Messier 35 (NGC 2168) DANCe

I. Membership, proper motions, and multiwavelength photometry[★]

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ABSTRACT

Context. Messier 35 (NGC 2168) is an important young nearby cluster. Its age, richness and relative proximity make it an ideal target for stellar evolution studies. The *Kepler* K2 mission recently observed it and provided a high accuracy photometric time series of a large number of sources in this area of the sky. Identifying the cluster's members is therefore of high importance to optimize the interpretation and analysis of the *Kepler* K2 data.

Aims. We aim to identify the cluster's members by deriving membership probabilities for the sources within 1° of the cluster's center, which is farther away than equivalent previous studies.

Methods. We measure accurate proper motions and multiwavelength (optical and near-infrared) photometry using ground-based archival images of the cluster. We use these measurements to compute membership probabilities. The list of candidate members from the literature is used as a training set to identify the cluster's locus in a multidimensional space made of proper motions, luminosities, and colors.

Results. The final catalog includes 338 892 sources with multiwavelength photometry. Approximately half (194 452) were detected at more than two epochs and we measured their proper motion and used it to derive membership probability. A total of 4349 candidate members with membership probabilities greater than 50% are found in this sample in the luminosity range between 10 mag and 22 mag. The slow proper motion of the cluster and the overlap of its sequence with the field and background sequences in almost all color-magnitude and color-color diagrams complicate the analysis and the contamination level is expected to be significant. Our study, nevertheless, provides a coherent and quantitative membership analysis of Messier 35 based on a large fraction of the best ground-based data sets obtained over the past 18 years. As such, it represents a valuable input for follow-up studies using, in particular, the *Kepler* K2 photometric time series.

Key words. proper motions – stars: kinematics and dynamics – open clusters and associations: individual: NGC 2168

1. Introduction

Different galactic environments, it is assumed, produce distinct populations during the star formation episodes. From very loose and young associations such as Taurus-Auriga, doomed to be dispersed very soon in the galactic gravitational well, to the very old halo population in massive globular clusters, there is a large gamut in ages, compactness, metallicity, internal dynamics, total mass, spatial distribution and distribution of the individual masses, perhaps indicating differences in the initial mass functions (IMF). It is clear that a significant improvement in the completeness of the census of different associations provides key information to understanding star formation and evolution.

[★] Table 3 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/575/A120>

In this context, the open cluster Messier 35 (NGC 2168, hereafter M 35) is very interesting in several aspects. First, it is a quasi-twin of the Pleiades cluster, with a similar age (Vidal 1973) but a different metallicity. Second, the *Kepler* K2 mission (Howell et al. 2014) has just provided exquisite photometric time series, so that a detailed distribution of the rotational periods for different masses will soon become available (e.g. Meibom et al. 2009). Moreover, M 35 is not so crowded that confusion is a major problem and its size (about 1 sq. deg) is very suitable for follow-up multiobject spectroscopy (Barrado et al. 2001a).

Several studies have provided estimates of other key cluster parameters, such as its age, census, and metallicity. Table 1 gives an overview of the cluster's properties found in the literature in the past 15 years. However, there is no a clear consensus for most of them. Sung & Bessell (1999) derived a distance modulus of $(m - M)_0 = 9.60 \pm 0.10$ corresponding to 832 pc,

Table 1. Overview of previous studies of M 35.

Reference	Distance (pc)	Age (Myr)	$E(B - V)$ (mag)	[Fe/H]
Reimers & Koester (1988)		70–100		
Sung & Bessell (1999)	832 ± 39	200 ⁺²⁰⁰ ₋₁₀₀	0.255 ± 0.024	
Barrado (2001)		180		
Barrado et al. (2001a)		>125		−0.21 ± 0.10
Kalirai et al. (2003)	912 ⁺⁷⁰ ₋₆₅	180		
Steinhauer & Deliyannis (2004)				−0.143 ± 0.014
Meibom et al. (2009)		134–161		
Geller et al. (2010)		133		
McNamara et al. (2011)	732 ± 145			

Table 2. Instruments used in this study.

Observatory	Instrument	Filters	Platescale [pixel ^{−1}]	Chip layout	Chip size	Field of view	Epoch(s)	Ref.
CFHT	UH 8K	R, I	0''.205	4 × 2	2k × 4k	29' × 29'	1996	1
CFHT	CFHT 12K	B, V, R, I, z	0''.201	6 × 2	2k × 4k	42' × 28'	1999, 2000, 2001, 2002	2
CFHT	MegaCam	g, r	0''.187	4 × 9	2k × 4k	1° × 1°	2003, 2005, 2011	3
CFHT	WIRC	H2	0''.304	2 × 2	2k × 2k	20' × 20'	2008, 2009, 2010, 2011	4
Subaru	Suprime-Cam	VR-Broad	0''.200	5 × 2	2k × 4k	34' × 27'	2005	5
INT	WFC	$g, Ha, He I, i, I, r, U, V$	0''.333	3 × 1 + 1	2k × 4k	34' × 34'	2000, 2002, 2003, 2005, 2008, 2009, 2010	6
KPNO (Mayall)	NEWFIRM	J, H, Ks	0''.400	2 × 2	2k × 2k	28' × 28'	2008	7
KPNO (Mayall)	MOSAIC1	VR-broad	0''.26	4 × 2	2k × 4k	36' × 36'	2006, 2009, 2010, 2011, 2012	8
KISO	2KCCD	B, V, R, I	1''.50	1 × 1	2k × 2k	50' × 50'	2002, 2003	9
SDSS DR9	SDSS camera	u, g, r, i, z	0''.396	6 × 5	2k × 2k	3°	2006	10

References. (1) Metzger et al. (1995); (2) Cuillandre et al. (2000); (3) Boulade et al. (2003); (4) Puget et al. (2004); (5) Miyazaki et al. (2002); (6) Ives (1998); (7) Autry et al. (2003); (8) Wolfe et al. (2000); (9) Itoh et al. (2001); (10) Ahn et al. (2012).

a reddening of $E(B - V) = 0.255 \pm 0.024$ mag and an age of 200^{+200}_{-100} Myr. Kalirai et al. (2003) pushed the cluster a little bit further, to 912^{+70}_{-65} pc and derived an isochrone fitting age of 180 Myr. More recently, McNamara et al. (2011) obtained a distance of 732 ± 145 pc from the internal proper motions. This dynamical distance and the radial velocity dispersion obtained by Geller et al. (2010) imply an age of 133 Myr, according to the same authors. Meibom et al. (2009) performed an age determination based on a completely different technique, gyrochronology, yielding a value between 134 Myr and 161 Myr. Reimers & Koester (1988), by using the white dwarf cooling age, derived an age in the range 70–100 Myr, whereas Barrado (2001), with the same technique, estimated 180 Myr. The rotation pattern suggests an age slightly older than the Pleiades (175 Myr compared to 125 Myr). The same conclusion is reached when the lithium abundances are compared. This is because the lithium dispersion, which is itself related to rotation for a given stellar mass, is no longer obvious for M 35 (Barrado et al. 2001a) while it is very significant in the case of the Pleiades (see, for instance Soderblom et al. 1993).

Regarding chemical composition, Steinhauer & Deliyannis (2004) quoted an unpublished work with a metallicity $[Fe/H] = -0.143 \pm 0.014$, very similar to the value obtained by our group ($[Fe/H] = -0.21 \pm 0.10$) using high spectral resolution data and spectral synthesis, (Barrado et al. 2001a).

The cluster is also relatively massive: Leonard & Merritt (1989) derived a central total mass in the range 1600–3200 $M_{\odot}$ using dynamical models. Our own estimate, for the central of 27.5×27.5 square arcmin, is $\sim 1600 M_{\odot}$, which allows for an exquisite determination of a complete stellar mass function (Barrado et al. 2001b, so far the deepest for M 35) which is

totally compatible with the IMF of much younger and unevolved clusters, such as such as Collinder 69 (Barrado et al. 2005; Bayo et al. 2011), and suggests that M 35 includes several tens of potential substellar members.

The goal of this paper is to complete the census reaching well inside the substellar domain and including the cluster outskirts up to a radius of 1° , providing multi-epoch, multiband photometry from public archives and from our recent observations.

2. Data sets

We searched the Canada France Hawaii Telescope (CFHT), National Optical Astronomical Observatory (NOAO), Subaru, Kiso, Sloan Digital Sky Survey (SDSS DR9, Ahn et al. 2012) and Isaac Newton Group (ING) public archives for wide field images of the cluster. Table 2 gives an overview of the data set found in these archives and in our own private archives.

In each case, we downloaded the raw data and associated calibration frames. We processed the individual raw images using an updated version of *Alambic* (Vandame 2002), a software suite developed and optimized for processing large multi-CCD imagers, which we adapted for the instruments used here. *Alambic* includes standard processing procedures, such as overscan, bias, and dark subtraction for the individual readout ports of each CCD, flat-field correction, bad pixel masking, CCD-to-CCD gain harmonization in the case of multichip instruments, fringing correction (when needed for the reddest filters), de-stripping, background subtraction, and nonlinearity correction in the case of near-infrared detectors.

Aperture, point spread function (PSF), and model photometry were extracted from the individual images using

Fig. 1. Estimated error on the proper motion as a function of i -band magnitude. The color scale represents the maximum time difference used for each measurement. The prediction for *Gaia* is over-plotted for comparison.

SEXTRACTOR (Bertin & Arnouts 1996) and PSFEX (Bertin 2011). The individual catalogs were then registered and aligned on the same photometric scale using SCAMP (Bertin 2006).

We derived the photometric zero-points using standard fields obtained for the same night whenever available or all-sky catalogues such as 2MASS (Skrutskie et al. 2006) in J, H and K_s , SDSS in g, r, i, z and IPHAS (Drew et al. 2005) in $H\alpha$. The zeropoint rms were typically in the range between 0.02 mag and 0.12 mag, and were added quadratically to the measurement uncertainty. We did not attempt to calibrate the nonstandard VR filters used with the Mosaic and SuprimeCam cameras and the He I narrow-band filter obtained with the WFC.

Proper motions for all the sources were computed using the method described in Bouy et al. (2013). The final residuals on the astrometric solution show a dispersion on the order of 11 ~ 12 mas. Figure 1 shows the estimated error on the proper motion as a function of i -band apparent magnitude. We note that the proper motion measurements are not tied to an absolute reference system such as the International Celestial Reference System (ICRS). They are nevertheless expected to be close to the ICRS since extragalactic sources and background stars largely dominate the sample and display very little motion with respect to the ICRS.

A final master catalog of all sources (338 892 in total) was then produced including the measured photometry in the $grizJHKs$ filters. We detected a total of 194 452 sources (approximately half) at more than two epochs, and the proper motions of these sources are also included. Since the main goal of the survey focuses on the study of M 35, only objects with $|\mu_\alpha \cos \delta| \leq 100$ mas yr⁻¹ and $|\mu_\delta| \leq 100$ mas yr⁻¹ were considered for the membership analysis.

3. Membership

We use the method described in Sarro et al. (2014) to derive membership probabilities of all the sources. Briefly, the method uses a training set – in this case the sample of candidate members from Barrado y Navascués et al. (2001) – to identify the features that most efficiently separate the cluster’s population from the field and background population among all combinations of proper motion, luminosities and colors available. In the case

Fig. 2. Spatial distribution of sources used as training set (green squares, from Barrado y Navascués et al. 2001) and of the 4349 sources of the final sample with membership probability greater than 0.5. Background image: 2MASS J -band.

of M 35, the best set was found to include the proper motions, the z , H , K_s luminosities and the $(r - z)$, $(r - i)$ and $(J - H)$ colors. Once the best set of colors, luminosities and proper motion is selected, a model of the cluster’s locus defined by the training set is fitted in the corresponding multidimensional space. A mixture of Gaussians is used for the proper motion diagram and principal curves for the cluster’s sequence in all color–magnitude and color–color diagrams. Membership probabilities are then computed using this first model. The highest probability members are selected as the new training set, and the models and the membership probabilities are recomputed until they converge.

This method was originally developed and optimized for clusters like the Pleiades, i.e. clusters with a relatively large proper motion and photometric sequence clearly separated from the field and background sequences in many color–magnitude diagrams. Unfortunately M 35 is a worst-case scenario for the method. Its proper motion is relatively small and its sequence largely overlaps with the field and background sequence in almost all color–magnitude and color–color diagrams. To limit the contamination and enhance the contrast between cluster members and field and background sources, we chose to restrict the analysis to a radius of 1° around the cluster’s center located at $\alpha = 06^h08^m54.0^s$, and $\delta = +24^\circ20'00''$ (J2000). Figure 2 shows their spatial distribution. It shows that the northwestern part of the survey was shallower than the rest of the survey, as fewer members were selected. It also shows that a number of high probability members have $(r - i)$ or $(i - K_s)$ color apparently inconsistent with the cluster’s sequence. Their high probability is due to their proximity to the isochrone in all other color–magnitude and color–color diagrams as well as to the cluster’s locus in the proper motion diagram. These sources, probably suffering from inaccurate photometry in one of these bands, illustrate the robustness of the selection method based on a high dimensional space.

Table 3 gives the astrometry, photometry and membership probability for the 338 892 unique sources detected in the corresponding area. Only the sources with a proper motion measurement have a membership probability (194 452 in total), as the availability of a proper motion measurement was a necessary

Fig. 3. Color magnitude and proper motion diagrams of the 194 452 sources of the sample detected at more than two epochs. *Left:* r vs. $r - i$. *Middle:* i vs. $i - K_s$. *Right:* proper motion diagram. Sources with a membership probability greater or equal to 0.5 are represented in the *top panels* with a color scale proportional to their probability. The remaining sources are represented in the *bottom panels*.

condition in our membership analysis. Using sources with membership probability greater or equal to 0.9, we derive a median proper motion for the cluster of $(\mu_\alpha \cos \delta, \mu_\delta) = (1.99, -0.23) \pm (0.82, 0.71) \text{ mas yr}^{-1}$, where the uncertainties correspond to the scaled median absolute deviation.

Figure 4 shows the membership distribution and cumulative distribution (computed from large to small values) for all the sources in the catalog. The vast majority of the sources has a membership probability of ≈ 0.0 . A monotonously decreasing distribution fills the probability range between 0 and 1.0, as the result of the loose constraints on the photometric and astrometric properties of the cluster.

NGC 2158 is an intermediate age ($1 \sim 2 \text{ Gyr}$) cluster at a distance of $\approx 3600 \text{ pc}$ (Carraro et al. 2002) located at a projected distance of only $25'$ from M 35. It is therefore included in the area covered by the present study and possibly contaminates the membership analysis. To estimate the level of contamination due to NGC 2158 members, we select all the sources located within $3'$ of its center. Given the distance and projected density profile of NGC 2158, the vast majority of these sources are expected to be members of NGC 2158. Figure 5 shows the sequence formed by these sources in various color-magnitude diagrams made of colors and luminosities used for the membership analysis presented here, and compares it to the sequence formed by objects with a probability of membership to M 35 greater than 0.5 according to our analysis. The two sequences overlap mostly at the bright end, and contamination must occur mostly above $i \lesssim 17 \text{ mag}$. We find that only 27 sources with a probability of membership to M 35 greater than 0.5 are located within $3'$ of NGC 2158, and 53 within $5'$. Given the projected size of NGC 2158 core, little contamination is expected beyond $5'$, and

Fig. 4. Distribution (blue, left scale) and cumulative distribution (red, computed from large to small values, right scale) of membership probabilities for the 194 452 sources of the sample.

the contamination by NGC 2158 members must not reach more than $1 \sim 2\%$ at most.

4. Conclusions

We have processed and analyzed a total of 4867 wide-field optical and near-infrared images of M 35 obtained from various public astronomical archives. The images cover 18 years of time

Fig. 5. Color-magnitude diagrams of the M 35 high probability members (≥ 0.5 , red dots) and of all the sources within $3'$ of NGC 2158 center (blue dots).

baseline and typically reach a depth of $21 \approx 22$ mag in the optical and ≈ 19 mag in the near-infrared, while saturation arises around $12 \sim 13$ mag at the bright end. This data set allows us to derive multiwavelength photometry from the optical to the near-infrared for 338 892 sources, and proper motions for 194 452 of them. We use these measurements to derive the membership probability of all the sources with a proper motion measurement. We obtain:

- 4349 candidate members with probability greater than 50%.
- 1726 candidate members with probability greater than 75%.
- 305 candidate members with probability greater than 95%.

These numbers are consistent with the census presented in [Barrado y Navascués et al. \(2001\)](#) over a smaller area. Contamination is expected to be significant as the locus of the cluster in the proper motion, color-magnitude and color-color diagrams overlaps largely with the field and background locus. This new study nevertheless provides a coherent and quantitative membership analysis of M 35 based on a large fraction of the best ground-based data sets obtained over the past 18 years.

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