Multi-Conjugate Adaptive Optics VLT imaging of the distant old open cluster FSR1415

Y. Momany\textsuperscript{1,2}, S. Ortolani\textsuperscript{3}, C. Bonatto\textsuperscript{4}, E. Bica\textsuperscript{4}, B. Barbuy\textsuperscript{5}

\textsuperscript{1}INAF: Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
\textsuperscript{2}ESO: European Southern Observatory, Alonso de Cordova 3107, Santiago, Chile
\textsuperscript{3}Universit\`a di Padova, Dipartimento di Astronomia, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy
\textsuperscript{4}Universidade Federal do Rio Grande do Sul, Departamento de Astronomia CP 15051, RS, Porto Alegre 91501-970, Brazil
\textsuperscript{5}Universidade de S\~ao Paulo, IAG, Rua do Mat\~ao 1226, Cidade Universit\`aria, S\~ao Paulo 05508-900, Brazil

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ABSTRACT

We employ the recently installed near infrared Multi-Conjugate Adaptive Optics demonstrator (MAD) to determine basic properties of a newly identified, old and distant, Galactic open cluster (FSR 1415). The MAD facility remarkably approaches the diffraction limit, reaching a resolution of 0.\textquoteleft'07 (in $K$), that is also uniform in a field of $\sim 1.8'$ in diameter. The MAD facility provides photometry that is 50% complete at $K \sim 19$. This corresponds to about 2.5 mag below the cluster main sequence turn-off. This high quality data set allows us to derive an accurate heliocentric distance of 8.6 kpc, a metallicity close to solar, and an age of $\sim 2.5$ Gyr. On the other hand, the deepness of the data allow us to reconstruct (completeness-corrected) mass functions indicating a relatively massive cluster, with a flat core MF. The VLT/MAD capabilities will therefore provide fundamental data in identifying/analyzing other faint and distant open clusters in the Galaxy III and IV quadrants.

Key words: instrumentation: adaptive optics – infrared: stars – techniques: photometric – Stars: Population II – Galaxy: open clusters and associations – Individual: FSR1415

1 INTRODUCTION

Open clusters are continuously affected by dynamical processes such as: (i) mass loss, linked to stellar evolution, mass segregation and evaporation; (ii) tidal interactions with the Galactic disk and bulge; and (iii) collisions with giant molecular clouds. These processes combined tend to accelerate the internal dynamical evolution which, as the cluster ages, results in significant changes in the cluster structure and mass function (Bonatto & Bica 2007, and references therein). Eventually, the majority of the open clusters will be dispersed in the Galactic stellar field, or become poorly-populated remnants (Pavani & Bica 2007, and references therein). In fact, open clusters older than $\sim 1$ Gyr are found preferentially near the Solar circle and in the outer Galaxy (e.g. Froebrich 1993; Bonatto et al. 2006), where the frequency of dynamical interactions with giant molecular clouds and the disk is low (e.g. Salaris, Weiss & Percival 2004; Upgren, Mesrobian & Kerridge 1972).

As a reflex of the above scenario, less than $\sim 18\%$ of the open clusters listed in WEBDA are older than 1 Gyr, with most of them located outside the Solar circle (see, e.g., Fig. 1 of Bonatto & Bica 2007). Granted the above aspects, the discovery and derivation of astrophysical parameters of old open clusters is expected to result in a better understanding of the dynamical processes that affect star clusters, with reflexes on star formation and evolution processes, dynamics of N-body systems, and the geometry of the Galaxy, among others.

In this framework, the construction of an old ($\geq 1$ Gyr), distant and complete open cluster sample acquires particular importance. An effort in this direction is the new catalogue of 1021 star cluster candidates that was recently presented by Froebrich et al. (2007a - hereafter FSR objects). It spans all Galactic longitudes (for $|b| < 20^\circ$), and is based on an over-density automated search algorithm applied to the 2MASS database. Examination of this catalogue has surprisingly allowed the detection of new globular clusters (FSR 1735, Froebrich, Meusinger & Scholz 2007; FSR 1744, Bonatto et al. 2007) and a number of old open clusters (e.g. FSR 1744, FSR 89, FSR 31. Bonatto & Bica 2007). We

\textsuperscript{1} The Two Micron All Sky Survey, available at www.ipac.caltech.edu/2mass/releases/allsky/
have examined many cluster candidates from this catalogue, and verified that several of these must have the turn-off (TO) much below the 2MASS limit. Thus, and for a few cases, the photometry provided by a 4m-class telescope was still not deep enough (Froebrich, Meusinger, Davis 2008; Froebrich, Meusinger & Scholz 2007), and consequently, 8m-class telescopes (provided that adaptive optics is available) were needed.

The recent availability of a Multi-Conjugate Adaptive Optics Demonstrator (MAD) at the VLT UT3-Melipal, and the public call for Science Verification encouraged us to propose JK observations of the faint cluster FSR 1415. Indeed, the inspection of the 2MASS colour-magnitude diagrams (CMDs) indicated the presence of either (i) a rich red clump; or (ii) a red horizontal branch. Disentangling between these two, similar, features allows one to infer the detection of a distant open cluster or a globular cluster, respectively. The results presented in this paper (Sect. 2) unequivocally point towards the detection of an old open cluster. We stress that there are very few photometric studies of Galactic star clusters with standard Adaptive Optics (Trumpler 14, Ascenso 2001) or with Multi-conjugate Adaptive Optics (Trapezium by Bouy et al. 2008, see also the case of the UKS2323-326 dwarf galaxy by Gullieuszik et al. 2008). FSR 1415 is a low latitude target projected almost orthogonally to the Galactic anti-centre direction (ℓ = 263.74°, b = −1.81°). The J2000 equatorial coordinates are: (α, δ)=(8h : 46m : 24s,−44° : 43m : 05s).

Although the present study addresses a single open cluster, it lays the basis for the identification of a complete sample of old open clusters in the IV Galaxy quadrant, known for a dearth of distant and old clusters. Ultimately, a complete sample will be useful for understanding the evolution of the disk, in particular concerning radial gradients and age-metallicity relations (Friel 1995; Rocha-Pinto et al. 2006; Maciel et al. 2007). In Sect. 2 we describe the instrument and observing procedures. In Sect. 3 we present the photometry and derive cluster parameters, including a study of the radial structure. In Sect. 4 we discuss the results of FSR 1415 in the context of other old open clusters and the properties of the disk. In Sect. 5 conclusions and perspective work on clusters with adaptive optics are presented.

### Table 1. Log of the MAD observations obtained on January 13th 2008.

| Filter | FWHM | airmass | DIT (sec.) | NDIT |
|--------|------|---------|------------|------|
| K      | 0′073 | 1.137   | 10         | 27   |
| K      | 0′073 | 1.129   | 10         | 27   |
| K      | 0′074 | 1.122   | 10         | 27   |
| J      | 0′145 | 1.248   | 10         | 27   |
| J      | 0′101 | 1.234   | 10         | 27   |
| J      | 0′176 | 1.221   | 10         | 27   |
| J      | 0′195 | 1.209   | 10         | 27   |

### Figure 1. The MAD mosaic of the 8 J and K dithered images of FSR 1415, East to the right North to the top. The overall circular field of view is ~ 1.8′ × 1.8′. The irregular shape of the mosaic is due to the lacking of a fifth dithered image. Border vignetting and other features (due to the movable scanning table) are unavoidable.

### Figure 2. The X and Y FWHM map (in pixels) of the 8 J and K mosaiced images. East to the right, North to the top. Crosses show the stars identified and used in the FWHM computation (1 pixel is 0″0028).

### 2 OBSERVATIONS

MAD was developed by the ESO Adaptive Optics Department to be used as a visitor instrument at Melipal in view of an application to ELT. It was installed at the visitor Nasmyth focus and introduces the concept of multiple reference stars for layer oriented adaptive optics corrections. This allows a much wider and more
uniform corrected field of view, providing larger average Strehl ratios and making the system a powerful diffraction limit imager. This is particularly important in crowded fields where the photometric accuracy is needed. For more details see [http://www.eso.org/projects/aot/mad/] and Marchetti et al. (2007). Indeed, the on-sky MAD commissioning of an ωCen field showed an enormous gain in angular resolution and light concentration such that very faint stars (K ∼ 20.5) were easily distinguished (at a 3σ level) in just 600 sec. exposures. In October 2007 we answered a call for science demonstration of MAD, and among other applications (see [http://www.eso.org/sci/activities/vltsv/mad/]) we were granted a total of 2 hours aimed at deriving the main properties of a distant cluster candidate (FSR 1415).

Within the field of view of the instrument, three reference bright stars were selected to ensure the optics correction. These stars had V magnitudes that ranged between 12.24 and 13.6, according to their GSC2.2 magnitude system. While the site seeing during the observations was ≈ 0.5′′, a diffraction limit in K of 0.′′07 was reached. Table 1 displays the logbook of the J and Ks (for brevity we use K) observations. The MAD infrared scientific imaging camera is based on a 2048 × 2048 pixel HAWAII-2 infrared detector with a pixel scale of 0.′′028. Given that the Detector Integration Time (DIT) is the amount of time during which the signal is integrated onto the detector diodes, while NDIT is the number of detector integrations that are obtained and averaged together, it follows that the total exposure time of a single raw image is simply NDIT × DIT. In our case, we obtained 4 dithered images in each filter, where DIT was fixed to 10 sec. and NDIT to 27. Thus, the total exposure time is 1080 sec. (18 min.) in J and K. The images were dark and sky-subtracted and then flat-fielded following the standard near infrared recipes (see for example Dutra et al. 2003 and Momany et al. 2003), all performed under the IRAF environment.

Figure 1 shows the mosaic of all 8 J and K images as constructed by DAOPHOT/MONTAGE2 task. Figure 2 shows the FWHM map with an overall regular distribution across the entire field of view with values ranging between ∼ 2.5 (0.′′07) and ∼ 4.5 (0.′′13), where the upper limit is mostly due to the fitting process in border zones with scarce stellar population. The superb VLT/MAD resolution is illustrated in Fig. 3, in a comparison with the 2MASS photometry.

2.1 Photometric Reduction

Stellar photometry was obtained by point spread function (PSF) fitting using the tested DAOPHOT II/ALLFRAME (Stetson 1994) package. ALLFRAME combines PSF photometry carried out on the individual images and allows the creation of a master list by combining images from different filters, thereby pushing the detection limit to fainter magnitudes. Once the FIND and PHOT tasks were performed, we searched for isolated stars to build the PSF for each single image. The final PSF was generated with a PENNY function that had a quadratic dependence on position in the frame.

2.2 Calibration

Calibration of the J and K data has been made possible by direct comparison of the brightest MAD non-saturated stars with their 2MASS photometry. Figure 4 shows the J and K magnitude differences between our MAD instrumental pho-
2.3 Photometric errors and completeness

Photometric errors and completeness were estimated from the artificial stars experiments following procedures similar to those in Momany et al. (2002) and Momany et al. (2005). More than 2300 stars were added to the single images, and these were placed in a suitable pattern of triangular meshes to avoid self-crowding and not closer than 40 pixels (1′′1). In particular, the distribution of the $J$ and $K$ magnitudes was not casual, and these were simulated in a way to reproduce the cluster main sequence and red giant branch loci. The images with the artificial stars added were then re-processed in the same manner as the original images. The results for photometric completeness and errors are presented in Fig. 5 and Fig. 6.

Figure 5 compares the nominal DAOPHOT II photometric errors (black dots) with those derived from the comparison between the magnitude of input simulated stars and the retrieved magnitudes. The light starred symbols report the mean photometric errors where the binning is that of a fixed number of 50 artificial stars. The comparison shows an overall consistency between the two derived errors, although there is a hint of a slightly higher photometric errors as derived from the artificial stars experiments. On the other hand, Fig. 6 summarizes the estimated photometric completeness of our data. The left panel of Fig. 6 shows the observed colour-magnitude diagram (CMD), whereas the middle panel displays the colour-magnitude distribution of the input $\sim$ 2300 artificial stars (orange dots obtained reproducing the MS and RGB fiducial line of the cluster) and the retrieved artificial stars (green dots). The distribution of the retrieved artificial stars reflects the increasing level of photometric errors and the lower completeness levels towards fainter magnitudes. The right panel compares the luminosity distribution of the input and output stars, whereas the light dashed line computes the output/input stars ratio (reflecting the completeness of the data). In calculating this ratio, only stars recovered in both the $J$ and $K$ images are considered. Thus, Fig. 6 shows that our CMDs are basically complete down to $K \sim$ 18.0, reaching a 50% completeness level around $K \sim$ 19.0. For a mean $(J-K)$ colour of $\sim$ 1.0, we report the $K$ completeness levels in Table 2.

Table 2. $K$-completeness levels as derived from the artificial stars experiments for an average $(J-K) \sim$ 1.0 of the input stars.

| $K$-mag. | Comp. (%) |
|---------|-----------|
| 12.0    | 100       |
| 12.5    | 100       |
| 13.0    | 100       |
| 13.5    | 100       |
| 14.0    | 100       |
| 14.5    | 100       |
| 15.0    | 100       |
| 15.5    | 100       |
| 16.0    | 100       |
| 16.5    | 99        |
| 17.0    | 98        |
| 17.5    | 98        |
| 18.0    | 95        |

3 ANALYSIS OF THE PHOTOMETRY

The left panel of Figure 7 displays our VLT/MAD colour-magnitude diagram of the entire FSR 1415 field ($\sim$ 1′.8 x 1′.8). Superimposed in light open circles are 2MASS stars falling in the same field. The CMD contains obvious open cluster features, i.e. the red giant branch (RGB), the red clump (RC), the main sequence turn-off (MSTO), and the expected cluster blue stragglers (BS) population. The later population is confused by the presence of nearby Galactic disk MS stars (the oblique sequence extending to $K \sim$ 11.0). It remains however that the two prominent open cluster features are the RC and the MSTO. Indeed, despite the relatively small MAD field of view, we sample to about 10 RC stars. The average location of these red clump stars is at $K = 13.82 \pm 0.03$ and $(J-K) = 1.34 \pm 0.03$. On the other hand, the MSTO is located at $K = 16.65 \pm 0.05$. Thus, the difference between...
the MSTO and RC is $\Delta K_{RC}^{TO} = 2.83 \pm 0.06$, typical of old open clusters.

Although no control field has been observed, the SKY single images (usually medianed to eliminate stars) can be treated just as a scientific image, and reduced similarly. This should provide us with an idea of the contaminant field population around FSR 1415. We stress the fact however that these SKY images are not obtained with a closed adaptive optics (AO) loop, thus the resultant CMD is clearly shallower. At $\sim 8'$ from the FSR 1415 one easily identifies a complete absence of RC stars. This is also confirmed by the 2MASS photometry in the same area, and therefore the identification of a genuine open cluster (left panel) is further confirmed.

### 3.1 A Blue Stragglers population?

To confirm the possible presence of a blue stragglers population in FSR 1415 one needs to account for the disk population around the cluster. In the absence of a deep CMD of the FSR 1415 surrounding environment, we attempt to solve this issue by the use of synthetic diagrams based on models of the Galaxy. The Besançon (2003) online simulator provides synthetic CMDs in specific line of sights for a given area. Applying the cluster Galactic coordinates and field of view, in Fig. 8 we over-plot the synthetic Galactic population in this line of sight and the observed CMD. Indeed, at latitudes of $b = -1.81^\circ$ one expects to detect only young stellar disk populations and this agrees with the oblique young MS extending to $K \sim 12.0$. There is however a significant difference in the star-counts of the synthetic MS and that expected in our observed CMD. This is due to the fact that the synthetic CMDs do not "suffer" photometric completeness effects. Employing our artificial stars experiments and the resultant photometric completeness curve, in the middle panel we “correct” the star-counts of the synthetic MS for photometric completeness. The middle panel shows that a remnant Galactic MS population remains present, and must be accounted for in any star-counts analysis of FSR 1415 populations. Dividing the CMD in cells of 0.5 and 0.4 in mag. $K$ and $(J-K)$ respectively, we derive the number of Milky Way MS stars and randomly subtract this contribution from the observed MAD diagram.

The right panel of Fig. 8 presents the result of this statistical decontamination process. Clearly, there remains a clump of MS stars at $K \sim 14.0$ and $(J-K) \sim 0.5$ and this can be explained as due to the small number statistics involved in the simulation. Nevertheless, the “cleaned” diagram now shows a clear bifurcation around the cluster MSTO, indicating the probable detection of the BS sequence.

To ascertain whether the FSR 1415 BS candidates are true cluster members we estimate the parameter $F_{RC}^{BS} = \log (N_{BS}/N_{RC})$ (see de Marchi et al. 2006) and check if this frequency is compatible with that in other open clusters. We count 14 BS stars vs 10 RC stars, providing a $F_{RC}^{BS}$ of 0.146. This is fully compatible with values for other open clusters (0.2 ± 0.2), indicating that we have probably detected a genuine BS population in FSR 1415. Interestingly, Figure 2 of Momany et al. (2007) compares the $F_{RC}^{BS}$ in different environment (spanning from open and globular clusters to nearby dwarf galaxies) and shows that open clusters and the lowest luminosity dwarf galaxies (e.g. the Bootes dwarf at $M_V = -5.5$) share the same BS frequency. This
has been interpreted as the consequence of the presence of an observational upper limit to the frequency production of primordial BS in low-density stellar systems.

### 3.2 Age, metallicity and distance

To enhance the signature of the cluster population with respect to the foreground disk contamination, in Fig. 8 we display the CMDs of FSR 1415 extracted within a radius of $r \leq 0.5'$. Despite the smaller field of view the extracted CMDs still show a well-populated RC and MSTO, ideal features for the derivation of the cluster age. As a first approach, we assume that the 4 stars at $J \approx 17$ are cluster sub-giants. We note indeed, that these stars survive our decontamination process (see the right panel of Fig 8). This granted, and following various tentative, in Fig. 9 we show our best isochrone match to the CMD. To place FSR 1415 in a bigger framework, in Figure 10 we display a schematic view of the Milky Way Galaxy (from Drimmel & Spergel 2001, see also Vallée 2008) in which the current age uncertainty. Table 3 summarizes the derived cluster parameters and errors.

### 3.3 Location in the Galaxy

In the derivation of the spatial Galactic coordinates of FSR 1415 one needs to assume the Sun’s distance from the Galactic centre ($R_\odot$). Interestingly, the last few years have witnessed a clear trend towards shorter distance scales with respect to the nominal value of $R_\odot = 8.0$ kpc (see Reid 1999). Indeed, Eisenhauer et al. (2003) derive $R_\odot = 7.6\pm0.3$ kpc, whereas Nishiyama et al. (2004) find $R_\odot = 7.5\pm0.35$ kpc, and Bica et al. (2006) report $R_\odot = 7.2\pm0.3$ kpc. The latter value is based on an updated globular cluster compilation and is adopted throughout this paper. We note however that recently Groenewegen et al. (2008), with Population II Cepheids and RR Lyrae stars, report a longer distance ($R_\odot = 7.94\pm0.37$ kpc). In conclusion, and assuming $R_\odot = 7.2\pm0.3$ kpc, we derive that the Galactocentric distance of FSR 1415 is $R_{GC} = 11.81\pm0.33$ kpc, which puts it $\approx 4.6$ kpc outside the Solar circle.

To place FSR 1415 in a bigger framework, in Figure 10 we display a schematic view of the Milky Way Galaxy (from Drimmel & Spergel 2001, see also Vallée 2008) in which...
its major features, spiral arms and bar, are outlined. Superimposed (as open triangles) we show the positions of 125 known old (≥ 1 Gyr) open clusters, taken from the WEBDA database (Mermilliod 1996). Their spatial distribution shows a clear detection “bias”, in the sense of a concentration towards the Sun and the Solar circle. In this context, FSR 1415 stands out as a distant cluster in quadrant III of the Galaxy, located at RGC = 11.81 kpc from the Galactic centre. Figure 10 shows that there are a handful of old open clusters in this direction, and that more old clusters await to be identified in quadrant IV. Besides their age, another interesting aspect of old clusters such as FSR 1415 is their identification as outer disk clusters. Indeed, the determination of their metallicity will be crucial in extending the structural parameters of FSR 1415 were derived from the VLT/MAD observations.

3.4 Structure

Structural parameters of FSR 1415 were derived from the cluster stellar radial density profile (RDP), which consists of the projected number-density of stars around the cluster centre. The RDP of FSR 1415 was built by merging the observed VLT photometry in the inner region and the 2MASS data in the outer part (e.g. Bonatto & Bica 2007). The field background was obtained from the 2MASS data and subtracted. The background-subtracted 2MASS profile has been scaled to match the VLT one by multiplying the 2MASS RDP by 28.9. The VLT profiles of FSR 1415 are limited to K = 19.0, which corresponds to the stellar mass ≈ 0.93 M⊙. We employ the observed photometry because the artificial stars do not take into account dynamical effects. The VLT/MAD central surface density is a factor ≈ 30 higher than that of the 2MASS profile, which is consistent with the ≈ 4 mag deeper VLT photometry.

In Fig. 11 we show the merged VLT/2MASS density profile. Star clusters have RDPs that can be described by some well-defined analytical profile. The most widely used are the single-mass, modified isothermal sphere of King (1966), the modified isothermal sphere of Wilson (1975), and the power-law with a core of Elson et al. (1987). These functions are characterized by different sets of parameters that describe the cluster structure. Since we are working with a RDP built from different photometric sets and that our goal here is basically to derive reliable structural parameters for FSR1415, we fit the RDP with the analytical 3-parameter

\[ \sigma(R) = \sigma_0 \left( \frac{1}{1+(R/R_c)^2} - \frac{1}{1+(R/R_t)^2} \right)^2 \]

function, where \( \sigma_0 \) is the central number-density of stars, and \( R_c \) and \( R_t \) are the core and tidal radii, respectively. This function is similar to that introduced by King (1962) to describe the surface brightness profiles in the central parts of globular clusters. Moreover, as discussed in Bonatto & Bica (2008) and Bonatto & Bica (2008) RDPs built with photometry as deep as in the present case produce very robust structural parameters when fitted with the 3-parameter King-like function. In such cases, RDPs yield similar parameters as with surface brightness profiles.

The results of the fit parameters indicate a core radius of \( R_c = 0.9 \pm 0.2 \) pc (corresponding to 2.6 ± 0.6 pc), and a tidal radius of \( R_t = 12.2 \pm 2.9 \) pc (35 ± 8 pc). Thus, most of the VLT/MAD observations are restricted to within the core. The resulting central density is \( \sigma = 462 \pm 118 \) stars arcmin\(^{-2} \) (55 ± 14 stars pc\(^{-2} \)). With respect to the 3-parameter King fit we note that the innermost RDP point at \( R \sim 0.07 \) pc (0.2 pc) shows a marginal 1σ stellar density excess. Although marginal in the case of FSR 1415, such a feature is characteristic of post-core collapse globular clusters (Trager et al. 1993). The presence of post-core collapse features in RDPs of old clusters has been previously detected, for instance, in the ~1 Gyr cluster NGC 3960 (Bonatto & Bica 2006).

3.5 Luminosity and mass functions

The observed luminosity and mass functions (LF, MF respectively) for the J and K bands were built using the parameters in Table 2. We applied a colour-magnitude filter to the observed photometry (Fig. 9) to minimize contamination (e.g. Bonatto & Bica 2007). Fig. 12 shows the LFs measured in the K band for the regions 0\(^{\circ}\)–0.3, 0.3–0.6, and 0\(^{\circ}\)–0.6. It is interesting to note that these LFs correspond to spatial regions contained within the core (Sect. 3.4) and differences among them might be related to dynamical effects inside the core. The actual number of member (i.e. decontaminated) stars included...
in the computation of the $R < 0.6'$ LF is 321, 307 of which are MS stars, while the remaining are evolved. Granted the isochrone solution derived in Sect. 3.2, we estimate (for the observed magnitude range) that the cluster stellar mass amounts to $390 \, M_\odot$ (367 $M_\odot$ as MS and 23 $M_\odot$ as evolved stars). Since completeness is an important issue (Sect. 2.3) for fainter stars, we show the completeness levels for 4 selected $K$ magnitudes. Besides the observed LFs, we also show the corresponding completeness-corrected ones. The observed LFs do not appear to change significantly within the core. The same applies to the completeness-corrected LFs.

Mass functions for the same spatial regions as the LFs were constructed by combining the two $J$ and $K$ indepen-
dent MFs (see, e.g. Bonatto & Bica [2007]). The MFs were computed for the mass range \( m > 0.87 M_\odot \), corresponding to \( J \lesssim 20.2 \) and \( K \lesssim 19.3 \). These are shown in Fig. 13 where the relatively small MF error bars reflect the statistical significance of the star counts. At first sight, the observed MFs are flat, showing small differences between the 2 innermost regions. There is however an important drop towards the low-mass stars. Although in principle this might be related to mass segregation inside the core, nevertheless, crowding and completeness should be taken into account before a similar conclusion can be established. To this purpose we also built the completeness-corrected MFs, (as done for the LFs, Fig. 12). As expected, a significant difference between the observed and the completeness-corrected MFs is observed for masses below 1.1 \( M_\odot \).

For a better description of the cluster MFs we fit these with the function \( \phi(m) \propto m^{-(1+\chi)} \), carried out for masses higher than \( m > 0.96 M_\odot \) (\( J \simeq 19.8, K \simeq 18.9 \)). The lowest-mass point, at \( \approx 0.88 M_\odot \), is exceedingly affected by completeness. The fit to the observed \( 0.0 - 0.6 \) MF (top panel) provides a slope of \( \chi = 0.06 \pm 0.10 \), significantly flatter than the \( \chi = 1.35 \) of Salpeter's [1955] initial mass function (IMF). However, when the same fit is applied to the completeness-corrected MF, the resultant slope increases to \( \chi = 1.0 \pm 0.2 \), thus steeper than the non-corrected MF but still flatter than Salpeter's. For the innermost region the fit to the completeness-corrected MF gives \( \chi = 1.1 \pm 0.4 \), which is the same slope derived for the intermediate region. Within uncertainties, the completeness-corrected MF slopes are uniform throughout the sampled region within the core, which suggests that we are not detecting significant differences in mass segregation effects in such a small spatial scale, at least for stars more massive than \( m \approx 1 M_\odot \). It may be that a dynamical effect such as mass segregation cannot be detected given the relatively high stellar mass range covered by the present observations, basically \( \gtrsim 1 M_\odot \), and that deeper data (and lower masses stars) is needed to ascertain this issue. In any case, the relatively flat core MF derived in Fig. 15 suggests that dynamical effects have affected the core as a whole.

The total stellar mass in the core can be estimated by using the MF derived for the region \( 0.0 - 0.6 \), and extrapolating it down to the H-burning mass limit, 0.08 \( M_\odot \). This procedure may over-estimate the total core stellar mass since it does not account for the evaporation of low-mass stars. Nevertheless, one can provide an upper limit to the cluster mass. With the observed MFs, we derive an extrapolated stellar mass of 730 \( M_\odot \). Since we are sampling \( \approx 2/3 \) of the core radius, the (observed) core mass would be about 2000 \( M_\odot \). Bonatto & Bica [2003] estimated that for Gyr-class OCs, in general, the extrapolated cluster mass is about 10 times that of the core. Thus, the total (observed and extrapolated) stellar mass of FSR 1415 would be about 2 \( \times 10^4 \) \( M_\odot \), which is comparable to those of low-mass globular clusters (Harris [1996] and references therein).

When applying the same arguments to the completeness-corrected MF, the total (upper limit) cluster mass is estimated to be \( \approx 3 \times 10^4 \) \( M_\odot \), i.e. \( \approx 50\% \) higher than the observed value. Once again, such a high mass estimate can be accounted for by the facts that (i) the cluster is significantly more extended than the VLT/MAD-sampled region (Fig. 11), and (ii) the MFs were extrapolated down to 0.08 \( M_\odot \) stars (while the observed mass range corresponds to stars more massive than \( \approx 0.9 M_\odot \)). In any case, both mass estimates are consistent with the large core (\( R_c \approx 2.6 \) pc) and tidal (\( R_t \approx 35 \) pc) radii. Overall, the above mass and radii estimates indicate a massive open cluster which shows evidence of an advanced dynamical state, given its relatively flat core MF. Thus, and in spite of being an outer massive disk cluster, FSR 1415 may present features of dynamical evolution, suggesting that it may underwent significant encounters with GMCs and other tidal effects.

4 CONCLUDING REMARKS

The present study shows that the cluster candidate FSR 1415 (Froebrich, Scholz & Raftery [2007]) is confirmed as a genuine old open cluster. Thus, the Froebrich et al. catalogue appears to be an important source of interesting clusters candidates and is worthy of further examination.

The high resolution and deep VLT/MAD \( J \) and \( K \) data of FSR 1415 have allowed an accurate determination of basic cluster parameters. It is of great importance to obtain similar high quality data for other outer disk open clusters and complement these with spectroscopic metallicity determinations. Consequently, one can explore the age-metallicity-position dependencies all across the Galaxy. But perhaps first of all we need to overcome the current selection bias of old open clusters in the III and IV Galaxy quadrants.

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