

# An HST/WFPC2 survey of bright young clusters in M 31

## IV. Age and mass estimates<sup>\*</sup>

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### ABSTRACT

**Aims.** We present the main results of an imaging survey of possible young massive clusters (YMC) in M 31 performed with the Wide Field and Planetary Camera 2 (WFPC2) on the Hubble Space Telescope (HST), with the aim of estimating their age and their mass. We obtained shallow (to  $B \sim 25$ ) photometry of individual stars in 19 clusters (of the 20 targets of the survey). We present the images and color magnitude diagrams (CMDs) of all of our targets.

**Methods.** Point spread function fitting photometry of individual stars was obtained for all the WFPC2 images of the target clusters, and the completeness of the final samples was estimated using extensive sets of artificial stars experiments. The reddening, age, and metallicity of the clusters were estimated by comparing the observed CMDs and luminosity functions (LFs) with theoretical models. Stellar masses were estimated by comparison with theoretical models in the  $\log(\text{Age})$  vs. absolute integrated magnitude plane, using ages estimated from our CMDs and integrated  $J, H, K$  magnitudes from 2MASS-6X.

**Results.** Nineteen of the twenty surveyed candidates were confirmed to be real star clusters, while one turned out to be a bright star. Three of the clusters were found not to be good YMC candidates from newly available integrated spectroscopy and were in fact found to be old from their CMD. Of the remaining sixteen clusters, fourteen have ages between 25 Myr and 280 Myr, two have older ages than 500 Myr (lower limits). By including ten other YMC with HST photometry from the literature, we assembled a sample of 25 clusters younger than 1 Gyr, with mass ranging from  $0.6 \times 10^4 M_{\odot}$  to  $6 \times 10^4 M_{\odot}$ , with an average of  $\sim 3 \times 10^4 M_{\odot}$ . Our estimates of ages and masses well agree with recent independent studies based on integrated spectra.

**Conclusions.** The clusters considered here are confirmed to have masses significantly higher than Galactic open clusters (OC) in the same age range. Our analysis indicates that YMCs are relatively common in all the largest star-forming galaxies of the Local Group, while the lack of known YMC older than 20 Myr in the Milky Way may stem from selection effects.

**Key words.** galaxies: star clusters – galaxies: individual: M 31 – supergiants – stars: evolution

## 1. Introduction

Much of the star formation in the Milky Way is thought to have occurred within star clusters (Lada et al. 1991; Carpenter et al. 2000); therefore, understanding the formation and evolution of star clusters is an important piece of the galaxy formation puzzle. Our understanding of the star cluster systems of spiral galaxies largely comes from studies of the Milky Way. Star clusters

in our Galaxy have traditionally been separated into two varieties, open and globular clusters (OCs and GCs hereafter). OCs are conventionally regarded as young ( $< 10^{10}$  yr), low-mass ( $< 10^4 M_{\odot}$ ), and metal-rich systems that reside in the Galactic disk. In contrast, GCs are characterized as old, massive systems. In the Milky Way, GCs can be broadly separated into two components: a metal-rich disk/bulge subpopulation, and a spatially extended, metal-poor halo subsystem (Kinman 1959; Zinn 1985, see also Brodie & Strader 2006; Harris 2001, for general reviews of GCs).

However, the distinction between OCs and GCs has become increasingly blurred. For example, some OCs are luminous and old enough to be confused with GCs (e.g., Phelps & Schick 2003). Similarly, some GCs are very low-luminosity systems (e.g., Koposov et al. 2007), and, at least one, has an age that is

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consistent with the OC age distribution (Palomar 1, Sarajedini et al. 2007). Moreover, a third category of star cluster, “young massive clusters” (YMCs) are observed to exist in both merging (e.g., Whitmore & Schweizer 1995) and quiescent galaxies (Larsen & Richtler 1999). Indeed, YMCs have been known to exist in the Large Magellanic Cloud (LMC) for over half a century (Hodge 1961). These objects are significantly more luminous than OCs ( $M_V \lesssim -8$  up to  $M_V \sim -15$ ), making them promising candidate young GCs. Once thought to be absent in the Milky Way, recent observations suggest that their census may be quite incomplete, as some prominent cases have been found recently in the Galaxy as well (Clark et al. 2005; Figer 2008; Messineo et al. 2009).

Thus, a picture has emerged that, rather than being distinct groups, OCs, YMCs and GCs may represent regions within a continuum of cluster properties dependent upon local galaxy conditions (Larsen 2003). The lifetime of a star cluster is dependent upon its mass and environment. Most low-mass star clusters in disks are rapidly disrupted via interactions with giant molecular clouds (Lamers & Gieles 2006; Gieles et al. 2007). These disrupted star clusters are thought to be the origin of much of the present field star populations (Lada & Lada 2003). Surviving disk clusters may then be regarded as OCs or YMCs, depending upon their mass. Star clusters in the halo may survive longer since they are subjected to the more gradual dynamical processes of two-body relaxation and evaporation. The clusters which survive for a Hubble time – more likely to occur away from the disk – are termed GCs (see also Krienke & Hodge 2007). To date, no known *thin* disk GCs have been identified in the Milky Way.

After the Milky Way, M 31 is the prime target for expanding our knowledge of cluster systems in spirals. However, our present state of knowledge about the M 31 cluster system is far from complete. Similar to the Milky Way, M 31 appears to have at least two GC subpopulations, a metal-rich, spatially concentrated subpopulation of GCs and a more metal-poor, spatially extended GC subpopulation (Huchra et al. 1991; Barmby et al. 2000). Also, again similar to the Milky Way GCs, the metal-rich GCs in M 31 rotate and show “bulge-like” kinematics (Perrett et al. 2002). However, unlike the case in the Milky Way, the metal-poor GCs also show significant rotation (Huchra et al. 1991; Perrett et al. 2002; Lee et al. 2008). Using the Perrett et al. (2002) data, Morrison et al. (2004) identified what appeared to be a *thin* disk population of GCs, constituting some 27% of the Perrett et al. (2002) sample. Subsequently, it has been shown that at least a subset of these objects are in fact young ( $\leq 1$  Gyr), metal-rich star clusters rather than old “classical” GCs (Beasley et al. 2004; Burstein et al. 2004; Fusi Pecci et al. 2005; Puzia et al. 2005; Caldwell et al. 2009).

Fusi Pecci et al. (2005, hereafter F05) presented a comprehensive study of bright young disk clusters in M 31, selected from the Revised Bologna Catalog<sup>1</sup> (RBC, Galleti et al. 2004) by color [ $(B - V)_0 \leq 0.45$ ] or by the strength of the  $H\beta$  line in their spectra ( $H\beta \geq 3.5 \text{ \AA}$ ). While these clusters have been noted since Vetesnik (1962) and have been studied by various authors, a systematic study was lacking. F05 found that these clusters, that they termed – to add to the growing menagerie of star cluster species – “blue luminous compact clusters” (BLCCs), are fairly numerous in M 31 (15% of the whole GC sample), they have positions and kinematics typical of *thin disk* objects, and their colors and spectra strongly suggest that they have ages (significantly) less than 2 Gyr.

Since they are quite bright ( $-6.5 \lesssim M_V \lesssim -10.0$ ) and – at least in some cases – morphologically similar to old GCs (see Williams & Hodge 2001, hereafter WH01), BLCCs could be regarded as YMCs, that is to say, candidate young GCs (see De Grijs 2009, for a recent review). In particular, F05 concluded that if most of the BLCCs have an age  $\geq 50$ –100 Myr they are likely brighter than Galactic open clusters (OC) of similar ages, thus they should belong to a class of objects that is not present, in large numbers, in our own Galaxy. Unfortunately, the accuracy in the age estimates obtained from the integrated properties of the clusters is not sufficient to determine their actual nature on an individual basis, i.e., to compare their total luminosity with the luminosity distribution of OCs of similar age (see Bellazzini et al. 2008, hereafter B08, and references therein).

In addition to the question of the masses and ages of these BLCCs, it has become clear that the BLCC photometric and spectroscopic samples in M 31 may suffer from significant contamination. Cohen et al. (2006, hereafter C06) presented NIRC2@KeckII Laser Guide Star Adaptive Optics (LGSAO) images of six candidate BLCCs. Their  $K'$  very-high spatial resolution images revealed that in the fields of four candidates there was no apparent cluster. This led C06 to the conclusion that some/many of the claimed BLCC may in fact be just *asterisms*, i.e. chance groupings of stars in the dense disk of M 31. The use of the near infrared  $K'$  band (required by the LGSAO technique) may be largely insensitive to very young clusters that are dominated by relatively few hot stars, which emit most of their light in the blue region of the spectrum. Hence, the imaging by C06 may be inappropriate to detect such young clusters (see, for example, the detailed discussion by Caldwell et al. 2009). In any case, the study by C06 suggests that the true number of massive young clusters of M 31 may have been overestimated.

Therefore, in order to ascertain the real nature of these BLCCs we have performed a survey with the Hubble Space Telescope (HST) to image 20 BLCCs in the disk of M 31 (program GO-10818, P.I.: Cohen). The key aims of the survey are:

1. to check if the imaged targets are real clusters or asterisms, and to determine the fraction of contamination of BLCCs by asterisms,
2. to obtain an estimate of the age of each cluster in order to verify whether it is brighter than Galactic OCs of similar age. Ultimately the survey aims to provide firm conclusions on the existence of a significant population of BLCCs (YMCs) in M 31, in addition to OCs (see Krienke & Hodge 2007, 2008, and references therein) and GCs.

In Perina et al. (2009a, hereafter Pap-I) we have described in detail the observational material coming from our survey, and the data reduction, and methods of analysis that we homogeneously adopt for the whole survey. We did that by taking the brightest of our surveyed clusters (VdB0) as an example. In this contribution we apply the same process to the whole sample, obtaining metallicity, reddening and age estimates for all the targets of our survey. We incremented our final sample of candidate M 31 YMC by including in the final analysis ten further clusters having age estimates available from the literature that are fully homogeneous with our own ones. In two companion papers, Hodge et al. (2009, Pap-II, hereafter) identified and studied clusters of lower mass (with respect to those studied here) that were serendipitously imaged in our survey, while Barmby et al. (2009, Pap-III, hereafter) studied the structure of the clusters that are the main targets of the survey.

The paper is organized as follows. The sample is described in detail in Sect. 2, where we also summarize the data reduction

<sup>1</sup> [www.bo.astro.it/M31/YMC](http://www.bo.astro.it/M31/YMC)

**Table 1.** Positional, photometric and spectroscopic parameters for the surveyed clusters.

Name	$X^a$ (arcmin)	$Y^a$ (arcmin)	$R$ (arcmin)	$B$	$V$	$(B - V)_0^{F05}$	$(B - V)_0^{t.w.}$	$H_\beta^{F05}$ (Å)	$H_\beta^{G09}$ (Å)	$f f^b$
B015D-D041	-19.27	9.22	21.36	19.11 ± 0.02	18.36 ± 0.03	...	0.15	7.32	...	1
B040-G102	-35.40	-11.92	37.35	17.54 ± 0.03	17.20 ± 0.04	0.18	0.11	7.41	7.58 ± 0.30	1
B043-G106	-33.62	-11.37	35.49	17.04 ± 0.03	16.77 ± 0.04	0.17	0.04	5.53	5.70 ± 0.30	1
B066-G128	-29.55	-13.17	32.35	17.56 ± 0.03	17.35 ± 0.04	0.25	-0.02	4.67	4.84 ± 0.30	1
B081-G142	-25.26	-12.36	28.12	17.36 ± 0.02	16.86 ± 0.03	0.43	0.20	7.98	8.15 ± 0.30	1
B257D-D073	45.98	4.02	46.16	18.41 ± 0.02	18.00 ± 0.04	...	0.01	5.49	5.66 ± 0.30	1
B318-G042	-52.14	-1.32	52.16	17.02 ± 0.03	16.82 ± 0.03	0.06	0.03	...	5.49 ± 0.12	1
B321-G046	-55.50	-7.41	55.99	17.82 ± 0.02	17.51 ± 0.03	0.11	0.06	6.29	6.85 ± 0.32	1
B327-G053	-47.67	-3.45	47.79	16.75 ± 0.03	16.58 ± 0.03	0.21	-0.03	4.09	3.78 ± 0.14	1
B376-G309	42.16	-10.67	43.49	18.35 ± 0.02	17.97 ± 0.04	0.34	0.08	...	6.40 ± 0.06	1
B448-D035	-43.16	-2.97	43.26	18.01 ± 0.03	17.46 ± 0.04	0.50	0.20	6.70	6.87 ± 0.30	1
B475-V128	45.00	4.06	45.18	17.55 ± 0.03	17.09 ± 0.04	0.20	0.11	5.96	6.13 ± 0.30	1
V031	-19.03	7.17	20.34	18.16 ± 0.03	17.62 ± 0.04	0.57	0.19	5.84	6.01 ± 0.30	1
B083-G146	19.83	22.08	29.68	17.85 <sup>d</sup>	17.09 <sup>d</sup>	0.65	0.56	3.75	1.75 ± 0.42	1
B222-G277	10.22	-16.16	19.12	18.00 ± 0.02	17.24 ± 0.03	0.57	0.56	8.47	4.46 ± 0.31	1
B347-G154	27.74	26.74	38.53	17.23 <sup>d</sup>	16.50 <sup>d</sup>	0.62	0.67	...	2.87 ± 0.17	2
B374-G306	41.13	-10.55	42.46	18.69 ± 0.03	18.23 ± 0.04	0.33	0.16	4.07	4.24 ± 0.30	1
NB16	1.96	4.19	4.63	18.83 ± 0.04	17.59 ± 0.10	0.55	0.99	...	3.34 ± 0.08	2
VdB0	-47.16	-4.33	47.36	14.94 ± 0.09 <sup>c</sup>	14.67 ± 0.05 <sup>c</sup>	0.12	0.07	4.30	4.50 ± 0.07	1
NB67-AU13	1.68	3.73	4.09	16.48 ± 0.02	15.92 ± 0.03	0.37	0.36	...	...	1

**Notes.**  $B$  and  $V$  magnitudes are from new aperture photometry performed on the CCD images of Massey et al. (2006), except for B083 and B347 that are not included in the area covered by that survey. <sup>(a)</sup>  $X$  and  $Y$  are projected coordinates in the direction along (increasing Eastward) and perpendicular to the major axis of M 31, in arcmin. <sup>(b)</sup>  $ff$  is a flag indicating if the target has been selected from Tables 1 or 2 of F05. <sup>(c)</sup> From Pap-I. <sup>(d)</sup> From the RBC. <sup>(t.w.)</sup> from this work:  $B$  and  $V$  from this table and  $E(B - V)$  as estimated in Sect. 3 from isochrone fitting. <sup>(F05)</sup> from Fusi Pecci et al. (2005);  $(B - V)_0$  are calculated assuming a single value of  $E(B - V) = 0.11$  for all the clusters. <sup>(G09)</sup> from Galleti et al. (2009).

procedure. In Sect. 3 we present the individual color magnitude diagrams (CMDs) and luminosity functions (LFs), we estimate ages, metallicities and reddening of each cluster. In Sect. 4 we derive the mass estimates for the clusters of our extended sample (including data from the literature), we compare our clusters with open and globular clusters of the Milky Way, and we compare our estimates with those from the recent and extensive analysis of young M 31 clusters by Caldwell et al. (2009, hereafter C09), that are based on integrated spectra. In Sect. 5 our main results are briefly summarized and discussed. Finally, in Appendix A we report on M 31 clusters or candidate clusters listed in the RBC that have been serendipitously imaged within our survey, and, in Appendix B, we report on the nature of candidate BLCC = YMC M 31 clusters that have an HST image in the archive, independent of this survey.

## 2. Description of the sample

Table 1 lists the target clusters of our survey and reports some positional and spectro-photometric parameters that were relevant for their selection. New homogeneous large-aperture ( $r_{\text{ap}} \sim 5'' - 10''$ , depending on the curve of growth of each cluster) integrated  $B$ ,  $V$  photometry for all the targets has been obtained from the publicly available CCD images by Massey et al. (2006), and calibrated using the published photometry from the same authors, as done in Pap-I for VdB0 (see Pap-I for further details).

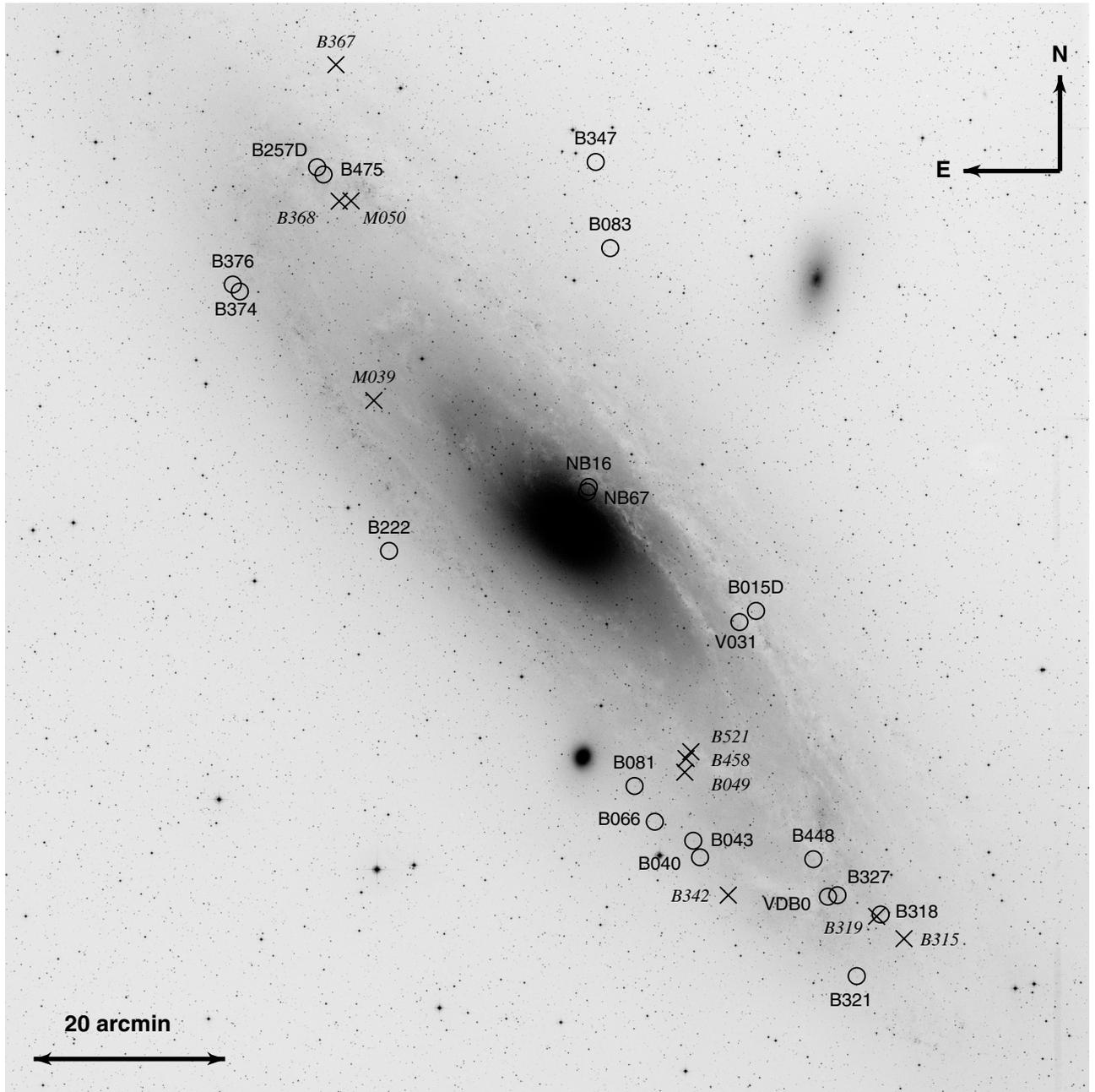
Figure 1 shows that the vast majority of the targets are projected onto the so-called 10 kpc ring (see Hodge 1992; Barmby et al. 2006, C09 and references therein), a site of ongoing star formation in the thin disk of M 31. The only exceptions are B347 and B083, that are significantly farther from the center of the galaxy, and NB16 that is projected onto the outer regions of the M 31 bulge. We will see below that these three clusters do not

fulfill the selection criteria by F05 for bona fide candidate YMCs and, in fact, they are likely old (see Sect. 3.3).

Eighteen of the twenty targets were drawn from Table 1 of F05, i.e. they were confirmed clusters<sup>2</sup> that were classified as genuine BLCC = YMC by these authors as they had  $H_\beta \geq 3.5$  Å or, when lacking a measure of  $H_\beta$ ,  $(B - V)_0 \leq 0.45$ . After a careful inspection of the HST archive, we excluded from the selection any cluster from Table 1 of F05 that had already been imaged with HST (serendipitously, in most cases, see Appendix B), and we chose the brightest 18 among the remaining ones. F05 assumed  $E(B - V) = 0.11$  for all the considered sample, in Sect. 3 we will show that the typical reddening of these clusters is significantly higher than this, in most cases  $E(B - V) \geq 0.20$ , in good agreement with the estimates by C09 (see Fig. 17). Hence, in general, the  $(B - V)_0$  colors derived here are bluer than those adopted by F05. Galleti et al. (2009, G09 hereafter) presented new estimates of the  $H_\beta$  index (with respect to those reported by F05), taken either from their own observations or from the recent literature. In Table 1 we report both the  $(B - V)_0$  and  $H_\beta$  values from F05 (that were used for the selection of the sample) and those derived here and in G09, when available<sup>3</sup>. In one case (B083) the new value of  $H_\beta$  is much lower than that reported by F05 (1.75 Å instead of 3.75 Å) and than the selection limit. Moreover, even with the new  $E(B - V)$  estimate derived here,  $(B - V)_0 = 0.551$ , significantly redder than the limit adopted for the selection. For these reasons B083 can no longer be considered

<sup>2</sup> RBC class  $f = 1$ , meaning that they have been classified as bona fide M 31 clusters by some author, based on their spectra and/or high resolution images.

<sup>3</sup> Note that the scales of the  $H_\beta$  index adopted by F05 and G09 are slightly different. The  $H_\beta \geq 3.5$  Å threshold by F05 translated into  $H_\beta \geq 3.7$  Å in the scale by G09 (see the latter paper for discussion and details).



**Fig. 1.** Location of the 20 targets of our survey (empty circles) projected against the body of M31. The  $\times$  symbols indicate the position of the additional ten young clusters we included in Sect. 4.

as a candidate YMC, as it does not fulfill the selection criteria when the newly available data are considered. The analysis of the CMD (in Sect. 3) will confirm that the cluster is in fact much older than genuine YMC, and possibly as old as classical GCs.

The remaining two targets (NB16 and B347) were selected from Table 2 of F05, including clusters not fulfilling their selection criteria for YMC but classified as young (or possibly young) by some author in the past. In both cases  $H_{\beta}$  were lacking at the time, and the new values reported by G09 are significantly below the selection threshold for a YMC. B347 is also much redder than  $(B-V)_0 = 0.45$ . On the other hand, we find  $(B-V)_0 = 0.399$  for NB16. In this case the criterion based on  $H_{\beta}$  must prevail over that based on de-reddened color as the former is reddening-independent, while relatively low photometric and/or reddening

errors can shift the color of this cluster above or below the selection threshold. In conclusion, the newly available data indicates that both NB16 and B347 are not good YMC candidates, as will be confirmed by their CMDs (see Fig. 12). Hence, just re-considering the original selection in the light of new estimates of integrated properties, our sample of bona fide YMC candidates is reduced to 17 objects, including VdB0 which was studied in detail in Pap-I.

Postage stamp images of all the targets, from our HST data, are presented in Fig. 2 (see Sect. 2.1). Inspection of the images reveal that all our targets are actually *genuine* clusters, with the only exception of NB67 that is a bright star projected into a dense background of M31 (disk) stars (see also Pap-III, for the light profiles of the clusters). For obvious reasons NB67 will be not considered further in the following analysis. A first

**Table 2.** Newly derived ages, metallicity and reddening for the target clusters and other clusters included in the analysis<sup>a</sup>.

Name	$\log(t)$	$\Delta\log(t)$	$Z$	$E(B - V)$	$M_v^b$
This survey					
B015D-D041	7.85	$\pm 0.15$	0.019	0.60	-8.53
B040-G102	7.90	$^{+0.20}_{-0.15}$	0.019	0.23	-7.80
B043-G106	7.90	$^{+0.20}_{-0.15}$	0.019	0.23	-8.22
B066-G128	7.85	$\pm 0.15$	0.019	0.23	-7.76
B081-G142	8.15	$\pm 0.15$	0.019	0.30	-8.60
B257D-D073	7.90	$^{+0.20}_{-0.15}$	0.019	0.40	-8.31
B318-G042	7.85	$\pm 0.15$	0.008	0.17	-7.98
B321-G046	8.23	$^{+0.10}_{-0.15}$	0.019	0.25	-7.57
B327-G053	7.70	$^{+0.15}_{-0.10}$	0.008	0.20	-8.51
B376-G309	8.00	$\pm 0.15$	0.019	0.30	-7.34
B448-D035	7.90	$^{+0.20}_{-0.15}$	0.019	0.35	-8.07
B475-V128	8.30	$\pm 0.20$	0.008	0.35	-8.00
V031	8.45	$\pm 0.15$	0.004	0.35	-8.12
VdB0	7.40	$\pm 0.30$	0.019	0.20	-10.03
B083-G146	>8.70	...	0.008	0.20	-8.00
B222-G277	>8.60	...	0.019	0.20	-7.66
B347-G154	>8.80	...	0.008	0.06	-8.16
B374-G306	>8.50	...	0.019	0.30	-7.09
NB16	>8.70	...	0.019	0.25	-7.69
P09b					
B049-G112	8.45	$\pm 0.20$	0.019	0.30	-7.84
B367-G292	8.30	$\pm 0.20$	0.019	0.25	-6.79
B458-D049	8.50	$\pm 0.20$	0.019	0.25	-7.40
B521	8.60	$\pm 0.30$	0.019	0.55	...
M039	8.50	$\pm 0.20$	0.019	0.10	-5.84
M050	8.75	$\pm 0.30$	0.019	0.15	-6.22
WH01					
B315-G038	8.00	$^{+0.15}_{-0.20}$	0.008	0.31	-8.96
B319-G044	8.00	$^{+0.15}_{-0.20}$	0.008	0.23	-7.57
B342-G094	8.20	$^{+0.15}_{-0.20}$	0.008	0.20	-7.36
B368-G293	7.80	$\pm 0.10$	0.019	0.20	-7.17

**Notes.** For five surveyed clusters only a lower limit to the age can be obtained from our CMDs. <sup>(a)</sup> The additional clusters are six clusters studied in Perina et al. (2009a), from HST archive data, and the four clusters studied by Williams & Hodge (2001). <sup>(b)</sup> Integrated  $V$  magnitudes from the RBC.

conclusion that can be drawn just from this preliminary analysis is that the incidence of spurious objects in our sample is of  $1/17 \simeq 6\%$ , much lower than hypothesized by C06. If we consider the set of 36 objects listed by F05 in their Table 1 for which HST images were available in the archive we obtain the same result (see Appendix B, for discussion and further details). Moreover, none of the considered clusters is in fact an *asterism* (including those considered in Appendix B)<sup>4</sup>. Finally, if we extend our analysis to all the objects classified as YMC by F05 that have been ever imaged with HST we find the same very low degree of contamination (see Appendix B). Hence we are dealing with a significant class of real stellar systems. A second

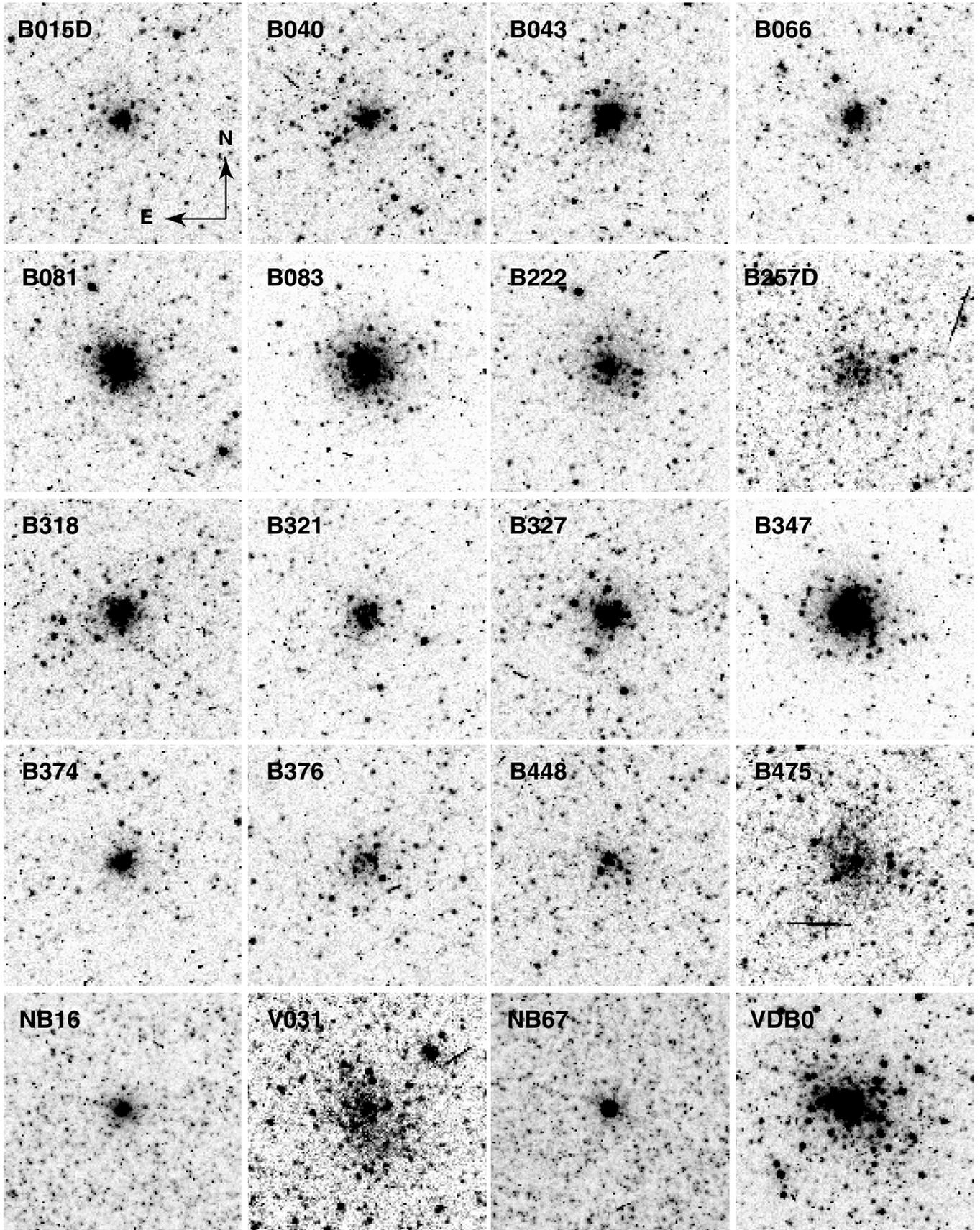
conclusion is that while some of the considered cluster appear quite extended and sparse (like, for example, B257D, B475, and V031), there are also rather compact globular-like clusters (like, B043, B081, and B327, as noted earlier B347 is likely old).

### 2.1. Observations, data reduction and assumptions

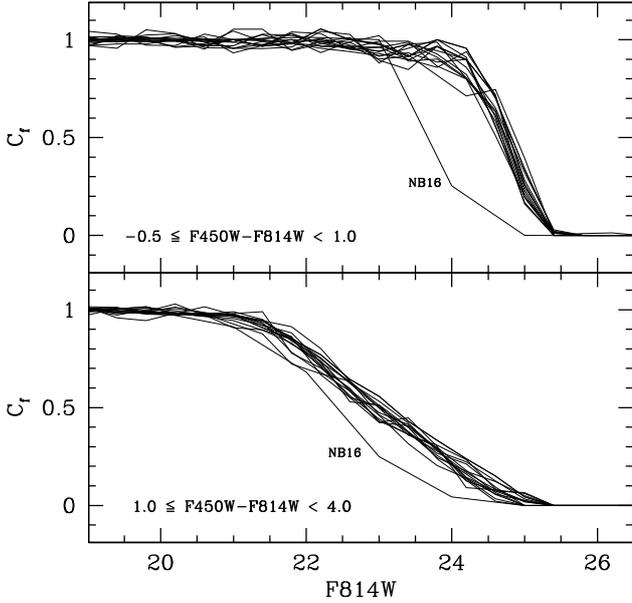
The characteristics of the survey data and the whole process of data reduction and data analysis that has been applied in this study is described in detail in Pap-I. In these section we briefly summarize the key characteristics of the dataset and of the process, for the convenience of the reader.

Two  $t_{\text{exp}} = 400$  s images per filter ( $F450W$  and  $F814W$ ) were acquired for each cluster with the Wide Field and Planetary

<sup>4</sup> Bright stars are well-known classical contaminants in lists of candidate M 31 clusters of any kind, see (Galletti et al. 2006a).



**Fig. 2.** *F450W* images of the 20 primary targets. Each image covers the central  $10'' \times 10''$  on the PC field ( $10'' = 38$  pc at the assumed M31 distance modulus of 24.47). North is up and East to the left.



**Fig. 3.** Completeness ( $C_f$ ) of the samples as a function of  $F814W$  magnitude, obtained from artificial stars experiments, for all the clusters of our survey (listed in Table 1) and for two different color ranges. The upper panel is for a color range enclosing the MS of young clusters, the lower panel is for a color range enclosing the red giant stars. The  $C_f(F814W)$  function of each cluster (for each color range) is computed considering only artificial stars enclosed in the radial range that is used to select the sample dominated by cluster stars that will be studied in the following (typically  $r \leq 5''$ , see Sects. 2.2 and 3). Note that all the  $C_f(F814W)$  functions are very similar, except for the case of the exceedingly compact (and crowded) cluster NB16, labeled in both panels.

Camera (WFPC2) on board of HST, keeping the target at the center of the PC field. Unlike the case of VdB0, treated in Pap-I, the clusters studied here have limiting radii significantly smaller than the size of the PC camera ( $\approx 39'' \times 39''$ , see Pap-III), therefore both the cluster population and the surrounding field can be studied using the PC images alone (see Sect. 2.2) without relying on the WF cameras. The analysis of the field population in the portions of the M 31 disk sampled by our WF images will be the subject of another contribution (Perina et al., in preparation).

Photometry of the individual stars has been obtained with HSTPHOT (Dolphin 2000a), a Point Spread Function fitting package specifically developed for WFPC2 data. The reduction process includes cleaning of cosmic-ray hits and bad pixels, correction for Charge Transfer Efficiency (CTE, Dolphin 2000b), and absolute photometric calibration in the VEGAMAG system (Holtzman et al. 1995; Dolphin 2000b). The images were searched for sources having peak intensities at  $3\sigma$  above the background. The output catalogs were cleaned of spurious and/or badly measured sources by selecting stars with HSTPHOT global quality flag = 1, *crowding* parameter  $< 0.3$ ,  $\chi^2 < 2.0$  and  $|\text{sharp}| < 0.5$ . The final catalogs containing position and  $F450W$ ,  $F814W$  photometry of the PC fields will be made publicly available through a dedicated WEB page<sup>5</sup>.

We estimated the completeness of our samples as a function of magnitude, color and position on the field by means of extensive artificial stars experiments (more than  $10^5$  artificial stars were simulated, per field of view, i.e. more than  $4 \times 10^5$  per cluster), as described in detail in Pap-I. Figure 3 show the completeness factor ( $C_f$ ) as a function of magnitude for all the

clusters, for two different color ranges (one covering the clusters' main sequence (MS) and one covering the Red (Super) Giant branches). The reported  $C_f$  curves refers to the circles enclosing most of the cluster population that are defined in Sect. 2.2, hence they are fully relevant for the following analysis. Note that the completeness conditions are very similar for all the clusters (including VdB0, presented in Pap-I), except NB16. This cluster is so compact that the considered region is much more crowded than all the other cases, thus the completeness is significantly worse. The typical photometric uncertainties as derived from the artificial stars experiments are  $\lesssim \pm 0.02$  for  $F450W \approx F814W \leq 21$ ,  $\lesssim \pm 0.05$  for  $F450W \approx F814W \leq 22.5$ , and  $\lesssim \pm 0.2$  for  $F450W \approx F814W \leq 24.0$  (see Pap-I, for details).

In the following we will always assume  $(m - M)_0 = 24.47$ , from McConnachie et al. (2005), corresponding to  $D = 783$  kpc. At this distance  $1''$  corresponds to 3.8 pc,  $1'$  to 228 pc. We adopt  $A_{F450W} = 4.015E(B - V)$  and  $A_{F814W} = 1.948E(B - V)$ , from Schlegel et al. (1998). We will use theoretical isochrones and LFs in the HST/WFPC2 VEGAMAG system from the set by Girardi et al. (2002, hereafter G02), considering only models in the range of metallicity  $\frac{2}{5}Z_\odot \lesssim Z \lesssim 2Z_\odot$ , that seem appropriate for young disk clusters. Details and discussion regarding the choices outlined above can be found in Pap-I.

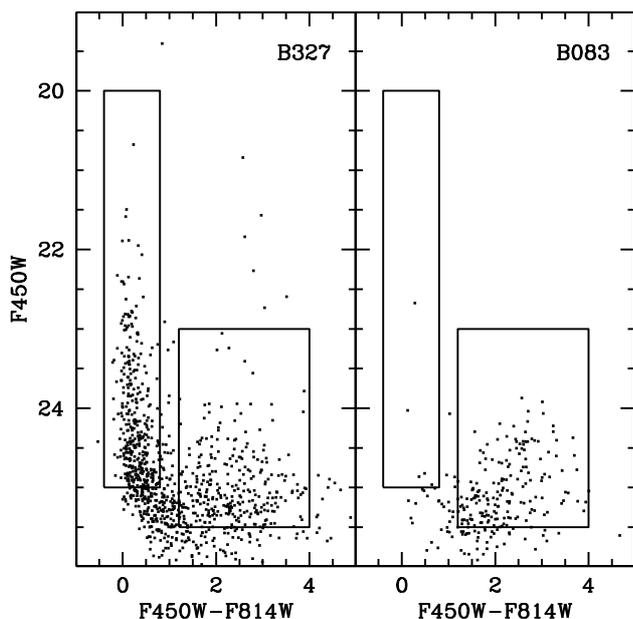
## 2.2. Radial selection and first classification

Before proceeding with the analysis of the CMDs of the clusters, we need to select – for each cluster – a sub-sample of the PC field that is as representative as possible of the cluster population, possibly minimizing the contamination by the surrounding M 31 field. Following Pap-I we adopt a radial selection, retaining in the final *cluster sample* the stars lying within a certain distance from the cluster center. To determine the selection radius to be adopted for each individual cluster we proceeded as follows:

- We defined two broad selection boxes on the CMD, one enclosing the bright MS typical of young clusters (Blue Box) and one enclosing a redder region that should be dominated by old stars at the tip of the red giant branch (RGB) but can enclose also intermediate-age asymptotic giant branch (AGB) and some red super giant (RSG) stars, as illustrated in Fig. 4 (Red Box).
- We derived surface-density radial profiles by counting stars selected in the two boxes on concentric annuli. To obtain smoother profiles with the relatively low number of stars available we adopted overlapping annuli of width  $1.8''$ , with a radial step of  $0.9''$  between subsequent annuli. The profiles from main sequence (MS) stars and from red stars (shown in Figs. 5 and 6) are normalized to the minimum surface-density encountered in the raster of radial annuli, that should be considered as roughly representative of the surrounding field. For example, the profiles of B066, in the middle left panel of Fig. 5, shows that at the center of this cluster the surface density of bright MS stars is  $\geq 20$  times higher than in the surrounding field, while there is no overdensity of red stars correlated to the cluster.
- Based on the scale of the detected overdensity we fixed the selection radius of each cluster (marked in the plots as a vertical dashed line), with the aim of isolating a circle that should be dominated by cluster stars. The typical selection radius is  $r \sim 5''$ .

In the following we will analyze only the CMDs of the radially selected samples, as the best representation of the population of

<sup>5</sup> [www.bo.astro.it/M31/YMC](http://www.bo.astro.it/M31/YMC)



**Fig. 4.** Selection boxes used for the stellar surface density profiles shown in Figs. 5 and 6, are superimposed on the CMD of two of the surveyed clusters taken as examples: a young cluster with a prominent MS (*left panel*) and an older cluster displaying just the tip of the RGB (*right panel*). The blue box at  $F450W - F814W \sim 0.5$  selects bright MS stars (young population), the faint redder box ( $F450W - F814W > 1.0$ ) selects red giant stars (old population). In a few cases, the boxes have been slightly shifted in color to best match the MS and RGB features of a cluster with higher reddening.

each cluster. The CMDs of the surrounding fields are shown in Fig. 7, for comparison with those of the respective clusters that are studied in detail in Sect. 3.

Figures 5 and 6 deserve some further comment. First of all, it has to be noted that all the clusters (at their centers) show an overdensity of a factor of  $\gtrsim 10$  with respect to the surrounding field, at least in one of the two profiles. The only exception is NB16 that is so compact that only a tiny corona is resolved into stars, resulting in a low ( $\sim 2\times$ ) overdensity of red stars (but see the light profile obtained in Pap-III). Note that in many cases, the very central region of the cluster is not fully resolved, thus the reported central overdensities are just lower limits to the true ones. Second, there are five clusters that show no sign of overdensity in the Blue Box. B083, B347, and NB16 have been discussed above; they cannot be considered as YMC candidates anymore. B222 and B374 on the other hand have both  $H_\beta > 3.5 \text{ \AA}$ . In four cases the cluster shows no sign of overdensity in the Red Box, in particular, B040, B043, B066, B327. In all the other cases, the overdensity is detected in both the Blue and Red boxes populations, even if not necessarily in similar degree. In general the overdensity from MS stars is larger than in RGB/AGB/RSG, as expected from evolutionary considerations (Renzini & Fusi Pecci 1988).

### 3. Age and metallicity

Once established that our targets are real clusters, the main purpose of our survey is to obtain a reliable age estimate for all of them from their CMDs. This will be done by comparison with theoretical isochrones from the set by Girardi et al. (2002, G02 hereafter, the models are in the same photometric system as the data; see Pap-I for a discussion about the choice of the

set of theoretical models), following the approach described in detail in Pap-I. The procedure provides a simultaneous estimate of the age, the reddening and the metallicity of each cluster under consideration, by eye-aided isochrone fitting. In Pap-I we have shown that the data from our survey can be used to reliably estimate ages in the range from  $\sim 10$  Myr to  $< 500$  Myr (also depending on the total mass of the considered clusters, i.e. on the number of stars populating the MS), from the luminosity and color of the Turn Off (TO) point. The distribution of RSG may help to constrain the metallicity of the population, while the color of the blue edge of the MS is the best indicator of the degree of interstellar extinction (see Pap-I).

In our sample, there are eleven clusters that have a significant number of MS stars brighter than  $F814W = 24.0$ . As the completeness of the sample is  $C_f \gtrsim 80\%$  above this limit, (in the color range enclosing the MS, see Fig. 3), reliable completeness-corrected LFs of the MS population can be obtained, and used to further constrain the age of these clusters, as one in Pap-I. All of these eleven clusters have ages lower than  $\approx 200$  Myr. They are homogeneously analyzed in Sect. 3.1. Also VdB0 belongs to this class but it is not considered here as it has been already treated in Pap-I.

Two clusters (B475 and V031) show a clear MS population only for  $F814W > 24.0$ . As their observed MS lie in a range where the completeness factor drops from  $C_f \sim 80\%$  to  $C_f \sim 0$  in  $\sim 2$  mag their LF would be strongly affected by large completeness corrections. For these reason we limit our analysis to isochrone fitting for these clusters (Sect. 3.2).

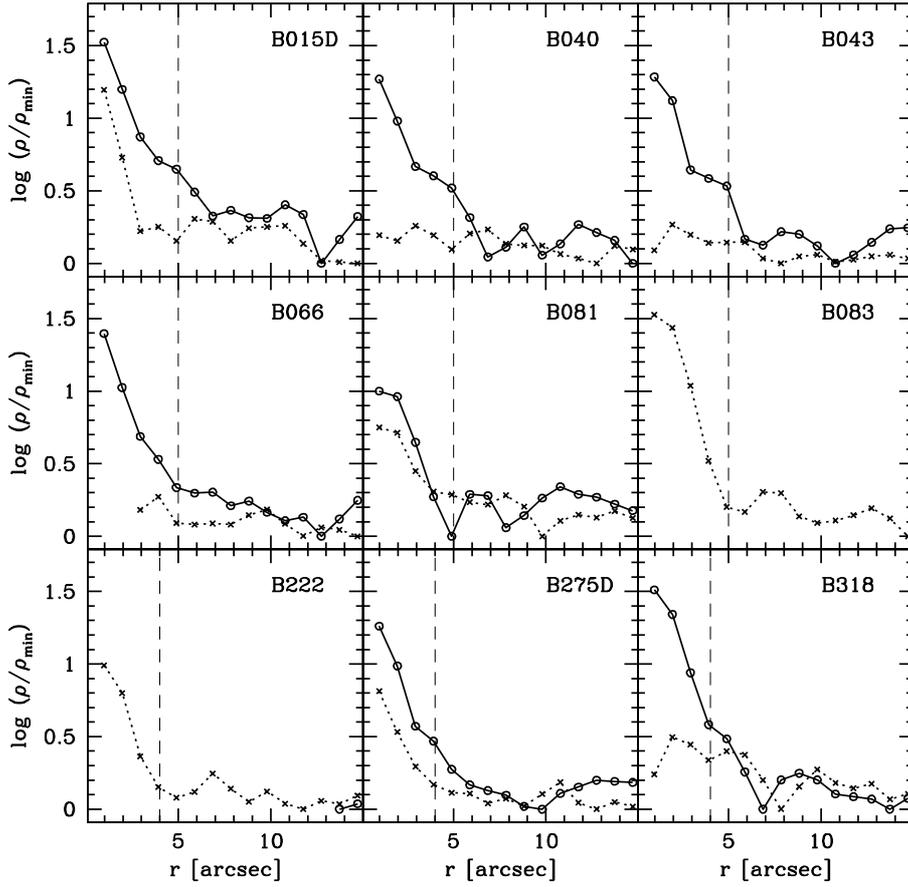
Finally, there are five clusters that do not display any obvious MS population in the range of magnitudes accessible with our data. For these clusters we can provide only a strong lower limit to their age, that must be older than 300–500 Myr. These clusters are discussed in Sect. 3.3. The final results of the analysis of the CMD presented below are reported in Table 2.

#### 3.1. Clusters with bright MS (age $< 200$ Myr)

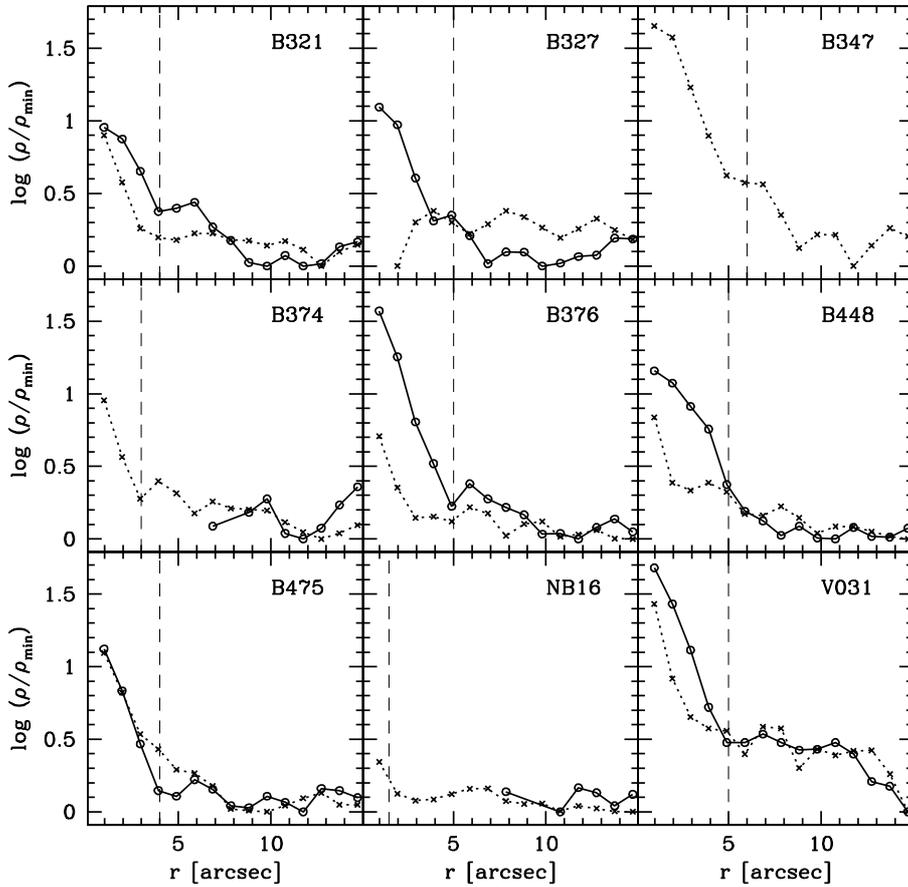
Figures 8–10 show the observed CMDs and LFs of the eleven clusters having a significant MS population brighter than  $F814W = 24.0$ . The boxes overplotted on the CMDs have been used to select the stars that were used to derive the LFs.

For each cluster we explored the space of parameters to find the isochrone and the reddening providing the best overall fit to the observed CMDs. As differential reddening may move stars toward the red and the presence of binary systems also has the effect of broadening the MS toward the red side, we searched for solutions where the theoretical MS fits the blue side of the MS. As noted above, the distribution of RSGs was used as a guide to fix the metallicity of the best-fit model (see Pap-I). Following the approach of Pap-I, we adopt  $Z = 0.019$  as the starting guess for the metallicity of the cluster, trying other metallicity only if this was required to better fit some feature of the CMD. A correct interpretation of the cluster CMD was aided by a comparison with the CMD of the surrounding field, to establish, for example, if a population of a few RSG can be considered as characteristic of the cluster or compatible with belonging to the field. The typical uncertainty on the reddening estimate is  $\pm 0.04$  mag (see Pap-I).

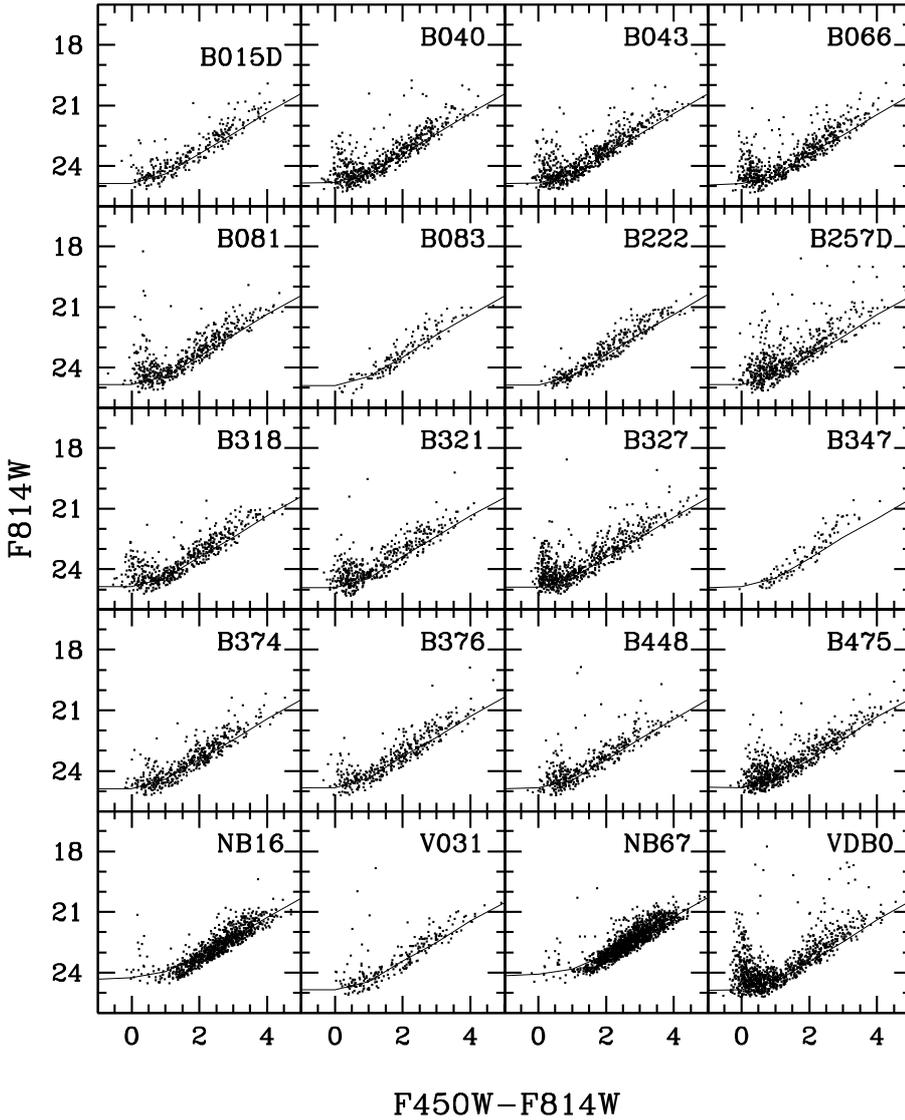
The theoretical LF of the isochrone that best-fits the observed CMD morphology (thick continuous line in the right panels) is compared to the observed LF (filled dots with error bars) to check the compatibility of the solution with the star counts (Salpeter's 1955 Initial Mass Function is adopted). In all the cases considered the adopted theoretical LF is in good agreement with the observations and, in particular, it reproduces the



**Fig. 5.** Stellar surface density profiles of the young (open circles connected by a continuous line) and old (crosses connected by a dashed line) populations (as defined by the selection boxes illustrated in Fig. 4) for nine of the surveyed clusters.



**Fig. 6.** Same as Fig. 5 for the remaining nine surveyed clusters.



**Fig. 7.** CMDs of the fields surrounding the target clusters. Only stars lying in the radial range  $5'' < r \leq 16.5''$  on the PC chips are plotted. The thin lines are the loci where the completeness reaches 50%.

sudden drop in star counts corresponding to the upper luminosity limit of the MS, a feature that is mainly sensitive to age (see Pap-I and references therein). Two theoretical LFs of the same metallicity as the main solution but different ages are used to show the maximum and minimum age that are not compatible with the observed LF. The difference between these values and the age of the best-fit solution are taken as the uncertainty associated with our age estimate. Nine of the eleven clusters considered in this section have ages between 50 Myr and 100 Myr. All of them show a recognizable (and in some cases sizable, see B040, for example) population of RSG stars, in addition to an obvious MS. The other two clusters, B081 and B321 have ages of 140 and 170 Myr, respectively.

### 3.2. Clusters with faint MS ( $200 \text{ Myr} \leq \text{age} \leq 500 \text{ Myr}$ )

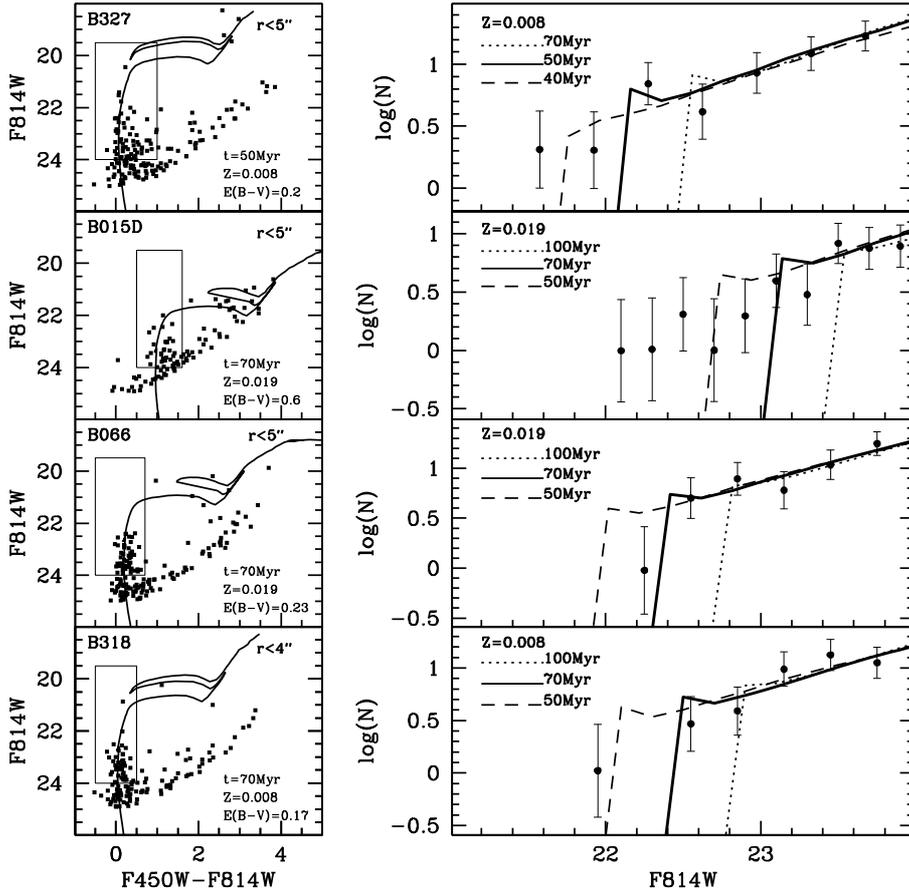
Figure 11 shows the CMDs of the two clusters whose MS is fainter than  $F814W = 24.0$ . The  $F450W$  magnitude is plotted here instead of  $F814W$  (adopted in Figs. 8–10) as this makes the faint MS of these clusters more clearly visible. The best fit isochrones are plotted as thick lines. The thin lines are isochrones having ages that bracket the age solutions that can be considered still compatible with the data. The difference in age

between these solutions and the assumed best-fit are adopted as the uncertainty associated with our age estimates for these cases (see Pap-I). The two clusters have ages of  $\approx 200 \text{ Myr}$  (B475) and  $\approx 280 \text{ Myr}$  (V031).

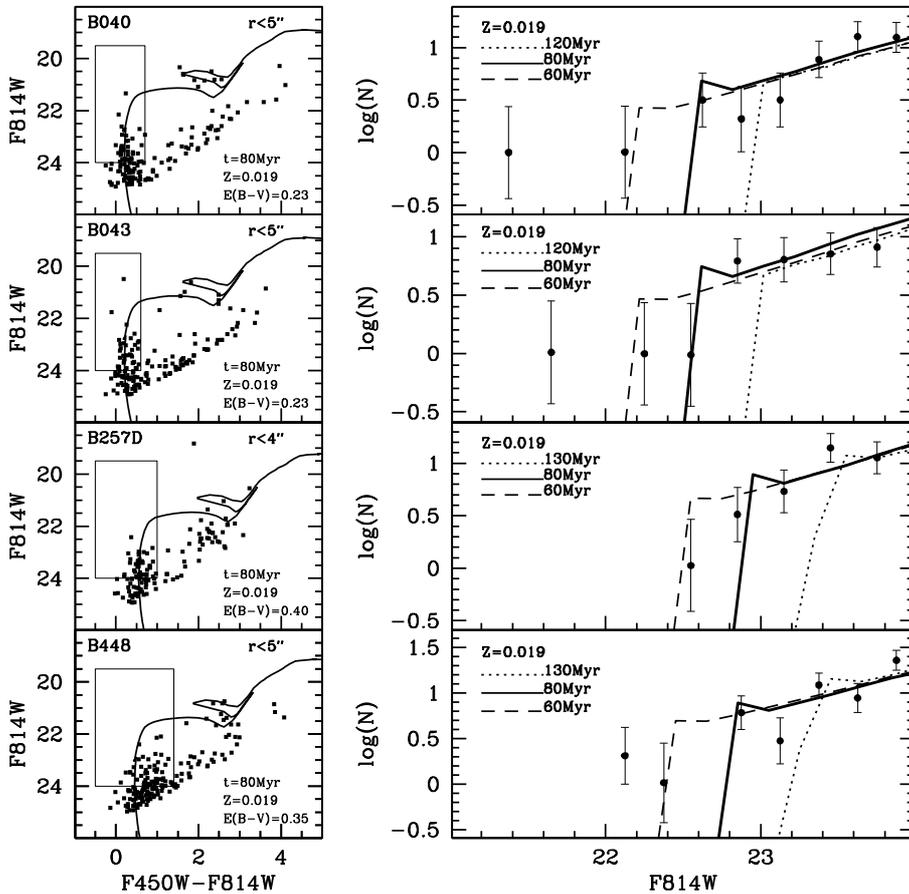
### 3.3. Clusters whose MS is not detected (age $> 500 \text{ Myr}$ )

Figure 12 shows the CMDs of the clusters that do not display a clear MS in the considered range of magnitudes. In each panel we plot (a) the “youngest” isochrone that is compatible with the observed CMD morphology, to provide a firm lower limit to the age of these clusters (thick continuous line), and, (b) a 12 Gyr old isochrone (thick dashed line), showing that the observed CMD is also compatible with very old ages. In all the cases we adopt the metallicity value that provided a satisfactory match of the color of the (putative) RGB.

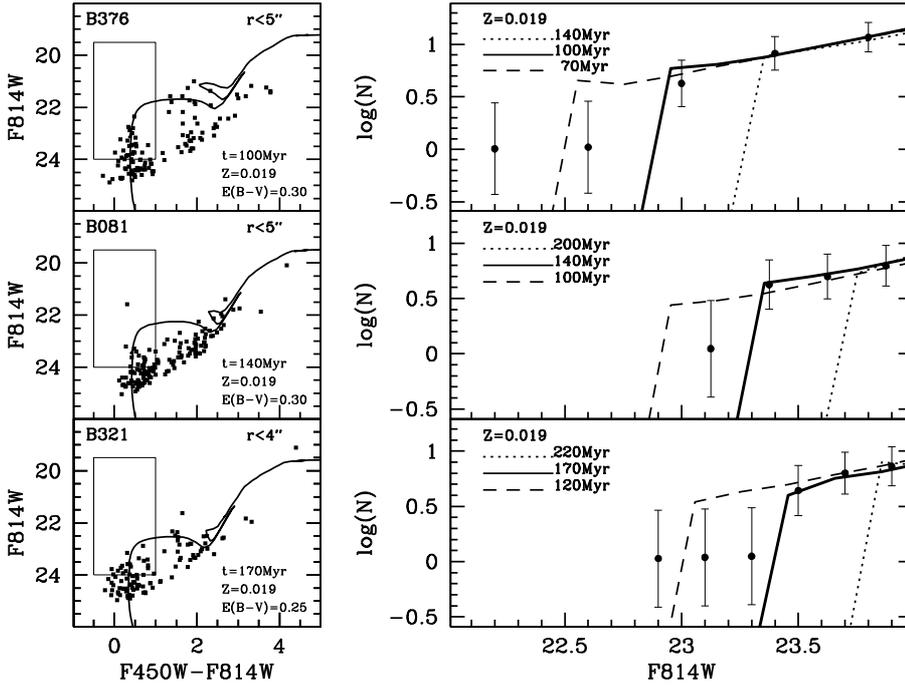
Three of the five clusters considered here (B083, NB16 and B347) have integrated properties that are compatible with old ages (see Sect. 2). B083 and B347 display a steep and well populated red sequence, much bluer than the limits imposed by the run of the completeness as a function of color (thin dotted lines), typical of the RGB of classical old (and metal deficient) GCs. The handful of stars resolved in NB16 are also compatible with



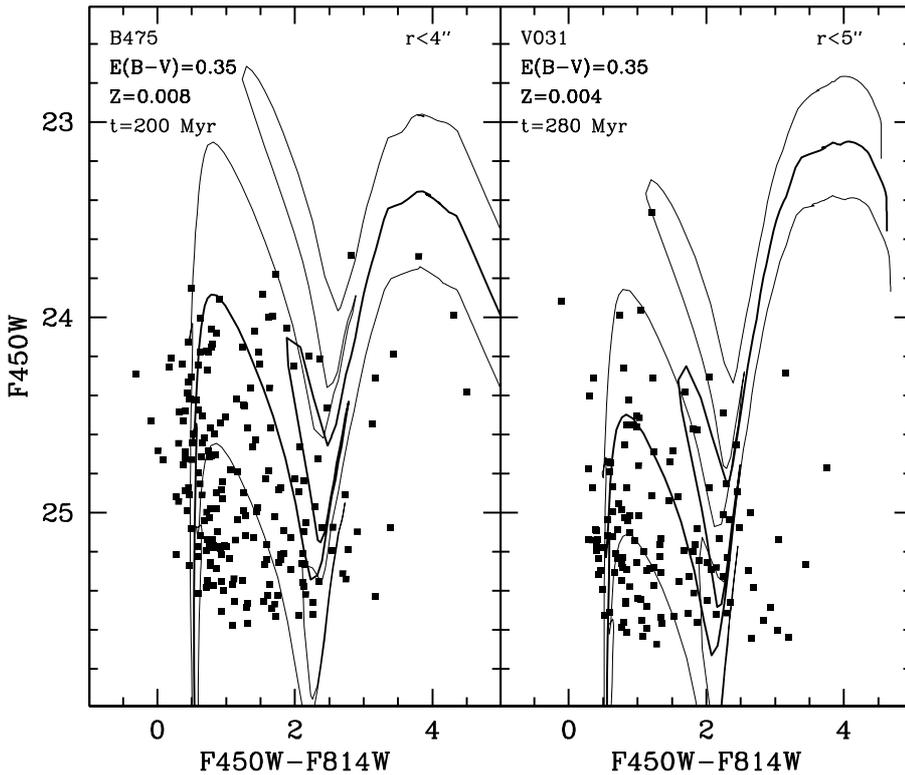
**Fig. 8.** *Left panels:* CMDs of the clusters B327, B015D, B066, and B318, displaying only stars within the radial selection reported in the upper right corner of each panel. The adopted best-fit value of the reddening and the age and metallicity of the best-fit isochrone (thick continuous line) are reported in the lower right corner of each panel. The rectangular boxes adopted to select the stars used to obtain the LFs shown in the right panels are also plotted. *Right panels:* the observed completeness-corrected LFs of the cluster MS (filled circles with error bars) are compared with theoretical models of different ages. The thick continuous line corresponds to the best-fit model shown in the CMDs. In all cases, it provides a reasonable fit to the observed LF and, in particular, to the sudden drop of star counts at the upper limit of the MS. The dotted and dashed lines are theoretical LFs corresponding to strong upper and lower limits to the age, respectively, as they are the nearest models that can be clearly excluded by the data. The theoretical LFs have been arbitrarily normalized to best match the three faintest observed points.



**Fig. 9.** Same as Fig. 8 but for the clusters B040, B043, B257D, and B448.



**Fig. 10.** Same as Fig. 8 but for the clusters B376, B081, and B321.



**Fig. 11.** Observed CMDs of the clusters B475 (left panel) and V031 (right panel) in the plane  $F450W$  vs.  $F450W - F814W$  where the MS population of these older clusters is more clearly visible. Only stars with the radial selection reported in each panel are plotted. The best-fit isochrone is plotted as thick line (age, metallicity and reddening values are reported in each panel). The thin isochrones bracket the upper and lower limits on the age, and correspond to age  $\approx 125$  Myr and 315 Myr for B475, and age 200 Myr and 400 Myr for V031.

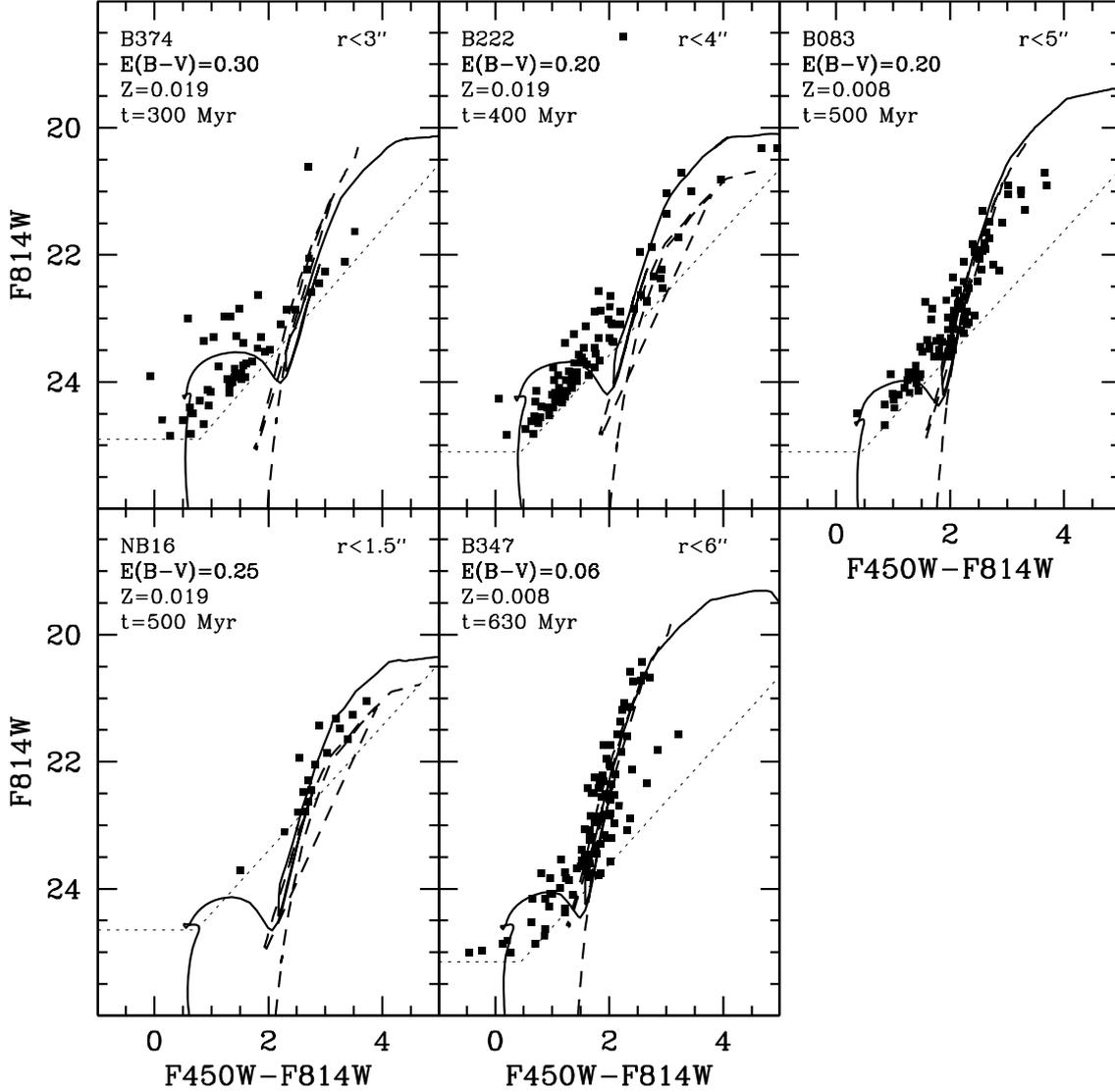
being near the tip of an old RGB, but their scarcity poses strong caveats on any interpretation.

B347 and B222 are more interesting cases: both have two independent concordant estimates of  $H_\beta$  indicating  $H_\beta > 4.0 \text{ \AA}$ , and both have some stars just above the detection limits in the blue, that may be compatible with the bright end of a fainter MS. The observational scenario is fully consistent with the hypothesis that these two clusters might be intermediate-age (age  $\sim 0.5\text{--}2$  Gyr). A deeper photometry follow-up is clearly required to settle the issue of the age of these clusters. It is worth noting

that a convincing case for an M31 cluster in the age range 1–8 Gyr with age estimated from a CMD has never been provided.

#### 4. Masses from ages and $J$ , $H$ , $K$ integrated photometry

In Table 2 we report the age, metallicity and reddening estimates obtained from the analysis of the CMDs presented above. To increase the sample of YMC to be considered in the following we added a total of 10 further clusters whose ages have been derived from CMDs obtained from HST data in a way fully



**Fig. 12.** CMDs of the clusters B374, B222, B083, NB16, and B347. Only stars within the radial selection reported in each panel are plotted. The thin dashed lines marks the locus where the completeness of the sample reaches  $\approx 0\%$  (see Pap-I), to illustrate the selection effects on the CMD morphology imposed by the run of limiting magnitude as a function of color. In each panel, the continuous line is the youngest age isochrone that is compatible with the observed CMD, providing a strong lower limit to the age of each cluster. The adopted age, metallicity and reddening values are reported in the upper left corner. The dashed line is a 12 Gyr old isochrone matching the color of the observed RGB. The metallicity of these old-age isochrones is  $Z = 0.001, 0.004, 0.001, 0.004,$  and  $0.001$  for B374, B222, B083, NB16, and B347, respectively.

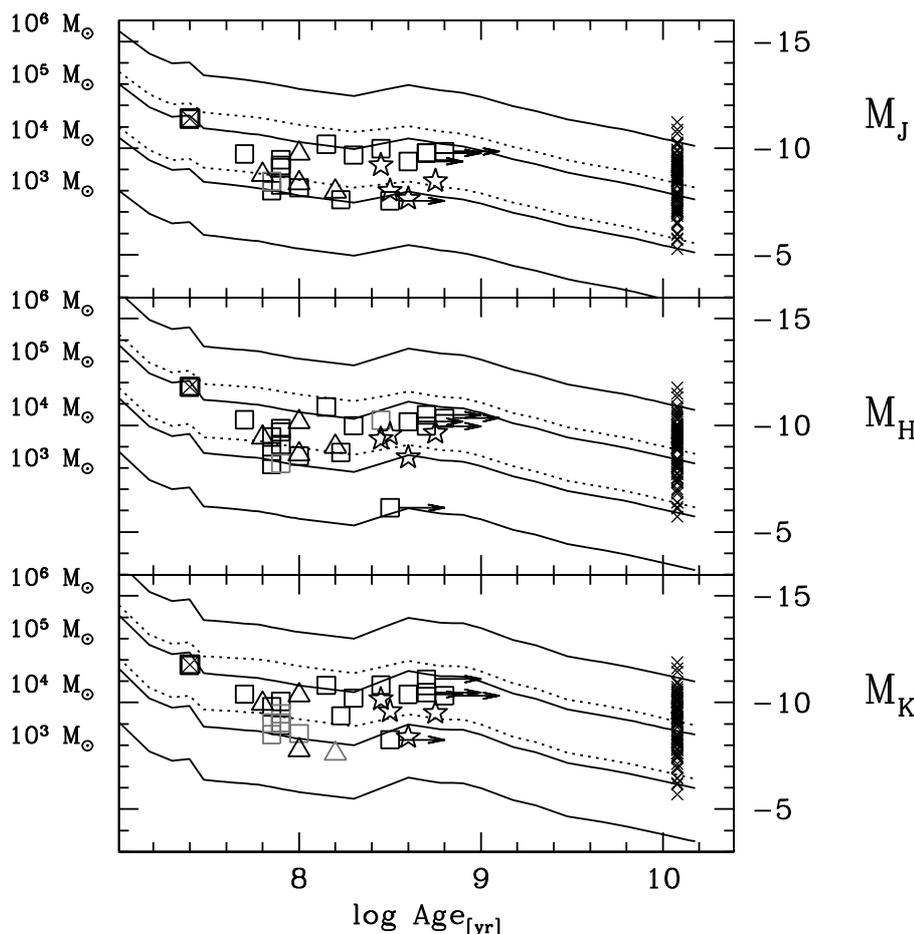
homogeneous with that adopted here. In particular we add six clusters from Perina et al. (2009b, P09b hereafter) and four clusters from Williams & Hodge (2001, WH01 hereafter; see Pap-I). All of them lie in the range of  $V$  luminosities typical of YMC ( $M_V \lesssim -6.5$ , according to F05), with the only (possible) exceptions of M050 and M039 that appear somewhat fainter than this, and of B521 that lacks an estimate of its  $V$  magnitude (but it is found to have a mass similar to other YMC, based on its near infrared magnitudes, see below). We decided to keep these clusters within our sample, being well aware that the threshold between the brightest of the clusters studied in Pap-II and Krienke & Hodge (2007, 2008) and the faintest clusters considered here is somewhat blurred, both by lack of a clear-cut definition and by observational uncertainties. In particular, Fig. 20, will show that some of the clusters studied in Pap-II appear to have masses typical of YMC. Still we preferred not to include these massive Pap-II clusters as main objects of the present analysis as most of them have their ages estimated from integrated colors, i.e. with significantly greater uncertainties than those obtained here from CMDs (see, e.g., Fig. 8 of Pap-II)<sup>6</sup>.

Five of the newly included clusters are projected onto the 10 kpc ring, as most of our original targets, four lie slightly nearer to the center of the galaxy, and one is in the outskirts of the visible disk (see Fig. 1). B049, B367, B458, B315 and B317 have two independent estimates of  $H_\beta$ , all of them higher than  $4.5 \text{ \AA}$  (F05, G09). B342 has just one estimate ( $H_\beta = 7.06 \text{ \AA}$ , FP05), while the other four clusters lack any measure of this index. B368 lacks  $H_\beta$  but has  $(B - V)_0 = 0.06$ . For M039, M050 and B521 there is no  $(B - V)_0$  estimate available. In any case all the six clusters from P09b and the four from WH01 have age  $< 1$  Gyr, as derived from their CMD.

To derive the most reliable estimate of the total stellar mass of the clusters in our sample we couple our age estimates with integrated near infrared (NIR) photometry, as stellar mass-to-light ratios in NIR bands have a much shallower dependence on age than their optical counterparts (see Pap-I for discussion). As the best estimate of the integrated  $J, H, K$  magnitudes we took the values of the  $r = 10''$  aperture magnitudes from the 2MASS-6X-PSC catalog (see Nantais et al. 2006), that is obtained from deeper observations (with respect to the normal 2MASS data, Skrutskie et al. 2006) over a limited region of the sky that,

<sup>6</sup> There are only two clusters from Pap-II having  $M_V \lesssim -6.5$  and ages estimated from their CMD, but also in these cases the associated age

uncertainties are relatively large, i.e. 0.5–0.6 dex in  $\log(\text{Age})$  vs. a typical uncertainty of 0.2 dex for our main sample, see Table 2.



**Fig. 13.** Log(age) vs. integrated magnitude plane for near infrared colors. The target clusters are represented as open squares (VdB0 as a crossed square), the clusters from P09b as open stars, and the clusters from WH01 clusters as open triangles, *IR* magnitudes are taken from Table 3. Note that B367 and M039 are not plotted because they lack NIR photometry in the 2MASS-6X-PSC catalog. The gray symbols show the clusters that have “null” error on *IR* magnitudes in the 2MASS-6X-PSC catalog. Integrated magnitudes of Galactic GCs ( $\times$  symbols) are taken from Cohen et al. (2007). The continuous lines are fixed-stellar-mass models from the set by Maraston (1998, 2005) for SSPs of solar metallicity, with a Salpeter’s initial mass function (IMF) and intermediate horizontal branch morphology. Note that in this plane, the dependence of the models from the assumed IMF, metallicity and HB morphology is quite small (see B08). The dotted lines are  $M = 10^4 M_{\odot}$  and  $M = 10^5 M_{\odot}$  iso-mass models assuming a Kroupa 2001 IMF instead of a Salpeter (1955) IMF, plotted here to illustrate the weak effect of assumptions on IMFs.

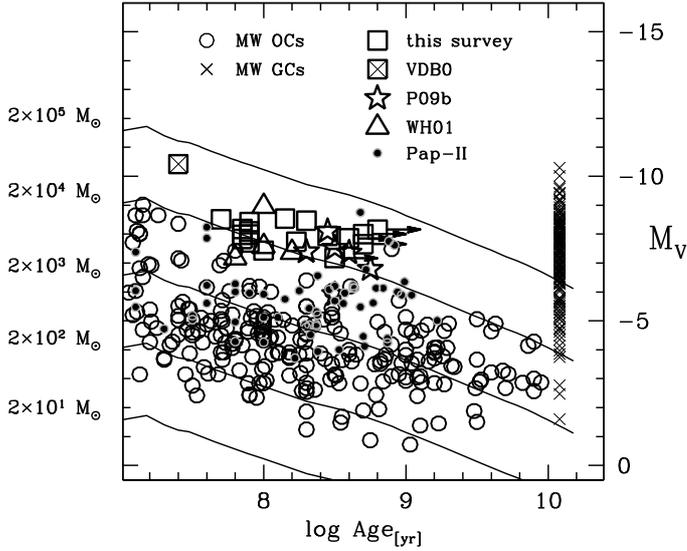
luckily, includes M 31. The adopted NIR photometry as well as the accurate positions reported in 2MASS-6X-PSC are listed in Table 3. Only two clusters have no valid measures in 2MASS-6X-PSC, i.e. B367 and M039. To preserve the homogeneity of the analysis we do not include these clusters in any of the following analyses that make use of mass estimates, however, for completeness, in Table 3 we provide a tentative mass estimate derived from the log(age) vs.  $M_V$  diagram presented in Fig. 14. The apparent magnitudes are transformed into absolute ones adopting the reddening estimates derived here (Table 2), the distance modulus (from McConnachie et al. 2005) and the reddening laws (from Rieke & Lebofsky 1985) adopted in Pap-I.

In Fig. 13 we compare the position of our clusters in the integrated (*J, H, K*) magnitude vs. log(age) plane with a grid of models of simple stellar population (SSP) of solar metallicity and various total mass, from the set by Maraston (1998, 2005, see Pap-I). In B08 and in Pap-I we have shown that the mass that can be deduced from these plots depends only weakly on the assumed metallicity and IMF. Here we get an independent estimate of the mass from each (*J, H, K*) plot and we take the weighted average of the three values as our final estimate. The uncertainties were obtained on each individual estimate from *J, H, K* by finding the maximum interval in mass that was compatible with the errors in age and in integrated magnitudes. Then the three values (per cluster) were combined into the final *weighted* error that is reported in Table 3 together with the final mass estimates.

It is very reassuring to note that the three plots provide very similar age estimates: all the clusters considered appear to have masses between  $\sim 10^4 M_{\odot}$  and  $\sim 10^5 M_{\odot}$ . The estimates from the three different NIR magnitudes typically agree within a factor

of 2. The adoption of a Kroupa (2001) IMF instead of that of Salpeter would change the mass estimates by less than a factor of 2 (Pap-I). The adoption of different sets of models would lead to a maximum difference of the same amount in the final mass estimates (we have compared the *M/L* predictions adopted here with those from the sets by Pietrinferni et al. 2004; Bruzual & Charlot 2003, in the age range that is relevant for our clusters). Finally, if models with age-dependent *M/L* are adopted (i.e. including the effects of differential mass loss, Kruijssen & Lamers 2008), the mass estimates for our clusters change by a mere  $\lesssim 20\%$  (see also Pap-III). Taking all of these factors into account it turns out that our mass estimates should be accurate within a factor of  $\lesssim 3$ , as confirmed also by the comparison with the independent estimates from Pap-III and C09.

There is only one case of significant disagreement in the position of a cluster in the different NIR passbands, i.e. B347 whose reported *H* magnitude implies a (lower limit) mass estimate nearly one order of magnitude lower than *J* and *K*. We attribute this occurrence to an error of the integrated *H* magnitude reported in 2MASS-6X as this value is at odds with that of all the other clusters while B347 is normal in all other respects. For instance it has a *J* – *K* color well within the range of the other clusters of the sample while its *H* – *K* color is more than one magnitude redder than any other. Finally we note that the independent lower limit mass obtained from the log(age) vs.  $M_V$  diagram (see Fig. 14), are in good agreement with that estimated from *J* and *K* magnitude for B347. Finally, as we have obtained just a lower limit to the age of B347 we do not provide an age estimate for this cluster. B347 as well as all the other clusters for which we can provide only a lower limit to the age are not



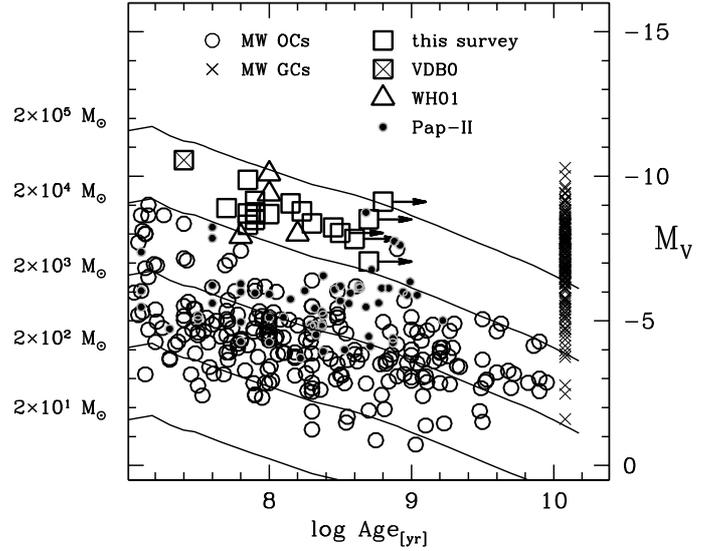
**Fig. 14.** Integrated  $V$  mag and total mass as a function of age for various samples of clusters. Galactic open clusters (OC, from the WEBDA database) are plotted as filled circles, Galactic globular clusters (GC,  $M_V$  from the most recent version of the Harris (1996) catalog, i.e. that of February 2003, the ages have been arbitrarily assumed to be 12.0 Gyr for all the clusters) are plotted as  $\times$  symbols. The target clusters are represented as open squares (VdB0 as a crossed square), the clusters from P09b as open stars, and the clusters from WH01 clusters as open triangles.  $M_V$  magnitudes of the target clusters and of the P09b clusters are from the new aperture photometry performed on the CCD images by Massey et al. (2006), except for B083 and B347 whose magnitudes are from RBC (see Table 1).  $M_V$  magnitudes of the WH01's clusters are from RBC. Log Age is from Table 2. Points with arrows have only lower limits to the age. Filled circles are M 31 OCs from Pap-II. The continuous lines are fixed-stellar-mass models from the set by Maraston (1998, 2005) for SSPs of solar metallicity, with a Salpeter's initial mass function (IMF) and intermediate horizontal branch morphology. Note that in this plane, the dependence of the models from the assumed IMF, metallicity and HB morphology is quite small (see B08). The outlier OC at log Age  $\approx$  9.0 is Tombaugh 1.

included in the analysis of Sect. 5 that is limited to the young clusters that constitute the main subject of our study.

#### 4.1. Comparison with Galactic open clusters

In Fig. 14 we show the log(age) vs. absolute magnitude plot analogous to Fig. 13 but using  $M_V$  instead of  $M_J$ ,  $M_H$ ,  $M_K$ . While NIR magnitudes are preferred to get reliable estimates of the stellar mass of our clusters (see Sect. 4 and Pap-I), the use of  $M_V$  allows us a direct comparison with different kinds of clusters for which integrated magnitudes in NIR passbands are lacking, Galactic OCs in particular (B08, Pap-I).

Inspection of Fig. 14 confirms the tentative conclusions of Pap-I (and F05). The distribution of our target clusters marginally overlaps with the high-mass tail of the Galactic OC distributions, but *the bulk of the sample of candidate YMC considered here is significantly more massive than Galactic OCs in the same age range*. In this sense, the brightest, most massive and youngest cluster of our sample, VdB0 having age = 25 Myr and  $M \approx 6 \times 10^4 M_\odot$ , may appear similar to the handful of massive young clusters recently identified in the Milky Way (see Fig. 2008; Messineo et al. 2009, hereafter M09, for recent reviews), that have masses between  $0.7 \times 10^4 M_\odot$  and  $4.0 \times 10^4 M_\odot$  and ages between 0.3 Myr and 18 Myr, according to M09. The



**Fig. 15.** Same as Fig. 14 but with  $M_V$  magnitudes of the target clusters and of the WH01's clusters obtained from fitting King (1966) models to our HST data, from Pap-III. The clusters from P09b are not included in the plot as they have not been considered in Pap-III.

other clusters of our sample have similar (or slightly greater) masses than the Galactic YMC but they are all significantly older (by a factor of  $>2\times$ , see Sect. 5 for further discussion). It is worth to note that the masses estimated from Fig. 14 are in agreement with those from Fig. 13, typically, within a factor of 2.

In Pap-I we showed that in the case of VdB0, an exceptionally extended cluster, the integrated magnitudes reported in the RBC were significantly underestimated. However our shallow HST exposures were not ideal to perform integrated photometry on such large areas (VdB0 cover the whole extent of the PC field). For these reasons we recurred to the new homogeneous CCD survey by Massey et al. (2006; see Pap-I for discussion) to obtain a reliable estimate of the total luminosity of that cluster; as said, the integrated  $B$ ,  $V$  magnitudes for the clusters considered here have been obtained from the same source and with the same method (Table 1). These cases are less problematic, as the clusters are more compact than VdB0. However, it seems wise to check how the comparisons shown in Fig. 14 may depend on the actual way in which  $M_V$  is estimated. To do that we present in Fig. 15, a new version of Fig. 14 in which the  $M_V$  values derived from Table 1 are replaced with  $M_V$  estimates obtained in Pap-III from profile fitting (with King 1966 models) performed on our HST images (with the same assumptions on distance and reddening adopted here). Again, it is very reassuring to note that the conclusions drawn above from Fig. 14 are fully confirmed also by the new set of  $M_V$  from Pap-III. In fact, the differences between the YMC of our sample and Galactic OCs are even more pronounced in the new plot, as the total  $V$  luminosities estimated in Pap-III are larger than the values adopted here by a factor of  $\approx 1.6$ , in average. For the reasons discussed in Pap-I and for homogeneity with that analysis we retain our ground-based  $M_V$  estimates as our reference.

It is interesting to note that the clusters identified by Krienke & Hodge (2007, 2008), and, by analogy, those found in Pap-II<sup>7</sup>, have an observed LF peaking around  $M_V = -3$  and virtually dropping to zero at  $M_V \approx -6$ , very similar to Galactic OCs (see

<sup>7</sup> It should be recalled that clusters listed in the RBC were excluded from the analysis performed in Pap-II.

Fig. 19), hence they appear as the natural counterpart of the OCs observed in the Milky Way.

In Pap-III the problem of the survival of our target clusters was discussed in some detail and dissolution times including the effects of internal and external evolution (Lamers & Gieles 2006), were computed. These values are reported also here, in Table 3, for convenience of the reader. The dissolution times of young clusters are all shorter than a Hubble time, hence it is likely that none of them will survive long enough to become old ( $\text{age} \geq 10$  Gyr), and some of them are probably in the latest phase of their dissolution (B321, B342; Pap-III). However, a few clusters have dissolution times longer than 1 Gyr, and it is not inconceivable that some of them may reach an age of several Gyr before dissolving into the M 31 disk (see Pap-III).

#### 4.2. Comparisons with Caldwell et al. (2009)

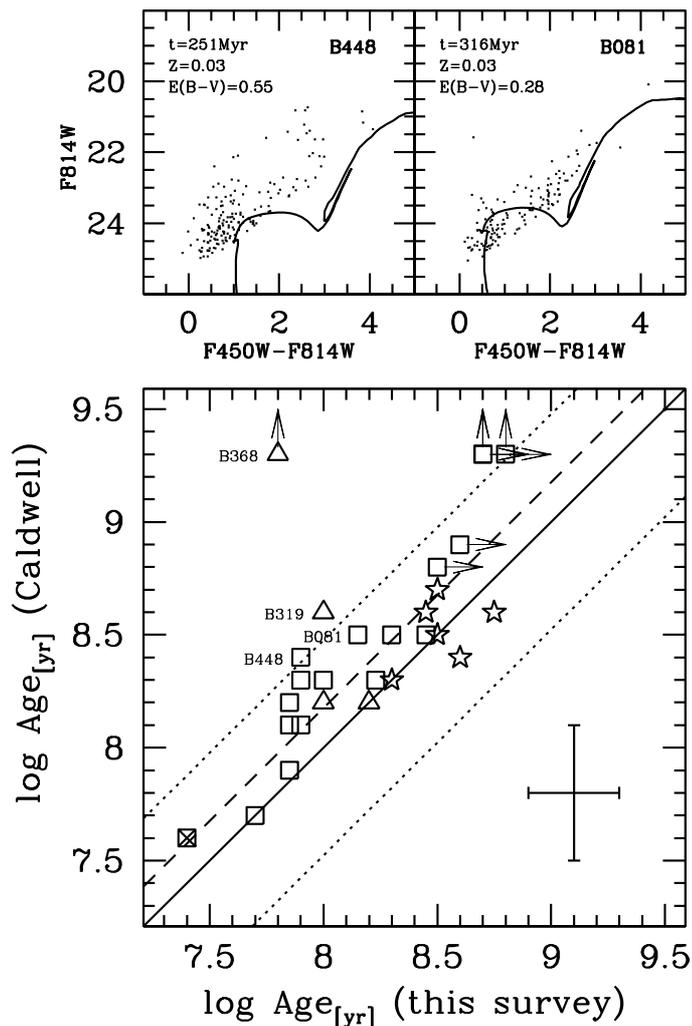
A comparison of the results obtained here from the analysis of our HST-WFPC2 CMDs with those of the extensive and the independent analysis by C09, based on high-quality integrated spectra is clearly worthwhile, in this context.

In the lower panel of Fig. 16, the age estimates from Table 2 are compared with those by C09. The two set of ages do agree within the uncertainties, but there is a clear systematic offset as C09 ages are larger than those listed in Table 2 by a factor of  $\approx 1.5$ , in average, and up to a factor of  $\approx 3$  in the worst case (we are considering only clusters having age estimates in both sets, not lower limits). We note that this systematic offset occurs also if one restricts the sample by WH01, and also to the three clusters for which C09 provides CMD-based age estimates of their own (see their Table 7), hence it is a characteristic feature of their spectroscopic age estimates.

A difference that may produce a systematic offset between our ages and those by C09 is that they adopt super-solar metallicity models ( $Z = 0.04$ ) for all the clusters, while we leave metallicity as a free parameter of our fit and, in fact, we adopt solar or less-than-solar metallicity models in all cases (see Table 2). If both sets of ages were derived from isochrones fitting the effect should be the opposite, i.e. a younger isochrone is required to fit a given CMD with a model of higher metallicity. However it is not clear if this general behavior is shared also by models of integrated spectra.

In the upper panels of Fig. 16 we show the two cases (among those included in our own survey) that display the widest difference between the two age estimates. We superposed on the observed CMDs the isochrones corresponding to the best-fit estimates by C09, corrected by the reddening provided by these authors. The case of B448 shows very clearly that the solution provided by C09 significantly overestimates the reddening, and it is not compatible with the observed CMD. In the case of B081, the comparison suggests that the choice of super-solar metallicity models by C09 may be particularly unsuitable for this cluster, leading to a larger-than-average error in the age estimate.

Two cases of especially remarkable differences occur also with the set by WH01 (open triangles in Fig. 16). B319 = G44 is considered also in Table 7 of C09, where a spectroscopic age of 0.28 Gyr is reported, to be compared to the CMD-based age estimated of 0.10 Gyr by WH01. Moreover the reported spectroscopic value is most probably a typo, as in Table 2 of C09 (their primary source of cluster ages) they report  $\log(\text{age}) = 8.6$  for B319 = G44, corresponding to 0.398 Gyr (the value that is plotted in Fig. 16). In any case, the spectrum appears to be reasonably fitted by a  $Z = 0.04$ , age = 500 Myr model (Caldwell, private communication), while the CMD shown by WH01 is clearly



**Fig. 16.** *Bottom panel:* comparison of the CMD-based ages from Table 2 with the ages obtained by C09 from integrated spectra. The symbols are the same as in Fig. 14. B257D is not plotted because it is not included in the C09 sample. The error bars show the average errors. The vertical arrows indicate clusters defined as “older than 2 Gyr” by Caldwell et al. (2009). The two clusters from our own survey for which the two independent estimates show the greatest difference are labeled (B448 and B081). *Top panels:* comparison of the observed CMD for B448 and B081 with the isochrone corresponding to the age, metallicity and reddening estimates provided by C09 for these clusters (values reported in the upper left corner of each panel). Note that in the case of B448 the reddening estimated by C09 is obviously too large, while in the case of B081, the metallicity assumed by C09 ( $Z = 0.03$  for all the clusters) seems the principal responsible for the mismatch.

not compatible with such an old age. The a-priori assumption of super-solar metallicity models by C09 may also be the origin of this mismatch. The case of B368=G293 (not included in Table 7 of C09), that is classified by C09 as “older than 2 Gyr” while the CMD by WH01 indicates age  $\lesssim 80$  Myr, has to be ascribed to a typographical error by C09; in fact the cluster was not observed by that authors (Caldwell, private communication).

Figure 17 shows the comparison between our estimates of  $E(B - V)$  and those by C09. In this case as well there is reasonable overall agreement, most of the differences being within the uncertainties. The most discrepant case is B448, already discussed above (see Fig. 16). Finally, in Fig. 18 the mass estimates are compared. Also in these cases the two set of estimates agree

**Table 3.** Newly derived masses and dissolution times for the studied clusters.

Name	$\alpha_{J2000}$	$\delta_{J2000}$	$J$	$H$	$K$	log Mass ( $M_{\odot}$ )	$\epsilon$ log Mass ( $M_{\odot}$ )	$t_{\text{diss}}^{\text{Pap-III}}$ (Myr)
B015D-D041	00 <sup>h</sup> 41 <sup>m</sup> 02.74 <sup>s</sup>	+41°06′36.63″	17.03 ± 0.42	15.37 ± 0.27	14.89 ± 0.25	4.2	0.09	112
B040-G102	00 <sup>h</sup> 41 <sup>m</sup> 38.90 <sup>s</sup>	+40°40′54.15″	15.48 ± 0.08	14.90 ± 0.19	14.50 ± 0.15	4.6	0.07	631
B043-G106	00 <sup>h</sup> 41 <sup>m</sup> 42.31 <sup>s</sup>	+40°42′39.86″	15.58 ± 0.07	15.50 ± 0.31	15.08 ± 1.00	4.4	0.10	3467
B066-G128	00 <sup>h</sup> 42 <sup>m</sup> 03.14 <sup>s</sup>	+40°44′48.55″	16.25 ± 0.19	15.81 ± 0.47	16.06 ± 1.00	4.2	0.08	891
B081-G142	00 <sup>h</sup> 42 <sup>m</sup> 13.59 <sup>s</sup>	+40°48′38.96″	14.55 ± 0.05	13.77 ± 0.07	13.76 ± 0.06	5.1	0.04	955
B257D-D073	00 <sup>h</sup> 44 <sup>m</sup> 59.35 <sup>s</sup>	+41°54′47.47″	15.28 ± 0.10	14.77 ± 0.20	15.53 ± 1.00	4.6	0.09	302
B318-G042	00 <sup>h</sup> 40 <sup>m</sup> 00.80 <sup>s</sup>	+40°34′09.06″	16.17 ± 1.00	16.39 ± 0.66	15.49 ± 1.00	3.8	0.29	1905
B321-G046	00 <sup>h</sup> 40 <sup>m</sup> 15.33 <sup>s</sup>	+40°27′45.98″	17.11 ± 0.45	15.88 ± 0.57	15.18 ± 0.29	4.2	0.13	200
B327-G053	00 <sup>h</sup> 40 <sup>m</sup> 24.12 <sup>s</sup>	+40°36′22.38″	14.91 ± 0.07	14.32 ± 0.10	14.14 ± 0.15	4.5	0.06	2754
B376-G309	00 <sup>h</sup> 45 <sup>m</sup> 48.38 <sup>s</sup>	+41°42′39.87″	16.59 ± 0.18	16.07 ± 0.80	16.02 ± 1.00	4.1	0.09	295
B448-D035	00 <sup>h</sup> 40 <sup>m</sup> 36.52 <sup>s</sup>	+40°40′14.94″	16.51 ± 0.34	16.45 ± 1.00	15.66 ± 1.22	4.1	0.16	115
B475-V128	00 <sup>h</sup> 44 <sup>m</sup> 55.92 <sup>s</sup>	+41°54′00.33″	15.10 ± 0.08	14.68 ± 0.12	14.38 ± 0.17	4.7	0.07	1445
V031	00 <sup>h</sup> 41 <sup>m</sup> 12.17 <sup>s</sup>	+41°05′30.21″	14.80 ± 0.06	14.42 ± 1.00	13.77 ± 0.11	4.8	0.10	1230
B083-G146	00 <sup>h</sup> 42 <sup>m</sup> 16.46 <sup>s</sup>	+41°45′20.53″	14.88 ± 0.05	14.62 ± 0.12	14.07 ± 0.13	>4.7	...	...
B222-G277	00 <sup>h</sup> 44 <sup>m</sup> 25.29 <sup>s</sup>	+41°14′11.62″	15.27 ± 0.13	14.41 ± 0.09	14.16 ± 0.08	>4.6	...	...
B347-G154	00 <sup>h</sup> 42 <sup>m</sup> 22.89 <sup>s</sup>	+41°54′27.40″	14.68 ± 0.05	14.17 ± 0.04	14.17 ± 0.18	>4.7	...	...
B374-G306	00 <sup>h</sup> 45 <sup>m</sup> 44.53 <sup>s</sup>	+41°41′55.10″	17.21 ± 0.50	18.50 ± 0.82	16.32 ± 0.84	>3.9	...	...
NB16	00 <sup>h</sup> 42 <sup>m</sup> 33.11 <sup>s</sup>	+41°20′16.48″	14.91 ± 0.09	14.11 ± 0.07	13.46 ± 0.11	>4.8	...	...
<b>P09b</b>								
B049-G112	00 <sup>h</sup> 41 <sup>m</sup> 45.59 <sup>s</sup>	+40°49′54.53″	15.53 ± 0.13	15.27 ± 0.23	14.42 ± 0.06	4.5	0.09	...
B367-G292	...	...	...	...	...	[4.3] <sup>a</sup>	[0.11]	...
B458-D049	00 <sup>h</sup> 41 <sup>m</sup> 44.60 <sup>s</sup>	+40°51′20.40″	16.69 ± 0.35	15.04 ± 0.15	14.96 ± 0.15	4.1	0.15	...
B521	00 <sup>h</sup> 41 <sup>m</sup> 41.80 <sup>s</sup>	+40°52′02.41″	17.32 ± 0.51	16.27 ± 0.43	16.28 ± 0.60	3.9	0.16	...
M039	...	...	...	...	...	[3.8] <sup>a</sup>	[0.16]	...
M050	00 <sup>h</sup> 44 <sup>m</sup> 40.83 <sup>s</sup>	+41°30′09.68″	16.14 ± 0.14	14.90 ± 0.19	15.01 ± 0.31	4.3	0.13	...
<b>WH01</b>								
B315-G038	00 <sup>h</sup> 39 <sup>m</sup> 48.51 <sup>s</sup>	+40°31′30.33″	14.99 ± 0.09	14.49 ± 0.10	14.24 ± 0.09	4.6	0.05	4074
B319-G044	00 <sup>h</sup> 40 <sup>m</sup> 03.03 <sup>s</sup>	+40°33′58.25″	16.30 ± 0.12	15.94 ± 0.47	16.78 ± 0.52	3.9	0.10	182
B342-G094	00 <sup>h</sup> 41 <sup>m</sup> 24.15 <sup>s</sup>	+40°36′48.55″	16.67 ± 0.48	15.57 ± 0.38	16.94 ± 1.00	4.0	0.17	214
B368-G293	00 <sup>h</sup> 44 <sup>m</sup> 47.50 <sup>s</sup>	+41°51′09.39″	15.89 ± 0.27	15.14 ± 0.35	14.60 ± 0.21	4.4	0.08	251

**Notes.** In a few cases the data allowed us to obtain only a lower limit to the mass.  $\alpha_{J2000}$  and  $\delta_{J2000}$  are from 2MASS-6X-PSC catalog,  $J, H, K$  are from  $r = 10''$  ap. phot. in the 2MASS-6X-PSC catalog. Note that  $err_{JHK} = 1.00$  corresponds to  $err_{JHK} = \text{null}$  in the 2MASS-6X-PSC catalog.<sup>(a)</sup> Estimated from Fig. 14, as these clusters lack NIR photometry. These mass estimates will not be used in the following to preserve the homogeneity of the sample.

within the uncertainties ( $1\sigma$  is a factor of 2.4), the strongest discrepancy is to be attributed to the overestimate of the age for B319 = G44 by C09 discussed above.

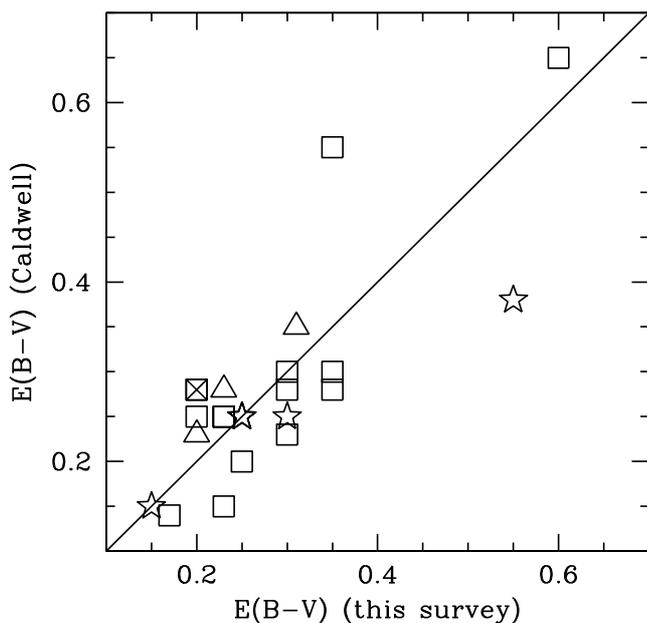
In conclusion, while we are unable to identify the reason of the (modest) systematic overestimate of the ages by C09, it has to be concluded that the agreement between the two independent sets of age, reddening, and mass estimates is quite satisfactory, if the observational uncertainties are taken into the due account.

## 5. Summary and discussion

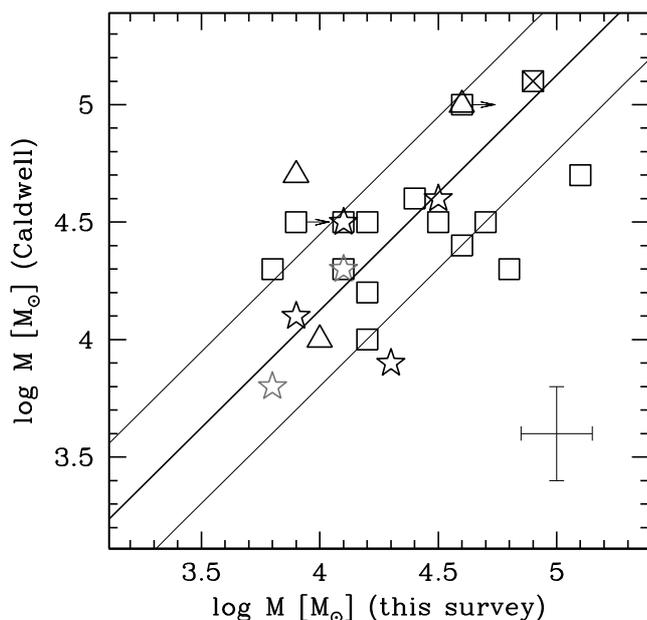
We presented the main results of a survey aimed at the determination of the nature of a sample of 20 candidate YMC in the thin

disk of M 31 (one of which, VdB0, was studied in Pap-I). One of the targets surveyed turned out to be a bright star projected onto the dense disk of M 31, and thus erroneously classified as a possible cluster. All the other targets were revealed to be genuine star clusters and we were able to obtain reliable CMDs for all of them. The main results from our own survey can be summarized as follows:

1. New integrated-light spectroscopy became available for many of our targets since the original selection was performed. Three of them (B083, NB16 and B347) were revealed by the new data to be not good YMC candidates as defined by F05. The CMDs obtained in this study confirms that they are likely old clusters.



**Fig. 17.** Comparison of the  $E(B - V)$  estimates from Table 3 with those by C09. The symbols are the same as in Fig. 14.



**Fig. 18.** Comparison of the masses estimates from Table 3 with those by C09. The symbols are the same as in Fig. 14. The grey symbols show the clusters that have “null” error on  $IR$  magnitudes in the 2MASS-6X-PSC catalog. The thick line is the  $M_{t,s.} = M_{C09}$  locus, the thin lines bracket the  $\pm 1\sigma$  range about this locus. The error bars show the average errors.

2. Among the remaining 17 targets, 16 are genuine clusters and one is in fact a star (NB67), as said above. Thus the fraction of spurious objects in our well-defined sample of BLCC=YMC is just  $1/16 = 6.2\%$ . Even excluding the two clusters considered at point 3., below, the incidence remains below 10%. The extended sample considered in Appendix B fully confirms these results. We must conclude that M31 YMC are not especially plagued by contamination from spurious sources and most of the clusters considered in the

original analysis by F05 should be real<sup>8</sup>. In particular, *asterisms*, suggested as a possible major contaminant of the sample by C06, are in fact found to be not a particular reason of concern, in this context (see also the discussion by C09).

3. Two of the sixteen genuine clusters (B374 and B222) have integrated properties compatible with being YMCs but they do not show a detectable MS in the range of magnitudes sampled by our CMDs. We can provide only an upper limit to the age of these clusters ( $\geq 300$  Myr), but the available data suggest that they are good candidate intermediate-age clusters that indeed would merit follow-up with deeper HST photometry.
4. The fourteen confirmed young clusters (including VdB0, studied in Pap-I) show a clear MS in the range of magnitudes sampled by our CMDs, hence we were able to obtain reliable estimates of their ages, reddenings and (an educated guess of) metallicities by comparison of the observed CMD and LF with theoretical models. Ten of them have ages in the range 25–100 Myr, the other four range between 140 Myr and 280 Myr. The adopted metallicities include  $Z = 0.004$  (one case),  $Z = 0.008$  (three cases), and  $Z = 0.019$  (solar metallicity, ten cases). The estimated reddenings range from  $E(B - V) = 0.06$  to  $E(B - V) = 0.60$ , with  $E(B - V) = 0.20$ – $0.30$  as most typical values.

To increment our final sample of YMC we included ten further clusters for which the age was estimated from their CMDs (obtained from HST imaging) with methods strictly homogeneous with those adopted here, from WH01 and P09b. In this way we assembled a final sample of 24 confirmed young clusters. For 22 of these we were able to obtain reliable estimates of the total stellar mass by coupling our age estimates with the integrated  $J, H, K$  magnitudes taken from the 2MASS-6X catalog. These clusters have masses ranging from  $0.6 \times 10^4 M_{\odot}$  to  $6 \times 10^4 M_{\odot}$ , with an average of  $\sim 3 \times 10^4 M_{\odot}$ <sup>9</sup>. Our estimates of ages and masses are in good agreement with recent independent studies based on integrated light spectra (see also Pap-III for the comparison with the results by Pfalzner 2009).

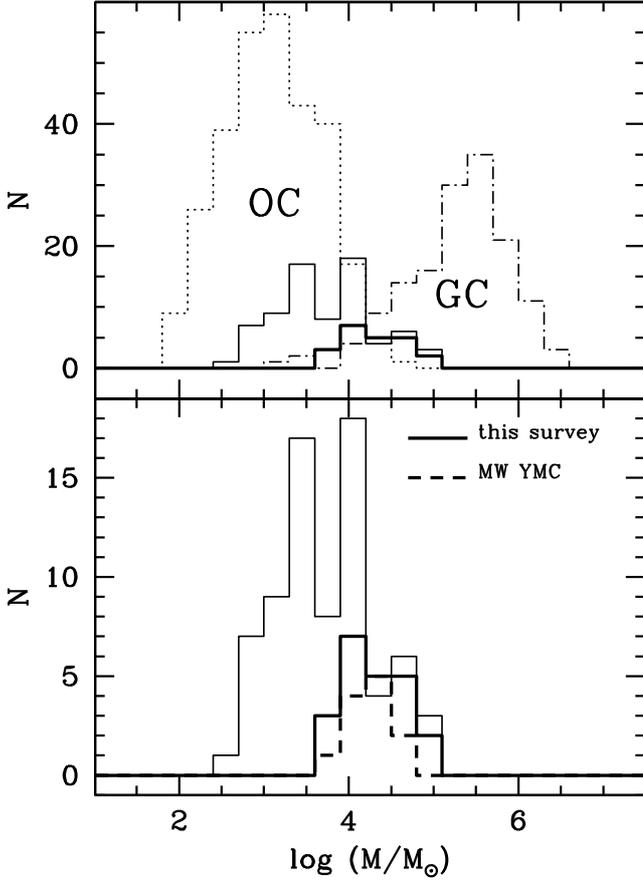
### 5.1. The nature of M31 YMC

In the upper panel of Fig. 19 the mass distribution of our extended sample of M31 YMCs is compared with the distributions of Galactic OCs and GCs (masses from B08). The clusters considered here appear to lie in the middle of the two distributions, overlapping with the high-mass end of the OCs and with the low-mass end of GCs. This comparison provide a further confirmation that the YMCs (=BLCCs) of M31 are indeed more similar to the YMCs of the LMC than to classical OCs of the Milky Way, i.e. the original hypothesis advanced in F05. This is in full agreement with the main conclusions by C09, obtained with a completely independent method (less sensitive to age than ours) on a wider sample.

The lower panel of Fig. 19 compares our clusters with the YMCs seen toward the center of the Milky Way as listed by M09. The two samples have very similar mass distributions, suggesting that they are also similar in nature. An obvious difference between the two sets of clusters was already suggested

<sup>8</sup> It may be useful to stress again that the clusters of our survey were selected among the class  $f = 1$  RBC entries, see Sect. 2 and Galletti et al. (2006a).

<sup>9</sup> The remaining two clusters, that lack NIR photometry, also have masses lying in the same range, according to the estimates obtained using the integrated  $V$  magnitude instead of  $J, H, K$  ones.



**Fig. 19.** *Upper panel:* the mass distribution of the sample of YMC studied here (from Table 3, thick continuous line) is compared with the mass distribution of Galactic OCs (dotted line) and Galactic globular clusters (dashed line). Masses of Galactic clusters are from B08. *Lower panel:* zoomed view of the distribution of M31 YMC compared with the distribution of the YMC of the Milky Way (dashed line; data from M09). The thin line shows the distribution of the M31 YMC sample merged with the sample of OC presented in Pap-II.

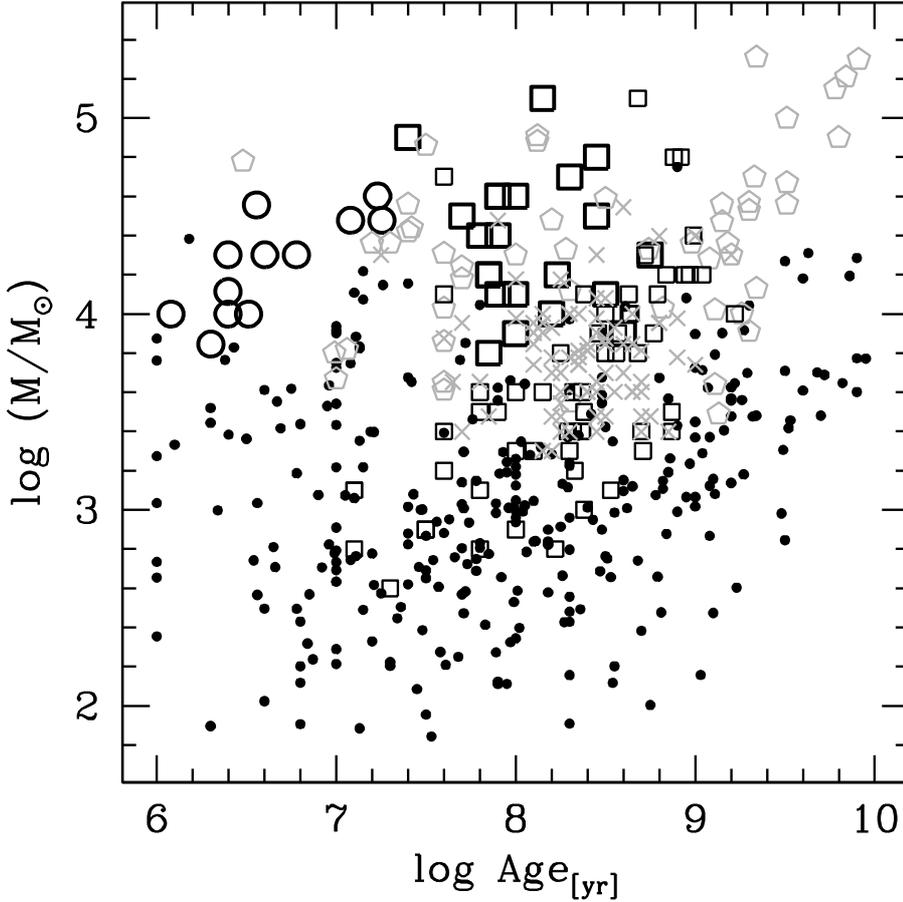
in Pap-I and is confirmed here: the M31 YMCs of our sample are significantly older than the YMC discovered until now in the Galaxy ( $\gtrsim 50$  Myr vs.  $\lesssim 20$  Myr; see below for possible explanations). We confirm that the M31 YMCs studied here have larger sizes (half-light-radii) with respect to their MW counterparts (see Pap-I and Pap-III); this seems in agreement with the age-size relations proposed by Pfalzner (2009; see Pap-III for discussion).

A more thorough comparison between various samples of YMCs is presented in Fig. 20, where Galactic OCs and YMCs, YMCs from M33 (San Roman et al. 2009; for further discussion on M33's star clusters see Sarajedini & Mancone 2007; Zloczewski et al. 2008; Park et al. 2009), the LMC, the Small Magellanic Cloud (McLaughlin & van der Marel 2006), and M31 are plotted together in a log(age) vs. log Mass diagram. Figure 20 is affected by a number of selection effects that deserve to be described in some detail.

1. The minimum mass threshold appears to increase with age (at least for age  $\gtrsim 10$  Myr, see the Galactic OCs if Fig. 20): this is due to the fact that the lower the mass of a cluster, the shorter is its dissolution time, as the cluster is less resilient to all the internal and external effects that may lead to its disruption (Gieles et al. 2007, Pap-III, and references therein).

The minimum mass threshold for samples in external galaxies is obviously due to the inherent magnitude limits.

2. Also the maximum mass threshold increases with age in log Age vs. log Mass plots (Hunter et al. 2003; Gieles 2009; the effect is clearly evident in Fig. 20 if one looks at the MW OCs, that cover the widest range in ages). This general behavior can be easily explained as a simple consequence of varying the sample size as a function of the age bin in the logarithmic scale. Assuming a power-law mass function and a constant cluster formation rate (CFR) the number of cluster per logarithmic age bin increases with age. For an exponent of the power law mass function ( $N(M) \propto M^{-\alpha}$ )  $\alpha = 2$ , that is a reasonable approximation for most of the observed cluster systems,  $\log M_{\max} \propto \log \text{Age}$  (see Gieles 2009, for detailed discussion and references).
3. While the lack of massive ( $M \gtrsim 10^4 M_{\odot}$ ) clusters older than 400 Myr in the Milky Way is probably real, the typical limiting magnitude ( $V \sim 27$ , Rich et al. 2005) of available CMDs of M31 clusters prevent us from drawing firm general conclusions about objects in that age range in M31. The cases of B222 and B374, treated here, are excellent examples of clusters that may populate that region of the diagram but lack a reliable age estimate because the available photometry is too shallow (see Puzia et al. 2005).
4. The lack of massive ( $\log(M/M_{\odot}) > 3.6$ ) M31 clusters younger than 25–50 Myr may be due to the contribution of several biases. First, such young clusters may be hard to select from the RBC as there are no objects bluer than  $(B - V)_0 \approx 0.0$  in the list of confirmed clusters (see F05). This is not surprising as the RBC was intended to be a catalog of globular clusters. Second, for ages  $\leq 8$  Myr the  $H_{\beta}$  index is expected to fall below the threshold adopted to select YMC candidates (see, for example, Fig. 7 of F05), thus (possibly) preventing the selection of these objects for our survey. Third, very young objects should have their luminosity dominated by a few massive stars near their centers, thus leading to objects that may appear more like blended stars than like a star cluster at the distance of M31, even in HST images, thus preventing their inclusions in lists of candidate YMCs. Fourth, it can be hypothesized a positive correlation between the age of the clusters and their height above the disk plane, such that the youngest clusters are more deeply embedded in the thin dust layer of the M31 disk, out of our reach even from our privileged point of view, while most/some of the older clusters would be visible just because they lie above the densest part of that layer. There are indications that this kind of correlation actually holds in our own Galaxy (V.D. Ivanov, private communication).
5. The lack of massive ( $\log(M/M_{\odot}) > 3.6$ ) MW clusters older than 25–50 Myr may also be associated with an observational bias. Galactic YMC have been identified as clumps of bright stars in the near and mid IR and the youngest clusters, having the brightest RSG, are easier to detect in this way. Moreover the sample of Open/YM Galactic clusters is limited (essentially by the effect of interstellar extinction in the Galactic disc) to a volume of a few kpc around the Sun, while M31 (or M33) YMCs can be selected over the whole disk of their parent galaxy, thus introducing a bias that favors the detection of rarer cluster species (massive clusters) in the latter galaxies with respect to the MW.
6. There seems to be a significantly under-dense region in Fig. 20, for masses  $\gtrsim 10^3 M_{\odot}$  and ages between  $\sim 15$  Myr and  $\sim 50$  Myr ( $7.2 \lesssim \log \text{Age} \lesssim 7.7$ ). The same feature was noted by Whitmore et al. (2007) in their study of the



**Fig. 20.** Comparison between Galactic OCs (small filled circles), M31 YMC from the present study (big open squares), MW YMC from M09 (big open circles), M31's clusters from pap-II (small open squares), Magellanic Clouds clusters (grey open pentagons), and M33's clusters (grey crosses) in the  $\log(\text{age})$  vs.  $\log \text{Mass}$  plane. Masses of Galactic OCs are from B08, masses of Magellanic Clouds clusters are from 2006 and masses of M33 clusters are from 2009. For M33 and the Magellanic Clouds only clusters younger than 10 Gyr are shown.

cluster system of the Antennae and it was attributed by a degeneracy in age dating from broad band colors occurring in that age range due to the prompt onset of the RSG phase (see Whitmore et al. 2007, for details, discussion and further references). Virtually all the clusters plotted in Fig. 20 had their ages estimated from the CMD of their stars (instead of broad-band colors, see also Pap-II), hence our sample should not be affected by this bias, at least in principle. However the coincidence of the feature with that noted by Whitmore et al. (2007) suggests that the same kind of bias against ages in that interval may be at work also in Fig. 20.

7. The samples of clusters from all the galaxies involved in Fig. 20 have been selected according to different criteria, by color, magnitude, etc.

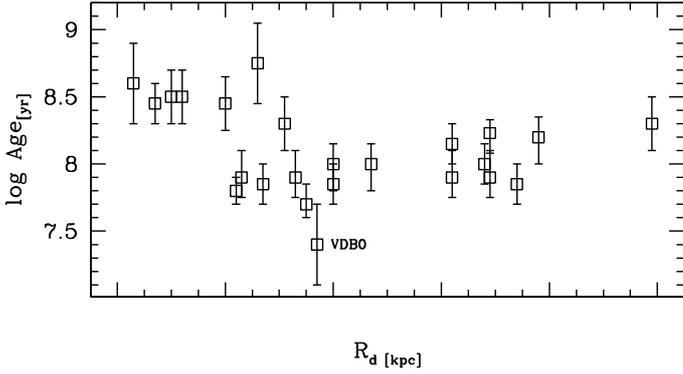
Given all the above considerations, it does not seem possible to draw any firm conclusion from the comparison shown in Fig. 20. The only straightforward conclusion is that *YMCs in the age range 50–500 Myr are relatively common in all the most massive star-forming galaxies of the Local Group* (M31, M33, LMC and SMC). The only exception (the Milky Way) may be ascribable to observational biases, but it cannot be excluded that it is instead (at least partly) associated with intrinsic properties of the Milky Way, that appears peculiar under several aspects with respect to the typical spiral galaxies (and to M31, in particular see Hammer et al. 2007; Yin et al. 2009). As the samples of M33 and M31 should be subject to the same kind of biases (as the distances are similar and the data have been collected with HST in both cases), the difference in the maximum mass limit between the two samples is likely real, and it can probably be ascribed to the difference in total mass between the disks of the two galaxies: larger disks should host more numerous populations of clusters,

thus enhancing the probability of producing clusters with higher (maximum) masses (see Gieles 2009, and references therein).

## 5.2. Radial trends

Given the wealth of data collected for our target clusters, it may be useful to look for correlations between their physical parameters, including their position within the M31 disk. Limiting the analysis to the young clusters (age < 1 Gyr), that constitute a more homogeneous sample of bona fide thin disk objects, it turns out that our sample is still too sparse for a thorough analysis of these correlations. In particular the covered ranges of age, mass and position are quite limited, thus not allowing us to reveal large scale trends, in most cases. Moreover, the adopted approach of CMD analysis provides just an educated guess of the metallicity of the clusters, aimed at obtaining the most reliable estimate of the clusters age, which was the main objective of our analysis. These limitations prevent the possibility of a meaningful study of the radial metallicity gradient with our data. It should also be recalled that the correlations between the structural parameters of the clusters (mass, radius, density etc.) have already been discussed in Pap-III, hence here we consider only age, mass, deprojected galactocentric distance ( $R_d$ ; assuming an inclination of  $i = 12.5^\circ$  of the disk with respect to the plane of the sky, see Simien et al. 1978; Pritchett & van den Bergh 1994),  $X$ ,  $Y$ , and reddening.

Having checked all the combination of parameters, the only correlation that appeared remarkable to us is presented in Fig. 21. It is a trend of decreasing age with galactocentric distance, that seems statistically significant if one considers the associated errors. Given the relatively limited range of galactocentric



**Fig. 21.** Age as a function of the deprojected galactocentric distance for the young clusters (open squares with error bars). The cluster VdB0 has been labeled as it is by far, the youngest of the whole sample.

distance covered, in our view the observed distribution can be interpreted in two ways:

- as a part of a larger trend resulting from an inside-out wave of cluster formation. In this case the trend toward older mean ages should continue at lower radii and Fig. 21 shows the transition between a regime of decreasing age with galactocentric distance and an asymptotic regime of constant age in the outermost fringes of the disk;
- more likely, as a sharp transition in the epoch of the highest rate of star/cluster formation occurring at the onset of the  $R_d \sim 10$  kpc “ring of fire”. This would be consistent with the well known burst of recent star formation that characterizes this prominent structure of the M 31 disk.

While not especially conclusive or insightful, the result shown in Fig. 21 gives a clear idea of how useful YMCs can be as tracers of the structure and evolution of the disk itself, in particular if large and reliable samples can be assembled.

### 5.3. Final remarks

This research has demonstrated that the conspicuous population of bright disk objects studied by F05 consists of genuine YMC, similar to those found in the LMC, SMC and M33 galaxies. These clusters may open a new window to the study of the recent star formation history in the disk of M 31. A systematic analysis over the whole extent of the M 31 disk may provide the opportunity to study a rich system of young clusters using a sample much less affected by selection biases than in our own Galaxy, and to better constrain the models of dynamical evolution of clusters within the disks of spiral galaxies. M 31 YMCs like those studied here provide also an excellent tracer of the disk kinematics in that galaxy, independent of (and in addition to) the HI gas. Recent wide-field surveys (Vancevicius et al. 2009; see also Pap-II) suggest that a rich harvest of genuine YMCs await to be discovered in the disk of our next neighbor giant galaxy in Andromeda.

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## Appendix A: RBC clusters serendipitously imaged in our survey

To ascertain the real nature of candidate M 31 clusters proposed by various authors is a daunting but necessary task to keep cluster catalogs as complete and clean as possible from spurious sources. There are several criteria that may be used to check candidates (see Galletti et al. 2006a, for references and discussion), but resolving them into stars by means of high spatial resolution imaging is by far the safest method of all. In addition to the clusters that were the main target of our survey, and to the low-luminosity clusters identified by Hodge et al. 2009, our WFPC2 images serendipitously included several clusters and candidate clusters listed in the RBC. Inspection of our images allowed us to place their classification on firmer footing. The results of this analysis are summarized in Table A.1. Their classification in the RBC has been modified accordingly. In Table A.1 we report the name of the object (Col. 1, name), the classification flag originally reported in the RBC (Col. 2, f), the name of the cluster that was the original target of the images (Col. 3, field), a flag indicating if the object was imaged with the PC or with one of the WF cameras (Col. 4, chip), and, finally, a comment on its classification as derived from the inspection of the new images. In some cases the classification remains uncertain (comments with “?”). In some cases the image reveals that the object is extended but do not clarify its nature (cluster/galaxy/HII region etc.), in these cases we report the comment “not a star”. An estimate of the radial velocity will suffice to definitely establish if these objects are M 31 clusters or background galaxies (see Galletti et al. 2006a). In some cases, some clusters that were among the main targets of our survey were serendipitously re-imaged in the WF field surrounding other targets. For obvious reasons these cases are not reported in Table A.1. On the other hand some clusters have been serendipitously imaged in two different pointings: in these cases we report the classification derived from both sets of images. Some of the clusters of Table A.1 were independently re-identified in Pap-II (B061D, B319, B014D, B256D, DAO84), for two of them a meaningful CMD was also obtained there (B061D and B319); this lends additional support to the reliability of their classification. Finally, we reported in the table also some clusters whose nature was already confirmed by previous HST imaging, for completeness (see the case of B319 = G044, observed by WH01).

It may be interesting to note that among the 19 RBC class  $f = 2$  (candidate clusters) objects listed in Table A.1, 3 turn out to be real clusters (or likely clusters), 5 are extended objects that lack the  $v_r$  measure needed to ultimately establish their membership to M 31, while 11 are non-clusters (or likely non-clusters), most of them being stars. According to this limited sample it can be concluded that the fraction of genuine M 31 clusters among class  $f = 2$  entries of the RBC ranges from  $\frac{3}{19} = 16\% \pm 14\%$  to  $\frac{8}{19} = 42\% \pm 12\%$ . These numbers should be considered as somewhat pessimistic as they are computed on a sample of clusters projected on the densest regions of the M 31 disk, where the probability of contamination from bright stars of M 31 is at its maximum. To give a rough idea of the number of genuine clusters that are still hidden among the candidates listed in the RBC one can take the 16% of the number of class = 2 RBC entries,

**Table A.1.** RBC clusters serendipitously imaged in our survey.

Name	$f^1$	Field	Chip	Comment
B014D	2	B015D	PC	cluster
B061D	2	NB16	WF	cluster
B256D	2	B257D	WF	cluster <sup>2</sup>
B256D	2	B475	WF	cluster <sup>2</sup>
SK067B	2	B015D	WF	not a star
SK071C	2	B475	WF	not a star
SK185B	2	B475	WF	not a star
B068D	2	NB16	WF	not a star
B068D	2	NB67	WF	not a star
B019D	2	V031	WF	not a star
NB64	2	NB16	WF	star?
NB64	2	NB67	WF	star?
SK091B	2	B066	WF	star
B048D	2	B081	PC	star
SK091C	2	B374	WF	star
SK188B	2	B475	WF	star
NB47	2	NB16	WF	star
SK083B	2	B043	WF	2 stars + nebula?
B057D	2	NB16	WF	2 stars
NB43	2	NB67	WF	2 stars
B192D	2	B327	WF	galaxy
SK194C	2	B376	WF	galaxy
B376	1	B374	WF	cluster
B257D	1	B475	WF	cluster
B319	1	B318	WF	cluster
DAO84	1	B374	WF	not a star <sup>3</sup>
DAO84	1	B376	WF	not a star <sup>3</sup>
SK047A	1	B081	WF	two stars
NB68	6	NB16	WF	star?
NB68	6	NB67	WF	star?
B113	6	NB16	WF	star?
SK069D	6	B083	WF	star
B185D	6	B318	PC	star
SK046D	6	B327	WF	star
B065D	6	NB67	WF	star
SK041D	6	B321	WF	two stars
B121	3	NB16	WF	star?
B121	3	NB67	WF	star

**Notes.** <sup>(1)</sup>  $f$  is the original RBC classification flag (1 globular cluster, 2 candidate globular cluster, 3 controversial object, 6 star/s). <sup>(2)</sup> While the visual inspection of the images does not permit a clear cut classification, the objective analysis performed in Pap-II recognizes B256D as a star cluster. <sup>(3)</sup> DAO84 has a radial velocity estimate that clearly identifies it as a member of M 31 (see the RBC).

i.e.  $0.16 \times 1049 \approx 168$ . A significant fraction of these may be YMCs ( $\geq 15\%$ , according to F05).

Considering the objects listed in Tables 1 and A.1, the survey images allowed us to verify the nature of 25 objects classified as genuine clusters (class  $f = 1$ ) in the RBC. We confirm that 23 of them are real clusters while 2 are (one or two) stars. From this number one can estimate the fraction of spurious sources among class  $f = 1$  RBC entries as  $\frac{2}{25} = 8\% \pm 8\%$ , that is remarkably low and is in excellent agreement with the estimate by G09 that finds  $\lesssim 4\%$  from a sample of 252 objects.

Considering the fraction of real clusters among class  $f = 1$  entries as 92% and that among  $f = 2$  entries as 16%, the expected number of genuine M 31 clusters in the RBC (GC+YMC) is estimated as  $\sim 630$ , while the number of old clusters (GCs)

should be  $\sim 530$ , in reasonable agreement with the results by Barmby et al. 2000 and F05. Note that, at present, the number of confirmed (likely) old clusters ( $f = 1$  and  $y = 0$ ) in the RBC is 418; correcting this for contamination leads to 384 bona-fide GCs, more than double than the number of GCs encountered in the Milky Way galaxy ( $\approx 150$ , Harris 1996).

## Appendix B: Other candidate M 31 YMCs with archival HST imaging

Before selecting the actual targets for our survey we searched the HST archive for YMC candidates, as listed in Table 1 (or Table 2) of F05, that had already been (serendipitously) imaged from HST. As the nature of these objects (cluster/asterism/star) can be determined from existing images they were not included in our final list of targets. In Table B.1 (referring to objectively selected candidates from Table 1 of F05) and Table B.2 (referring to candidates suggested from various authors adopting different criteria, from Table 2 of F05) we list the results of that research. In these tables we report: (1) the cluster name(s); (2) the HST program number(s) of the retrieved images; (3) the instrument(s); and (4) the filter(s) used to obtain the inspected images; (5) the classification of the object based on the inspection of the HST images, following the approach adopted in Table A.1, above, and, finally; (6) the classification provided by C09 based on their spectra and/or on ground-based imaging (S indicates that the objects was classified by from its spectrum, I indicates that the object was classified with imaging, SI means that both imaging and spectrum were considered for the classification, according to C09). At the epoch when the table was compiled (September 2009), 36 out of the 66 objects listed in Table 1 of F05 (including those studied in this paper) had one (or more) images in the HST archive: 34 of them are recognized as *real* star clusters from the inspection of the available HST images, while 2 are stars. This leads to a fraction of spurious objects in the sample of  $5.5\% \pm 4.0\%$ , in full agreement with the fraction we obtained from our original sample (Sect. 2). Analogously, 14 out of 21 objects listed in Table 2 of F05 (including those studied in this paper) had one (or more) image(s) in the HST archive: 13 of them are recognized as *real* star clusters from the inspection of the available HST images, while 1 is a star. This leads to a fraction of spurious objects in the sample of  $7.1\% \pm 7.4\%$ , again in full agreement with the fraction we obtained from our original sample (Sect. 2) and with the above results. Note that (a) all the classifications we obtained from HST imaging confirm those independently obtained by C09 for the same objects, and (b) all the objects listed in Table B.2. were classified as clusters by some other author before (see F05).

Of the 37 objects in Tables B.1 and B.2 lacking HST-based classification, 31 are classified as *clusters* by C09; the remaining 6 have uncertain classification. Coupling the results from HST and C09 it turns out that 60 of the 66 objects from Table 1 of F05 are real clusters, two are stars, and four have uncertain classification; 18 of the 21 objects from Table 2 of F05 are real clusters, one is a star, and two have uncertain classification. We thus conclude that the large majority ( $\geq 90\%$ ) of the objects identified (or proposed) by F05 as (possibly) young clusters are indeed genuine star clusters. Finally, three clusters listed in the RBC but not comprised in the study by F05 where found in Pap-II to have age  $< 1$  Gyr (B014D, B061D, B256D).

**Table B.1.** Classification of candidate young clusters listed in Table 1 of F05.

Name	Obs-ID	Camera	Filters	Class HST	Class C09
B008-G060	10 407	ACS/WFC	<i>F606W F435W</i>	cluster	cluster(SI)
B028-G088					cluster(SI)
B040-G102	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B043-G106	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B047-G111					cluster(S)
B049-G112	10 407(10631)	ACS/WFC	<i>F435W F606W</i>	cluster	cluster(SI)
B057-G118	10 407(10631)	ACS/WFC	<i>F435W F606W</i>	cluster	cluster(SI)
B066-G128				cluster	cluster(SI)
B069-G132	10 273	ACS/WFC	<i>F555W F814W</i>	cluster	cluster(SI)
B074-G135					cluster(S)
B081-G142	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B083-G146	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(S)
B091-G151	10 273	ACS/WFC	<i>F555W F814W</i>	cluster	cluster(SI)
B114-G175	5907	WFPC2	<i>F555W F814W</i>	cluster	cluster(SI)
B160-G214	9480(10273,7426)	ACS/WFC, WFPC2	<i>F775W F555W F814W F606W</i>	cluster	cluster(SI)
B170-G221					cluster(SI)
B210-M11	9709	WFPC2	<i>F606W</i>	cluster	cluster(SI)
B216-G267					cluster(SI)
B222-G277	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B223-G278					cluster(SI)
B237-G299					cluster(SI)
B281-G288					cluster(SI)
B295-G014					cluster(S)
B303-G026					cluster(SI)
B307-G030					cluster(SI)
B314-G037					cluster(SI)
B315-G038	8296	WFPC2	<i>F336W F439W F555W</i>	cluster	cluster(SI)
B318-G042	8296(10818)	WFPC2	<i>F336W F439W F450W F555W F814W</i>	cluster	cluster(SI)
B319-G044	8296	WFPC2	<i>F336W F439W F450W F555W F814W</i>	cluster	cluster(SI)
B321-G046	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B322-G049					cluster(SI)
B327-G053	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B331-G057	6699	WFPC2	<i>F555W F814W</i>	cluster	cluster(SI)
B342-G094	8296	WFPC2	<i>F336W F439W F555W</i>	cluster	cluster(SI)
B354-G186					cluster(S)
B355					possible star(S)
B358-G219					candidate
B367-G292	10 407	ACS/WFC	<i>F435W F606W</i>	cluster	cluster(SI)
B368-G293	8296	WFPC2	<i>F336W F439W F555W</i>	cluster	cluster(I)
B374-G306	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B376-G309	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B380-G313					cluster(SI)
B431-G027					cluster(SI)
B443-D034					cluster(SI)
B448-D035	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)

**Table B.1.** continued.

Name	Obs-ID	Camera	Filters	Class HST	Class C09
B451					possible star(I)
B453-D042					cluster(SI)
B458-D049	10 407	ACS/WFC	<i>F435W F606W</i>	cluster	cluster(SI)
B475-V128	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B480-V127					cluster(SI)
B483-D085					cluster(SI)
B484-G310					cluster(SI)
B486-G316					cluster(S)
B189D-G047					cluster(SI)
VDB0-B195D	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
NB21-AU5	10 006	ACS/WFC	<i>F435W</i>	cluster	cluster(SI)
NB67	10 818	WFPC2	<i>F450W F814W</i>	star	star(SI)
NB83	5907	WFPC2	<i>F555W F814W</i>	star	star(SI)
B006D-D036					cluster(SI)
B012D-D039					cluster(SI)
B015D-D041	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B111D-D065	9794	WFPC2	<i>F336W F439W F555W F675W F814W</i>	cluster	cluster(SI)
B206D-D048					cluster(SI)
B257D-D073	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(I)
DAO47					cluster(SI)
V031	10 818(9709)	WFPC2	<i>F450W F606W F814W</i>	cluster	cluster(SI)

**Table B.2.** Classification of candidate young clusters listed in Table 2 of F05.

Name	Obs-ID	Camera	Filters	Class HST	Class C09
B015-V204					cluster(SI)
B030-G091	6671	WFPC2	<i>F555W F814W</i>	cluster	cluster(SI)
B090	10 260	ACS/WFC	<i>F606W F814W</i>	cluster	cluster(SI)
B101-G164					cluster(SI)
B102	10 260	ACS/WFC	<i>F606W</i>	star	star(SI)
B117-G176	9087	WFPC2	<i>F336W</i>	cluster	cluster(SI)
B146	10118(5435)	ACS/WFC, WFPC2	<i>F160BW F255W F300W F814W</i>	cluster	SLH
B154-G208	9087	ACS/WFC	<i>F435W</i>	cluster	cluster(SI)
B164-V253					cluster(SI)
B197-G247					cluster(SI)
B214-G265					cluster(SI)
B232-G286	8059	WFPC2	<i>F300W F450W F606W F814W</i>	cluster	cluster(SI)
B292-G010	10 631	ACS/WFC	<i>F435W F606W</i>	cluster	candidate
B311-G033	6671(11081)	WFPC2	<i>F555W F606W F814W</i>	cluster	cluster(SI)
B324-G051	6699	WFPC2	<i>F555W F814W</i>	cluster	cluster(SI)
B328-G054	6699	WFPC2	<i>F555W F814W</i>	cluster	cluster(SI)
B347-G154	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(S)
B423	idate				candidate
B468	5112	WFPC2	<i>F555W F814W</i>	cluster	cluster(I)
NB16	10 818	WFPC2	<i>F450W F814W</i>	cluster	cluster(SI)
B150D					candidate

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