Near-infrared photometry
of the intermediate age open clusters IC 166 and NGC 7789[*]

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Abstract. We present and discuss new photometric data obtained with an IR camera in the J and K pass-bands for the intermediate age open clusters IC 166 (936 stars in total) and NGC 7789 (1030 stars in total). IC 166 is a poorly studied open cluster for which no IR data was available previously, while NGC 7789 is a well studied open cluster.

We show that IC 166 is of intermediate age (about 1.0 Gyr), with a reddening E(V-K) $\approx$ 1.3 (corresponding to E(B-V) = 0.50) and a true distance modulus $(m - M)_o = 13.25$. These values are significantly different from previous determinations.

NGC 7789 is found to be a 1.4 Gyr open cluster. The metallicity derived with the method developed by Tiede et al (1997) is found to be closer to the spectroscopic estimate than previous photometric studies.

Key words: techniques: photometric – Galaxy: open clusters and associations: general – Galaxy: open clusters and associations: individual: IC 166 – Galaxy: open clusters and associations: individual: NGC 7789

1. Introduction

The Galactic Disk intermediate age open clusters are those clusters whose ages range between the Hyades and IC 4651 (Carraro et al 1999a). They are fundamental templates to study the internal structure of Main Sequence (MS) stars with mass between 1.0 and $2.0 M_\odot$. In particular, they can be used to check the importance and the amount of the core overshooting during the H-burning phase (Carraro et al 1993, Rosvick & Vandenberg 1998).

Usually the comparison between observational data and theoretical models is done by means of the Color Magnitude Diagrams (CMDs) and the dating operation of the stellar ensembles by means of isochrone fitting, luminosity functions and star counts. For stellar clusters, obtaining reasonable age estimates requires knowledge of cluster reddening, distance and metallicity. IR photometry is particularly useful to obtain cluster

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[*] Based on observations taken at TIRGO

Table 1. Basic parameters of the studied clusters. Diameters are taken from Lyngå (1987) catalogue.

Cluster	$\alpha_{2000.0}$ $hh\,mm$	$\delta_{2000.0}$ ^{o}	l ^{o}	b ^{o}	Diameter $(\prime)$
IC 166	01 52 30.8	+61 35 47.5	130.08	-0.19	7
NGC 7789	23 57 02.0	+54 46 42.1	115.49	-5.36	25

reddening when combined with optical photometry. Additionally, it is possible to get an estimate of the cluster metallicity whenever a Red Giant Branch (RGB) is visible (Tiede et al. 1997).

This study is a part of a general project of observations of galactic open clusters in the infrared (Vallenari et al. 1999, Carraro et al. 1999b). In this paper we present IR camera photometry in the K and J pass-bands for two intermediate age open clusters, IC 166 and NGC 7789. IC 166 is a poorly studied open cluster for which no previous IR data exist, while NGC 7789 is a rather well-studied open cluster, for which up to now IR data were available only for a handful of stars. Table 1 summarizes some general properties of the two target clusters. Diameters are taken from the Lyngå (1987) catalogue of open clusters.

The plan of the paper is as follows. In Sect. 2 we describe the data acquisition and reduction; Sect. 3 is devoted to the analysis of the data for IC 166, while Sect. 4 is dedicated to NGC 7789. Sect. 5 draws our conclusions.

2. Observations and data reduction

J (1.2 μm) and K (2.2 μm) photometry of the two clusters was obtained with 1.5m Gornergrat Infrared Telescope (TIRGO) equipped with the Arcetri Near Infrared Camera (ARNICA) in October 1997. ARNICA relies on a NICMOS3 256×256 pixels array (gain=20 e$^-$/ADU, read-out noise=50 e$^-$ angular scale=$1''$/pixel, and 4×4arcmin field of view). Through each filter 4 partially overlapping images of each cluster were obtained, covering a total field of view of about 8×8 arcmin, in short exposures to avoid sky saturation. Details of the observations are given in Table 2. The night was photometric with a seeing of $1''$-$1.5''$. Figs. 1 and 2 present the mosaics of the 4 frames obtained per cluster in K passband.
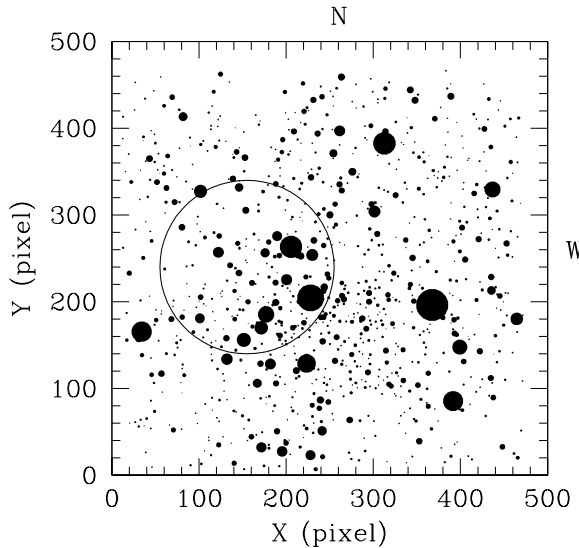
Fig. 1. A mosaic of the four CCD frames in K band covering the studied region of IC 166. North is on the top, east on the left. The circle defines the region of the cluster observed by Burkhead (1969).
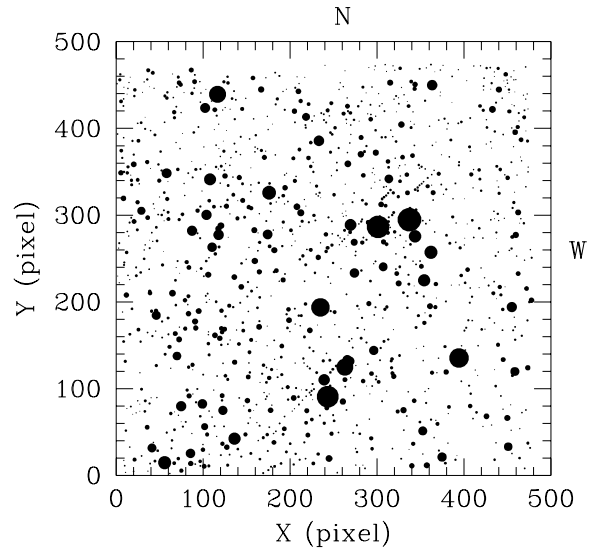

Fig. 2. A mosaic of the four CCD frames in K band covering the studied region of NGC 7789. North is on the top, east on the left.

Table 2. Observation Log-Book. The coordinates listed below refer to the center of the mosaic.

Cluster	α	δ	Date	Exposure Times (sec)	
	(2000)	(2000)		J	K
IC 166	01 52 21.6	61 52 12	Oct, 24, 1997	700	920
NGC 7789	23 57 10.9	56 45 05	Oct, 24, 1997	636	920

The data were reduced subtracting from each image a linear combination of the corresponding skies and dividing the results by the flat-field. We make use of the Arnica package (Hunt et al. 1994) in IRAF and Daophot II. The conversion of the instrumental magnitude j and k to the standard J, K was made using stellar fields of standard stars taken from Hunt et al. (1998) list. About 10 standard stars per night have been used. The relations in usage per 1 sec exposure time are for IC 166:

$$J = j + 19.51 + k_J \times 1.04 \tag{1}$$

$$K = k + 18.94 + k_K \times 1.06 \tag{2}$$

and for NGC 7789:

$$J = j + 19.51 + k_J \times 1.04 \tag{3}$$

$$K = k + 18.94 + k_K \times 1.03 \tag{4}$$

where k_J and k_K (the extinction coefficients, in magnitudes per airmass) are 0.25 and 0.10, respectively.
The standard deviation of the zero points are 0.03 mag for the J and 0.04 for the K magnitude. This error is only due to the linear interpolation of the standard stars. However the calibration uncertainty is dominated by the error due to the correction from aperture photometry to PSF fitting magnitude. Taking this into account, we estimate that the total calibration error is about 0.1 mag both in J and in K passbands. The photometric errors, as produced by DAHPHOT are 0.02, 0.05 and 0.1 at J equal to 8, 12 and 16 mag, respectively, and slightly lower in the K band. Accordingly, the maximum error in the color amounts to about 0.25.

Fitting photometry was a natural choice, due to the number of stars to be measured and the concentration of stars (crowding) in some cluster regions, where PSF wings overlap. The standard stars used for the calibration do not cover the entire colour range of the data, because of the lack of stars redder than $(J - K) \sim 0.8$. From our data, no colour term is found for K mag, whereas we cannot exclude it for the J magnitude.

The data tables are available upon request from the authors.

3. IC 166

IC 166 (C0149+615, OCL 334, Trumpler class II 1 r) is a faint, distant and possibly old cluster (King 1964). The only photometric study was done by Burkhead (1969), who obtained BV photographic photometry for about 200 stars in the central region of the cluster, covering a circular area of $2.45'$ (see Fig. 1) and reaching $V = 19.0$. He reported also UBV photo-electric photometry for 20 stars out of the cluster region. The derived CMD shows a wide MS, with the Turn-off-point (TO) located at $V \approx 17.0$ and $(B-V) \approx 1.1$; the Herzsprung gap and a conspicuous clump of red stars are also seen. There is no evidence for RGB stars, which implies that the cluster is intermediate in age between the Hyades and NGC 7789 (Carraro et al. 1999a). Burkhead (1969) could not determine the reddening due to the lack of photometry in U band for cluster members. Assuming E(B-V) ≈ 0.80, he found a distance modulus $(m-M)_V \approx 12.6$, and a distance of 3.3 kpc from the Sun. Finally, inspecting the Palomar Sky Atlas, he estimated a diameter of about 5 arcmin.
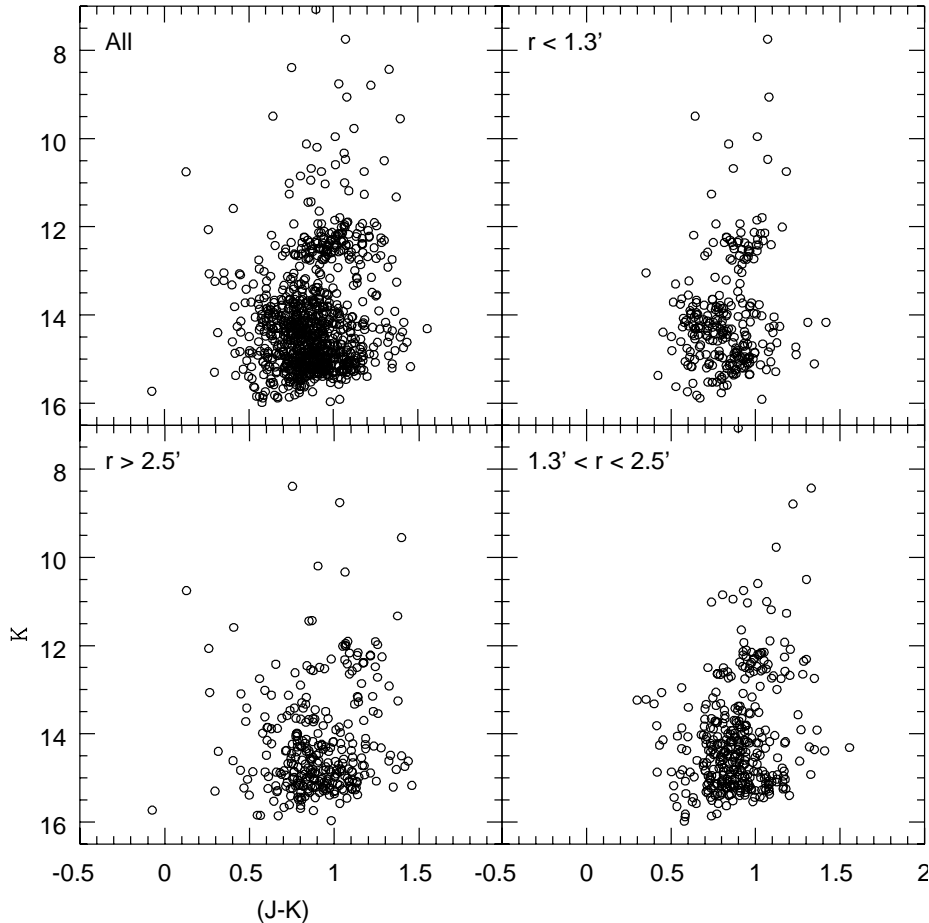
Fig. 3. CMD for IC 166 in different areas of the covered region.

3.1. The color-magnitude diagram

The CMD of IC 166 in the plane K vs $(J - K)$ is shown in Fig. 3. The upper left panel shows the CMD for all the detected stars, the upper right for the stars lying in the same region as Burkhead (1969) photometry (see also Fig. 1). The lower left panel shows the stars outside $2.5'$ from the cluster center, and finally the lower right shows the CMD in the region between about $1.3'$ and $2.5'$ from the cluster center. The cluster center has been fixed on the top of the star # 1 in the Burkhead second quadrant.

We cover a region of $8' \times 8'$, whose center is offset by $1'$ with respect to the Burkhead (1969) photometry. Nonetheless we cover almost all the cluster region. Our CMD shows a wide MS and a sparse RGB clump. The MS extension is the same as the optical one from Burkhead (1969). The contamination of foreground stars is considerable in the upper left panel, whereas the cluster clearly dominates in the upper and lower right panels. A representative contaminating disk population is better visible in the lower left panel, outside the Burkhead (1969) radius. This confirms that the Burkhead (1969) radius estimate ($\approx 2 - 3$ arcmin) is basically correct.

From the global CMD morphology we can confirm that IC 166 is an intermediate age open cluster, as old as NGC 2477 (1.0 Gyr, Carraro & Chiosi 1994), but younger than NGC 7789 (1.6 Gyr, Gim et al. 1998).

3.2. Reddening

Useful information about the reddening of IC 166 can be derived by combining optical and infrared photometry. We found 30 stars in common between our study and Burkhead (1969). Singling out the MS stars, we are left with 8 stars. These are plotted in the plane (J-K) vs (V-K) (see Fig. 4) and (J-K) vs (B-V) (see Fig. 5). Superimposed are Zero Age MS for Z = 0.009 metallicity taken form Bertelli et al. (1994). The fit in Fig. 4 has been obtained by shifting the ZAMS with E(V-K) = 1.35 ± 0.50 and E(J-K) = 0.25 ± 0.10, corresponding to a ratio E(V-K) / E(J-K) ≈ 5.4, close to the value 5.3 reported by Cardelli et al. (1989). From Fig. 5 we get E(B-V) = 0.50 ± 0.20 and E(J-K) = 0.25 ± 0.10. This gives a ratio E(J-K) / E(B-V) ≈ 0.50 which again is close to the value 0.52 from Cardelli et al. (1989). These results, although consistent, are to be taken as provisional, until a deeper optical and IR photometry will be available.

3.3. Distance and age

Distance and age are inferred by fitting the CMD of IC 166 (see Fig. 6) with theoretical isochrones (Bertelli et al. 1994).

The metal content of IC 166 has been determined by Friel & Janes (1993) using moderate resolution spectroscopy of 4 giant stars. [Fe/H] is -0.32 ± 0.20, which translates into the theoretical metal abundance value Z = 0.009 (Bertelli et al. 1994).
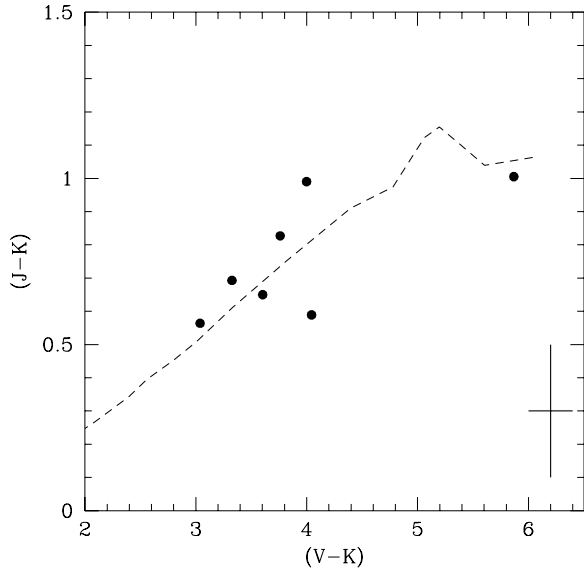
Fig. 4. Two colors diagram for MS stars in common between our study and Burkhead(1969). Dashed line is a ZAMS from Bertelli et al. (1994) shifted by $E_{(V-K)} = 1.35$ and $E_{(J-K)} = 0.25$. The cross in the right bottom corner shows the photometric error bar indicating the maximum error in colors for the data points.

Fig. 5. Two colors diagram for MS stars in common between our study and Burkhead(1969). Dashed line is a ZAMS from Bertelli et al. (1994) shifted by $E_{(B-V)} = 0.50$ and $E_{(J-K)} = 0.25$. The cross in the right bottom corner shows the photometric error bar indicating the maximum error in color for the data points.

Adopting the reddening value derived above (E(J-K) = 0.25), and the spectroscopic metallicity from Friel & Janes (1993), we obtain an acceptable fit with a 1.0 Gyr isochrone. In fitting the isochrone to the CMD we have looked at the TO magnitude and at the mean clump magnitude, since the shape of the MS below the TO is not well defined. This implies that it is difficult to give an error to the age until a deeper photometry is available.

The mean clump magnitude allows us to derive the apparent distance modulus. We obtain $(m - M)_K \approx 14.00 \pm 0.30$, but the true distance modulus turns out to be $(m - M)_{o,K} \approx 13.25$, which puts IC 166 4.5 ± 0.6 kpc from the Sun. This value for the distance is significantly larger than the Burkhead (1969) estimate. We ascribe this result to the different value we find for the cluster reddening.

4. NGC 7789

NGC 7789 is a populous intermediate age open cluster very well studied in the past. The most recent photometry is from Gim et al. (1998), who studied 15,000 stars within a radius of $\approx 18'$ from the cluster center, and which the reader is referred to for more detailed informations on this important cluster.

The fundamental parameters of this cluster have been determined several times: NGC 7789 is about 1.6 Gyr old (Gim et al. 1998); the available metallicity determinations range from -0.26 to -0.62, as measured by the index [Fe/H] (Friel & Janes 1993, Tiede et al. 1997); reddening amounts to E(B-V) = 0.35, while true distance modulus is $(m - M)_0 = 11.30$. Near IR photometry is reported by Manteiga et al. (1991) for a sample of 14 presumed blue stragglers in the field of NGC 7789 to test the binary hypothesis for these stars, and by Frogel & Elias (1988) for a sample of 10 bright red giants to study the mass
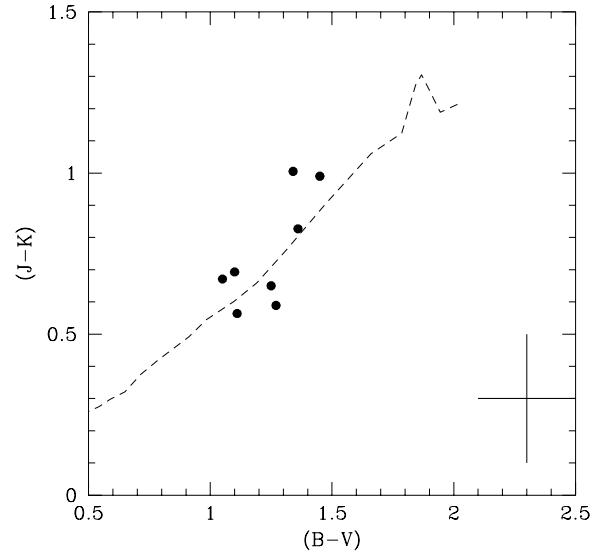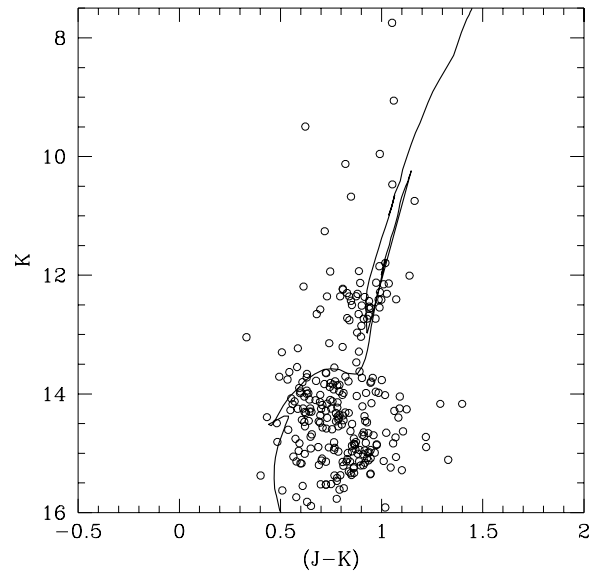

Fig. 6. The CMD for all the stars in the central region of IC 166. Superimposed is a $Z = 0.009$ isochrone for an age of $1\ Gyr$. See the text for any detail.

loss mechanism during the RGB climbing. We find 6 stars in common with Frogel & Elias (1988), namely the stars #193, #304, #329, #494, #501 and #669, according to the Küstner (1923) numbering. The photometric comparison of these stars provides a good agreement, with the mean differences being:

$$K_{FE} - K_{VCR} = -0.04 \pm 0.02 \qquad (5)$$

$$(J - K)_{FE} - (J - K)_{VCR} = 0.05 \pm 0.03 \qquad (6)$$

where the suffix FE refers to Frogel & Elias (1988), and VCR to the present study. The errors reported are the standard de-
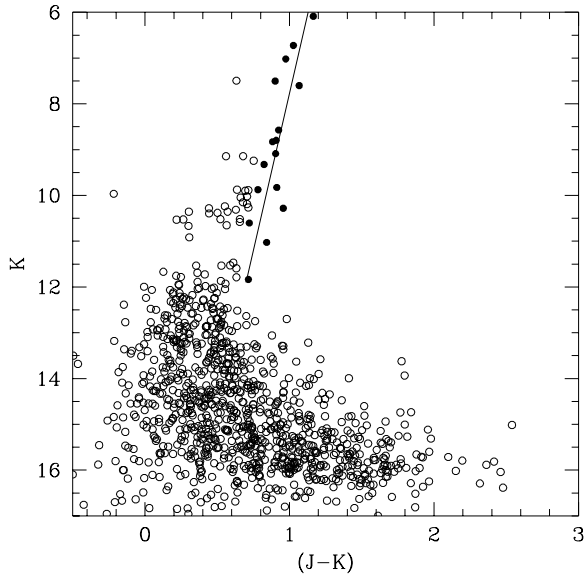
Fig. 7. The CMD for all the stars in the region of NGC 7789. The solid line represents a least squares fit to the presumed RGB stars (filled circles).

Fig. 8. Two color diagram for the MS stars brighter than J =14 in common between our study and Gim et al(1998). Dashed line is a Z= 0.010 ZAMS taken from Bertelli et al. (1994) shifted by E(V-K) = 0.85 and E(J-K) = 0.15. The cross in the bottom right corner shows the photometric error bars indicating the maximum error in color for the data points.

viations around the mean values. Using this small sample we cannot outline any clear trend with colors or magnitudes.

4.1. The color-magnitude diagram

Our study covers a region within $8'$ of the cluster center (see Fig. 2). We obtain photometry for about 1030 stars down to $K \approx 17.0$. This allows us to present the first CMD of NGC 7789 in the infrared. This is shown in Fig. 7. The MS is quite wide, and shows the TO at $K \approx 12.0$ and $(J - K) \approx 0.25$. A prominent clump is situated at $K \approx 10.5$ and $0.4 < (J - K) < 0.7$. The RGB is defined by the stars plotted by us with a different symbol (filled circles).

The overall morphology is typical of an intermediate age open cluster (Carraro et al. 1999a).

4.2. Metallicity

The CMD diagram in the IR allows us to derive an independent estimate of the cluster abundance by using the photometric method originally developed by Kuchinski & Frogel(1995) for metal rich globular clusters, and then applied by Tiede et al. (1997) for a sample of intermediate age open clusters. This method correlates the slope of the RGB, defined as $\Delta(J - K)/\Delta K$ with the cluster metallicity, measured by the index [Fe/H]. For globulars the relation reads:

$$[Fe/H] = -2.98 - 23.84 \times (GBslope). \qquad (7)$$

Tiede et al. (1997) found that Eq. (7), when applied to open clusters rather than globulars, tends to underestimate open cluster metallicity. For instance, in the case of NGC 7789 they found [Fe/H] = -0.62 by using Eq. (7), whereas the spectroscopic determination is [Fe/H] = -0.26. For this reason they give a new
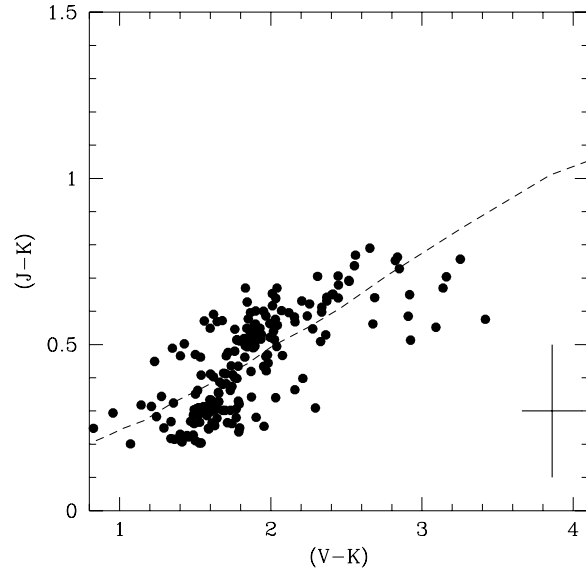
calibration of the relation, which provides new values for the coefficients when dealing with different populations (globulars, open, or bulge clusters). For open clusters, the modified relation reads:

$$[Fe/H] = -1.639 - 14.243 \times (GBslope). \qquad (8)$$

To find the RGB slope we performed a least squares fit to the RGB stars as indicated in Fig. 7. This implies an RGB slope $\Delta(J - K)/\Delta K$ of -0.097 $\pm$ 0.007. By using the relation (8), we obtain [Fe/H] = -0.25 $\pm$ 0.11. The reported error has to be considered as an optimistic estimate, since it does not take into account the uncertainties in the coefficients of Eq. 8, and the sensitivity of the RGB slope to the method adopted for its computation. However the value we find implies a metal content close the spectroscopic estimate (-0.26 $\pm$ 0.06, Friel & Janes 1993).

4.3. Reddening

As for IC 166, we combine together optical and infrared photometry. We found 980 stars in common between our study and the optical photometry of Gim et al. (1998). Out of these we consider MS the stars brighter than $J = 14$ and in the color interval $0.2 < (J - K) < 0.8$, to limit disk stars contamination. These MS stars are plotted in Fig. 8. Although the scatter is large, a reasonable fit can be obtained shifting a Z = 0.010 ZAMS taken from Bertelli et al. (1994) by E(J-K) = 0.15 $\pm$ 0.06 and E(V-K) = 0.85 $\pm$ 0.20. This way the ratio $E_{(V-K)}/E_{(J-K)}$ comes out to be ≈ 5.6, close to the value 5.3 reported by Cardelli et al. (1989). Adopting the value 0.52 (Cardelli et al. 1989) for the ratio $E_{(J-K)}/E_{(B-V)}$ we obtain E(B-V) ≈ 0.30.
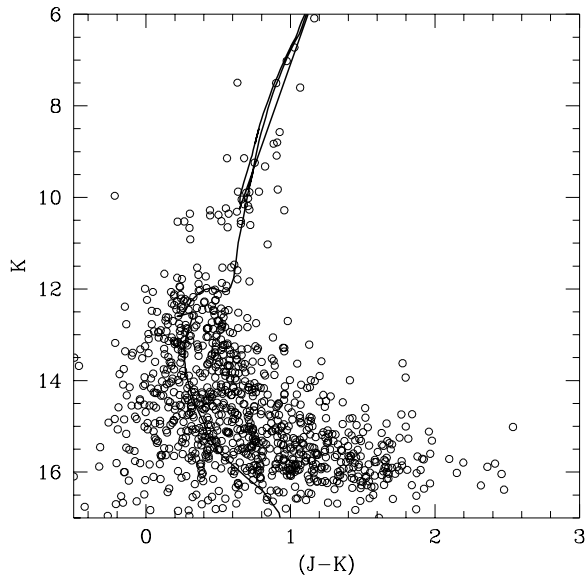
Fig. 9. The CMD for all the stars in the region of NGC 7789. Superimposed is a $Z = 0.010$ isochrone for an age of $1.4\ Gyr$. See text for any detail.

Fig. 10. The CMD for all the stars in the region of NGC 7789. Superimposed is a $Z = 0.010$ isochrone for an age of $1.4\ Gyr$. See text for any detail.

4.4. Distance and age

Assuming the metallicity to be $Z = 0.010$, we have performed a fit to the CMD (see Fig. 9) with a 1.4 Gyr isochrone. The best solution has been obtained by adjusting the isochrone with a color excess E(J-K) = 0.15 and an apparent distance modulus $(m - M)_K = 11.70$. This implies a true distance modulus $(m - M)_o = 11.25$, close to the accepted estimate, and a color excess E(B-V) = 0.29, in agreement with the solution derived from the two colors diagram, but marginally smaller than the most accepted estimate.

The fundamental parameters derived above are supported by the fit we performed in the V vs $(V - K)$ plane (see Fig. 10), where the superimposed 1.4 Gyr isochrone has been shifted by E(V-K) = 0.75 and $(m - M)_V = 13.20$. We point out that looking at Fig. 9, it is not possible to reproduce the color of the RGB.

5. Discussion and conclusions

We have presented and discussed new IR camera data for two intermediate age open clusters, IC 166 and NGC 7789. IC 166 was poorly studied before, while NGC 7789 is a very well studied cluster. Our results can be summarized as follows:

- IC 166 is a faint and distant intermediate age open cluster about 1 Gyr old;
- for the first time we are able to determine the reddening and distance modulus of this cluster, which is located 4.5 kpc from the Sun; much deeper photometry is required to obtain a better comparison with stellar models.
- NGC 7789 is shown to be 1.4 Gyr old; we find estimates for the cluster parameters consistent with values in the literature;
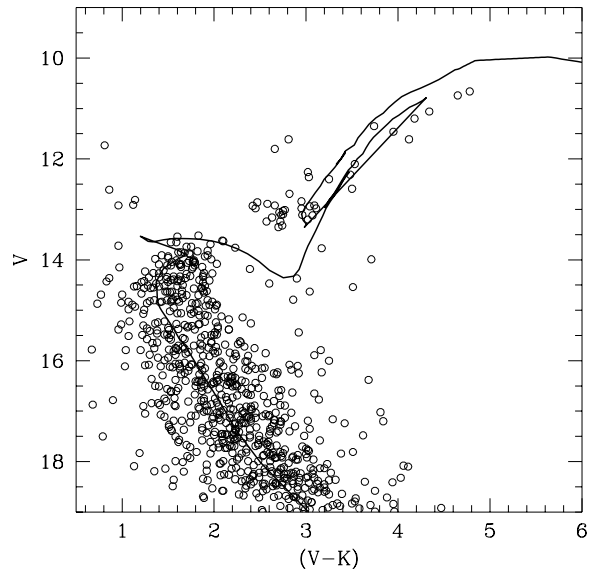
- we obtain an independent photometric metallicity estimate which is close to the spectroscopic one.

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