We present the first results of a large spectroscopic survey of globular clusters and candidate globular clusters in the nearby M 31 galaxy. The survey is aimed at the classification of known candidate M 31 clusters and at the study of their kinematic properties. We obtained low-resolution spectroscopy ($\lambda/\Delta \lambda \approx 800 - 1300$) for 133 targets, including 76 yet-to-confirm candidate clusters (i.e. with no previous spectroscopic information), 55 already-confirmed genuine M 31 clusters, and 2 uncertain candidates. Our observations allowed a reliable estimate of the target radial velocity, within a typical accuracy of $\sim \pm 20$ km s$^{-1}$. The observed candidates have been robustly classified according to their radial velocity and shape parameters that allowed us to confidently discriminate between point sources and extended objects even from low-spatial-resolution imagery. In our set of 76 candidates clusters we found: 42 newly-confirmed bona-fide M 31 clusters, 12 background galaxies, 17 foreground Galactic stars, 2 H$\alpha$ regions belonging to M 31 and 3 unclassified (possibly M 31 clusters or foreground stars) objects. The classification of a few other candidates not included in our survey has been also reassessed on various observational bases. All the sources of radial velocity estimates for M 31 known globular clusters available in the literature have been compared and checked, and a homogeneous general list has been obtained for 349 confirmed clusters with radial velocity. Our results suggest that a significant number of genuine clusters ($\geq 100$) is still hidden among the plethora of known candidates proposed by various authors. Hence our knowledge of the globular cluster system of the M31 galaxy is still far from complete even in terms of simple membership.

**Key words.** Galaxies: individual: M 31 – Galaxies:star clusters – catalogs — Galaxies: Local Group
An updated survey of globular clusters in M 31

I. Classification and radial velocity for 76 candidate clusters *

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Abstract.

1. Introduction

Since the dawn of extragalactic astronomy (Hubble (1932)), the study of the globular cluster (GC) system around the Andromeda galaxy (M31) stand out as an important field of investigation, providing the ideal counterpart to compare with the GC system of our own Galaxy and a testbed for observational techniques to be applied to GC systems of more distant galaxies. In present days it is possible to compare directly integrated properties and resolved Color Magnitude Diagrams (CMD) of M31 clusters, as recently attained with the Hubble Space Telescope (HST) (see, e.g. Fusi Pecci et al. (1996), Brown et al. (2004), Rich et al. (2005)).

In spite of a similar mass and morphology, M31 is recognized to display several differences in its stellar and clusters content with respect to the MW. For instance, the halo stellar populations of the two galaxies (the typical environment of most GCs) widely differ in average metallicity; while stars in the MW halo are predominantly metal poor ($(\langle Fe/H \rangle \approx -1.6$ dex (Laird et al. 1983)), those in the outer regions of M31 have $(\langle Fe/H \rangle \approx -0.5$ dex (see, for example, Holland et al. 1996; Bellazzini et al. 2003; Rich et al. 2003; Durrell et al. 2004, and references therein). The GC system of M31 is much more populous than that of the MW, with more than 300 confirmed clusters, to compare with the $\sim 150$ of the MW. In particular, Barmby et al. (2001) estimated the total number of M31 GCs to be $475 \pm 25$, i.e. more than a factor of three larger than in the Milky Way. It is quite clear that understanding the reasons of such striking differences may shed light on the formation histories of the two galaxies and, at large, on the general process of galaxy formation.

Since early systematic surveys (see, among others, Vetešnik (1962), van den Bergh (1967; 1969), Baade & Arp (1964), Sargent et al. (1977), Crampton et al. (1985), Battistini et al. (1980; 1982; 1987; 1993), Sharov et al. (1995), Mochejska et al. (1998), Barmby et al. (2000), and references therein), most of the known M 31 GC candidates (hereafter GCCs) have been typically identified by visual inspection of wide-field photographic plates, and a more exhaustive analysis with CCD cameras is still partially lacking. On this line, a few recent studies (see, for example, Racine (1991), Barmby & Huchra (2001), Mochejska et al. (1998), Huxor et al. (2004; 2005), Barmby et al. (2001), Perrett et al. (2003), Fusi Pecci et al. (2005), Beasley et al. (2004), Puzia et al. (2005)) have clearly shown that this kind of new-generation surveys may significantly change our knowledge of the number and nature of the clusters harbored in the M 31 system. To date, there are still hundreds of known GCCs (~700, see Galleti et al. (2004), henceforth G04) whose nature remains to be ascertained.

Most of these candidates pertain to the faint-end tail of the GC luminosity function which, at present, is far from complete (see Fig. 1). Battistini et al. (1980; 1982; 1987; 1993), ranked the majority of cluster candidates according to a quality class (from “A” to “E” in the sense of decreasing confidence level) related to their appearance on the original images. The upper panel of Fig. 1 shows that the majority of class A and B candidates have already been confirmed (either spectroscopically or,
in a few cases, by high resolution images), while most of class C and D targets remain to be explored. In any case, one has to consider that any comprehensive sample of M 31 GCs should forcibly rely on coarse databases whose homogeneity is difficult to assess. On the other hand, a catalog of M31 clusters as complete and homogeneous as possible is clearly overdue, and this is a fundamental step for any meaningful comparison with other systems. In this framework we have started a long-term project to step ahead with this ambitious goal.

In G04 we re-analyzed the photometric and classification data available in the literature, reporting coarse photometry to a self-consistent CCD-based magnitude scale, and providing infrared information for several hundred GCCs as well, with JHK magnitudes from the 2MASS database (Skrutskie et al. (2006)). The resulting catalog (Revised Bologna Catalog, hereafter RBC1) contains at present 1164 entries, including all the already confirmed clusters, the known but yet-to-confirm candidates, and the proposed candidates whose “non-M31-GC” nature has been definitely established. We believe that keeping record of the latter objects is very useful all the way, not only to avoid duplicating observations, but also to characterize the observing properties of the typical contaminants, in order to tune up selection criteria and maximize the return of future observational campaigns (see G04 for details and discussion).

For reader’s better convenience, it may be useful to recall again the RBC classification scheme, as originally used in G04.

The classification flag c can therefore assume the following values: c = 1 confirmed clusters, c = 2 candidate clusters, c = 3 uncertain candidates, c = 4 background galaxies, c = 5 H α regions, c = 6 foreground stars. In addition, as a result of the present discussion (see Sect. 4.3, below), we will also introduce here a new class (c = 7) including asterisms/associations.

As a further line of attack in our work, we are carrying on a survey of GCCs located at large (projected) distance from the center of M 31, a nearly unexplored realm. A first pilot run of the survey led to the discovery of B514 (Galleti et al. (2005), hereafter G05), the outermost cluster of the Andromeda galaxy ever known.

Finally we have undertaken a large spectroscopic follow up of known candidates, to assess their nature and study their physical properties. This is the subject of the present paper, where we deal with classification and kinematic of 76 M 31 GCCs never surveyed before.

In the following Sec. 2 we briefly introduce the problem of M 31 GCCs classification, and describe the observational material and its reduction procedures. Sect. 3 is devoted to radial-velocity estimates for our sample and the comparison of our results with other spectroscopic datasets available in the literature. Sect. 4 deals with the classification of the observed candidates and in Sect. 5 we use the kinematical information for the updated sample of confirmed clusters to estimate the mass of M 31. Finally, in Sec. 6 we summarize and discuss our results.

In a companion paper (Galleti et al., in preparation) we will complete our study by assessing the problem of a self-consistent metallicity scale for M 31 GCs, relying on homogeneous measures of the Lick indices (Trager et al. (1998)).

2. Observations and data reduction

A spectroscopic database of 133 targets has been collected through different observing runs along 2004/05, carried out at the Roque de los Muchachos (La Palma, Spain) observing facilities of the 3.5m Telescopio Nazionale Galileo (TNG) and the 4.2m William Herschel telescope (WHT), and at the “G.B. Cassini” 1.52m telescope of the Loiano Observatory (Italy). Our sample comprises 76 M 31 GCCs, while further 55 confirmed clusters (c = 1 RBC flag) were included to consistently match our results with other external data sources in the literature, together with 2 more questioned objects that need a more definitive spectroscopic assessment. The survey mainly aims at achieving accurate radial-velocity measurements for a wide sample of M 31 GCCs through low-resolution long-slit and fiber spectroscopy.

The kinematical piece of information alone can easily discriminate between genuine M 31 GCs and the most relevant class of spurious contaminants, i.e. background galaxies. The nature of the latter sources can in fact be recognized because of their cosmological recession velocities (typically $6000 \lesssim c\zeta \lesssim 50000$ km s$^{-1}$, see G04), much larger (and opposite in sign) than the systemic velocity of M31 (namely $V_r \approx -301$ km/s, Van den Bergh (2000)).

On the other hand, radial velocity alone may not be sufficient to discriminate between M 31 GCs and foreground interlopers – mostly MW stars – the other major source of con-
tamination for our sample. In these cases one has to recur to morphological criteria in order to confidently discriminate between point (i.e. stars) and extended sources (GCs). To assess this important point, we also complemented our spectroscopic analysis with supplementary imagery, taken at the Loiano telescope, for an independent but largely overlapping sample of 86 RBC objects. We will return on Sec. 4 for a full discussion of these results.

### 2.1. WYFFOS Data

Most of our sample has been observed during the nights of Nov 21 and 22 2004, using the AutoFib2+Wide Field Fibre Optic Spectrograph (WYFFOS; Telting & Corradi (2000)), mounted at the WHT prime focus. We adopted the R1200B grating, covering the \(\lambda l = 4000 \rightarrow 5700 \, \text{Å} \) spectral range with a FWHM wavelength resolution of 2.2 Å. WYFFOS is equipped with a mosaic of two EEV-42-80 CCDs, windowed and mosaiced such as to have \(\approx 4300 \times 4200 \, \text{px}^2 \) in total, that were read in 2 \(\times\) 2 binning mode, with a scale of 0.4 Å/pixel. We used the Small Fibre module, which is made of 150 1.6 arc-sec science fibres, and 10 fiducial bundles for target acquisition and guiding. Four different fibre configurations were set up in order to target a total of 183 confirmed clusters and GCCs.

A total of 10 science exposures ranging from 1200 to 2700 sec were acquired (four in the first night and six in the second night). Calibrating exposures included bias, sky and lamp flat-field, and He/Ne comparison lamps. For each of the four pointings we typically allocated a fraction of \(\sim 30\% \) of the whole fibre configuration to simultaneously sample the sky level. The sky emission was also probed before and after each target exposure by dithering the same fibre configuration. No substantial differences were found between the two procedures (see Fig. 2 for an illustrative example), and we eventually decided to apply option (i) for our analysis.

Two M 31 globular clusters (namely B225 and B158), for which very accurate radial velocity estimates are available in the literature (Dubath & Grillmair [1997]), were observed in two different pointings and used as reference templates to set radial-velocity zero point. These reference spectra reach \(S/N > 50\) per pixel, to be compared with a typical \(S/N \approx 10\) for the GCC spectra. Two exposures for each scientific target have been acquired. The same strategy has been adopted also for the runs described below.

The poor seeing conditions (FWHM \(\sim 1.5''\)), in addition to thin-cloud sky coverage during both observing nights, and the less-than-perfect positioning of some fibres eventually limited the final signal-to-noise of several faint targets. For this reason only 116 out of the 183 targets ended up with a useful spectrum for our analysis.

### 2.2. BFOSC Data

Long-slit spectra for 8 relatively bright \((V \leq 16.5)\) targets were obtained with the low-resolution spectrograph BFOSC (Gualandi & Merighi [2001]) operated at the Loiano Observatory. The detector was a thinned, back illuminated EEV CCD, with \(1300 \times 1340 \, \text{px}^2\). The observations were carried out under typical seeing conditions (FWHM \(\sim 1.5''\)), on six nights during 2004 (Sep 18-19, Nov 16-17) and 2005 (Jan 02-05). With a 1.5 arcsec slit, the adopted setup provided a FWHM spectral resolution \(\Delta \lambda = 4.1 \, \text{Å} \) \((\lambda/\Delta \lambda \approx 1300)\) covering the...
range $\lambda \theta = 4200 \rightarrow 6600$ Å. We took a He-Ar calibration-lamp spectrum after each scientific exposure, maintaining the same telescope pointing. Exposure times were typically 45 minutes, yielding spectra with a characteristic $S/N \approx 8$ per resolution element.

During each observing night and with the same instrumental setup, we also collected accurate ($S/N > 70$) observations of four radial-velocity template targets, namely the same M 31 GCs adopted for the WYFFOS run (B158 and B225) plus stars HD 12029 and HD 23169 (heliocentric radial velocities from the SIMBAD database). Bias, flat field, and sky subtraction were carried out using standard packages in IRAF, as described in Galleti et al. (2005).

### 2.3. DOLORES Data

The imager/spectrograph DoLoRes at the TNG was used in the nights of Sep 8 and Oct 8, 2004, to acquire long-slit spectra of 9 M 31 GCCs. DoLoRes is equipped with a $2048 \times 2048$ px$^2$ thinned and back-illuminated Loral CCD array providing a $9.4' \times 9.4'$ field of view. The adopted MRB grism yielded a resolution of 6 Å FWHM ($\lambda/\Delta \lambda = 875$) with a 1'' slit, across a $\lambda \lambda = 3800 \rightarrow 6800$ Å spectral range. We typically exposed 10–15 minutes, reaching $S/N \approx 13$ per resolution element. A He-lamp spectrum was acquired after each science frame for wavelength calibration. Again, during each night we obtained good ($S/N \geq 50$) spectra for the template clusters B158 and B225. The data reduction procedure was the same as for the BFOSC data.

### 3. Radial velocities

The heliocentric radial velocities ($V_r$) of GCCs were obtained by cross-correlation with the templates spectra, using the IRAF/fxcor package (see Tonry & Davis (1979) for details of the technique). We applied a square filter to dampen the highest and lowest frequency Fourier components, that heavily masked the narrow peaks in the power spectrum. We then fitted the power peaks with Gaussians. The typical internal velocity errors on a single measure were $\sim 19$ km s$^{-1}$ for WYFFOS, $\sim 50$ km s$^{-1}$ for BFOSC and $\sim 65$ km s$^{-1}$ for DoLoRes spectra.  

For each target we cross-correlated two independent spectra with (at least) four template spectra, obtaining $\geq 8$ semi-independent estimates of radial velocity. We take the average of these values as our final $V_r$, and the standard deviation as our final uncertainty on $V_r$. The typical uncertainties are $\sim 14$ km s$^{-1}$ for WYFFOS data, $\sim 19$ km s$^{-1}$ for BFOSC, and $\sim 33$ km s$^{-1}$ for DoLoRes data.

The list of the observed targets is reported in Table 1 together with their apparent V magnitude and V-K color (cols. 2 and 3, from G04), the estimated $V_r$ and the associated uncertainty (cols. 4 and 5), the original quality class (col. 6), according to Battistini et al. (1993, 1997), and the instrument used to obtain the spectra (col. 7).

#### 3.1. Comparisons with previous studies

Our subsample of 57 already confirmed M 31 GCs in Table 1 allows a thorough comparison with other samples of radial velocities for M 31 clusters available in the literature [van den Bergh (1969) henceforth V69); Huchra et al. (1982); Huchra...
Table 1. Radial velocities of observed GGCs and GCs.

| Name          | V   | V-K | $V_r \pm \sigma(V_r)$ [km s$^{-1}$] | Instrum. |
|---------------|-----|-----|-------------------------------------|----------|
| B003          | 17.57 | 2.03 | $-351 \pm 34$ A WYFFOS              |          |
| B022          | 17.36 | 1.85 | $-407 \pm 14$ A WYFFOS              |          |
| B032          | 17.61 | 4.55 | $-516 \pm 8$ B WYFFOS               |          |
| B060          | 16.75 | 2.61 | $-484 \pm 25$ A DoLoRes             |          |
| B067          | 17.25 | 1.99 | $-377 \pm 10$ A DoLoRes             |          |
| B070          | 17.07 | 2.25 | $-301 \pm 15$ A WYFFOS              |          |
| B071          | 17.79 | 2.41 | $-479 \pm 8$ B WYFFOS               |          |
| B077          | 17.50 | 2.94 | $-681 \pm 25$ A DoLoRes             |          |
| B087          | 17.93 | 3.82 | $-382 \pm 16$ B WYFFOS              |          |
| B099          | 16.74 | 3.15 | $-200 \pm 11$ A WYFFOS              |          |
| B110          | 17.91 | 3.22 | $-376 \pm 25$ B WYFFOS              |          |
| B111          | 18.60 | 2.27 | $-414 \pm 10$ A WYFFOS              |          |
| B155          | 17.97 | 3.25 | $-401 \pm 34$ B WYFFOS              | E BFOSC  |
| B162          | 17.48 | 3.65 | $-146 \pm 8$ A WYFFOS               |          |
| B168          | 17.63 | 4.11 | $-190 \pm 14$ B WYFFOS              |          |
| B169          | 17.08 | 3.14 | $-177 \pm 7$ A WYFFOS               |          |
| B187          | 17.17 | 2.85 | $-130 \pm 10$ A WYFFOS              |          |
| B189          | 16.99 | 3.34 | $-148 \pm 8$ A WYFFOS               |          |
| B194          | 17.19 | 2.08 | $-354 \pm 21$ A WYFFOS              |          |
| B215          | 17.13 | 2.90 | $-164 \pm 3$ A WYFFOS               |          |
| B245          | 16.56 | 2.99 | 6200 ± 1400 C WYFFOS                |          |
| B247          | 17.66 |      | $-532 \pm 17$ C WYFFOS              |          |
| B248          | 18.84 | 1.94 | $-524 \pm 21$ C WYFFOS              |          |
| B253          | 18.01 | 1.76 | $-722 \pm 35$ C DoLoRes             |          |
| B257          | 17.58 | 2.10 | $-496 \pm 16$ C WYFFOS              |          |
| B324          | 18.79 | 2.84 | $-170 \pm 5$ B WYFFOS               |          |
| B362          | 17.61 | 2.09 | $-81 \pm 14$ A WYFFOS               |          |
| B371          | 17.54 | 2.22 | $-127 \pm 18$ B WYFFOS              |          |
| B388          | 17.96 | 3.17 | $-50 \pm 9$ B WYFFOS                |          |
| B419(*)       | 18.18 | 2.69 | 41600 ± 600 C DoLoRes               | B BFOSC  |
| B426(*)       | 17.52 | 2.74 | 16900 ± 600 C DoLoRes               |          |
| B469(*)       | 17.58 | 2.60 | 21900 ± 600 C WYFFOS                |          |
| B471          | 17.12 | 3.63 | 30200 ± 1200 C WYFFOS               |          |
| B473          | 17.46 | 1.51 | $-11 \pm 14$ C WYFFOS               |          |
| B502D         | 17.44 | 3.43 | $-526 \pm 21$ D WYFFOS              |          |
| B521D         | 17.50 | 2.59 | $-7 \pm 6$ D WYFFOS                 |          |
| B522D         | 17.80 |      | $-354 \pm 24$ D WYFFOS              |          |
| B525D         | 17.83 | 3.88 | $-479 \pm 25$ D WYFFOS              |          |
| B527D         | 17.60 | 1.61 | $-50 \pm 7$ D WYFFOS                |          |
| B534D         | 17.50 | 2.97 | $-347 \pm 25$ D DoLoRes             |          |
| B536D         | 17.10 | 5.54 | $-7$ D WYFFOS                       |          |
| B541D         | 17.90 | 2.65 | $-289 \pm 11$ D WYFFOS              |          |
| B545D         | 18.30 | 2.66 | $-313 \pm 16$ D WYFFOS              |          |
| B546D         | 17.00 |      | $-327 \pm 24$ D WYFFOS              |          |
| B571D         | 17.60 | 2.04 | $-229 \pm 11$ D WYFFOS              |          |
| B739D         | 17.90 |      | $-12 \pm 13$ D WYFFOS               |          |
| B799D         | 17.80 |      | $-394 \pm 25$ D WYFFOS              |          |
| B909D         | 17.20 | 3.63 | $-94 \pm 8$ D WYFFOS                |          |
| B969D         | 17.30 | 3.96 | $-203 \pm 15$ D WYFFOS              |          |
| B919D         | 17.15 | 2.45 | $-8 \pm 13$ D WYFFOS                |          |
| B126D         | 18.00 | 2.98 | $-92 \pm 8$ D WYFFOS                |          |
| B147D(*)      | 17.96 | 38800 ± 600 D DoLoRes               |          |
| B148D(*)      | 16.31 | 2.20 | 16800 ± 300 D BFOSC                 |          |
| B158D(*)      | 16.50 | 2.69 | 16800 ± 300 D DoLoRes               |          |
| B168D(*)      | 18.45 | 38600 ± 600 D DoLoRes               |          |
| B213D         | 17.07 | 1.73 | $-19 \pm 9$ D WYFFOS                |          |
| B215D         | 16.79 | 2.53 | $-266 \pm 12$ D WYFFOS              |          |
| B217D         | 17.88 | 2.14 | $-135 \pm 8$ D WYFFOS               |          |
| B221D         | 17.77 | 3.32 | $-50 \pm 8$ D WYFFOS                |          |
| B226D         | 18.73 | 3.38 | $-9 \pm 8$ D WYFFOS                 |          |
| B237D         | 18.02 | 2.82 | $10 \pm 8$ D WYFFOS                 |          |
| B234D         | 18.05 | 2.14 | $-53 \pm 8$ D WYFFOS                |          |
| B250D         | 17.46 | 4.31 | $-442 \pm 21$ D WYFFOS              |          |
| B255D         | 17.92 |      | $-107 \pm 14$ D WYFFOS              |          |
| B260D         | 17.07 | 2.45 | $-93 \pm 6$ D WYFFOS                |          |
| B275D         | 18.11 | 2.26 | $-13 \pm 6$ D WYFFOS                |          |
| B685          | 16.26 | 2.55 | $8 \pm 6$ E WYFFOS                  |          |

(*): Sources with line-emission spectrum.

(†): original quality-class flag according to Battistini et al. (1980; 1982; 1987).
To recover the possible systematic offsets between different data sources, we divided the overall database in two categories, i.e. $V_r$ measurements coming from low-resolution spectroscopy ($\sigma(V_r) = 10-100$ km s$^{-1}$), and those derived from high-resolution echelle spectra ($\sigma(V_r) \approx 10$ km s$^{-1}$). In particular, the latter class includes the works of Dubath & Grillmair (1997) and Peterson (1989), who provided radial velocities of M 31 clusters with a notably high accuracy ($\sigma(V_r) \leq 3$ km s$^{-1}$) and excellent agreement for the objects in common. We therefore decided to merge both samples into a single High Resolution (HR) set of 24 clusters, referring however to the Dubath & Grillmair (1997) $V_r$ value for the clusters in common. The HR set will provide the backbone of a comprehensive velocity scale joining measures from all the available sources.

In Fig. 4 we present a comparisons of our output for the cluster subsamples in common with the low-resolution observations by H91, P02, F93 and B00. In all cases the overall agreement is good, within the combined uncertainties of the two considered datasets. The comparison with H91 suggests the presence of a small systematic, also confirmed by the comparison with HR measures. The agreement with P02 is particularly good. Since the typical accuracy of this set is very similar to ours, the relatively low dispersion around the mean ($\sigma = 20.8$ km s$^{-1}$) is a further support to our estimated $V_r$ uncertainties. The large scatter of the differences with $V_r$ estimates by B00 is not particularly satisfactory, but the handful of clusters in common prevents any further conclusion. Unfortunately, none of the HR cluster is included in the B00 sample. The comparison of the B00 velocities with the P02 sample (not shown here) reveals a good general agreement but also several cases of serious inconsistency with 7 out of 21 clusters in common exceeding a ±100 km s$^{-1}$ difference in the velocity estimates.

### 3.2. Consistency checks: towards a single homogeneous list of radial velocities

The comparisons with the HR set is presented in Fig. 4 where each panel reports the mean $V_r$ difference and standard deviation for the different samples after a 2-$\sigma$ clipping iteration.

The agreement of our $V_r$ estimate with the HR ones, for the 12 clusters in common, is excellent. There is no sizable zero-point difference and again the standard deviation witnesses the good accuracy of our measures. The same is true for the P02 and the F93 sets, although the latter shows a larger scatter due to a lower intrinsic accuracy of the data. The match with the H91 sample confirms, on the contrary, the presence of a systematic, as already suggested before and noted by H91 themselves. We eventually applied the zero-point correction of Fig. 4 to this dataset, while we left untouched the P02 and F93 samples, the zero-point differences being much smaller than the involved statistical uncertainties. As for the B00 and J98 data, both samples have no clusters in common with the HR sample and we had to compare them with other low-resolution observations. No systematic offset is needed, although one should notice several cases of striking outliers in each sample.

V69 presented a list of radial velocities for 44 bright M31 GCs and GCCs. The comparison with the HR velocities for the 19 clusters in common reveals a small systematic ($V_{69} - V_{HR} = -15.3 \pm 28.0$ km s$^{-1}$), after one outlier rejection. Since all of the V69 targets have been re-observed by several authors in more recent studies, typically with a better accuracy, we decided to retain the V69 estimates only as an external check for controversial cases.

Once verified the self-consistency of all the available datasets we merged all the sources into one single catalog of M 31 cluster radial velocities, tied to the HR set. This resulted from a weighted average of multiple measures, carefully checked on a cluster-by-cluster basis. In general, a weighted mean was iterated after 2-$\sigma$ clipping. When only two incompat-
ible measures (at $>2\sigma$) were available, we chose the one with lowest uncertainty. The overall compatibility among multiple measurements from different sources is, in general, very good. We found 18 cases of marginal $>2\sigma$ deviation of one measure and 9 cases of serious incompatibility, a few of which already noted by P02. The latter nine cases probably deserve further checks and we shortly mention them: for B104 we adopted $V_r = -395 \pm 10$ km s$^{-1}$ from B00, while J98 reports $V_r = +120 \pm 42$ km s$^{-1}$; for B109 we adopted $V_r = -372 \pm 12$ km s$^{-1}$ from P02 while H91 reports $V_r = -633.6 \pm 24$ km s$^{-1}$; for B064D we adopted $V_r = -72 \pm 10$ km s$^{-1}$ from B00 while J98 reports $V_r = +191.0 \pm 62$ km s$^{-1}$; for B119 we adopted the weighted mean between the estimates by P02 and J98, $V_r = -310.1 \pm 11.1$ km s$^{-1}$, rejecting $V_r = -137 \pm 10$ km s$^{-1}$ by B00; for B124 we adopted $V_r = +70 \pm 13$ km s$^{-1}$ from B00, while J98 reports $V_r = -75 \pm 22$ km s$^{-1}$ (the possibility of a typo should also be considered in this case); for B301 we adopted the weighted mean between the estimates by P02 and J98, $V_r = +30 \pm 20$ km s$^{-1}$ by B00; for B337 we adopted $V_r = +50 \pm 12$ km s$^{-1}$ from B00, while F93 reports $V_r = -232 \pm 26$ km s$^{-1}$; for B350 we adopted the weighted mean between the estimates by B00 and H91 $V_r = -467.3 \pm 12.7$ km s$^{-1}$, rejecting $V_r = -251.7 \pm 26$ km s$^{-1}$ by F93; finally, for B380 we adopted $V_r = -13 \pm 12$ km s$^{-1}$ from P02 while B00 reports $V_r = -121 \pm 31$ km s$^{-1}$. At least for the cases in which only two incompatible estimates are available (B104, B109, B124, B337, B380, B064D), a third independent estimate is highly desirable. Also among the 18 cases of not-so-strong incompatibility there are four cases in which we had to choose between two estimates based on the accuracy of the single estimates alone (B008, B047, B144, B314). For B131 we obtained $V_r = -337 \pm 3.0$ km s$^{-1}$ while H91 report $V_r = -444.6 \pm 28$ km s$^{-1}$; for this we had to recur to V69 reporting $V_r = -450$ km s$^{-1}$, supporting the H91 estimated, that we eventually adopted.

In the following we will use the merged dataset described above as our source of $V_r$ measures for M 31 GCs.

### 4. Classification

Figure 5 displays the radial velocity distribution of confirmed M31 GCs (empty histogram). The distribution is centered on the galaxy systemic velocity (i.e. $V_r = -301.0$ km s$^{-1}$, van den Bergh (2000)) and has a standard deviation $\sigma = 160.0$ km s$^{-1}$. The distribution is significantly flatter than a Gaussian curve because most of M 31 GCs partake the overall disk rotation around the galaxy center (see B00 and references therein). As we mentioned in Sec. 2, just on the basis of the kinematical piece of information, distant background galaxies can easily be excluded as they have typically $V_r \gg +300$ km s$^{-1}$.

To study the contamination by foreground MW stars we obtained a synthetic sample of Galactic stars over the magnitude range $16.0 \leq V \leq 19.0$, as spanned by our 76 GCCs, in a field of $3^\circ \times 3^\circ$ around the position of M31, from the Besançon Galactic Model (Robin et al. 2003). Down to this magnitude limit and across the observed field the synthetic sample predicts more than $10^4$ stars; their radial velocity distribution is approximately Gaussian, with mean $\langle V_r \rangle = -29.6$ km s$^{-1}$ and $\sigma = 42.6$ km s$^{-1}$, in excellent agreement with the sample of confirmed stars in the RBC (G04).

Since the available sample of confirmed GCs (obviously) has not been obtained from the observation of all the sources down to $V = 19.0$ in a $3^\circ \times 3^\circ$ field, a direct comparison between the two samples would be greatly misleading. As a reasonable and conservative normalization, we assume that the global catalog of 1164 objects contains as many foreground stars as (presently) confirmed GCs having $V_r$ estimates, i.e. 313 stars. To limit the effects of fluctuations due to low-number statistics, we extracted at random from the whole synthetic catalog 100 samples of 313 stars and we obtained the $V_r$ distribution for each of them. The shaded histogram is the average of these 100 distributions.

From Fig. 5 it can be safely concluded that GCCs with $V_r \leq -301.0$ km s$^{-1}$ cannot be MW stars, hence they must be bona fide M31 clusters. According to the above assumptions the expected number of MW stars with $-301.0 < V_r \leq -150.0$ km/s is $\leq 4$, i.e. $\sim 1\%$ of the whole sample. On the other hand, for $V_r > -150.0$ the contamination by MW stars is likely very significant, preventing a fully reliable discrimination between foreground stars and M 31 GCs based on the radial velocity alone. According to these considerations, we decided to classify as bona fide M31 GCs all the candidates with $V_r \leq -150.0$ km s$^{-1}$, requiring further investigation for those with higher $V_r$ (see Sect. 4.1, below). Note that our approach

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3 See Updates & Revisions [http://www.bo.astro.it/M31/](http://www.bo.astro.it/M31/)
is more conservative with respect to the majority of previous studies that, in general, considered as genuine M 31 GCs all the candidates with velocity within \( \pm 3 \sigma \) from the systemic velocity of M31, in absence of clear evidence of discriminative features in the spectra and/or HST imaging revealing the stellar nature of the candidate (see, for example, B00, P02). On the contrary, Fig. 5 strongly suggests that GCCs with \( V_\text{r} \) around \( -30.0 \pm 120 \text{ km s}^{-1} \) (65 objects in the RBC database, most of them “confirmed” GCs by virtue of their radial velocity alone) should be very carefully considered as they might likely include a certain fraction of misclassified MW stars. Clearly, any observation assessing the non-pointlike nature of these objects would be extremely valuable in this sense (see Sect. 4.1, below).

Using the above described criteria, for our 76 GCCs of Table 1 we are left with

(a) 35 genuine M 31 GCs with \( V_\text{r} \leq -150.0 \text{ km s}^{-1} \);
(b) 12 background galaxies, with high recession velocity and/or line-emission spectra;
(c) 2 M 31 Ha regions (never observed before);
(d) 27 candidates, with \( -150.0 < V_\text{r} < +100.0 \text{ km s}^{-1} \), possibly compatible both with M 31 GCs and with MW stars, that will be further analyzed in the following.\(^4\)

### 4.1. Source morphology and foreground star contamination

To further investigate the nature of the 27 GCCs of item “d” above we acquired deep white-light BFOSC images of each field. In imaging mode, BFOSC has a pixel scale of 0.58”/px and a total field of view of 13.0’ × 12.6’. All the observations have been obtained in 2005, during the nights of Aug 7-9, Sep 2, 11 and 29, Oct 4 and Nov 7. The exposure times ranged between 3 and 10 minutes, depending on target brightness and atmospheric conditions. The nights were clear (but not photometric) with a typical seeing around 1.5-2 arcsec FWHM.

The pointings were accurately chosen in order to include in each frame one (or more) of the 27 targets and a number of confirmed M 31 GCs. This eventually allowed to extend our morphological analysis to a supplementary sample of 56 “confirmed” GCs plus 3 controversial targets.\(^5\)

Images have been bias and flat-field corrected with standard reduction procedures. Relative photometry, FWHM and morphological parameters of each source in the frame - down to a 5 \( \sigma \) threshold over sky noise - were obtained with Sextractor (Bertin & Arnouts 1996). Only non-saturated and isolated sources were retained in the final catalogs (SExtractor quality flag “0”).

\(^4\) According to our constraints on the value of \( V_\text{r} \), also the controversial object B341 in Table 1 (class c = 3 in the original RBC classification) should eventually be comprised in the bona-fide confirmed M 31 GCs supporting the original classification by P02. The case of B409 deserves, on the contrary, further discussion (see Sect. 4.1.3).

\(^5\) We also verified \textit{a posteriori} that, out of these 59 objects, 13 further entries from Table 1 were serendipitously imaged. They are B042, B100, B193, B224, B228, B229, B232, B240, B265, B344, B347, B366, B045D (see Table 2).

In spite of the limited spatial resolution of the images, a fair assessment of the GCC morphology was made possible by a purely differential approach relying on the comparison with accurate point-spread function (PSF) estimates and on the study of the apparent isophotal radius of the detected objects. The relatively wide field of view of BFOSC allowed in fact a simultaneous high-S/N imagery of the target together with hundreds of field stars, and at least a couple of confirmed M 31 GCs. Hence, the nature of the considered candidate was established by direct comparison with surrounding stars and extended sources on the same frame.

In particular, the apparent target size was probed \( a) \) in terms of its relative excess compared to the local PSF (namely, by defining a ratio parameter \( R = [\text{target FWHM}/\text{PSF FWHM}] \) and \( b) \) in terms of its departure from the isophotal flux \((F)\) vs. isophotal area \((A)\) empirical relationship for stars to be suitably set in each individual frame according to the overall image quality.\(^6\) Both \( F \) and \( A \) are natural outputs of Sextractor (respectively FLUX_ISO and ISOAREA_IMAGE parameters), and one could verify empirically that essentially all stars roughly obey a \( A \propto F^{1/2} \) relationship being enclosed within a 0.1 dex wide strip in the \( \log F \) vs. \( \log A \) plane, corresponding to a variation of the measured FWHM of \( \pm 5\% \) (see Fig. 6). Of course, hot pixels and cosmic rays appear as off-strip “sub-point-like” objects, while any source significantly more extended than the stellar PSF stands out in the F-A plot for its larger apparent size for a given magnitude level. To some extent, our approach recalls the classical diagnostic tools used, for instance, for high-redshift galaxy recognition (e.g. Kron 1980, Koo et al. 1986, Molinari, Buzzoni & Chincarini 1990).

Figure 4 is an illustrative example for a field matching two GCCs (open pentagons) and five already confirmed clusters (solid triangles). While all the five confirmed GCs are univocally identified as extended objects in the F-A plane, one of the candidates appears as an extended source, while the other one is compatible with a stellar point source. Accordingly, from the inspection of the individual F-A diagrams, we assigned to all the 27 candidates under consideration the flag E (extended) or PS (point source). In the following we will refer to this flag as the F-A flag or, for brevity, the flag.

The \( R \) parameter and the F-A plane provide two nicely complementary tools to judge the candidate extension since \( R \) is mainly sensitive to the core of the target image, while \( A \), as the area within the outermost isophote, is more sensitive to the wings of the image. This is very well suited to study GC candidates since profiles of globular clusters may significantly vary, depending on their concentration parameter \( C \) (King 1966). For instance, high concentration clusters may have such compact cores that are essentially indistinguishable from point sources but a significant difference with respect to genuine point sources can be detected looking at the wings of the image, sampling the faint halo of the cluster (see, Buonanno et al. 1982).

\(^6\) Note that the limiting isophote is set at a \( S/N = 5 \) ratio per pixel element on each frame. This corresponds, in general, to a different surface brightness magnitude depending on image quality and sky conditions.
Table 2. Morphological analysis for previously confirmed M31 GCs.

| Name  | Vr ± σ(Vr) [km s⁻¹] | R   | F-A flag | c(1) |
|-------|---------------------|-----|----------|------|
| B213  | -545 ± 11 1.15 E 1   |     |          |      |
| B265  | -496 ± 16 1.10 E 1   |     |          |      |
| B209  | -460 ± 11 1.18 E 1   |     |          |      |
| B015D | -445 ± 12 1.31 E 1   |     |          |      |
| B093  | -447 ± 12 1.25 E 1   |     |          |      |
| B031  | -433 ± 12 2.33 E 1   |     |          |      |
| B161  | -413 ± 12 1.20 E 1   |     |          |      |
| B221  | -406 ± 12 1.24 E 1   |     |          |      |
| B021  | -403 ± 12 1.29 E 1   |     |          |      |
| B228  | -457 ± 26 1.43 E 1   |     |          |      |
| B100  | -376 ± 25 1.45 E 1   |     |          |      |
| B467  | -342 ± 12 1.26 E 1   |     |          |      |
| B043D | -344 ± 12 1.51 E 1   |     |          |      |
| B037  | -338 ± 12 1.30 E 1   |     |          |      |
| B042  | -338 ± 10 1.14 PS 1  |     |          |      |
| B401  | -333 ± 25 1.26 E 1   |     |          |      |
| B059  | -332 ± 12 1.24 E 1   |     |          |      |
| B391  | -325 ± 12 3.73 E 1   |     |          |      |
| B045D | -313 ± 16 1.22 E 1   |     |          |      |
| B024  | -310 ± 34 1.09 E 1   |     |          |      |
| B222  | -303 ± 10 1.36 E 1   |     |          |      |
| B382  | -302 ± 12 1.12 E 1   |     |          |      |
| B164  | -294 ± 12 1.20 E 1   |     |          |      |
| B091  | -290 ± 12 1.31 PS 1  |     |          |      |
| B047  | -291 ± 12 1.19 E 1   |     |          |      |
| B354  | -283 ± 26 1.14 E 1   |     |          |      |
| B210  | -265 ± 12 1.18 E 1   |     |          |      |
| B214  | -258 ± 12 1.12 E 1   |     |          |      |
| B344  | -252 ± 13 1.34 E 1   |     |          |      |

(1) New classification flag, according to the RBC notation (see also Sect. 1). The newly determined class of the three object for which we modify previous classification is reported in parentheses.

Fig. 6. F-A diagram for one of the images we analyzed (as an example). All the detected sources are plotted as small points. Filled triangles correspond to already confirmed clusters, empty pentagons to the candidate clusters under consideration. The continuous lines enclose the locus of points sources. Extended objects are expected to populate the upper left corner above the strip, while cosmic spikes and CCD cool/hot pixels must be confined to the lower right corner of the plot.

It may be useful to have an idea of the sensitivity of the adopted technique, i.e. what is the size of the most compact M31 GC that can be recognized as an extended object by our diagnostics. To this aim we performed a series of tests using the half-light radii (rhl) of globular clusters as the characteris-tic scale that is more appropriate in this context. According to Djorgovski (1993), half-light radii of Galactic GCs range from 0.8 pc to 20 pc, and more than 75% of his sample (118 GC with estimates of the half-light radius) have rhl > 2.0 pc. We translated these linear radii into angular radii at the distance of M31 (D = 783 kpc, see Sect. 5.1, below) and we convolved them with the Half Width at Half Maximum (HWHM) of the PSF of our images. Finally, we found the minimum rhl that provides a convolved profile larger than that of a point source by a factor ≥ 1.05. It turns out that we are able to pick up clusters having rhl as small as 1.5 pc (corresponding to 0.4", at the distance of M31), if the seeing is 2.0" FWHM, and we are sensitive to rhl > 2.0 pc if the seeing is 3.0" FWHM. Note that the radii of the isophotes adopted to compute ISOAREAIMAGE are typically a factor 2 larger than half-light radii, hence the effective sensitivity of the F-A diagram should be significantly better than these figures. This is confirmed by a direct comparison that can be made on three M31 clusters included in the present programme that have an estimate of rhl from HST data (Barmby & Huchra (2001)), namely B167 (rhl = 0.33"), B232 (rhl = 0.66"), and B240 (rhl = 0.80""). All of them are clearly identified as extended objects in the F-A diagram and their R parameters are 1.15, 1.09 and 1.23, respectively (see Table 2). Therefore, we conclude that the image analysis technique adopted here is able to recognize the extended nature of the large majority of M31 clusters even with low-resolution im-
ages, provided that the target image is of high signal-to-noise so that the image profile is well constrained.

4.1.1. Checking previously confirmed “genuine” clusters with \( V_r \leq -150.0 \) km s\(^{-1}\)

Table 2 reports the results of the image analysis described above for the M 31 clusters previously confirmed by other authors that were included in our BFOSC imaging survey. The first 42 entries in the table concern clusters that have \( V_r \leq -150.0 \) km s\(^{-1}\), and can be unambiguously identified as genuine GCs on the basis of their radial velocity alone, according to our previous arguments. We note that all of them have \( R \geq 1.07 \), and all except three have \( R \geq 1.10 \). Only two clusters obtain the PS flag based on their position in the F-A diagram, but both of them have quite large R, 1.14 and 1.31 for B042 and B091, respectively. Hence our morphologic criteria correctly recognize all the genuine M 31 GCs considered here as extended objects.

Also based on these results, we can complete our classification scheme and devise the following supplementary criteria for GCCs with \( V_r > -150.0 \) km s\(^{-1}\):

(a) a candidate is classified as a “bona fide M31 cluster” (\( c = 1 \) in Tables 2, 3, and 4) if \( R \geq 1.10 \), independently from the assigned flag, or if \( R > 1.05 \) and F-A flag “E”.

(b) it is classified as a “bona fide star” (\( c = 6 \)) if \( R \leq 1.05 \) and F-A flag “PS” or if \( R \leq 1.0 \).

(c) it is considered as an “uncertain object” (\( c = 3 \)) if \( 1.0 < R \leq 1.05 \) and flag “E”, or \( 1.05 < R < 1.10 \) and flag “PS”. These non-decidable cases can be resolved only with further data and/or analysis.

The overall classification picture for the whole GCC sample of Table 2 and the following ones is summarized in Fig. 4.

4.1.2. Image analysis for previously “confirmed” clusters with \( V_r > -150.0 \) km s\(^{-1}\)

The last 14 entries of Tab. 2 concern clusters previously confirmed by other authors, that have \( V_r > -150.0 \) km s\(^{-1}\), i.e. a range of velocity that may suffer from contamination by MW stars. As noted in Sect. 4., those that have been confirmed only by virtue of their radial velocity may deserve further analysis to obtain a firm classification. According to the above criteria, 12 of these candidates are classified as genuine M31 GC, one (B366) is classified as “uncertain” and one (B355) is classified as “bona fide star”. It is interesting to note that B355 was classified as a confirmed GC by Perrett et. al. (2002) relying only on its radial velocity. Finally, B216 makes a case on its own that will be discussed in detail in Sect. 4.3.

4.1.3. Image analysis for candidates with \( V_r > -150.0 \) km s\(^{-1}\)

The results of the image analysis for the 27 GCCs from our sample of Table 1 with \( V_r > -150.0 \) km s\(^{-1}\) are reported in Table 3. According to the above criteria, 7 of them are classified as genuine GCs (namely B162, B187, B189, B371, B388, B909D, and B255D), 17 are flagged as stars and 3 remain uncertain. We note that all the newly confirmed clusters are very clearly recognized as extended: all of them have flag “E” and R ranges between 1.15 and 2.5. Note also that 5 of the 6 candidates in the range \(-150 < V_r < -100 \) km s\(^{-1}\) turned out to be genuine GCs, while for the 21 targets with \( V_r > -100 \) km s\(^{-1}\) we only detect 2 clusters and 16 bona fide stars. This further confirms how severely star contamination can affect in the range of \( V_r \) around \(-30 \pm 130 \) km s\(^{-1}\).

4.1.4. A few controversial objects

The three entries of Table 2 concern candidates that obtained different classifications from different authors. B055 was classified as genuine GC by P02, based on its radial velocity, while B00 classified it as a star. Our image analysis indicates unambiguously that B055 is an extended object, thus confirming the classification by P02. B212 was classified GC by H91 and “star” by B00 and our analysis does not help to resolve the controversy.

Object B409 was classified as a GC by F93, based on its radial velocity alone, and it was classified as a background

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**Table 3. Morphological analysis for the 27 M31 globular clusters candidates of Table 1 with \( V_r > -150.0 \) km s\(^{-1}\)**

| Name  | \( V_r \pm \sigma(V_r) \) [km s\(^{-1}\)] | class\(^{c}\) | R\(^{c}\) | F-A flag\(^{c}\) | c\(^{c}\) |
|-------|----------------------------------------|-------------|--------|----------------|-----|
| B189  | -148 ± 8                               | A 1.26      | E 1    | 1              |
| B162  | -146 ± 8                               | A 1.27      | E 1    | 1              |
| B213D | -136 ± 9                               | D 1.04      | PS 6   |                |
| B187  | -130 ± 10                              | A 1.47      | E 1    | 1              |
| B371  | -127 ± 18                              | B 1.38      | E 1    | 1              |
| B255D | -107 ± 14                              | D 2.5       | E 1    | 1              |
| B126D | -92 ± 18                               | D 1.06      | PS 6   |                |
| B090D | -94 ± 8                                | D 1.15      | E 1    | 1              |
| B260D | -93 ± 15                               | D 1.03      | PS 6   |                |
| B362  | -81 ± 5                                | A 1.09      | PS 3   |                |
| B330D | -62 ± 18                               | D 1.01      | PS 6   |                |
| B364D | -54 ± 7                                | D 0.99      | PS 6   |                |
| B243D | -53 ± 18                               | D 1.03      | PS 6   |                |
| B368  | -50 ± 19                               | B 1.34      | E 1    | 1              |
| B027D | -50 ± 7                                | D 0.99      | PS 6   |                |
| B221D | -50 ± 8                                | D 1.05      | PS 6   |                |
| H126  | -19 ± 10                               | / 1.06      | PS 3   |                |
| NB70  | -17 ± 15                               | E 1.02      | PS 6   |                |
| B275D | -13 ± 6                                | D 0.98      | PS 6   |                |
| B073D | -12 ± 13                               | D 1.02      | PS 6   |                |
| B226D | -9 ± 8                                 | D 1.00      | PS 6   |                |
| B109D | -10 ± 15                               | D 1.03      | PS 6   |                |
| B021D | -6 ± 7                                 | D 1.05      | PS 6   |                |
| NB65  | 8 ± 6                                  | E 1.03      | PS 6   |                |
| B237D | 10 ± 8                                 | D 1.03      | PS 6   |                |
| B473  | 11 ± 7                                 | E 1.00      | PS 6   |                |
| B213D | 19 ± 9                                 | D 1.06      | PS 3   |                |

\(^{c}\) Quality flag according to the Battistini et al. (1981, 1983, 1985, 1989) classification scale.

\(^{c}\) Target apparent size, relative to the PSF (namely \( R = \) target FWHM/PSF FWHM).

\(^{c}\) E(xtended) or P(oint) S(ource) classification obtained from the F-A diagram.

\(^{c}\) RBC classification flag as in Tab. 2 see Sect. 1.)

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**Table 4. Candidates with controversial classifications**

| Name  | \( V_r \pm \sigma(V_r) \) [km s\(^{-1}\)] | R | F-A flag\(^{c}\) | c\(^{c}\) |
|-------|----------------------------------------|---|----------------|-----|
| B055  | -308 ± 8                               | 1.27 | E 1              |
| B121  | -24 ± 33                               | 1.08 | PS 3              |
| B409  | -40 ± 10                               | 1.00 | PS 6              |

\(^{c}\) Classification flag as in Tab. 2 see Sect. 1.)
Fig. 7. Summary of the adopted classification criteria illustrated in the R vs. \( V_r \) diagram, where different symbols are used according to the value of the F-A flag of the targets. Circles represent extended objects (F-A flag = E) while triangles are point-like sources (F-A flag = PS). \textit{Bona fide} stars (c=6) are colored light-grey, \textit{bona fide} GCs (c=1) are plotted in darker grey, while the sources that cannot be firmly classified within our scheme (c=3) are colored in the darkest grey. The box in the upper-left corner encloses stars and candidates whose nature requires the use of all the three parameters to be classified (\( V_r, R, F-A \) flag). The regions of the plot corresponding to different classifications are labeled. Note that most of the clusters with \( R \geq 1.5 \) (Tab. 2 and 3) do not appear in this plot for the sake of graphical clarity.

According to the updated RBC sample, the relative source partition of \textit{bona fide} [galaxies: GCs: stars] among the entries with available \( V \) and \( K \) photometry and \( (V - K) \geq 3.0 \) is found to be \([47: 102: 10]\), while the corresponding frequency blue-ward of the \( (V - K) \) threshold is \([11: 202: 27]\). Taken at their face value, these numbers suggest that about 2/3 of the whole \( (V - K) \geq 3.0 \) GCCs might eventually confirm to be genuine clusters, while our performance should raise to a nearly 85% for \( (V - K) < 3.0 \) candidates (see G04).

On the other hand, one has to admit that these figures are at odds with the empirical evidence from the present analysis, as for the whole sample of 71 GCCs of Table I with firm classification we find \([galaxies: GCs: stars]\) = \([12: 42: 17]\), with a remaining fraction of 5 \( H_r \) regions and unclassified objects (again, see Fig. for a summary). Thus, about one in two of our targets eventually revealed to be a genuine globular, in spite of the fact that over 70% of our GCC sample is bluer than \( (V - K) \geq 3.0 \), and an \textit{a priori} distribution should be expected such as \([galaxies: GCs: stars]\) = \([9: 57: 7]\) and 3 unclassified objects.

These figures lead us to the following conclusions:

(a) As far as deeper M 31 GCC surveys are carried out (and naturally include poorer and more “blurred” targets), the galaxy contamination becomes marginally more important, with an increasing contribution of blue spirals and star-forming systems. This is especially evident when we plot the galaxy \( (V - K) \) distribution along the different Battistini et al. image-quality classification, as in Fig. Fortunately, this bias can in principle be fully overcome as any spectroscopic identification would easily discriminate these spurious emission-line objects (note, for instance, that 9 out of...
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Fig. 8. Apparent $V − K$ vs. $B − V$ color distribution for the 45 targets of Table 1 with available $B, V, K$ photometry (big markers on the plot) compared to the corresponding RBC classification groups (small markers). Big pentagons are the bona-fide ($c = 1$ RBC flag) M 31 globular clusters of this study, solid dots are background galaxies ($c = 4$), solid triangles mark M 31 H II regions ($c = 5$), and star markers are MW stellar interlopers ($c = 6$) and M 31 asterisms ($c = 7$). The arrow indicates the reddening vector corresponding to $E(B − V) = 0.1$. The main stellar locus for stars of different spectral type (F0,F5, G0, G5 dwarfs and K0, K5, and M0 giants from Johnson (1966)) is superposed to the data, as well as the expected apparent colors vs. redshift for the Buzzoni (2005) template galaxy models for elliptical, spiral (type Sb) and irregular (type Im) Hubble types. Galaxy colors are tracked from $z = 0$ to 0.5 (as labeled on the plot). The stellar locus and the galaxy models have been reddened assuming $E(B − V) = 0.1$. Note that the main background contaminants to M 31 GCCs (i.e. ellipticals and nucleated spirals within $z ≲ 0.2$) are always redder than $V − K = 3.0$ while only star-forming spirals and irregulars (as well as MW stars) become the prevailing contaminants at bluer colors.

12 recognized galaxies in our Table 1 sample display some Balmer and/or [OIII] emission).

(b) Between galaxy and star contaminants, the latter become increasingly important as far as class C-D-E Battistini et al. candidates are surveyed (we find 17 stellar interlopers vs. 7 expected cases).

4.3. Contamination by asterisms/associations

Radial velocities and image analysis are very effective tools to find out the most abundant sources of contamination, i.e. background galaxies, foreground stars and HII regions. However, they can be mocked by a further and much subtler kind of contaminants. Small stellar associations, very young M 31 open clusters (whose integrated luminosity is dominated by a few massive stars), and even perspective asterisms due to chance alignment of M 31 stars (and/or one or a few stars embedded into, or projected onto, a nebula) can easily mimics a typical faint GCC, when observed in low spatial-resolution images. Clearly, this class of contaminants is expected to affect faint and blue GCCs, especially those projected onto the disc of M 31. Cohen, Matthew & Cameron (2006) recently provided direct evidence of at least four such special cases among spectroscopically confirmed clusters, using exquisite spatial-resolution images obtained with adaptive optics. To account for these “new” kind of contaminants, we introduce a new classification type, class $c = 7$, corresponding to asterisms/associations of M31 stars.

In spite of the possible occurrence of these “fake” stellar aggregates, whose real occurrence needs however to be more firmly assessed on a statistical basis, it is clear that, in any case, the final word on the real nature of M 31 GCCs must come from the physical resolution of the composing stars, through very high-resolution imaging (i.e., at HST or with adaptive-optic ground telescopes).

Among the clusters revealed to be asterisms by Cohen et al. (2006), there is one, B216, we classify as a genuine GC in Table 2 based on its velocity and apparent morphology.
ies (solid triangles) become an increasing contaminant source among class C–D cluster candidates. See text for a discussion.

Fig. 9. The $V – K$ color distribution for confirmed background galaxies ($c = 4$ flag) in the whole RBC sample vs. original quality class according to the Battistini et al. [1980, 1982, 1987, 1993] scheme. Blue ($V – K < 3.0$) late-type galaxies become an increasing contaminant source among class C–D cluster candidates. See text for a discussion.

While the other asterisms in the Cohen et al. list cannot be independently assessed from our low-resolution imagery, both the BFOSC and the DSS frames for B216 appear hardly compatible with the nearly empty field imaged by Cohen et al. However, we carefully checked the location of this field (with the precious collaboration of J. Cohen) and the listed target coordinates, and we must conclude that B216 is indeed not a real cluster.

4.4. Independently checked candidates

As a duty cycle operation to maintain an updated release for the RBC, we periodically search the HST archive for intentional or serendipitous images of M 31 GCCs that can potentially reveal the true nature of the objects. A systematic survey of the available material is ongoing. Here we report only a few cases in which a clear and indisputable confirmation can be achieved from a thorough inspection of the images, i.e. objects partially resolved into stars or obvious foreground stars or asterisms.

– A new, clearly resolved, cluster has been identified by L.F. in deep F555W and F814W ACS/WFC images (see Fig. 10). The cluster has no counterpart in the RBC and is located at $\alpha_{2000} = 00^h42^m28.05^s$, $\delta_{2000} = 41^\circ33'24.5''$. According to the nomenclature adopted in G04 and G05 we christen the newly found cluster Bologna 515 (B515).
– The candidate B056D is clearly recognized as a genuine cluster on several deep ($t_{exp}$ up to 2370 s) ACS/WFC images taken in different filters, by different teams.
– NB83, classified as genuine cluster by B00 based on its radial velocity ($V_r = -150 \pm 14.0$ km s$^{-1}$) is clearly recognized as a star in deep F555W and F814W images taken with the WFPC2. Note that the radial velocity is in the range where contamination by MW stars can occur (see Sect. 4.1).
– B102, classified as genuine cluster by H91 and P02 based on its radial velocity ($V_r = -235.4 \pm 11.7$ km s$^{-1}$) is recognized as an asterism formed by two stars superposed to a nebulosity in deep ACS/WFC images taken in different filters.
– The candidate NB92 is recognized as a bright (likely foreground) star in deep ACS/WFC and in shallow WFPC2 images taken in various filters.
– The candidate B162, that we classified as a genuine cluster based on its radial velocity ($V_r = -146 \pm 8$ km s$^{-1}$) and on its extendedness (see Tab. 3), is clearly recognized as a genuine cluster also on several deep ($t_{exp}$ up to 2370 s) ACS/WFC images taken in different filters, by different teams.
– The candidate G137, that we recognized as an HII region from its spectrum, appears as a bright point-source surrounded by an asymmetric nebula on deep ACS/WFC images, thus confirming our spectroscopic classification.
– B118, NB99, NB100, NB106, classified as stars in the RBC are recognized as stars also in deep ACS/WFC images, thus confirming the existing classification on a much firmer basis.

In summary, we identified a new cluster (B515), one candidate is recognized as genuine clusters (B056D), two objects previously believed to be genuine clusters has been reclassified as foreground star and asterism (NB83 and B102, respectively), one candidate has been firmly classified as a star (NB92), and the existing classification of seven other objects (B118, B162, B137, NB99, NB100 and NB106) has been fully confirmed.

5. An updated sample of confirmed M31 GCs

As a result of our spectroscopic and imaging survey of Table candidates, we have provided 42 newly confirmed bona-fide

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Fig. 10. The newly identified cluster B515 from F606W HST/ACS imagery. The scale and the orientation of the image are reported.
M 31 clusters, while a total of 34 GCCs should in fact be comprised among background galaxies, foreground stars or Hn regions. Our study increases the total number of confirmed M 31 GCCs from 337 to 368 and the number of confirmed GCs having a radial velocity estimate from 313 to 349.

While a thorough analysis of the integrated properties (including Lick indices) of the newly confirmed clusters is demanded to Paper II of this series (see Sect. 1), a first glance to their composing stellar populations is provided in Fig. 11 where we compare the new GCs with the already confirmed ones (from G04) and with the Buzzoni (1989) theoretical models for Simple Stellar Populations (SSPs), in the reddening-corrected J-K vs. B-K plane (see James et al. 2005 for a thorough discussion of this diagnostic plane). It is clear that most of the new clusters have the typical integrated colors of classical old globulars, and they appear to span the whole metallicity range covered by previously known M 31 GCs.

In terms of GC luminosity function, our survey provides a strong contribution in the 17.0 < V ≤ 18.0 range, where we add 30 new clusters to the 120 previously known objects (see Fig. 12). The 42 newly confirmed clusters are distributed along all of the Battistini et al. classes from A to D, but we remarkably increased (+75%) the surveyed fraction of class D candidates.

It is important to consider that only 172 candidates of class D and E have been scrutinized to date. Since 67 of them turn out to be genuine clusters (∼35%) and ∼500 candidates of these classes still need to be confirmed, one might conclude that over 100 genuine clusters are still hidden in this harvest of “intermediate/low-quality” targets. Hence, large surveys, as the one presented in this paper, are badly needed to eventually reach a truly complete sample of M 31 clusters.

5.1. A basic application: the M 31 mass estimate

A preliminary application of the basic kinematical properties of our enlarged sample provides results in excellent agreement with the more specific analysis by P02. The mean systemic velocity of the M 31 GC system (after a 2-σ clipping procedure) is \(\langle V_{GC}\rangle = -296 \pm 12 \text{ km s}^{-1}\), the median is \(\sim 297 \pm 14 \text{ km s}^{-1}\). The overall velocity dispersion is \(\sigma = 158 \pm 10 \text{ km s}^{-1}\).

\[\text{Fig. 11. Distribution of confirmed M31 clusters in the reddening-corrected } J - K \text{ vs. } B - K \text{ plane. } E(B - V) = 0.11 \text{ is assumed for all M31 clusters. Small filled circles are previously confirmed clusters, pentagon markers are the newly confirmed clusters studied in the present paper. SSP model sequences by Buzzoni (1989), for fixed ages (i.e. 15 Gyr for the upper sequence and 2 Gyr for the lower sequence) and varying metallicity (from [Fe/H] = -2 to a solar value, at equal steps of 0.5 dex, see big solid dots in the sense of increasing } J - K \text{ color along the sequences) are superposed. A Salpeter IMF slope and a red horizontal branch morphology is assumed in the models.}\]
In Fig. 13 we show the distribution of the M31-centric velocities of confirmed GCs as a function of the projected distance from the center along the major axis of the galaxy (X, see G04, and references therein). To obtain a more easily readable plot we limited to the range $-30 \text{kpc} < X < +30 \text{kpc}$, while the outermost cluster in our catalog (B514, see G00) lies at $X = 59.6 \text{kpc}$.

The well known rotation pattern of M31 GCs (see van den Bergh (2000), P02, and references therein) is clearly visible in Fig. 13 with a flattening occurring for $|X| \gtrsim 7 \text{kpc}$. Averaging and 2-$\sigma$ clipping velocities as a function of $X$ in boxes 4 kpc wide, we obtain an amplitude of the overall rotation pattern of $134 \pm 15 \text{ km s}^{-1}$, again in very good agreement with P02.

As an example of the possible applications of the newly obtained large and homogeneous database of radial velocities of M31 GCs, we obtained a simple estimate of the mass of M31 within $R \approx 60 \text{ Kpc}$, using the Projected Mass Estimator (PME, Bahcall & Tremaine 1981). Adopting the version by Heisler et al. (1985) of the PME

$$M_P = \frac{C}{\pi G N} \sum_i^{N} V_i^2 r_i$$

and assuming an isotropic velocity distribution ($C = 32$), P02 obtained for M 31 a total mass $M_{\text{tot}} = 4.1 \pm 0.1 \times 10^{11} \text{ M}_{\odot}$, by using 319 dynamical probes (GCs) out to a radius of $\approx 27 \text{kpc}$ from the galaxy center. Under the same assumptions, from our enlarged sample of 349 GCs out to $\approx 60 \text{kpc}$ from the galaxy center (projected distance, $R_p$), we obtain $M_{\text{rot}} = 4.4 \pm 0.2 \times 10^{11} \text{ M}_{\odot}$. It has to be noted that the uncertainties on the actual isotropy degree of the underlying velocity distribution contributes an additional factor $\sim$2 to the quoted uncertainties. Note also that the estimate is unchanged if we exclude from the sample the presumably young clusters identified in Fusi Pecci et al. (2005) as belonging to the thin disc of M31. The obtained value is well within the range spanned by the most recent estimates of the mass of M 31, as listed by Evans & Wilkinson (2000) in their Table 6. The agreement with previous estimates obtained using GCs as tracers (Federici et al. 1993, P02) is also quite good.

The Bahcall & Tremaine (1981) PME was originally conceived for test particles to probe a central point-mass gravitational source. As an illustrative exercise, we can suitably approach this condition by restraining our analysis to the 14 most distant clusters in our sample, with $R_p > 20.0 \text{kpc}$, and maintain the isotropy hypothesis (i.e. $C = 16$, in eq. 1 above). With these constraints we obtain $M_{\text{rot}} = 4.3 - 7.0 \times 10^{11} \text{ M}_{\odot}$, where the reported range has been obtained by a jackknife resampling technique (Lupton 1993). This estimate is in good agreement with the results by Federici et al. (1993) and with the recent independent estimates by Carignan et al. (2006) and Chapman et al. (2006).

The above estimates rely on methods that assume that the adopted tracers follow the mass density profile of the probed potential, that is not the case for GCs systems, in general. To overcome this problem Evans et al. (2003) introduced a new mass estimator that doesn’t require any coupling between the distribution of the tracers and the underlying mass distribution. As an example of application, Evans et al. (hereafter E03) provide an estimate of the mass of M31 based on GCs, obtaining $M = 1.2 \times 10^{12} \text{ M}_{\odot}$. With the same assumptions as Evans et al. we obtain $M_{\text{rot}} = 2.9 \times 10^{11} \text{ M}_{\odot}$ for the rotational component (to compare with $M_{\text{rot}} = 3.0 \times 10^{11} \text{ M}_{\odot}$ found by E03) and $M_{\text{pres}} = 2.1 \times 10^{12} \text{ M}_{\odot}$ for the pressure component (to compare...
with \( M_{\text{pres}} = 0.9 \times 10^{12} \, \text{M}_\odot \) found by E03). The total mass is \( M = 2.4 \times 10^{12} \, \text{M}_\odot \), a factor 2 larger than the E03 estimate. Part of this difference is due to the larger value of the M31 distance adopted here with respect to E03. Our experiments, however, indicates that the results from this method are quite sensitive to the the way in which the rotational and pressure components are disentangled: the very simple rotation pattern adopted here (see Fig. 1[2] introduces a large uncertainty in our result. Once the above factors are taken into account the agreement with E03 is satisfying, at least in this preliminary stage of the analysis. 

A detailed analysis of the kinematics of the M 31 GC system and the galaxy mass profile is deferred to the completion of our remote-cluster search, currently in progress (see Galletti et al. 2005).

6. Summary and conclusions

We have presented the first results of a large spectroscopic and imaging survey of candidate clusters in M 31. The survey allowed us to confidently classify 76 candidates whose nature was previously unknown: 42 of these resulted new M 31 GCs, while 12 have been recognized as background galaxies, 2 are M 31 Hn regions, while the remaining 17 objects are foreground stars and 3 unclassified objects (possibly M 31 clusters or foreground stars). An estimate of the radial velocity has been obtained for all the 42 newly recognized clusters as well as for an additional sample of 55 M 31 GCs previously confirmed by other authors and two controversial objects. The various set of radial velocities for M 31 GCs available in the literature has been reported to the same scale, multiple measures have been averaged (see Sect. 3.2 for details), and a final merged catalog has been produced (see Tab. 1, Online material). The present analysis has increased the sample of confirmed M 31 cluster from 337 to 369 members, and the number of confirmed GCs with a radial velocity estimate is increased from 313 to 349.

While the main basis for the classification work was provided by radial velocities, we have also implemented a method to distinguish between point and extended sources on low-resolution imaging that allows – in many cases – to disentangle genuine M 31 clusters and MW stars when radial velocity alone leads to controversial conclusions. We also provide a safe classification for few candidates not included in our survey based on the inspection of publicly released high spatial resolution images from the HST general archive.

6.1. The Revised Bologna Catalog V2.0

All the present observational material has been consistently implemented to update the RBC, now available on line in its latest V2.0 release. Future minor updates of the catalog will be described and commented in the RBC web page (http://www.bo.astro.it/M31/) where all the catalog database can be retrieved as ASCII files.

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