ACCESS: NIR luminosity function and stellar mass function of galaxies in the Shapley supercluster environment

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ABSTRACT

We present the near-infrared luminosity and stellar mass functions (SMFs) of galaxies in the core of the Shapley supercluster at $z = 0.048$, based on new $K$-band observations carried out at the United Kingdom Infrared Telescope with the Wide Field Infrared Camera in conjunction with $B$- and $R$-band photometry from the Shapley Optical Survey, and including a subsample ($\sim 650$ galaxies) of spectroscopically confirmed supercluster members. These data sets allow us to investigate the supercluster galaxy population down to $M_K^* + 6$ and $M = 10^{8.75} \, M_\odot$.

For the overall 3 deg$^2$ field, the $K$-band luminosity function (LF) is described by a Schechter function with $M_K^* = -24.96 \pm 0.10$ and $\alpha = -1.42 \pm 0.03$, a significantly steeper faint-end slope than that observed in field regions. We investigate the effect of environment by deriving the LF in three regions selected according to the local galaxy density and observe a significant ($2\sigma$) increase in the faint-end slope going from high-density ($\alpha = -1.33$) to low-density ($\alpha = -1.49$) environments, while a faint-end upturn at $M_K > -21$ becomes increasingly apparent in the lower density regions. The galaxy SMF is fitted well by a Schechter function with $\log_{10}(M^*) = 11.16 \pm 0.04$ and $\alpha = -1.20 \pm 0.02$. The SMF of supercluster galaxies is also characterized by an excess of massive galaxies that are associated with the brightest cluster galaxies. While the value of $M^*$ depends on the environment, increasing by 0.2 dex from low- to high-density regions, the slope of the galaxy SMF does not vary with the environment. By comparing our findings with cosmological simulations, we conclude that the environmental dependences of the LF are not primarily due to variations in the merging histories, but to processes which are not treated in the semi-analytical models, such as tidal stripping or harassment. In field regions, the SMF shows a sharp upturn below $M = 10^9 \, M_\odot$, close to our mass limit, suggesting that the upturns seen in our $K$-band LFs, but not in the SMF, are due to this dwarf population. The environmental variations seen in the faint end of the $K$-band LF suggest that these dwarf galaxies, which are easier to strip than their more massive counterparts, are affected by tidal/gas stripping upon entering the supercluster environment.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Shapley supercluster – galaxies: evolution – galaxies: photometry – galaxies: luminosity function, mass function – galaxies: stellar content.

1 INTRODUCTION

The properties and evolution of galaxies are strongly related to their environment (e.g. Blanton et al. 2005a; Rines et al. 2005; Baldry et al. 2006), through the mass and merging histories of their host dark matter haloes, and the impact of different physical mechanisms (e.g. Treu et al. 2003) that are linked in various ways to the local galaxy density and the properties of the intergalactic medium. In the local Universe this environmental dependence has been investigated and observed in the distribution of galaxy luminosities and stellar masses, providing constraints on the assembly of galaxies over cosmic time (see below).

Since the near-infrared (NIR) light is dominated by established stellar populations rather than by recent star formation activity, the NIR luminosity function (LF) can be considered as a reliable estimator of the stellar mass function (SMF; Gavazzi, Pierini &
Balogh et al. (2001) investigated the dependence of the infrared galaxy LF and the associated galaxy SMF on the environment and spectral type by means of the 2MASS and Las Campanas Redshift Survey (LCRS; Shectman et al. 1996) for galaxies brighter than $M_I = -19$ mag. In field environments, the LF of galaxies with emission lines turns out to have a much steeper faint-end slope ($\alpha = -1.39$) compared to that of galaxies without emission lines ($\alpha = -0.59$). On the other hand, in the cluster environment, even the non-emission line galaxies have a steep faint-end LF ($\alpha = -1.22$). This difference is almost entirely due to the non-emission line galaxies which dominate the cluster population and present a slope close to that of the overall field. Thus, they suggested that the cluster population is built up by accreting field galaxies with little effect other than the cessation of star formation. Differences in the shape of the LF for late- and early-type cluster galaxies have been found by Huang et al. (2003), the late-type galaxies having a systematically fainter $M^*$ and steeper faint-end slope. A possible faint-end upturn in the $H$-band LF was already suggested by De Propris et al. (1998; see also Andreon & Pelló 2000) for the Coma cluster outlining the steep trend of dwarf galaxies down to $M^*+5$, even if they did not provide a precise estimate of the faint-end slope because of possible field contaminations. An increase in the faint-end slope of Coma was recently observed at 3.6 $\mu$m by Jenkins et al. (2007) indicating a large number of faint red galaxies. However, Rines & Geller (2008) found no such upturn for Virgo, based on a fully spectroscopically confirmed sample, and suggested that many of the photometrically selected red sequence galaxies which contribute to the upturns seen in other clusters are background galaxies.

Finally, the tight correlation between the total galaxy NIR luminosity and the cluster binding mass (Lin, Mohr & Stanford 2003, 2004; Ramella et al. 2004) allows us to probe that the global $K$-band M/L decreases with the cluster radius (Rines et al. 2004), showing that the environment affects the shape of the LF also within the clusters.

We note that most of the previous works are based on the 2MASS data which have a detection sensitivity (10$\sigma$) of $K = 13.1$ mag for extended sources (Cole et al. 2001; $K = 13.57$ mag according to Bell et al. 2003), limiting studies of the environmental impact on the NIR LF to only a sample of local clusters (e.g. Virgo) or limiting to magnitudes of $-M^* + 2$ (e.g. Rines et al. 2004). However, the dominant processes that quench star formation, and therefore transform galaxies, depend crucially on the galaxy mass (e.g. Haines et al. 2006a, 2007), and the strong bimodality in the properties of galaxies about a characteristic stellar mass of $\sim 3 \times 10^{10} M_\odot$ ($\sim M^* + 1$; Kauffmann et al. 2003) implies fundamental differences in the formation and evolution of giant and dwarf galaxies (e.g. Keres et al. 2005; Dekel & Birnboim 2006). This issue needs data sets reaching much fainter luminosities than those of the 2MASS to be investigated in order to obtain, in general, an overall picture of galaxy evolution and, in particular, to establish the contribution of the dwarf galaxy population to the total stellar mass in the local universe and the physical origin of the faint-end upturn claimed. The recent development of wide-field NIR imagers on 4-m class telescopes such as United Kingdom Infrared Telescope (UKIRT)/Wide Field Infrared Camera (WFCAM) and KPNO/NEWFIRM has opened the possibility of NIR surveys to be more sensitive covering many square degrees (e.g. UKIRT Infrared Deep Sky Survey (UKIDSS)), allowing the $K$-band LF of nearby clusters to be obtained covering not only the cluster cores, but also the entire virialized regions.

In this context, we study the $K$-band LF of the Shapley supercluster core (SSC) down to the dwarf regime (reaching $\sim M^* + 6$) with the aim of (i) quantifying the environmental impact on the shape.
of the NIR LF, (ii) deriving the stellar masses of the supercluster galaxies and (iii) investigating the mechanisms driving galaxy evolution as function of the galaxy mass. This work is carried out in the framework of the joint research programme A Complete Census of Star-formation and nuclear activity in the Shapley Supercluster (ACCESS) aimed at determining the importance of cluster assembly processes in driving the evolution of galaxies as a function of galaxy mass and environment within the Shapley supercluster (see Section 2). In Section 3, we describe the data sets. In Section 4, we derive the NIR galaxy LFs obtained through background subtraction in the whole observed field and we study the ongoing effects of environment by comparing the LFs of galaxies in three different regions of the supercluster, characterized by high, intermediate and low densities, respectively; we also compare NIR and optical LFs. The galaxy SMF is presented in Section 5. The results are discussed in Section 6, and the summary and conclusions of this work are given in Section 7.

Throughout the paper, we adopt a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. According to this cosmology, 1 arcmin corresponds to 60 kpc at $z = 0.048$ and the distance modulus is 36.66.

2 THE ACCESS PROJECT

ACCESS (PI: P. Merluzzi) is a project whose aim is to distinguish among the mechanisms which drive galaxy evolution across different ranges of mass examining how, when and where the properties of galaxies are transformed by their interaction with the environment. Since the most dramatic effects of environment on galaxy evolution should occur in superclusters, where the infall and encounter velocities of galaxies are greatest ($>1000 \, \text{km s}^{-1}$), groups and clusters are still merging, and significant numbers of galaxies will be encountering the dense intracluster medium (ICM) of the cluster environment for the first time; we choose to study the core region of the Shapley supercluster (Shapley 1930). The SSC is the richest and most dynamically active region in the local Universe and hence represents a unique laboratory for studying the effects of the hierarchical assembly of structures on galaxy evolution.

The multiwavelength data set available for this project includes panoramic imaging in UV [Galaxy Evolution Explorer (GALEX); PI: R. J. Smith], optical [European Southern Observatory (ESO) Wide Field Imager (WFI) archive data], NIR (UKIRT/WFCAM; PI: R. J. Smith) and mid-infrared (Spitzer; PI: C. P. Haines), all of which cover at least a 2 degree$^2$ area of the SSC (see Fig. 1). Furthermore, high signal-to-noise ratio (S/N) medium-resolution optical spectroscopy (AAOmega; PI: R. J. Smith) was obtained for a sample of 541 galaxies in the SSC field (Smith, Lucey & Hudson 2007, 2009), of which 448 are supercluster members ($0.039 < z < 0.056$). For this sample, 371 galaxies have $B$, $R$ and $K$ photometry. The spectroscopic sample is enlarged to $\sim650$ galaxies with published data, NASA Extragalactic Database for bright objects, and 6dF data. New medium-resolution integral-field spectroscopy will be provided by the Wide Field Spectrograph (WiFeS; Dopita et al. 2007) at the Australian National University 2.3-m telescope.
A large programme of WiFeS observations (PI: M. Dopita and P. Merluzzi) started in 2009 April. Finally, archive X-ray and radio data are also available. The depth (e.g. $B = 22.5$ mag, $R = 22$ mag, $K = 18$ mag) and a high S/N of the data allow the investigation of the photometric and spectroscopic properties of supercluster galaxies well into the dwarf regime (e.g. Mercurio et al. 2006, hereafter MMH06; Gargiulo et al. 2009).

The main scientific goals of ACCESS are to search for the ram pressure effects, to probe galaxy merging and galaxy harassment and ‘suffocation’, to determine the frequency and the radial distribution of cluster AGN, to obtain a statistical census of obscured star formation in cluster galaxies, to correlate obscured star formation with hierarchical cluster assembly, to compare mid-IR, optical, radio and UV star formation indicators, and to investigate the Fundamental Plane of low-mass early-type galaxies. Partners of this collaboration are the Universities of Durham and Birmingham (UK), the Italian National Institute of Astrophysics with the Observatory of Capodimonte and the Australian National University (FP7-PEOPLE-IRSES-2008, grant agreement no. 230634).

3 THE DATA

The new NIR data analysed in this paper are complemented by panoramic $B$- and $R$-band imaging from the Shapley Optical Survey (SOS; MMH06; Haines et al. 2006h, hereafter HMM06). In Fig. 1, the optical and NIR survey are superimposed. In the following, we describe the two surveys and their data products.

3.1 The Shapley Optical Survey

The SOS comprises wide-field $B$- and $R$-band imaging covering a 2.0 deg$^2$ region towards clusters A3562, A3558 and A3556 which form the core of the Shapley supercluster at $z \sim 0.05$.

The observations were carried out with the WFI camera, a mosaic of eight $2046 \times 4098$ pixel CCDs giving a field of view of $34 \times 33$ arcmin$^2$, and mounted on the Cassegrain focus of the 2.2-m MPG/ESO telescope at La Silla. The survey is made up of eight contiguous fields, each with total exposure times of $1500$ s in the $B$ band and $1200$ s in the $R$ band, and typical full width at half-maxima (FWHMs) of 0.7–1.0 arcsec. The data were retrieved from the ESO archive and reduced using the ALAMpics pipeline (version 1.0; Vandame 2004) and calibrated to the Johnson–Kron–Cousins photometric system using the observations of Landolt (1992) standard stars. The sources are then extracted and classified using SExtractor (Bertin & Arnouts 1996), resulting in galaxy catalogues which are both complete and reliable (i.e. free of stars) to $R = 22.0$ mag and $B = 22.5$ mag. A full description of the observations, data reduction and production of the galaxy catalogues is described in MMH06.

3.2 The $K$-band survey

The $K$-band survey of the SSC was carried out at the UKIRT with the WFCAM in 2007 April. The WFCAM instrument consists of four $2048 \times 2048$ Rockwell detectors with a pixel scale of 0.4 arcsec. The four detectors are spaced by 94 per cent of their active area. A single exposure covers an equivalent area of 0.19 deg$^2$ and four interleaved exposures are required to achieve a filled tile of 0.865 on a side (0.78 deg$^2$). We observed a mosaic of five complete tiles, covering a 3.043 deg$^2$ (of which $\sim 2$ deg$^2$ overlap with the SOS) region centred on the SSC, which comprises three Abell clusters A3556, A3558 and A3562 and two poor clusters SC 1327–312 and SC 1329–314, as shown in Fig. 1. The total exposure time for each field is 300 s, reaching $K = 19.5$ mag at 5$\sigma$, with typical FWHMs of 0.9–1.2 arcsec.

The data were pipeline processed at WFCAM Science Archive (WSA)/Cambridge Astronomy Survey Unit, reducing the frames and performing astrometric and photometric calibration with respect to the 2MASS (Irwin et al. 2004). The zero-point uncertainty is $0.015$ mag and astrometry accuracy is $< 0.1$ arcsec (Irwin et al. 2004).

For each frame, a photometric catalogue was derived by using SExtractor (Bertin & Arnouts 1996). We measured magnitudes within a fixed aperture of 17 arcsec diameter, corresponding to $\sim 8$ kpc at $z \sim 0.05$, and Kron (Kron 1980) magnitudes, for which we used an adaptive aperture with diameter $a \cdot r_{\text{Kron}}$, where $r_{\text{Kron}}$ is the Kron radius and $a$ is a constant. We chose $a = 2.5$, yielding $\sim 94$ per cent of the total source flux within the adaptive aperture (Bertin & Arnouts 1996). We measured the Kron magnitude for all the objects in the catalogue and adopted it as the total magnitude. LFs were computed by means of Kron magnitudes, while aperture magnitudes were used for measuring galaxy colours. Since we derive galaxy colours using the same apertures at both optical and NIR wavelengths, we checked the effects of seeing variations among the wavebands by degrading the $R$-band image to the seeing of the $K$-band image. Comparing the aperture magnitudes in the original and the degraded image, we find a difference which is an order of magnitude lower than the photometric error, as expected since the aperture is large compared to the seeing.

Particular care is needed to avoid stellar contamination due to the high number density of both stars and galaxies in this field (the Galactic latitude of this field is $+30^\circ$) which increases the frequency of star–star and star–galaxy blends that can be misclassified as a single galaxy. For the star/galaxy classification, we make use of the optical photometry when available in the sense that objects observed in both $R$ and $K$ bands were classified as stars and galaxies according to the $R$-band classification.\(^6\) As shown in table 3 of MMH06, at $R = 20.0–20.5$ mag, only 2 per cent of the stars were misclassified as galaxies. According to the typical $R - K$ colour of early-type galaxies at $z \sim 0.05$ (Poggianti 1997), this magnitude range corresponds to $K \sim 17.5–18.0$ mag. The contamination of misclassified stars is taken into account in the galaxy LF determination. For those objects observed in the $K$ band having no optical magnitude measurement, we use the distribution of sources in the stellarity index (SI) parameter of SExtractor versus Kron magnitude ($K$) diagram to separate stars and galaxies. We classified as stars those objects whose SI value is larger than a given threshold: $SI_{\text{lim}} = 0.8$. This value of $SI_{\text{lim}}$ has been chosen by adding simulated stars and galaxies to the $K$-band images and measuring their SI and $K$ parameters by means of SExtractor, in the same way as for real sources. Simulated stars and galaxies were randomly generated in a magnitude range of $K = 12–20$ mag using software 2dPHOT (La Barbera et al. 2008).

The completeness of the $K$-band catalogue was estimated by measuring the percentage of simulated galaxies and stars which are recovered by SExtractor as a function of the $K$-band magnitude. The completeness function was found to be strongly dependent on the source density and is therefore different for each $K$-band frame. In fact, in high-density regions the catalogue is $\sim 65$ and

\(^6\)The $R$-band WFI mosaic is the deepest and highest resolution data obtained for this project, reaching $M^* + 7$, and is therefore generally used as reference for our multiwavelength surveys.

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~50 per cent complete at $K = 17.5$ mag and $K = 18.0$ mag, respectively, while in low-density regions it is ~100 and ~80 per cent complete at $K = 17.5$ mag and $K = 18.0$ mag, respectively. We correct galaxy counts using a different completeness function for each $K$-band frame, i.e. by taking both the crowdedness and magnitude effects fully into account for each galaxy, when determining its contribution to the counts in a given magnitude bin. By weighting each galaxy by the locally estimated completeness of the survey, we are able to obtain unbiased comparisons of the galaxy counts in different environments. Since in the high-density region the completeness is less than 50 per cent beyond $K = 18.0$ mag, we adopted this conservative limit as the magnitude to which the catalogues can be reliably corrected for incompleteness when determining the galaxy LF. At this limiting magnitude, the accuracy of the completeness functions is better by 5 per cent and is taken into account in the error budget of each galaxy. The final catalogues consist of 18,534 galaxies with $K \leq 18$ mag.

4 NIR LUMINOSITY FUNCTIONS

The $K$-band galaxy LF of the SSC has been derived down to the magnitude limit $K = 18$ mag accounting for interlopers by the statistical subtraction of the background contamination. We chose this approach since we do not have spectroscopic information complete for whole of the galaxy sample in the magnitude range considered (being ~90 per cent complete for $R < 16$ mag or $K < 13.5$), and the available photometry ($B$, $R$ and $K$ bands) does not allow us to derive accurate photometric redshifts. The number counts in the supercluster field have been obtained by weighting each galaxy’s contribution to a given magnitude bin according to its completeness. We also correct for the contamination of the misclassified stars. Absolute magnitudes were determined using the k- and evolutionary corrections for early-type galaxies at $z \sim 0.05$ from Poggianti (1997). The large observed area and the depth of the survey are suitable for investigating the effects of environment within the supercluster.

4.1 Background galaxy subtraction

Since the area covered by the SSC observations lies completely within the overdensity corresponding to the core complex, it is not possible to use the outer regions of the survey to estimate the background/foreground contribution to the galaxy counts. Therefore, we performed the statistical subtraction of field galaxies by means of a control field observed with the same instrument at a suitable depth. A similar or larger area is necessary in order to reduce the effects of field-to-field variance and small number statistics.

To this aim, we chose the UKIRT Infrared Deep Sky Survey (UKIDSS) Deep Extragalactic Survey (DXS; Lawrence et al. 2007) which aims to map 35 deg$^2$ of sky to a magnitude limit of $K = 20.8$ mag at 5σ. Since our $K$-band photometry is 50 per cent complete down to $K = 18.0$ mag, the UKIDSS DXS data are suitable to estimate field galaxy counts.

The background contamination was estimated from three control fields from the UKIDSS DXS third data release (Warren et al., in preparation) reaching the required depth. In particular, we considered 24 multiframes of ~0.19 deg$^2$, covering a total area of ~4.55 deg$^2$ over three regions of sky (Table 1), with exposure times of $\geq 360$ s in $K$. We note that this area is significantly larger than that covered by any published table of galaxy counts reaching $K = 18$ or deeper, the surveys of Väisänen et al. (2000) and Kümmel & Wagner (2001) limited to areas of ~0.9 deg$^2$, and reaching just $K = 17–17.5$. The $K$-band catalogues were obtained from the WSA (Hambly et al. 2008), selecting from the dxsDetection table the isolated (pprbits $\leq$ 1) objects with non-stellar morphologies (class = 1).

Since we have accounted statistically for the incompleteness effects in the $K$-band survey (see Section 3.2), we can subtract the control field counts from those obtained in the Shapley area in order to obtain supercluster member counts. In this case, following Bernstein et al. (1995) the background counts are estimated as the mean of the control field counts corrected for the ratio between the observed areas (equation 1 of Bernstein et al. 1995), and errors on the background counts are estimated through an empirical approach as the rms of the counts in each control field with respect to the mean estimated over the whole area (equation 2 of Bernstein et al. 1995). For the background counts, scaling the rms value to the whole area, we obtain an uncertainty on the mean counts of ~11 per cent at $K < 13.5$ mag, where small number statistics dominates, and less than 3 per cent at $K = 18$ mag. For a Gaussian distribution, the standard deviation estimated from three samples is within a factor of 2 from the true value in 80 per cent of the trials. Since each field is smaller than the $K$-band survey, we overestimate the field-to-field variance among larger fields, taking into account the fact that the fluctuations due to galaxy clustering are smaller for wider fields. Following Ellis & Bland-Hawthorn (2007), we estimate that the field-to-field variance is overestimated of about the 15 per cent. Using this method, the error on background counts accounts for the Poissonian fluctuations and the field-to-field variance. We also include the error related to the photometric uncertainties which is estimated by means of 100,000 Monte Carlo simulations, changing the galaxy luminosities according to the photometric error and recomputing the number counts in each magnitude bin.

These galaxy number counts were found to be consistent with field galaxy counts from the Calar Alto Deep Imaging Survey (CADIS; see Huang et al. 2003), a medium deep $K$-band survey with a total area of 0.2 deg$^2$ and a completeness magnitude of 19.75 mag (see Fig. 2). We also agree with the counts of the ALHAMBRA survey given by Cristóbal-Hornillos et al. (2009) covering 0.44 deg$^2$ and reaching $K_S = 19.5$ mag. We note that Ellis & Bland-Hawthorn (2007), who have combined numerous published galaxy number counts over a wide range of passbands and magnitudes, obtained galaxy counts in the range $13 < K < 18$ that are 10–15 per cent higher than ours, but are based on small patches of sky (~1 deg$^2$) and show significant variations from one magnitude bin to another as surveys fall out of the sample.

The counts of SSC galaxies were defined as the difference between the counts detected in the supercluster fields and those estimated for the background (equation 3 of Bernstein et al. 1995). Then, the uncertainties were measured as the sum in quadrature of fluctuations in the background and in the supercluster counts (equation 4 of Bernstein et al. 1995).
best-fitting values of the K-band Schechter function parameters are $M_K^* = -24.96 \pm 0.10$ and $\alpha = -1.42 \pm 0.03$. The confidence contours on $\alpha$ and $m^*$ are shown in the small panel in Fig. 3, and were derived by randomly shifting galaxy number counts according to their uncertainties and recomputing the best-fitting Schechter function for each realization. The fit parameters and associated $\chi^2$ statistics are listed in Table 2.

The NIR LF trend derived in the 3 deg$^2$ area of the SSC agrees with the results of Mobasher & Trentham (1998) who found $\alpha = -1.41$ in the magnitude range $-19.5 < M_K < -16.5$, although they studied only a 41.1 arcmin$^2$ region of the Coma cluster core corresponding to about 10 arcmin$^2$ at the Shapley redshift.

In Fig. 3, we plot for comparison the field K-band LF by Jones et al. (2006) who found $M_K^* = -24.60$ and $\alpha = -1.16$. The two LFs appear consistent down to $M_K^* = -23$, but the faint-end slope for the SSC is steeper than that measured in the field at a $>3\sigma$ level. The field value of $M_K^*$ is also not consistent with that obtained for the SSC with a single Schechter function, with $M_K^*$ being brighter for the SSC than for the field, at the $3\sigma$ level according to the confidence contours in fig. 10 of Jones et al. (2006).

4.3 The effect of environment

Balogh et al. (2001), using 2MASS data, were the first to detect environmental variances in the NIR LF. This environmental effect was then questioned by Rines et al. (2004) who found that the cluster LFs derived in the virial regions and in the infall regions are very similar, although both poorly fitted by a Schechter function. However, in their work, which is also based on the 2MASS, they noted that at magnitudes fainter than the completeness limit the LF in the infall regions may indicate a steeper faint-end slope which should be investigated by means of deeper data sets.

In order to investigate the effects of the environment we derived and compared the LFs in three different regions of the supercluster, characterized by high, intermediate and low densities of galaxies (see Fig. 1) where galaxy densities are $\rho > 1.5$, $1.0 < \rho \leq 1.5$ and $0.5 < \rho \leq 1.0$ galaxies arcmin$^{-2}$, respectively. The local density of $R < 21$ mag galaxies, $\Sigma$, was determined across the R-band WFI mosaic (i.e. in a 2 deg$^2$ area; see Fig. 1). We derive $\Sigma$ by using an adaptive kernel estimator (Pisani 1993, 1996), in which each galaxy $i$ is represented by a Gaussian kernel, $K(\sigma) \propto \exp(-r_i^2/2\sigma_i^2)$, whose width $\sigma_i$ is proportional to $\Sigma_i^{-1/2}$, thus matching the resolution locally to the density (see MMH06 for more details).

In the left-hand panel in Fig. 4, we show the K-band LFs of galaxies in the high- (filled circles), intermediate- (open circles) and low-density (crosses) regions covering areas (in the SOS/K-band survey overlap) of $\sim 0.115$, 0.330 and 1.062 deg$^2$, respectively, together with their fits with a Schechter function (continuous, long-dashed and short-dashed lines, respectively). The background subtraction was performed as for the total LF by simply scaling the counts with the area values because of the complex geometry of the three density regions. Fig. 5 shows the confidence contours of the best-fitting Schechter function for the three density regions. The faint-end slope becomes steeper from high- to low-density environments varying from $-1.33$ to $-1.49$, being inconsistent at the $2\sigma$ confidence level (c.l.) between high- and low-density regions. We note that in this investigation the results are also more robust than those obtained for the total LF against variations in background galaxy counts, since we are considering denser supercluster regions, and furthermore the control field is significantly larger than the regions of different environments.
This result seems to be in contradiction with previous works (e.g. Balogh et al. 2001; Croton et al. 2005) who found an LF trend that varies smoothly with local density and/or environment. It should be noted that these studies are based on the 2MASS which allows us to investigate the luminosity distribution only down to about $M^* + 2$ at the redshift of Shapley, while we consider a much fainter galaxy population which is more likely affected by environmental-related processes (e.g. Haines et al. 2007).

It is also worth pointing out that comparing the flat NIR LF measured for field galaxies by recent surveys (e.g. 6dFGRS; Jones et al. 2006) with our slope in the low-density environment, one has to take into account that, since we are still in the cluster environment, this region can be suitably associated to the infall region rather than to the field. On the other hand, the LF slopes obtained by the Cluster And Infall Region Nearby Survey (CAIRNS; Rines et al. 2004) in both cluster virial and infall regions are consistent with the value derived for the overall SSC with a single Schechter function.

According to the $\chi^2$ statistics, in all the three environments the fit with a single Schechter function cannot be rejected, but there is some ‘structure’ evident in the residuals: the fit systematically under- and over-predicts the observed counts as a function of magnitude. The LFs instead suggest a bimodal behaviour due to the presence of an upturn for faint galaxies, which cannot be described by using a single Schechter function. To successfully model these changes in slope and to compare our results with our optical LFs (see Section 4.4), we fit our data with a composite Gaussian $+$ Schechter (G+S) LF (Fig. 4, central panel) and the sum of two Schechter (S+S) functions (Fig. 4, right-hand panel). Looking at Fig. 4 and Table 2 we note that the G+S and S+S fits significantly improve the data description, particularly in the low-density region, where according to the reduced $\chi^2$ the probability of the fit is $P(\chi^2 > \chi^2_{\nu}) \sim 99.6$ and 99.8 per cent for the G+S and S+S functions, respectively, against $P(\chi^2 > \chi^2_{\nu}) \sim 46$ per cent for the single Schechter function. Since the function fitting the faint end is poorly constrained by the data (the faint component dominates only in the last three magnitude bins), in order to estimate the uncertainties on the parameters characterizing the LF at fainter luminosities, $m^*_f$ and $\alpha_f$, we proceed as follows. Fixing all the best-fitting parameters except $m^*_f$ or $\alpha_f$, we randomly shift the galaxy number counts according to their uncertainties and then recompute the best-fitting functions obtaining a range of values for $m^*_f$ and $\alpha_f$. The faint-end slope becomes steeper from high-/intermediate- to low-density environments varying from $-1.65$ to $-1.74$ with the G+S fit.

<table>
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<tr>
<th>Region</th>
<th>Function</th>
<th>$m^*/\mu$</th>
<th>$m^*/\mu$</th>
<th>$\alpha/\sigma$</th>
<th>$m^*_f$</th>
<th>$m^*_f$</th>
<th>$\alpha_f$</th>
<th>$\chi^2$</th>
<th>$P(\chi^2 &gt; \chi^2_{\nu})$ (per cent)</th>
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<td>-1.42</td>
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<td>G+S</td>
<td>13.81</td>
<td>-22.85</td>
<td>1.97</td>
<td>12.58±0.12</td>
<td>-24.08</td>
<td>-1.65±0.03</td>
<td>0.58</td>
<td>83.46</td>
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<td>High density</td>
<td>S+S</td>
<td>11.57</td>
<td>-25.09</td>
<td>-1.22</td>
<td>16.64±0.29</td>
<td>-20.02</td>
<td>-2.05±0.50</td>
<td>0.74</td>
<td>68.28</td>
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<tr>
<td>Int density</td>
<td>S</td>
<td>11.47</td>
<td>-25.19</td>
<td>-1.44</td>
<td></td>
<td></td>
<td></td>
<td>1.30</td>
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<tr>
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<td>-22.85</td>
<td>1.90</td>
<td>12.47±0.11</td>
<td>-24.19</td>
<td>-1.64±0.02</td>
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<td>-1.26</td>
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<td></td>
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<td></td>
<td>1.00</td>
<td>44.78</td>
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<td>1.58</td>
<td>14.13±0.11</td>
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</tr>
<tr>
<td>Low density</td>
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<td>12.50</td>
<td>-24.16</td>
<td>-1.04</td>
<td>15.72±0.14</td>
<td>-20.94</td>
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<td>0.18</td>
<td>99.77</td>
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</table>

Figure 4. The K-band LFs of galaxies in the three cluster regions corresponding to high- (filled circles), intermediate- (open circles) and low-density (crosses) environments. In the left-hand, central and right-hand panels, the continuous, long-dashed and short-dashed lines represent the fits with Schechter, G+S and S+S functions, respectively. The counts are per half-magnitude bin.
4.4 Comparison with optical LFs

In order to investigate the processes responsible for changing the shape of the galaxy LF, we compare the trends observed for the optical and the NIR LFs. Since the NIR LF is expected to approximate the SMF, while the optical LFs are more sensitive to the galaxy star formation history (SFH), both are needed for investigating the nature of galaxies which dominate the faint end. For instance, a steep optical LF can be compatible with a flat SMF if dwarf galaxies have their luminosities boosted by starbursts, a scenario which can be probed by comparison to the NIR LF.

The optical LF of the SSC derived in the SOS (see MMH06) cannot be described by a single Schechter function due to the dips apparent at \(M^* + 2\) in both \(B\) and \(R\) bands and the clear upturn in the counts for galaxies fainter than \(B\) and \(R \sim 18\) mag. Instead, the sum of a Gaussian and a Schechter function, for bright and faint galaxies, respectively, is a suitable representation of the data. Furthermore, we observed significant environmental trends in the form of a dip which becomes deeper and a faint-end slope which becomes steeper with decreasing density. In particular, the slope values become significantly steeper from high- to low-density environments varying from \(-1.46\) to \(-1.66\) in the \(B\) band and from \(-1.30\) to \(-1.80\) in the \(R\) band, being inconsistent at more than 3\(\sigma\) c.l. in both bands. Such a marked luminosity segregation is related to the behaviour of the red galaxy population: while red sequence counts are very similar to those obtained for the global galaxy population, the blue galaxy LFs are well described by single Schechter functions and do not vary with the density. We explained these results in terms of the galaxy harassment scenario, in which the late-type spirals that represent the dominant population at \(\sim M^* + 2\) are transformed by galaxy harassment into passively evolving dwarf spheroids, and in the process become \(~1\)–\(2\) mag fainter due to mass loss and an ageing stellar population without new star formation. The observed changes in the shape of the LF can be considered as reflecting the changes in the mixture of galaxy morphological types with environment described by the morphology–density relation, from late-type dominant (and hence a steep faint end to the LF) in low-density regions to early-type dominant (with a shallower faint end to the LF) in the cluster cores (Binggeli, Sandage & Tammann 1988; de Lapparent 2003).

In Fig. 6 we compare the shape of the composite G+S \(B\) (left-hand panel), and \(R\) (central panel) LFs, derived in MMH06, with the relative \(K\)-band LFs (right-hand panel) in the three density regions. Both LFs (optical and NIR) are steeper in the low-density regions. However, the NIR LFs only marginally indicate an absence of \(M^* + 2\) galaxies in low-density environment.

The study of the optical LFs showed that it is the red galaxy populations that turn out to contribute to the change of the LF trend with environment, in particular to the steepening of the faint-end slope. This is at odds with what is found in the field where the faint end is populated by galaxies of smaller masses, later morphologies, bluer colours, later spectral types and stronger line emission (e.g. Balogh et al. 2001; Madgwick et al. 2002). On the other hand, in clusters the LF of early-type galaxies is found to be steeper than in the field (De Propris et al. 2003). We should also take into account that at least part of the red galaxies contributing the Shapley LFs in different supercluster environments may not be passive; Haines, Gargiulo & Merluzzi (2008) studying a volume-limited sample (0.005 < \(z\) < 0.037) of local galaxies found that \(~30\) per cent of red sequence galaxies in the optical colour–magnitude diagram show signs of ongoing star formation from their spectra and this contamination is greater at faint magnitudes (\(M_r > -19\) mag).

Figure 5. The 1\(\sigma\), 2\(\sigma\) and 3\(\sigma\) confidence regions for the \(K\)-band Schechter parameters (right-hand panel in Fig. 4) for the three cluster regions corresponding to high- (solid contours), intermediate- (dotted) and low-density (dashed) environments.

Figure 6. Galaxy LFs \(B\)-band (left-hand panel), \(R\)-band (central panel) and \(K\)-band (right-hand panel) in the high- (filled circles), intermediate- (open circles) and low-density (crosses) environments. The long-dashed and short-dashed lines represent the G+S best fit for intermediate- and low-density environments respectively and the continuous line is the Schechter best fit for high-density regions.
5 THE GALAXY STELLAR MASS FUNCTION

The combined optical and NIR data allow us to derive the distribution of galaxy stellar masses. The sample we analyse is in the magnitude range $10 \leq K \leq 18$ and refers to the $\sim 2$ deg$^2$ area covered by both the SOS and our $K$-band imaging. We note that although the area of the NIR survey is slightly different from that of the SOS, both surveys map the same kinds of environment from low to high density (see the isodensity contours in Fig. 1).

One of the main concerns in deriving the SMF of SSC galaxies is the foreground/background contamination that has to be estimated and corrected for. A wealth of spectroscopic data in the region covered by optical and NIR photometry already exists, comprising about 650 galaxy redshifts (see Section 2) corresponding to $\sim 90$ per cent of $R < 16$ mag galaxies. In order to extend the magnitude range and improve the statistics, we need to adopt a complementary approach for those galaxies without spectroscopic information. We use the probability that galaxies are supercluster members as derived by HMM06 following Kodama & Bower (2001). We consider separately the three cluster environments as well as the remaining galaxies in the SOS and construct two-dimensional histograms with bins of a width of 0.4 mag in $R$ and 0.2 mag in $B - R$ to properly map the galaxy colour–magnitude distribution. The number counts in each bin are then compared with those expected for a suitable field region, normalized to have the same overall area. For this purpose, we used a 4.3 deg$^2$ region of deep $BVR$ imaging from the Deep Lens Survey (Wittman et al. 2002). The probability that a randomly selected SOS galaxy belongs to the supercluster is then determined from the ratio of the number counts obtained for that bin from the SOS and DLS (equation 1 of HMM06). For those galaxies with available redshifts, the probability is set to 1 for $0.035 < z < 0.056$ or 0 otherwise.

The stellar masses of galaxies belonging to the Shapley supercluster, according to the previous criteria, contribute to the galaxy SMF according to their likelihood of belonging to the Shapley supercluster.

5.1 Derivation of stellar masses

The stellar masses of galaxies belonging to the Shapley supercluster are estimated by means of stellar population models constrained by the observed optical and infrared colours. It is well known that stellar masses estimated using the fit to the multicolour spectral energy distribution (SED) are model dependent and subject to various degeneracies. In order to reduce such degeneracies, we have used a large grid of complex stellar population models by Maraston (2005) with a Salpeter initial mass function (IMF) covering a wide range of parameters. We use SEDs with the SFH parametrized as $\Psi(t) \propto \exp(-t/\tau)$, with $\tau$ between 1.0 and 20.0 Gyr, ages between 0.001 and 14 Gyr and metallicities in the range 0.5–2.0 $Z_\odot$. We note that the metallicity of low-mass galaxies can be lower (e.g. Smith et al. 2009), but at present complex stellar population models do not explore such a low metallicity range. The synthetic spectra are shifted to the galaxy spectroscopic redshift, if known, or to the median supercluster redshift $z = 0.05$. Then for each of them we compute the $B$, $R$ and $K$ magnitudes by adopting the Calzetti (2001) extinction. Since in the photometric calibration of the $B$ band the colour term

The redshift range is derived from the redshift distribution of galaxies in the SOS field with available spectroscopy.

Our $B$-band photometry agrees within the zero-point uncertainties ($\sim 0.03$ mag) with that obtained by WINGS (Varela et al. 2009) using independent WFI $B$-band observations for a subset of the SOS field.

The most appropriate evolutionary history is selected by fitting the optical + NIR photometry, and the mass is estimated by normalizing the best-fitting SED to the observed $K$-band magnitude. This choice of model grid parameters yields a fairly uniform coverage of colour space and well represents the SEDs of the galaxies in the sample. The uncertainty on the resultant stellar mass was estimated by performing Monte Carlo simulations, shifting the galaxy colours according to their corresponding uncertainties and recomputing the mass each time. Further sources of uncertainty in the fitting technique are the error on redshift, which is fixed at $z = 0.05$ for those galaxies without available spectroscopic redshift. We perform Monte Carlo simulations by randomly shifting SEDs in the redshift range $0.035 < z < 0.056$ adopted to select spectroscopic confirmed supercluster members. This contribution to the mass uncertainty is negligible, since it is at least one order of magnitude lower than that due to the photometric errors. Besides this, the main source of uncertainty is the adopted IMF (see Bell & de Jong 2001). Bell et al. (2003) found that, using the simple stellar populations with different IMFs, stellar masses can be systematically increased by $\sim 0.1$ dex or decreased by $\sim 0.45$ dex, thus resulting in an overall rescaling of the stellar mass. A zero-point shift to the stellar mass scale would not affect any of our environment analyses, which are explicitly differential.

The average error on the mass evaluation is $\sim 20$ per cent and turns out to be 10–15 and 30–35 per cent for galaxies with probabilities greater and less than 0.5 of being supercluster members, respectively.

5.2 Galaxy stellar mass function

Fig. 7 shows the SMF of galaxies with $10^{8.75} M_\odot < M < 10^{12} M_\odot$. Based on our $K$-band completeness limit of $K = 18$, we conservatively derive the SMF down to $M = 10^{8.75} M_\odot$, which

$\log_{10} \mu (\langle h_70^{-2} M_\odot \rangle)$

Figure 7. SMF of galaxies in the SSC (see text). The continuous line indicates the best single Schechter fit to the data. In the small panel, the 1, 2 and 3σ c.l. of the best-fitting parameters for $\alpha$ (x-axis) and $\log_{10} \mu$ (y-axis) are shown.

$B - R$ is not negligible, as discussed in MMH06, we use the WFI $B$ filter in order to compute $B$ magnitudes\(^7\) from the models.

\[ \mu \propto \exp\left(-\frac{M - M_\text{ref}}{\sigma}\right) \]

\[ \log_{10} \mu (\langle h_70^{-2} M_\odot \rangle) \]

\[ \alpha = -1.20 \]

\[ \log_{10} \mu = 11.16 \]

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corresponds to the estimated stellar mass of the quiescent galaxy population at our $K$-band limit. Fitting a single Schechter function, the recovered parameters are $\log_{10}(M^*) = 11.16$ and $\alpha = -1.20$ whose uncertainties are given by the confidence contours in Fig. 7. We check the robustness of our result against possible completeness issues of the galaxy sample used in deriving the SMF. According to their location in the $R - K$ versus $K$ colour–magnitude diagram, only 5 per cent of the galaxies in the $K$-band catalogue which are possible supercluster members (i.e. which lie along or below the red sequence) do not have available estimates of probability. These galaxies are uniformly distributed in the magnitude bins and mostly lack optical data (and hence probabilities) due to their location near bright stars, which produce large ghosts in the optical data. We also note that the low-mass galaxies we may have lost would contribute to increase the low-mass-end slope of the SMF.

For what concerns the observed trend of the galaxy SMF, the slope is in agreement with previous works concerning the SMF of field galaxies (Cole et al. 2001; in the mass range of $10^8$–$10^{11.5} M_\odot$; Panter, Heavens & Jimenez 2004; in the mass range of $10^9$–$10^{12} M_\odot$). On the other hand, the faint-end slope of the SSC turns out to be shallower than the value given by Balogh et al. (2001) for the local mass function of cluster galaxies (2MASS/LCRS) although the latter is affected by a large uncertainty ($\Delta \alpha \sim 0.1$ at 1$\sigma$). The value of $M^*$ is higher than that observed in the field (e.g. Bell et al. 2003), as expected for cluster environment. The SMF of supercluster galaxies is characterized by an excess of massive galaxies that is associated with the brightest cluster galaxies (BCG).

In Fig. 8, we show the SMF for the different supercluster environments. Unlike the case of the LF, no environmental trend is seen in the slope of the SMFs (see Fig. 9). On the other hand, the $M^*$ increase from low- to high-density regions and the excess of high-mass galaxies remains dependent on the environment. We remark that the uncertainty due to the adopted IMF (see Section 5.1) does not affect our analysis since the stellar masses at a fixed epoch will be all changed by the same amount.

6 DISCUSSION

6.1 The faint-end upturn in the $K$-band LFs

We observed a steep faint-end slope for the Shapley supercluster $K$-band LF (Fig. 3) obtaining $\alpha = -1.42$, similar to values observed for the cluster LFs of Mobasher & Trentham (1998) and Andreon & Pelló (2000). De Propris et al. (1998) observed a steeper slope of $\alpha = -1.7$ deriving the NIR LF for a wider area ($29.2 \times 22.5$ arcmin$^2$) of the Coma cluster (corresponding to $\sim 15 \times 11$ arcmin$^2$ at $z \sim 0.05$) down to $H = 16$ mag ($K \sim 15.7$), but the authors conservatively consider this result as an indication of a steep LF for dwarf galaxies rather than a precise estimate of the slope. On the other hand, other studies found a less steep or flat faint-end slope in the NIR LF for cluster galaxies (e.g. Lin et al. 2004).

The steep slope of the cluster LF has been discussed considering the otherwise flat LF of field galaxies (e.g. Cole et al. 2001) and how the environmental effects could shape the galaxy LF. Balogh et al. (2001; see also Croton et al. 2005) demonstrated that there is a statistical difference between the cluster and field galaxy NIR LFs, with a brighter $M^*$ and a steeper faint-end slope for clusters with respect to the field. An interpretation can be inferred from the trends observed for the LFs of early- and late-type field galaxies. Huang et al. (2003) found that the later-type galaxies have a fainter $M^*$ and a steeper slope with respect to the early-type galaxies in the field. Their faint-end slope for late-type galaxies is equal to the value we obtained for the SSC ($\alpha = -1.42$), although for a brighter sample. This suggests a scenario whereby the faint-end upturn in the cluster LF is due to late-type objects accreted from the field. This scenario is further supported by the result of Harsono & De Propris (2007) who did not detect the upturn in two intermediate redshift clusters indicating that this feature has recent origins.

By considering the LFs of the Shapley supercluster in different density environments, we found a steepening of the faint-end slope.
which changes from $\alpha = -1.33$ to $\alpha = -1.49$, being inconsistent at 2\sigma c.l. between high- and low-density regions. Moreover, the general shape of the LFs in the low-density region turns out to be better reproduced using the combination of G+S functions. This observed bimodality in the LF and its variation with environment suggest a scenario where bright and faint galaxy populations have followed different evolution histories and indicate that an environmental effect such as galaxy harassment and/or ram pressure stripping could be responsible for shaping the LF. This entails that the environment is responsible for the final mixture of the galaxy types, in particular for the faint/low-mass galaxies.

The stellar and/or field contamination can artificially produce the faint-end upturn. We carefully checked the issues of the stellar contamination (see Section 3.2) and chose a control field characterized by a deeper limiting magnitude and a larger area with respect to the Shapley K-band survey in order to rely on the star/galaxy classification and to account for the field-to-field variance. Assuming the trend we observed to be real, we make a simple exercise to understand how the survey depth can affect the measured shape of the LF. In Fig. 10 we show that the slope of the faint end becomes clearly steeper as the depth of the sample is increased in all the supercluster environments, demonstrating the need for such deep data sets to understand the role of environment on galaxy evolution.

The observed trend with environment is more dramatic for the Shapley optical LFs obtained by MMH06. In particular, the faint-end slope becomes steeper at a $>3\sigma$ significance level from high- ($\alpha_B = -1.46$, $\alpha_R = -1.30$) to low-density environments ($\alpha_B = -1.66$, $\alpha_R = -1.80$) in $B$ and $R$ bands. Also the bimodality of the galaxy LF, commonly observed for rich clusters (e.g. Yagi et al. 2002; Mercurio et al. 2003), turns out to be more evident in the optical bands. We note that the SOS is about 1.5 mag deeper in the $R$ band with respect to the $K$ band considering $R - K = 2.6$.

6.2 The galaxy stellar mass function

The SMFs derived for the supercluster galaxies are in general agreement with those obtained by Baldry et al. (2006) who using SDSS data did not find changes in the slope of the SMF with environment, except for changes in the characteristic mass which increases with the local density. We do find a steeper slope: $\alpha = -1.20 \pm 0.02$ instead of $\alpha \simeq -1$ of Baldry et al. (2006) who did not quote error estimates. This discrepancy might be due to systematic uncertainties in the mass derivation; in fact, using the MOPED algorithm, Panter et al. (2004) obtained for the SDSS data $\alpha = -1.159 \pm 0.008$ which is consistent within the errors with our findings. Another source of discrepancy can be due to the use of the $K$-band data to estimate the galaxy stellar masses, but the slope obtained by Bell et al. (2003) combining 2MASS and SDSS data sets is significantly lower ($\alpha = -0.86$) with respect to those of SSC in all environments. As shown by Bell et al. (2003), the difference here may be due to the fact that the 2MASS misses low surface brightness galaxies. They estimated the $K$-band flux and stellar masses from the optical photometry for the galaxies not detected in the $K$ band and produced a $g$-band-derived SMF with $\alpha = -1.10$.

Baldry, Glazebrook & Driver (2008) found a strong low-mass upturn below $M = 10^9 M_\odot$ analysing the NYU-VAGC, their SMF being fitted by an S+S function with, in the low-mass end, $\alpha = -1.58 \pm 0.02$. An upturn in the SMF was also shown by Jenkins et al. (2007) for the Coma cluster by means of Spitzer Infrared Array Camera (IRAC) observations. They observed a steep increase in two different Coma regions below $M = 10^8 M_\odot$ with $\alpha \sim -2$ (but they did not quantify the trend with a fit of the data).

The fact that we do not observe any upturn in the SMF of the Shapley supercluster can be related to the different mass ranges or to environmental differences. Jenkins et al. (2007) and Baldry et al. (2008) extend their analysis to $M = 10^{11} M_\odot$ and $M = 10^9 M_\odot$, respectively, with the faint-end upturn becoming evident at $M < 10^9 M_\odot$, very close to our mass limit of $M = 10^{7.5} M_\odot$. This suggests that the reason why we see an upturn in the $K$-band LF, but not in the SMF, is that the galaxies which cause the faint-end upturn are star-forming galaxies with a low stellar M/L and stellar masses in the range $10^8 < M < 10^9 M_\odot$. This would be consistent with Bolzonella et al. (2009) who found that the upturn was due to late-type galaxies, but inconsistent with the finding of MMH06 in which the upturn appeared due to red sequence galaxies.

Jenkins et al. (2007) analysed two regions of the Coma cluster: one in the cluster centre (0.733 deg$^2$ corresponding to $\sim 2.1$ Mpc$^2$) and one off-centre region (0.555 deg$^2$ corresponding to $\sim 1.6$ Mpc$^2$) located $\sim 1.7$ Mpc south-west. The area of the SSC covered by both the SOS and the $K$-band survey is $\sim 30$ Mpc$^2$. Therefore, we are studying a much larger area that comprises infall regions as well as cluster cores. Dynamical analysis indicates that at least a region of a radius of 11 Mpc centred on the central cluster A 3558, and possibly the entire supercluster, is past turnaround and is collapsing (Reisenegger et al. 2000), while the core complex itself is in the final stages of collapse, with infall velocities reaching $\sim 2000$ km s$^{-1}$. This difference in the environments may be responsible for differences in the SMF for the two cosmic structures. Another possible issue can be related to the background subtraction (see Rines & Geller 2008).

Investigating the environmental effect on the SMF in the SSC, we find that both $M^*$ and the excess of galaxies at the bright end increase as foreseen by the hierarchical models where the most massive galaxies formed in the density peaks. On the other hand, the faint-end slope does not change in the different supercluster environments suggesting that the mechanism that is acting in shaping...
the LF (see Section 4.3) does not significantly affect the galaxy stellar masses.

6.3 Comparison with the simulations

We should expect changes in the $K$-band LF with environment to reflect two processes: (i) the effect of the diverse merging histories of galaxies in different environments within the context of the hierarchical merging scenario, in which cluster galaxies are likely to have formed earlier and had a more active merger history than field galaxies that form in the smoother low-density regions, and (ii) the later impact of environmental processes such as tidal stripping, which may drastically reduce the stellar mass of galaxies in high-density regions. While it is very difficult to quantify the latter’s contribution to the galaxy luminosity/mass function, we can attempt to measure the former contribution by comparison to the cosmological numerical simulations.

To this aim, we extracted galaxy catalogues in the vicinity of the 20 most massive dark matter haloes from the Millennium simulation (Springel et al. 2005), corresponding to galaxy clusters with masses of $7-23 \times 10^{14} M_\odot$ and velocity dispersions ($800 < \sigma < 1400 \text{km s}^{-1}$). These simulations cover a $(500 h^{-1} \text{Mpc})^3$ volume, producing DM halo and galaxy catalogues based on the SAMs of Bower et al. (2006) and Font et al. (2008) for which positions, peculiar velocities, absolute magnitudes and halo masses are all provided at 63 snapshots to $z = 0$, allowing the orbit of each galaxy with respect to the cluster centre to be followed. We select member galaxies from these 20 clusters that have $M_K < -17.5$ and lie within 5 Mpc of the cluster centre, and show in Fig. 11 the stacked $K$-band cluster LFs of galaxies as a function of the projected cluster-centric distance, scaled by the $r_{500}$ value of each cluster’s DM halo. We show the LFs obtained from both the Bower et al. (2006) (thick lines) and Font et al. (2008) (thin lines) SAM galaxy catalogues, and the four curves correspond to $r < 0.5r_{500}$, $0.5 < r < 1.0r_{500}$, $1.0 < r < 2.0r_{500}$ and $r > 2.0r_{500}$, respectively. For comparison, the $r_{500}$ values for the clusters in the SSC derived from Chandra X-ray observations (Sanderson, Ponman & O’Sullivan 2006; Haines et al. 2009) are 1.29 Mpc ($22.9 \text{arcmin at } z = 0.048$) for A 3558, 0.91 Mpc (16.1 arcmin) for A 3562 and SC 1327-312 and 0.76 Mpc (13.5 arcmin) for SC 1329-317. By inspection of Fig. 1, our high-, intermediate- and low-density regions correspond approximately to the $r < 0.5r_{500}$, $0.5 < r < 1.0r_{500}$ and $1.0 < r < 2.0r_{500}$ radial bins, respectively.

It is immediately apparent from Fig. 11 that there is little if any environmental dependence of the $K$-band LF, except at the very bright end ($M_K < -26$), while equally there are no significant differences between the two SAMs. This is confirmed if we compare the best-fitting single Schechter functions derived to the SAM LFs, with $M_K^* = -24.42 \pm 0.04$, $\alpha = -1.134 \pm 0.007$ for $r < 0.5r_{500}$ and $M_K^* = -24.37 \pm 0.03$, $\alpha = -1.167 \pm 0.003$ for $r > 2.0r_{500}$. Similarly, if we select just those galaxies which have already passed through the cluster core (based on following their orbits), and hence are most likely to correspond to the red sequence population, we find no significant variation in the LFs with the cluster-centric radius. There is also no sign of an upturn at faint magnitudes, although we note that the SAM galaxy catalogues start to become incomplete at $M_K > 10^{14} \text{M}_\odot$ due to the limited mass resolution in the Millennium simulation (Bower et al. 2006). The only clear difference among the LFs is the excess at the extreme bright end ($M_K < K^*-2$) in the inner cluster region, due to the BCG population. Moreover, the $\chi^2$ test gives a probability of 0 per cent that the observed and SAM LFs are drawn by the same parent distribution.

Although the merging history of galaxies at the faint end ($M_K > -20$) may not be fully resolved by the SAMs, we may expect at least their stellar masses (and hence $K$-band luminosities) to be reasonably robust (Bower et al. 2006). In previous works discussing the presence of a dip in the galaxy LF, the merging of $L^*$ galaxies has been suggested as a possible pathway to form the dip. However, the consistency of the LFs with the cluster-centric radius suggests that the variations observed in the Shapley supercluster (Fig. 6) are not primarily due to variations in the merging histories of galaxies, this being a process that should be well described by the SAMs. Instead, processes such as tidal stripping or harassment of infalling spiral galaxies, which are not yet included in the SAMs, seem more plausible pathways to produce the observed variations in the galaxy LFs.

Figure 11. Composite $K$-band LFs for the 20 most massive clusters in the Millennium simulation, based on the SAMs of Bower et al. (2006) (thick lines) and Font et al. (2008) (thin lines), in bins of projected cluster-centric radius. The four curves correspond to $r < 0.5r_{500}$ (solid lines), $0.5r_{500} < r < 1.0r_{500}$ (dashed lines), $1.0r_{500} < r < 2.0r_{500}$ (dot-dashed lines) and $r > 2.0r_{500}$ (dot-dot-dashed lines).

7 SUMMARY AND CONCLUSIONS

It is well known that the NIR luminosities provide a more reliable estimate of the stellar masses compared to the optical ones due to the fact that the M/L in the NIR vary by at most a factor 2 across a wide range of SFHs (Bell & de Jong 2001) in comparison to the much larger variations of the M/L (up to a factor of 10) observed at optical wavelengths. In addition, the effects of the extinction are much weaker at infrared wavelengths than in the optical ones, and $k$-corrections for infrared colours are only weakly dependent on the Hubble type and vary slowly with redshift (e.g. Poggianti 1997). In our study, we exploit new deep ($K = 18$ mag) $K$-band imaging of the SSC complemented by the deep optical imaging down to $B = 22.5$ mag and $R = 22$ mag from the SOS, and a spectroscopically confirmed supercluster sample of $\sim 650$ galaxies across the same field which is $\sim 90$ per cent complete at $R < 16$ mag. We present an analysis of the $K$-band LF of galaxies as a function environment...
and we derive the galaxy SMF in order to constrain the physical mechanisms that transform galaxies in different environments as a function of the galaxy mass.

Our results are summarized as follows.

(i) The K-band LF can be fitted by a single Schechter function, with $M^*_K = -24.96 \pm 0.10$ and $\alpha = -1.42 \pm 0.03$ in agreement with previous works of comparable depth.

(ii) The K-band LF faint-end slope becomes steeper from high-to low-density environments varying from $-1.33$ to $-1.49$, being inconsistent at the 2$\sigma$ c.l. (see Table 2), indicating that the faint galaxy population increases in low-density environments. Such an environmental dependence confirms our finding for the optical LFs derived in the same supercluster regions although the changes in slope are less dramatic at NIR wavebands.

(iii) The observed trend of the galaxy SMF presents a slope in agreement with previous works concerning the SMF of field galaxies (Cole et al. 2001; Panter et al. 2004). The value of $M^*$ is higher with respect to that observed in the field (e.g. Bell et al. 2003), as expected for cluster environment. The SMF of supercluster galaxies is characterized by an excess of massive galaxies that is associated with the cluster BCGs. Discrepancies with previous work that observed a strong faint-end upturn (Jenkins et al. 2007; Baldry et al. 2008) can be related to the different mass ranges investigated and/or environmental differences in the analysed structures.

(iv) Differently from the LF, no environment effect is found in the slope of the SMFs. On the other hand, the $M^*$ increase from low- to high-density regions and the excess of galaxies at the bright end is also dependent on the environment. This trend is in general agreement with the results of Baldry et al. (2006).

In order to interpret our findings, we use the Millennium simulation which produces DM halo and galaxy catalogues based on SAMs. The cluster NIR LFs obtained using the simulated catalogues do not show any significant variation with the cluster-centric radius, thus suggesting that the variations observed in the LFs of the Shapley supercluster are not driven by variations in the merging histories of the galaxies, but are likely related to processes such as tidal stripping or harassment of infalling galaxies.

By comparing the effect of environment at optical and NIR wavebands in shaping the LFs and taking into account that the slope of the galaxy SMF is invariant with respect to the environment, it seems that the physical mechanism responsible for the transformation of galaxy properties in different environment are related to the quenching of the star formation rather than mass loss.

This suggests that the mechanism responsible for shaping the LF and SMF is partially related to the mass loss due to tidal stripping or galaxy harassment, but gas stripping by the ICM can also affect the galaxy population removing the cold gas supply and thus rapidly terminating ongoing star formation. All of these mechanisms require a dense ICM and so their evolutionary effects on massive galaxies are limited to the cores of clusters, but can extend to poorer environments for dwarf galaxies which are easier to strip. The infalling galaxies are probably of late type (see MMH06) that are affected by gas stripping entering in the supercluster. On the other hand, the depth of the NIR survey could affect the present results by not allowing us to detect an upturn of the SMF which can be detected at a mass range lower than that reached here (see Jenkins et al. 2007).

In order to identify the mechanisms which drive galaxy evolution in the supercluster environment, we undertake a survey with the integral field spectrograph WiFeS which will provide a unique data set to investigate in detail the stellar populations and kinematics for a subsample of the Shapley galaxies.

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