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A study of the young open cluster Collinder 359

NICOLAS LODIEU

Department of Physics & Astronomy, University of Leicester, UK

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Abstract. We present the first deep, optical, wide-field imaging survey of the young open cluster Collinder 359, complemented by near-infrared follow-up observations. This study is part of a large programme aimed at examining the dependence of the mass function on environment and time. We have surveyed 1.6 square degree in the cluster in the I and z filters with the CFH12K camera on the Canada-France-Hawaii 3.6-m telescope down to completeness and detection limits in both filters of 22.0 and 24.0 mag, respectively. Based on their location in the optical ($I-z$,I) colour-magnitude diagram, we have extracted new cluster member candidates in Collinder 359 spanning 1.3–0.04 $M_{\odot}$, assuming an age of 100 Myr and a distance of 450 pc for the cluster. We have used the 2MASS database as well as our own near-infrared photometry to confirm the membership of the optically-selected cluster candidates. Additionally, we have obtained optical spectroscopy and employed chromospheric activity as a further criterion to assess the membership of candidates.

Key words: Open clusters and associations: individual: Collinder 359 — Stars: low-mass, brown dwarfs — Techniques: photometric — Techniques: spectroscopic

1. The open cluster Collinder 359

Collinder 359 (Melotte 186; R.A. = $18^{\rm h}01^{\rm m}$, dec = $+02°54'$) is located in the constellation of Ophiuchus around the B5Ib supergiant 67 Oph. The cluster was first identified by Melotte (1915) who described it as "a large scattered group of bright stars around 67 Ophiuchi, covering an area of about 6 square degrees". Later, Collinder (1931) labelled the cluster as "a group of about 15 stars with no appreciable concentration on the sky and no well-defined outline". He listed 13 cluster members and provided coordinates, photometry, spectral types, and proper motions. However, more recent CCD photometry conducted by Van't Veer (1980) and Rucinski (1980, 1987) rejected half of the candidates as members using isochrone fitting, leaving 6 probable cluster members. The cluster proper motion is comparable to the motion of its most massive member, 67 Oph and is estimated as μ_{α} cos$_{\delta}$ = 0.4 and $\mu_{\delta} \sim -8.0$ mas/yr based on HIPPARCOS parallaxes (Perryman et al. 1997; Baumgardt, Dettbarn, & Wielen 2000).

1.1. The age of the cluster

Wielen (1971) derived an age of 20–50 Myr with a mean value of 30 Myr using isochrone fitting based on three-colour photometry available in large catalogues of open clusters (Becker & Fenkart 1971). Abt & Cardona (1983) studied the distribution of Ap stars in open clusters as a function of age and put an upper limit of 30 Myr on the age of Collinder 359, assuming that 67 Oph is a member of the cluster. Both results are in agreement and consistent with the most recent estimate of 30 Myr from Kharchenko et al. (2004; personal communication).

We have estimated the age of Collinder 359 and its associated error using its most massive members, following the turn-off main-sequence approach applied to α Per by Stauffer et al. (2003). The best isochrone fits to the location of Alpha Per (open square) and 67 Oph (filled circle) in the ($B-V$,M_V) colour-magnitude diagram (Fig. 1) are 50 and 60 Myr, respectively. The uncertainty on the HIPPARCOS parallax (Perryman et al. 1997) of 67 Oph translates into a 20 Myr uncertainty on the cluster age. We note that the lithium test (Rebolo, Martín, & Magazzù 1992) applied to the Pleiades (70 Myr vs. 125 Myr; Stauffer et al. 1998) and α Per (50 Myr vs. 90 Myr; Stauffer et al. 1999) led to older ages than the turn-off main-sequence method (Mermilliod 1981), suggesting that Collinder 359 could be as old as α Per. To summarise we will assume an age of 100 Myr for Collinder 359 throughout this work. This figure is conservative in that it will not miss any potential members.

Correspondence to: nl41@star.le.ac.uk

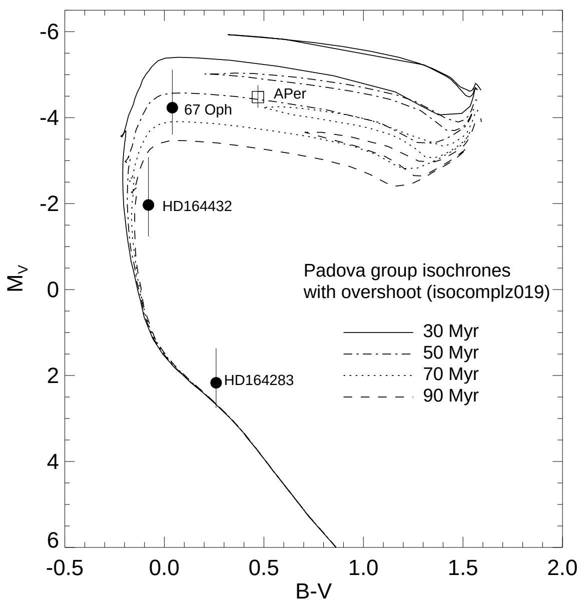

Fig. 1. ($B-V$,M_V) colour-magnitude diagram. The position of the F5 supergiant Alpha Per (open square), the B5 supergiant 67 Oph, HD 164432 (B3), and HD 164283 (A0) (filled circles) are indicated. Overplotted are the solar metallicity evolutionary models with moderate overshoot from the Padova group (Girardi et al. 2000) for 30 Myr (solid line), 50 Myr (dot-dashed line), 70 Myr (dotted line), and 90 Myr (dashed line). The vertical lines crossing the filled circles represent the errors on the HIPPARCOS parallax (Perryman et al. 1997). The best fit is obtained for ages of 50 Myr and 60 Myr for α Per and Collinder 359, respectively.

1.2. The distance of the cluster

Based on isochrone fitting of early-type stars, Collinder (1931) derived a distance ranging from 210 pc to 290 pc for Collinder 359. New CCD photometry by Van't Veer (1980) and Rucinski (1980, 1987) rejected half of the original members, yielding a revised distance of 436 pc. In the 5^{th} edition of the Open Cluster Data Catalogue, Lyngå (1987) quoted a distance of 200 pc based on the Bochum-Strasbourg magnetic tape catalogue of open clusters. The HIPPARCOS parallax measurement of the supergiant 67 Oph suggests a distance of 435^{+220}_{-110} pc (Perryman et al. 1997). Trigonometric parallaxes of five photometric members from HIPPARCOS yielded distances between 260 and 280 pc for Collinder 359 (Loktin & Beshenov 2001). Combining the HIPPARCOS and Tycho 2 catalogues, a list of about 100 possible cluster members were extracted by Kharchenko et al. (2004, personal communication) based on their location in the cluster and their proper motions, yielding a distance of 650 pc and an age of 30 Myr from isochrone fitting. To summarise, the distance of Collinder 359 is not well established and we will adopt a mean distance of 450 ± 200 pc to take into account the large uncertainties on the distance.

2. The wide-field optical survey

2.1. The CFHT Key Programme

We have carried out a CFHT Key Programme centred on wide-field optical imaging in a variety of environments within the framework of the European Research Training Network "The Formation and Evolution of Young Stellar Clusters" to examine the sensitivity of the low-mass stellar and substellar IMF to time and environment. Other goals were to address the most pressing issues concerning low-mass stars and BDs, including their formation, their distribution, and their evolution with time. The survey was conducted with a large-CCD mosaic camera (CFH12K) in the I and z filters down to a detection limit of $I = 24.0$, covering a total of 80 square degrees in star-forming regions, open clusters, and in the Hyades. The observations were carried out in I and z to optimise the search for very-low-mass stars and brown dwarfs. This choice was motivated by the discoveries of new brown dwarfs in the Pleiades by Moraux et al. (2003) using the same telescope, camera, and set of filters. The R and I filters might however be more adequate to extract solar-type members belonging to the cluster. Collinder 359 was selected as a pre-main-sequence open cluster with an age of 30 Myr and a distance of 250 pc for this programme based on the parameters given in the Webda Open Cluster Database[1].

2.2. Optical observations and data reduction

Five CFH12K frames were obtained on 18 and 20 June 2002 in Collinder 359 in the I and z filters, covering a 1.6 square degree area in the cluster (Table 1). Figure 2 displays the location of the five CFH12K fields-of-view within the cluster and Table 1 gives the journal of the observations. Thirteen possible members as listed by the pioneering work of Collinder (1931) are plotted as filled circles in Fig. 2. The CFH12K frames were chosen to avoid bright cluster members.

Table 1. Coordinates (J2000) of the five CFH12K pointings ($42' \times 28'$) along with the journal of observations obtained in the open cluster Collinder 359. The times of observations are in UT and correspond to the beginning of the short exposures in the I-band.

Field	R.A.	Dec	Obs. Date	Time of obs.
A	18 01 06.6	+02 07 26	2002–06–18	08h19m15s
B	18 02 36.9	+03 37 52	2002–06–18	09h07m43s
C	17 57 36.9	+03 37 56	2002–06–18	09h56m07s
D	17 56 16.4	+02 29 46	2002–06–18	11h52m24s
E	18 05 55.7	+03 28 58	2002–06–20	12h29m20s

The initial data reduction was provided by the Elixir pipeline (Magnier & Cuillandre 2004) and includes bias subtraction, flat-fielding, correction for scattered light in the I and z bands, combining the dithered frames in case of long exposures, and astrometric solution provided in the header

[1] The Webda database, maintained by J.-C. Mermilliod, is to be found at http://obswww.unige.ch/webda

of the fits files. Standard stars were observed throughout the nights and were monitored constantly by the Elixir/Skyprobe tool to provide accurate zero-points.

Conditions were photometric with a seeing around 0.8 arcsec, except for Field E, observed on the night of 20 June affected by clouds. Three sets of exposures were taken: short (2 sec), medium (30 sec), and long (300 sec in I and 360 sec in z), yielding completeness and detection limits of 22 and 24 mag, respectively, in both passbands.

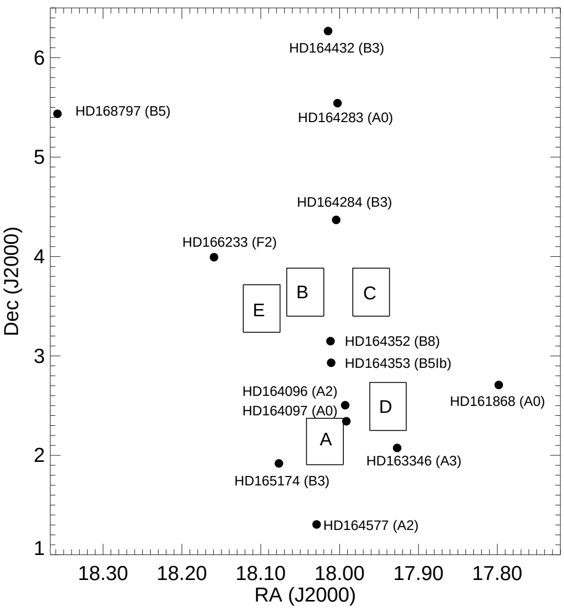

Fig. 2. Location of the five CFH12K pointings (A–E) shown as boxes within the cluster area defined by the Open Cluster Database webpage. The 13 possible cluster members listed by Collinder (1931) are displayed as circles with their names and spectral types.

2.3. Optical photometry

We have used the SExtractor software and PSFex package (Bertin & Arnouts 1996) to extract the photometry from the optical images. We have favoured the point-spread function (PSF) fitting to the aperture one because it provided more precise photometric measurements for faint sources.

The data reduction procedure was identical for each CFH12K field-of-view and is briefly described below. First, we have combined the I and z images to increase the signal-to-noise ratio and allow a better astrometry of faint sources. Second, we have run SExtractor and PSFex to extract coordinates and magnitudes for all detected sources by using a model PSF for each chip and each field. Afterwards, we have applied the zero points listed on the Elixir webpage[2] to calibrate our photometric measurements. The nominal CFH12K zero points for the I- and z-bands were ZP(I) = 26.184 ± 0.023 and ZP(z) = 25.329 ± 0.031, respectively. Finally, the I and z catalogues were cross-correlated by matching pixel coordinates. The final output catalogue contains the pixel and celestial coordinates, I and z magnitudes, as well as other parameters, including the full-width-half-maxima and the ellipticity of the source.

[2] http://www.cfht.hawaii.edu/Instruments/Elixir/stds.2003.06.html

3. New cluster member candidates

3.1. Optical colour-magnitude diagram

The final ($I - z$,I) colour-magnitude diagram for all detections in the 1.6 square degree area surveyed in Collinder 359 is presented in Fig. 3. Overplotted are the 100 Myr NextGen (solid line; Baraffe et al. 1998) and the DUSTY (dashed line; Chabrier et al. 2000) isochrones, assuming a distance of 450 pc for the cluster. The large filled dots characterise all optically-selected cluster member candidates in Collinder 359. The horizontal dashed line at $I \sim 20.5$ mag corresponds to the hydrogen-burning limit at $0.072\,M_\odot$. We have considered an interstellar absorption law with A_I = 0.482 mag for the I-band (Rieke & Lebofsky 1985) to draw the reddening vector. We have assumed a linear fit between the interstellar absorption in I and J (A_J = 0.282 mag) for the z-band, yielding A_z = 0.382 mag. The gap seen between the optically-selected candidates and the isochrones in the ($I - K$,I) colour-magnitude diagram (Fig. 4) might suggest the presence of extinction along the line of sight to the cluster unless the estimated age and distance are in error.

3.2. Selection of cluster member candidates

The extraction of member candidates in open clusters generally consists in selecting objects located to the right of the ZAMS (Leggett 1992) shifted to the distance of the cluster. We have chosen the evolutionary models from the Lyon group to select candidates in Collinder 359. We have employed the NextGen isochrones (solid line in Fig. 3; Baraffe et al. 1998) for effective temperatures higher than 2500 K (corresponding to $0.050\,M_\odot$ at the age and distance of the cluster) and the DUSTY (dashed line in Fig. 3; Chabrier et al. 2000) isochrones for lower temperatures (and masses).

After examination by eye, the final list of cluster member candidates contains a total of 628 objects with I = 11.3–22.5 mag over 1.6 deg^2 area surveyed in Collinder 359. The distribution of the ellipticity shows that 95 % of the objects have an ellipticity smaller than 0.15 and FWHM between 1.8 and 3.0, corresponding to a seeing of $\sim$ 0.4–0.6 arcsec.

We have possibly missed some bona-fide cluster members for various reasons. First, we did not cover the whole cluster, implying that many more members remain to be discovered. Second, our saturation and completeness are such that we missed bright and faint cluster members. Finally, source blending, cosmic rays, dead columns, bad pixels, and small inter-CCD gaps are additional effects that prevent us from detecting every member over the surveyed area.

4. Near-infrared photometry of candidates

The galactic latitude of Collinder 359 is b = +12.5°, intermediate between α Per (b = −7°) and the Pleiades (b =

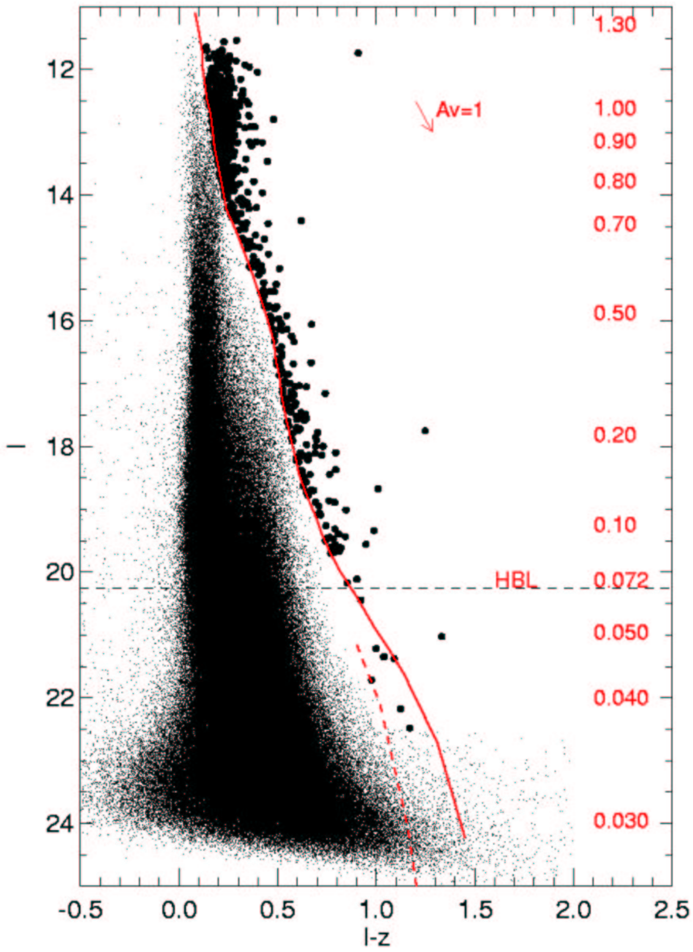

Fig. 3. Colour-magnitude diagram ($I-z$,I) for the intermediate-age open cluster Collinder 359 over the full 1.6 square degree area surveyed by the CFH12K camera. The large filled dots are all optically-selected cluster member candidates spanning 1.30–0.04 $M_\odot$, assuming an age of 100 Myr and a distance of 450 pc. Overplotted are the NextGen (solid line; Baraffe et al. 1998) and the DUSTY (dashed line; Chabrier et al. 2000) isochrones for 100 Myr, assuming a distance of 450 pc for the cluster. The dashed line at $I \sim 20.25$ mag indicates the stellar/substellar boundary at 0.072 $M_\odot$. The mass scale (in $M_\odot$) is given on the right side of the graph for the assumed age and distance for the cluster. A reddening vector of A_V = 1 mag is indicated for comparison purposes.

$-24°$). Therefore, the sample of optically-selected candidates in Collinder 359 is inevitably contaminated by foreground and background objects, including galaxies, reddened giants, and field dwarfs. We took special care in the removal of extended objects from the candidate list so that we expect field dwarfs and background giants to be the major source of contamination. To address this issue we have used the $I-K$ optical-to-infrared colour to weed out contaminants. This method was previously successfully applied to other clusters, including the Pleiades (Zapatero Osorio et al. 1997), α Per (Barrado y Navascués et al. 2002), and IC2391 (Barrado y Navascués et al. 2001).

First of all, we have cross-correlated the sample of candidates with the 2MASS database (Skrutskie et al. 1997). All but a dozen cluster member candidates brighter than I = 17 mag have a 2MASS counterpart within a 2 arcsec matching radius. This limit in the I-band corresponds to the 2MASS completeness limit of K_s = 14.3 mag. Consequently, the sample is complete to 97 % down to I = 17 mag.

Additional photometry is required for fainter objects due to the large errors on the 2MASS magnitudes. We have carried out follow-up observations for candidates with I = 17–22 mag to estimate the contamination at low-masses and across the stellar/substellar boundary. We have obtained K' photometry for 65 additional targets using the CFHTIR camera on the CFH 3.6-m telescope and MAGIC on the Calar Alto 2.2-m telescope. Five candidates lie to the left of the 100 Myr isochrone in the ($I-K$,I) diagram, implying that they are likely non-members. About 300 optically-selected candidates remain to be observed for membership assessment.

Figure 4 shows the location of the optically-selected candidates in Collinder 359 in the ($I-K$,I) optical-to-infrared colour-magnitude diagram. Objects with 2MASS magnitudes are displayed with a plus sign while targets from our own near-infrared follow-up observations are shown as filled circles. The solid and dashed lines represent the 100 Myr NextGen and DUSTY isochrones, respectively, at a distance of 450 pc. The isochrones are drawn using the I filter from

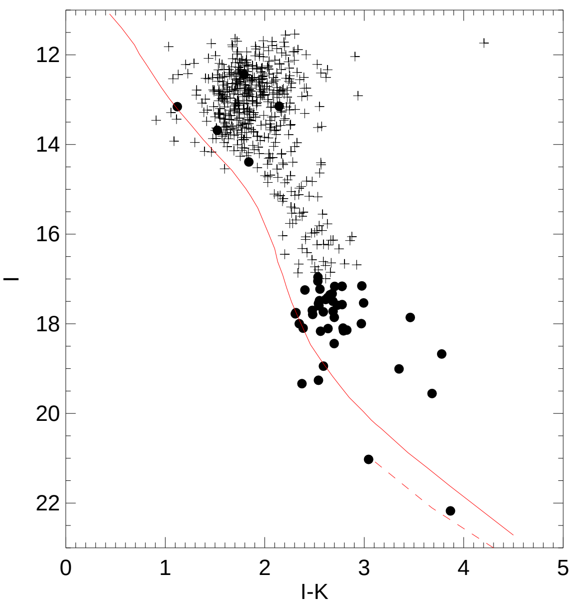

Fig. 4. Colour-magnitude diagram ($I - K$,I) for the optically-selected candidates selected in the open cluster Collinder 359. The plus symbols denotes candidates with 2MASS photometry whereas the filled circles have been observed with the CFHTIR and MAGIC cameras. Overplotted are NextGen (solid line; Baraffe et al. 1998) and the DUSTY (dashed line; Chabrier et al. 2000), assuming an age of 100 Myr and a distance of 450 pc for Collinder 359.

the CFH12K camera and the K_s filter from 2MASS (courtesy I. Baraffe). Note that the K' and K_s magnitudes are very similar and do not affect the membership of the candidates.

5. Contamination of the optical sample

In this section, we discuss the level of contamination in the sample of optically-selected candidates using the ($I - K$,I) colour-magnitude diagram (Fig. 4) on the one hand and a statistical aproach on the other hand.

Combining the optical and optical-to-infrared colour-magnitude diagrams, most of the candidates brighter than I = 17.0 mag remain probable candidates. Only a dozen are rejected as members, yielding a contamination of a few percent (Fig. 4). This simple analysis is however inadequate as both diagrams show a wide sequence of objects with $I \leq 15$ mag due to merging of the cluster and field star sequences.

At fainter magnitudes, the cluster sequence becomes clearer and extends down to I = 22 mag in the optical diagram. We rejected 5 optically-selected cluster candidates out of 58 in the magnitude range I = 17–22 mag from the optical-to-infrared diagram, yielding a contamination of $\sim 9\,\%$ across the stellar/substellar boundary. However, most of the rejected candidates are fainter than I = 19 mag, making it hard to set limits on the contamination in this part of the diagram due to small number statistics.

We classified the cluster candidates into two subsamples on the basis of their location in the ($I - K$,I) colour-magnitude diagram (Fig. 4):

1. Probable members: these objects lie to the right of the NextGen+DUSTY isochrones, assuming d = 450 pc. Their colours are consistent with cluster membership.
2. Non-members: objects with colours bluer than those predicted by the isochrones, assuming d = 450 pc.

Moreover, the analysis of a control field obtained within the framework of our CFH12K survey in the IC4665 open cluster reveals a contamination level of 85 % and 70 % in the stellar and brown dwarf regimes, respectively. These figures are much higher than the expected contamination from the ($I - K$,I) diagram and possibly represent a lower limit for Collinder 359 due to its lower galactic latitude ($b \sim +12°$) and larger distance compared to IC4665 ($b \sim +17°$; 350 pc).

6. Optical spectroscopy of candidates

We have initiated extensive spectroscopic follow-up observations to further confirm the membership of candidates in Collinder 359. We have carried out optical spectroscopy of $\sim$ 100 candidates with three different telescopes and instruments: the DOLORES spectrograph on the Telescopio Nazionale di Galileo, the AF2/WYFFOS multi-fibre spectrograph mounted on the William Herschel Telescope both in La Palma (Canary Islands), and the Twin spectrograph on the Calar Alto 3.5-m telescope. The results presented here are only preliminary as some data are still under analysis. We have recently obtained additional spectroscopy using the 2dF multi-fibre spectrograph on the Anglo-Australian Telescope.

We have computed the pseudo-equivalent widths of the Hα emission line at 6563 Å to further assess the membership of the selected cluster candidates. Although not definite, the presence of Hα used as a proxy for chromospheric activity, has proven successful in confirming photometrically-selected candidates in young open clusters (Hodgkin, Jameson, & Steele 1995). This criterion is however not valid for stars with masses above $\sim 0.3\,M_{\odot}$ because they have already reached the main-sequence at an age of 100 Myr (Steele & Jameson 1995). Therefore, additional high-resolution spectroscopy is required to investigate the lithium abundances and radial velocities of the most massive candidates in Collinder 359 (Martín & Montes 1997).

For fainter magnitudes ($I \geq 16$ mag) and lower masses, we have measured equivalent widths ranging from 3 to 12 Å for 16 out of 58 candidates (filled circles in Fig. 5). The level of activity found in those candidates with spectral types ranging from M2 to M4 is in agreement with studies in the Pleiades (Hodgkin et al. 1995) and α Per (Prosser 1994). The number of sources with Hα in emission represent a lower limit as our spectroscopic sample is still incomplete but suggests a large contamination by field stars as pointed out by the analysis of a control field (§5). The contamination of $\sim 70\,\%$ is larger than the values derived from studies in α Per (Barrado y Navascués et al. 2002) and the Pleiades (Moraux et al. 2003). Additionally, the objects with optical spectroscopy have masses close to the transition where dwarfs become fully convective depending on the distance and age of the cluster. Hence, chromospheric activity and gravity-sensitive features might not be suitable criteria to assess membership,

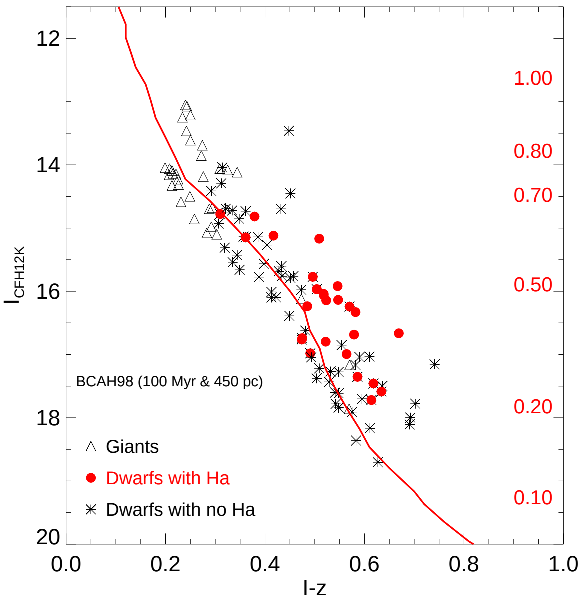

Fig. 5. Colour-magnitude diagram ($I - z$,I) for the selected cluster candidates with optical spectroscopy. Star symbols represent M dwarfs with no sign of chromospheric activity while the filled circles are M dwarfs which exhibit Hα in emission. Open triangles are classified as giants, thus definite non members. The 100 Myr NextGen isochrone (solid line; Baraffe et al. 1998) is overplotted, assuming a distance of 450 pc for Collinder 359.

requiring higher resolution spectroscopy. We note that the resolution of our optical spectra is too low to detect lithium in absorption and the objects under study not late enough to be genuine cluster brown dwarfs.

7. Conclusions

We have presented a deep, wide-field, optical survey in the young open cluster Collinder 359 complemented by near-infrared photometry and optical spectroscopy. We have revised the age of the cluster to 100 Myr using theoretical isochrones with moderate overshoot and assumed a mean distance of 450 pc from various sources. We have extracted several hundreds of cluster candidates with masses between 1.3 and 0.03 M$_\odot$. We would like to point out that Collinder 359 is a loose cluster and its sequence of bright members is not well defined. Finally, Collinder 359 is very close to the sky to IC 4665. Both clusters harbour similar proper motion, age, and distance, suggesting a possible interaction between both clusters at earlier stages. Alternatively, Collinder 359 could be a moving group and not a cluster because of the small number of bright members observed its location in the sky.

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