their metallicity are indicated in each panel. See the text for the age, reddening and distance modulus of the shown models.

Figure 6. V, V−I synthetic CMDs of the models shown in Fig. 6. The empirical CMD is in the top panel. The type of stellar models adopted for the synthetic CMDs and their metallicity are indicated in each panel.

Table 5. Values for the reddening $E(B−V)$ computed from the spectroscopic temperatures and the Alonso et al. (1999) calibrations, derived from the $B−V$ and the $V−K$ colours. Last column gives the average values.

| Id | Id | $E(B−V)$ | $E(B−V)$ | $E(B−V)$ |
|----|----|----------|----------|----------|
| BDA |   | (B−V)    | (B−V)    | (B−V)    |
| 28  | 4358 | 0.227    | 0.226    | 0.2265   |
| 41  | 4351 | 0.365    | 0.356    | 0.3605   |
| 50  | 4324 | 0.320    | 0.315    | 0.3175   |

The striking difference seen in the CMDs between the observed lower MS population and the one modeled is due to the strong evaporation of low-mass cluster stars and is also visible in the LFs. The LFs of the different best cases coincide at faint magnitudes, where the LF is dominated by field objects, and are barely distinguishable from each other at bright magnitudes.
5 Spectroscopic Data

Three clump stars in NGC 3960 were selected among the true cluster members on the basis of the radial velocities (RVs) measured by Friel & Janes (1993), later confirmed by Mermilliod et al. (2001) and by our own measures. They were observed in 2001 (February and April) with FEROS (Fiber-fed Extended Range Optical Spectrograph) mounted at the 1.5m telescope in La Silla (Chile) at R = 48000, with a wavelength coverage of λλ 3700-8600 Å; a log of the observations is given in Table 1 together with photometric information. The averaged spectra for each stars have high signal to noise ratio; S/N is 100 for stars 28 and 41, and 80 for star 50 (measured near 6150 Å). The heliocentric RVs perfectly agree with the ones in Mermilliod et al. (2001) for stars 28 and 41 (4358 and 4351 in our numbering system). Star 50 (4324 in our numbering system) is a long period spectroscopic binary and our 3 spectra taken on the same night can not produce a significant average value; with RV ~ -15 km s⁻¹ they appear compatible with the known RV and amplitude of the RV curve (Mermilliod et al. 2001: RV = -22.31 km s⁻¹, K = 12.92 km s⁻¹).

These spectra have been obtained, reduced, and analyzed exactly as described in Bragaglia et al. (2001) and Carretta et al. (2004, 2005). Here we present the results and refer to those papers for a detailed description of the method used.

Equivalent widths (EWs) were measured employing an updated version of the ROSA spectrum analysis package (Gratton 1988). As usual, we restricted to the 5500-7000 Å spectral range for Fe lines, and employed the entire spectrum for the other species. Sources of oscillator strengths and atomic parameters are the same as Gratton et al. (2003).

Effective temperature (T_{eff}) and gravity (log g) for each star were derived from the spectra using the excitation and ionization equilibria for iron, respectively. The microturbulent velocity (v_t) was derived assuming the relation between log g, v_t, and T_{eff} (Carretta et al. 2004). These parameters, along with iron abundances, are shown in Table 1. Errors were estimated as in Carretta et al. (2004). They comprise a systematic part (due e.g., to uncertainties in the adopted oscillator strengths) and a random part (due e.g., to the different S/N ratios) that represents the internal error; random errors have been found to be 62 K in T_{eff}, 0.25 dex in log g, 0.17 km s⁻¹ in v_t, and 0.05 dex in [A/H]. Sensitivity of the parameters on the internal errors can be found in tab. 3 of Carretta et al. (2005).

As our spectroscopically determined temperatures are reddening-free, we can derive an independent measure of the reddening. We entered the spectroscopically determined T_{eff}'s into the colour-temperature transformations by Alonso, Arribas & Martínez-Roger (1999) and obtained de-reddened colours to be compared to the observed ones based on our B, V photometry and the 2MASS J, K values (Cutri et al. 2003). The reddening for the three stars is given in Table 1. We estimate errors on these E(B − V)'s to be at most 0.02-0.03 mag, assuming a conservative error of ±0.1 dex in metallicity and 90 K in T_{eff}. E(B − V) values from B − V and V − K [adopting E(V − K) = 2.75(E(B − V));
Cardelli et al. 1989] are almost identical for each star (less than 0.01 mag at the most). The average reddening is $E(B-V)=0.301$, with large differences among the three stars (rms = 0.068). Even if the spectroscopic sample is very small, both average value and scatter around it are compatible with what we derived ($E(B-V)=0.29$, $\Delta E(B-V)=0.05$) from the photometric data of the central part of the cluster, where all three stars are located.

6 CHEMICAL ABUNDANCES

The iron abundances derived from $EW$'s were checked using synthetic spectra of about 20-25 selected iron lines, as amply described in Carretta et al. (2004). The average difference between abundances derived from $EW$'s and from synthesis is $-0.05$ dex, without a systematic trend, so we deemed to have achieved the accuracy in continuum tracing and $EW$ measurement attainable with these spectra. When we average the three stars we obtain $[\text{Fe/H}]=-0.12 \pm 0.02$, rms 0.05 dex; this error bar is simply the standard error of the mean.

This metallicity is based on high resolution spectroscopy, the best technique to derive accurate chemical abundances, so it should supersede other measurements, to which anyway we may compare it. From the synthetic CMD method we find $Z = 0.01$ or 0.02, i.e. $[\text{Fe/H}]=-0.3$ or 0. Literature values (see Introduction) range from $[\text{Fe/H}]=-0.68$ (based on Washington photometry, that gives systematically lower results) to $\approx -0.3$ (DDO photometry and low resolution spectroscopy) or $-0.06$ (another calibration of DDO photometry).

Abundances were also derived for the light elements Na, Al, for the $\alpha$-process elements Mg, Al, Ca, Ti I and II, the Fe-group elements Sc II, V, Cr I and II, Mn, Co, Ni, and for the $n$-capture element Ba II. We corrected the Na abundance for departures from LTE following Gratton et al. (1999), while those of Sc, V, Mn, Co, and Ba have hyper-fine structure (HFS) taken into account whenever necessary. Abundances of C, N, O are deferred to a dedicated paper since they require synthetic spectrum analysis. Results for each star and the cluster averages are presented in Table 6 together with the reference solar values adopted.

Abundances from different ionization stages (Ti I and Ti II, Cr I and Cr II) are in very good accord, endorsing the adopted atmospheric parameters. The three stars do not seem to show scatter in any of the abundances, as we already found for the other OCs studied. The $\alpha$-elements have a value slightly over solar (+0.10), while Na is clearly overabundant (+0.32), in line with the old OC population (Friel et al. 2003, Carretta et al. 2005). NGC 3960 does not show any striking peculiarity, and its composition will be considered in conjunction with the ones of the other OCs in our sample in forthcoming papers.

7 SUMMARY AND DISCUSSION

We have analyzed photometric and high resolution spectroscopic data for the open cluster NGC 3960, and found age, distance, reddening and metallicity using the synthetic CMD method and fine abundance analysis. Our best estimates are: age of 0.9 Gyr or 0.6 Gyr (using stellar models with/without overshooting), $(m-M)_0=11.6 \pm 0.1$, $E(B-V)=0.29 \pm 0.02$ (with a differential reddening $\Delta E(B-V)=0.05$), metallicity between solar and half of solar from the photometry and $[\text{Fe/H}]=-0.12$ (rms 0.05) dex from the spectra.

These value are in good agreement with J81 and the most recent investigation of this cluster (P04), taking into account the different methods and assumptions.

At the distance of NGC 3960 derived from the synthetic CMDs (2.1 kpc from the sun) the external field observed at 30 arcmin from the cluster centre is at 18.3 pc. The fact that it clearly contains stars falling on the MS of the cluster CMD shows that these stars have been able to travel this distance from their original birthplace. We have found that about half of the cluster stars fainter than $V = 15$ (i.e. with mass lower than $\sim 1.6 \, M_\odot$) are likely to have evaporated from the central region.

Existence of segregation and evaporation is in agreement with what P04 found from their analysis. They derived the luminosity and mass functions, corrected for the presence of field stars, for the central part of the cluster (see their figs. 15 and 16); their mass function drops below about 1 $M_\odot$, because of the combination of incompleteness and mass segregation that moves the lighter stars outside the considered radius (larger than ours: 7 arcmin).

The differential reddening values of 0.1 in $E(B-V)$ in the central area of 4 arcmin radius agrees with the amount proposed by P04 for the same zone, although they suggest the higher value of $\Delta E(V-I)=0.57$ over their much larger field of view. The average (central) reddening resulting from the best fitting synthetic CMDs is supported by the two-colours diagram. It also compares very well with the literature values (except Schlegel et al. 1998) and with that inferred from the spectroscopic analysis of the clump stars that show some evidence of differential reddening too.

Analysis of FEROS spectra of three clump stars was used to derive the detailed chemical composition of the cluster, determining abundance of iron, $\alpha$-elements and heavier elements. Their behaviour is similar to what has usually been found for old open clusters.

The cluster metallicity derived from our high-resolution spectra, $[\text{Fe/H}]=-0.12$, corresponds to a metal mass fraction $Z=0.015$. This value is between those available for the stellar evolutionary tracks and this explains the ambiguity in the choice between the $Z=0.01$ and the $Z=0.02$ synthetic models. We consider this result as quite favourable, taking into account that the stellar model metallicity depends on a series of parameters, such as opacities, photometric conversions, etc.

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