The Munich Near-Infrared Cluster Survey – I. Field selection, object extraction, and photometry

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ABSTRACT
The Munich Near-IR Cluster Survey (MUNICS) is a wide-area, medium-deep, photometric survey selected in the $K'$ band. It covers an area of roughly one square degree in the $K'$ and $J$ near-IR pass-bands. The survey area consists of 16 $6' \times 6'$ fields targeted at QSOs with redshifts $0.5 < z < 2$ and 72 $8' \times 13'$ stripes targeted at ‘random’ high Galactic latitude fields. Ten of the QSO fields were additionally imaged in $R$ and $I$, and 0.6 deg$^2$ of the randomly selected fields were also imaged in the $V$, $R$, and $J$ bands. The resulting object catalogues were strictly selected in $K'$, having a limiting magnitude (50 per cent completeness) of $K' \sim 19.5$ mag and $J \sim 21$ mag, sufficiently deep to detect passively evolving systems up to a redshift of $z \lesssim 1.5$ and luminosity of $0.5L^*$. The optical data reach a depth of roughly $R \sim 23.5$ mag. The project’s main scientific aims are the identification of galaxy clusters at redshifts around unity and the selection of a large sample of field early-type galaxies at $0 < z < 1.5$ for evolutionary studies. In this paper – the first in a series – we describe the survey’s concept, the selection of the survey fields, the near-IR and optical imaging and data reduction, object extraction, and the construction of photometric catalogues. Finally, we show the $J - K'$ vs. $K'$ colour–magnitude diagramme and the $R - J$ vs. $J - K'$, $V - I$ vs. $J - K'$, and $V - I$ vs. $V - R$ colour–colour diagrammes for MUNICS objects, together with stellar population-synthesis models for different star-formation histories, and conclude that the data presented is suitable for extracting a catalogue of massive field galaxies in the redshift range $0.5 \lesssim z \lesssim 1.5$ for evolutionary studies and follow-up observations.

Key words: surveys – infrared: galaxies – galaxies: photometry – galaxies: evolution – cosmology: observations

1 INTRODUCTION

Directly observing the evolution of individual galaxies with time is, unfortunately, not possible. Therefore we must rely on investigating the statistical properties of the whole galaxy population as a function of redshift, trying to draw conclusions from ensemble properties on the evolution of typical members of these ensembles, and thus facing difficulties, like, for example, discriminating between luminosity evolution and number density evolution.

Much work has been invested in this field, resulting in a lot of progress in the last decade which has seen many imaging and redshift surveys being undertaken using different selection techniques in wave-bands from the UV to the sub-mm. These surveys have a wide range of scientific applications, from the detection of high-redshift galaxy clusters to the study of the evolution of ‘normal’ field galaxies.

The earlier optically and near-IR selected redshift and imaging surveys, among others Broadhurst, Ellis, & Shanks (1988), Colless et al. (1990), Lilly, Cowie, & Gardner (1991), Glazebrook et al. (1994), and Cowie et al. (1994), laid the path to the landmark CFRS (Canada-France Redshift Survey; Lilly et al. 1995a), an I-band selected redshift survey mapping the evolution of the galaxy population out to $z \sim 1$. Also many ‘pencil-beam’ surveys have been carried out, the most prominent being the Hubble Deep Field North and South (Williams et al. 1996; Williams et al. 2000) and their ground-based imaging and spectroscopic follow-ups, allowing us a first glimpse at the galaxy population at $2.5 \lesssim z \lesssim 4.5$. The inability to determine redshifts spectroscopically for all objects where multi-band imaging data is available (because of limited telescope resources, either in observing time or in collecting
area), caused photometric redshift determination techniques to gain attention again (Baum 1962, Koo 1985, Fernández-Soto, Lanzetta, & Yahil 1999, Benítez 2000). This, and the wide-field imagers becoming available in the optical and also in the near-infrared wavelength regime, made multi-band imaging surveys a very promising option for further studies in galaxy evolution.

Selection in a single pass-band introduces different (and sometimes subtle) selection effects, a well-known fact which need not necessarily be considered at the disadvantage of the resulting object database, as long as the selection function is well-understood and under control. These selection effects can be used deliberately for probing different galaxy populations and different aspects of their evolution. While selection in blue pass-bands is used to study star forming sources, selection in the near-IR is predominantly sensitive to the light of old stellar populations. Near-IR k-corrections are small even at redshifts above unity and insensitive to the spectral type of the observed objects (Cowie et al. 1994) and to short-lived bursts of star formation, as has been pointed out by Kauffmann & Charlot (1998). Thus near-IR selected surveys are thought to be much less biased with respect to the mix of spectral types compared to optically selected surveys. Furthermore, the uncertainties resulting from inhomogeneous dust absorption are minimal in the near-IR. It has therefore been concluded that near-IR selection is a feasible attempt at a selection in stellar mass (Rix & Rieke 1993; Brinchmann & Ellis 2001).

The Munich Near-Infrared Cluster Survey (MUNICS) is an attempt at closing the gap between previously undertaken infrared-selected deep pencil-beam surveys (Gardner, Cowie, & Wainscoat 1993; McLeod et al. 1993; Cowie et al. 1994; Djorgovski et al. 1995; Williams et al. 1996; Baracco et al. 1997) and relatively shallow wide-area surveys (Mobasher, Sharples, & Ellis 1993; Glazebrook et al. 1994; Gardner et al. 1997), simultaneously profiting from the advantages of near-infrared surveys.

MUNICS is a wide-area, medium-deep, photometric survey selected in the K’ band. One part of the surveyed fields was centred on known quasars, while the rest was randomly selected at high Galactic latitudes. It covers an area of roughly one degree square in the K’ and J bands with optical follow-up imaging in the I, R, and V bands for a large fraction of the total surveyed area.

The resulting object catalogues are strictly selected in K’ with a limiting magnitude of K’ ~ 19.5 mag and J ~ 21 mag, sufficiently deep to detect passively evolving systems up to a redshift of z < 1.5 and luminosity of 0.5L* (see Fig. 1). The optical data reach a depth of roughly R ~ 23.5 mag.

This paper is laid out as follows. Section 2 presents the survey’s scientific aims and concept. The required sensitivity in terms of limiting magnitudes, the selection of the survey fields as well as the photometric system adopted are described. In Section 3 we give an overview of the observations and discuss the reduction of the near-IR and optical imaging data. Section 4 contains the data analysis. The methods for object detection, photometry, and object classification are discussed, and a first analysis of the survey’s completeness as well as number counts in five colours are presented.

2 SURVEY CONCEPT AND LAYOUT

2.1 Scientific aims

The project’s main scientific aims are the following. First, to identify clusters of galaxies at high redshift by detecting their luminous early-type galaxy population. As has been shown in the last years, the early-type galaxy population in clusters is well in place at redshifts of at least 0.8 (Stanford, Eisenhardt, & Dickinson 1995; Stanford et al. 1997; Stanford, Eisenhardt, & Dickinson 1998, de Propris et al. 1999). Given the small k-corrections in the K’ band, this makes selection in the near-IR a promising approach to detect clusters at redshifts around unity, complementing selection in other optical bands. Clusters of galaxies allow to find large numbers of massive galaxies at higher redshift and thus represent unique laboratories to study the evolution of galaxies in high-density regions as a function of redshift, and in contrast to the evolution of similar galaxies in the field. Furthermore, the evolution of the number density of clusters is a promising test of cosmological models, depending sensitively on the density parameter Ω0 (Eke, Cole, & Frenk 1996; Bahcall, Fan, & Cen 1997; Bahcall & Fan 1998; Eke et al. 1998). While the number of clusters known at redshifts z > 0.5 is steadily increasing (mostly due to X-ray selection), samples selected uniformly in the optical and near-IR wavelength ranges are still deficient.

Cluster detection at high redshifts is strongly biased towards the most massive systems, mainly because of lack of detection sensitivity for lower mass systems. Finding also less massive systems is important when reasoning about hierarchical galaxy formation models, since the galaxies in the densest environments formed earlier, so by looking only at the most dense environments one is effectively pushing the epoch of collapse, merging, and star formation out to higher redshifts and further away from the observational window. Therefore we decided to centre a subset of the MUNICS
fields on known quasars hoping to increase the chance of detecting clusters in their environment.

Secondly, a statistically well-defined sample of the early-type galaxy population in the field can be constructed from our catalogues, which will be used to study the evolutionary history of such objects in the redshift range $0 < z < 1$ by means of the $K$-band selected luminosity function, the luminosity density at near-infrared wavelengths, and the two-point correlation function. Again, $K$-band selection offers unique opportunities due to the close connection between near-IR luminosity and stellar mass (Brinchmann & Ellis 2000), and thus allows direct assessment of the predictions of hierarchical galaxy formation theories.

Thirdly, the nature of extremely red objects (EROs; Elston, Rieke, & Rieke 1988; Hu & Ridgway 1994) will be examined. EROs, usually defined in terms of $R - K$ greater than or approximately equal to 5 at moderately faint $K$-band magnitudes of $K \geq 18$, are thought to be either high-redshift early-type galaxies or heavily extincted starburst galaxies (Cimatti et al. 1999; Smail et al. 1999), the relative contribution of the two sub-populations being yet highly uncertain. Due to the small areas of the surveys available so far, even the surface density of these objects is not reliably known (Thompson et al. 1999). Since they mostly are $R$-band ‘dropouts’, having the possibility to detect such objects in the MUNICS data in the $I$ and $J$ bands, together with the large field covered, will enable us to gain valuable information on their nature.

2.2 Limiting sensitivity

Fig. 1 shows stellar population synthesis models in the $J - K'$ plane for different star-formation histories, a SFR($t$) $\propto \delta(t)$ Simple Stellar Population (SSP), and 3 exponential star formation rates SFR($t$) $\propto \exp(t/\tau)$ with $\tau = 1$, 3, and 10 Gyr. The onset of star formation occurs at $z = 4$ in all models. The populations are normalised to have a luminosity of $L_B^*$ at the present epoch, according to the type-dependent luminosity function of the Virgo cluster as given by Sandage, Binggeli, & Tammann (1988). The adopted values for $M_B^*$ are $M_B^* = -21.5$ for the SSP model (elliptical/S0 galaxy), $M_B^* = -20.5$ for $\tau = 1$ (Sa-Sb spiral), $M_B^* = -19.5$ for $\tau = 3$ (Sc), and $M_B^* = -17.5$ for $\tau = 10$ (Sd and later). The cosmology is $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.3$, $\Omega_M = 0.7$.

The SSP models are taken from Maraston (1998). The distinguishing feature of that synthesis method is the adaption of the fuel consumption theorem to evaluate the energetics of the post main-sequence evolutionary phases. The models used here have solar metallicity and age ranging from 30 Myr to 15 Gyr. The Initial Mass Function (IMF) is a power law $\psi(M) \propto M^{-(1+x)}$ with Salpeter exponent $x = 1.35$ down to a lower mass limit of 0.1$M_\odot$. The optical and infrared colours predicted by these SSP models are calibrated against Milky Way and Magellanic Cloud globular clusters and compared to similar models from the literature in Maraston (1998). Fig. 1 also shows an SSP model by Bruzual & Charlot (1993) using the 1995 version of their code, with solar metallicity and a Salpeter IMF. The models evolve similarly up to redshifts of $\sim 1$. The differences in colour are likely due to the different treatment of the post main sequence stages and are discussed in Maraston (1998).

Following the predictions of these models, the limiting magnitudes in the near-IR wave-bands have been chosen to be 19.5 mag in $K'$ and 21.0 mag in $J$, such that early-type objects having luminosities of $\geq 0.5L_\odot^*$ at the present epoch can be detected in $K'$ virtually at any redshift, and in $J$ up to a redshift of $z \leq 1.5$, assuming passive evolution.

This is in agreement with the findings of the CFRS, which has shown that, while the luminosity function of the population of blue field galaxies shows significant signs of evolution in the redshift range $0.2 < z < 1$ – explainable by brightening or increase in space density – the redder part of the population (roughly redder than Sc) shows no signs of evolution of its luminosity function in the same redshift range (Lilly et al. 1995b). The latter is interpreted in terms of brightening of the individual galaxies through passive evolution counterbalanced by negative density evolution, such that the luminosity function of the early-type population effectively does not evolve.

2.3 Field selection

The MUNICS survey consists of two sets of near-IR target fields, one set of single camera pointings having an effective field of view of $6' \times 6'$ pointed towards quasars, and a second set of $28' \times 13'$ fields constructed from mosaics of pointings targeted at random high Galactic latitude fields. This second set of fields was selected to contain no bright stars, nearby bright galaxies, and known nearby clusters of galaxies, and furthermore, to have low Galactic reddening (which is all together difficult to accomplish together with the prerequisite of having no bright star within the field, given our field size).

A total of 16 fields targeted towards quasars with redshifts $0.5 < z < 2$ were observed. These fields will be referred to as ‘quasar fields’ hereafter, labelled Q1...Q16. The quasars were selected from the seventh edition of the Veron-Cetty & Veron (1999) catalogue. The selection criteria were $B < 19.0$ mag, $0^\circ < $ Dec $< 65^\circ$, $0^\circ < $ RA $< 18^\circ$, and $0.5 < z < 2$. Six of these quasars are not detected in the radio bands of the catalogue (6 cm and 11 cm) and are therefore considered radio quiet. The remaining 10 are radio loud.

A second set of 7 fields was targeted at high Galactic latitude ‘empty’ fields, i.e. free of bright stars ($V < 17$ mag) and known nearby extragalactic objects. These fields will be called ‘mosaic fields’ hereafter, for they are mosaiced images in the near-IR. They are labelled S1...S7. Each such field is laid out as a stripe of $4 \times 2$ IR pointings, yielding an area of $28' \times 13'$. For technical reasons, namely that four near-IR pointings can be completed in $K'$ and $J$...
Figure 3. Relative transmission of MUNICS V, R, I, J, and K′ filter (solid curves) curves including quantum efficiency of the CCD (V, R, and I) and Rockwell HAWAII near-IR array (J and K′), as well as the atmospheric transmission in the near-IR. Relative transmission curves of standard Johnson-Kron-Cousins V, R, and I filters, as well as J and K′ are shown for comparison (dotted curves).

Figure 4. Comparison of R−J vs. V−R (upper panel) and J−K vs. R−I (lower panel) colours derived by convolving stellar SEDs (see text) with the MUNICS filter curves (open circles) with a sample of bright stars (R < 21) identified in the MUNICS fields S2 f1–f4 (crosses), S4 f1–f4 (x), S6 f5–f8 (squares), and S7 f5–f8 (triangles).

2.4 Photometric system

The MUNICS imaging observations were carried out partly using non-standard filters, or imperfect realisations of standard filters (see Section 2.3 below). Since the colours of objects in the MUNICS catalogues extend to much redder colours than any available photometric standard stars, we decided to work in the MUNICS instrumental photometric system and not to transform magnitudes into the standard Johnson-Kron-Cousins system. Linear transformation to the Johnson-Kron-Cousins system would have caused magnitude errors up to 1 mag, because the true transformations are highly non-linear, especially for red objects. The MUNICS photometric zero-points are in the Vega system.

Note that, since comparison of the object’s colours with spectral synthesis models is intended (e.g. for deriving photometric redshifts or discussing the nature of EROs), it is important that the observed colours and the synthetic colours are consistent with respect to the filter set.

Accurate measurements of the transmission curves of the glass filters and quantum efficiencies of the detectors were obtained and applied in all subsequent synthetic photometry. The filter curves are shown in Fig. 3.

Such accurate knowledge of the filter system allows a reliable calibration of different bands via colour-colour diagrams of stars which are compared with synthetic stellar sequences obtained from the convolution of SEDs from stellar libraries with the transmission curves. The absolute photometric zero-points can then be derived from a single photometric observation in one band only.

Fig. 4 shows a comparison of R−J vs. V−R (upper panel) and J−K vs. R−I (lower panel) colours derived by convolving stellar SEDs with the MUNICS filter curves with a sample of stars detected in the MUNICS mosaic fields. The stellar SEDs used for computing the synthetic colours are taken from the Bruzual-Persson-Gunn-Stryker spectral library (Gunn & Stryker 1983; Strecker, Erickson, & Witte...
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born 1979), covering spectral types O5 to M8. The agreement be-
tween the synthetic photometry and the data along the stellar loci in
colour–colour space demonstrates that the constructed filter curves
match the actual ones and that the photometric zero-points are mu-
tually consistent in the optical and the near-IR regime (see also
Sect. 5.2 and Sect. 5.3). It is worth noting that we have no cool gi-
ant stars or supergiants in the MUNICS sample (as those would occupy
the redder sequence in $J-K$ at $R-I \gtrsim 1.5$) and no stars of earlier
type than roughly late F to G.

3 OBSERVATIONS AND DATA REDUCTION
3.1 Infrared observations and data reduction
The $K'$-band and $J$-band imaging was obtained using the Omega-
Prime camera \cite{Bizenberger98} at the prime focus of the Calar
Alto 3.5-m telescope. Omega-Prime is equipped with a HAWAII 1024$^2$
HgCdTe array. The image scale is 0.396 arcsec
per pixel, resulting in a 6.75′ $\times$ 6.75′ field of view. The $K'$
filter ($\lambda_0 = 2.12 \mu m$, $\Delta \lambda = 0.35 \mu m$; see \cite{Wainscoat92})
was used because it significantly reduces the thermal background
seen by the detector relative to the standard $K$ filter, thus gaining
sensitivity. Table 3 lists all observing runs undertaken to present
date.

The $K'$-band data were observed using a dithering pattern
consisting of 16 positions within an area of 30′′ $\times$ 30′′ laid out on a
$4 \times 4$ grid with 10′′ spacing between adjacent grid points. The data
were recorded using a randomized sequence of these 16 positions.

On each position 28 seconds of net exposure time were col-
clected, divided into several shorter exposures as necessary depend-
ing on the ambient temperature and thus the level of the thermal
background. The length of the single exposures was always chosen
such that non-linearity of the detector was negligible.

This 16 position cycle was repeated 3 times yielding 48 frames
and a total exposure time of 1344 s. The $J$-band images were
observed using the same dithering pattern with longer integration
times of 80 s on each position and therefore needed only one cycle,
giving a total of 1280 s.

The near-IR mosaic fields consist of four such Omega-Prime
pointings arranged in a $2 \times 2$ configuration with 6′ offset in each
direction measured from field centre to field centre. Each mosaic
then covers a total area of 162 square arc minutes, counting only
the central area with the longest total exposure time and removing
overlaps and borders due to the dithering pattern (see Fig. 3).

On photometric nights, standard stars from the UKIRT Faint
IR Standard Stars catalogue \cite{Casali92} were observed several
times during the night at different air masses to determine the photometric zero point and the atmospheric extinc-
tion coefficient. To increase the number of standard star measure-
ments available for each night, the calibrations of further stars in the
UKIRT fields by \cite{Hunt98} were included. Night-to-
night variations in the zero-point were typically less than 0.1 mag.
Targets observed during non-photometric nights were re-observed
(with shorter exposure time) at least once during photometric con-
ditions to assure accurate photometric calibration. The typical for-
mal uncertainties in the zero-points were 0.05 mag in $K'$ and
0.06 mag in $J$. The extinction coefficients were found to be sta-
table for all runs with typical values around 0.08 $\pm$ 0.025 mag per
airmass in $K'$ and 0.12 $\pm$ 0.02 mag per airmass in $J$. By compar-
ison with synthetic photometry as explained in Sect. 2.4, we con-
clude that additional systematic errors in the near-IR calibration
as well as systematic offsets between the near-IR and the optical
wave-bands cannot be larger than $\sim 0.1$ mag.

The data were reduced using standard image processing algo-
rithms within IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}. For each frame a sky frame was constructed from typically 6 to 12 (temporally) adjacent frames where bright
objects and detector defects have been masked out, and which were
scaled to have the same median counts. These frames were then
median-combined using clipping to suppress fainter source and
otherwise deviant pixels to produce a sky frame. The sky frame
was scaled to the median counts of each image before subtraction
to account for variations of sky brightness on short time-scales. The
sky-subtracted images were flat-fielded using dome flats to remove
pixel-to-pixel fluctuations in quantum efficiency. The frames were
then registered to high accuracy using the brightest $\sim 10$ objects
and finally co-added, again using clipping to suppress highly de-
viant pixels due to cosmic ray events and defective pixels on the
array, after being scaled to airmass zero and to a common photo-
metric zero-point.

The $2 \times 2$ mosaic images were produced by registering the
images using objects in the overlap regions, simultaneously cross
checking the photometric calibration. Before combining, the im-
ages were adjusted to have the same background counts computed
from the mode of the pixel values in ‘empty’ sky regions of the
images to correct for residual differences in sky brightness. Abso-
late astrometric calibration of the images is discussed in Sect. 5.3
below.

3.2 Optical observations and data reduction
Optical imaging of the mosaic fields was performed at the Calar
Alto 2.2-m telescope in the $V$, $R$, and $I$ bands using the Calar Alto
Faint Object Spectrograph (CAFOS) focal reducer in direct imaging
mode. CAFOS was equipped with a SiTe 2048$^2$ CCD detector,
yielding a resolution of 0.53 arcsec per pixel and a circular field
of view (due to vignetting by optics) of 16′ in diameter. The $V$
band filter used was a standard Johnson filter, the $R$-band filter was an $R_2$ filter ($\lambda_0 = 0.648 \mu m$, $\Delta \lambda = 0.168 \mu m$), slightly narrower and
bluer than Kron-Cousins $R$. The $I$-band filter was an RG780 fil-
ter with the red cutoff set by the CCD (see Fig. 3). Total exposure
times were 2700 s in $V$ and $I$, and 1800 s in $R$, divided into several
shorter exposures taken with offsets of $\sim 15''$, depending on the
presence of bright stars and on seeing conditions to avoid too many
saturated objects.

The quasar fields were imaged using the Imaging Grism In-
mument (IGI) at the 2.7-m telescope of McDonald Observatory,
using a 1024$^2$ TK4 CCD (7′ field of view) and Mould $R$ and $I$
interference filters. Exposure times 1800 s in $R$ and 2700 s in $I$, again
divided into several shorter exposures.

The optical CCD data were reduced in a fairly standard man-
ner using IRAF, except for cosmic ray cleaning. The frames were
bias/overscan corrected and then flat-fielded using a combination
of dome flats and sky flats. The $J$-band frames showed consider-
able fringing. Fringe images were created from the affected series
of science exposures and occasionally also from twilight flats by
medianing de-registered images after masking bright sources by
hand as necessary. In some cases it was necessary to subtract a low

The data were reduced using standard image processing algo-
rithms within IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}. For each frame a sky frame was constructed from typically 6 to 12 (temporally) adjacent frames where bright
objects and detector defects have been masked out, and which were
scaled to have the same median counts. These frames were then
median-combined using clipping to suppress fainter sources and
otherwise deviant pixels to produce a sky frame. The sky frame
was scaled to the median counts of each image before subtraction
to account for variations of sky brightness on short time-scales. The
sky-subtracted images were flat-fielded using dome flats to remove
pixel-to-pixel fluctuations in quantum efficiency. The frames were
then registered to high accuracy using the brightest $\sim 10$ objects
and finally co-added, again using clipping to suppress highly de-
viant pixels due to cosmic ray events and defective pixels on the
array, after being scaled to airmass zero and to a common photo-
metric zero-point.

The $2 \times 2$ mosaic images were produced by registering the
images using objects in the overlap regions, simultaneously cross
checking the photometric calibration. Before combining, the im-
ages were adjusted to have the same background counts computed
from the mode of the pixel values in ‘empty’ sky regions of the
images to correct for residual differences in sky brightness. Abso-
late astrometric calibration of the images is discussed in Sect. 5.3
below.
order fit to the overall background in the science frames prior to construction of the fringe image to account for changes in the illumination pattern present in the images in the case where a bright star was close to the image border. The fringe images were then finally being added using the positions of ~ 15 bright objects for determination of the offsets between the individual frames.

During photometric nights, photometric standard stars were observed and programme fields with insecure calibrations were re-observed with short exposures. The run at the Wendelstein 0.8-m telescope was devoted to such re-calibration to have independent calibrations for the fields. For each field, a photometric zero point and the atmospheric extinction were determined. No colour terms were fitted to the calibration such re-calibration to have independent calibrations for the fields. For each field, a photometric zero point and the atmospheric extinction were determined. No colour terms were fitted to the calibration. The extinction coefficients were usually consistent with a Rayleigh atmosphere, with a few nights showing higher extinction, albeit within the variations typical for Calar Alto.

The re-imaging system of CAFOS causes substantial radial distortion of the image which had to be dealt with before co-adding the offset images. Therefore the frames were rectified using the known distortion equation, a polynomial of fourth order in the distance from the optical axis (K. Meisenheimer, private communication).

If necessary, variations in the background intensity across the frames caused by scattered light were fitted and subtracted in each individual frame. The images were then corrected for atmospheric extinction and scaled to a common photometric zero-point before finally being added using the positions of ~ 15 bright objects for determination of the offsets between the individual frames.

Table 1. The MUNICS mosaic and quasar fields

| Field | Mosaic/QSO | $z_{QSO}$ | $\alpha$ (J2000) | $\delta$ (J2000) | Filters | $K'$ seeing | $E(B-V)$ | Remarks |
|-------|------------|-----------|-----------------|-----------------|---------|-------------|----------|---------|
| S1    | f1–f2      | 14:49:25  | +65:55:31       | KJIRV           | 1.01''   | 0.017       |          | (1)     |
| S2    | f1–f4      | 03:06:41  | +00:01:12       | KJIRV           | 1.30''   | 0.080       |          | (3)     |
| S3    | f1–f4      | 03:15:00  | +00:07:41       | KJIRV           | 0.95''   | 0.094       |          | (3)     |
| S4    | f5–f8      | 03:14:05  | +00:07:41       | KJIRV           | 2.52''   | 0.094       |          | (3)     |
| S5    | f1–f4      | 09:03:44  | +30:02:56       | KJIRV           | 1.11''   | 0.025       |          | (3)     |
| S6    | f1–f4      | 10:24:01  | +39:46:37       | KJIRV           | 1.17''   | 0.012       |          | (3)     |
| S7    | f1–f4      | 10:25:14  | +39:46:37       | KJIRV           | 1.32''   | 0.009       |          | (3)     |
| S8    | f1–f4      | 11:55:58  | +65:35:55       | KJIRV           | 1.21''   | 0.019       |          | (3)     |
| S9    | f1–f4      | 11:57:56  | +65:35:55       | KJIRV           | 1.41''   | 0.015       |          | (3)     |
| S10   | f1–f4      | 13:33:41  | +16:51:44       | KJIRV           | 1.12''   | 0.029       |          | (3)     |
| Q1    | J000701.3+002224 | 0.87 | 00:07:01 | +00:22:42 | KJIR | 1.39'' | 0.073 | PB 5741; (4) |
| Q2    | J000750.9+031733 | 1.10 | 00:07:51 | +03:17:32 | KJIR | 1.07'' | 0.020 | PB 5753; (4) |
| Q3    | J005444.0+144646 | 0.91 | 00:54:44 | +14:46:47 | KJIR | 1.30'' | 0.054 | PHL 892; (4) |
| Q4    | J005905.6+000651 | 0.72 | 00:59:06 | +00:06:52 | KJIR | 1.00'' | 0.027 | PHL 923 |
| Q5    | J010026.8+043941 | 0.53 | 01:00:27 | +04:39:41 | KJIR | 1.06'' | 0.024 | UM 81; (4) |
| Q6    | J011033.4+015446 | 0.71 | 01:10:35 | +01:55:37 | KJIR | 1.29'' | 0.028 | MS 01080+0139; (4) |
| Q7    | J011517.9+065317 | 1.20 | 11:55:28 | +65:38:10 | KJIRV | 1.62'' | 0.017 | 4C 65.13 |
| Q8    | J025937.5+003736 | 0.53 | 02:59:38 | +00:37:37 | KJIR | 1.33'' | 0.090 | US 3472 |
| Q9    | J025937.5+003736 | 0.53 | 02:59:38 | +00:37:37 | KJIR | 1.33'' | 0.090 | US 3472 |
| Q10   | J115517.9+653917 | 1.20 | 11:55:28 | +65:38:10 | KJIRV | 1.62'' | 0.017 | 4C 65.13 |
| Q11   | J122033.9+334312 | 1.51 | 12:20:34 | +33:43:10 | KJIR | 1.22'' | 0.012 | 3C 270.1 |
| Q12   | J133355.8+164904 | 2.08 | 13:33:40 | +16:48:14 | KJIR | 1.86'' | 0.022 | PB 3977 |
| Q13   | J133411.6+550125 | 1.25 | 13:34:12 | +55:01:25 | KJIR | 1.59'' | 0.007 | 4C 55.27 |
| Q14   | J135704.5+191906 | 0.71 | 13:57:05 | +19:19:07 | KJIR | 1.72'' | 0.060 | PKS 1354+19 |
| Q15   | J135817.6+575205 | 1.38 | 13:58:18 | +57:52:05 | KJIR | 1.89'' | 0.010 | 4C 58.29 |
| Q16   | J171938.4+480413 | 1.08 | 17:19:38 | +48:04:13 | KJIR | 1.79'' | 0.019 | PG 1718+481 |

Field coordinates are given with respect to the image centres. QSO designations according to Veron-Cetty & Veron (1996).

(1) Mosaic incomplete in the near-IR.
(2) Near-IR data quality poor.
(3) Good data quality in all five wave-bands.
(4) Radio quiet QSO.
Astrometric solutions were computed for all by the Universit¨at M¨unchen.

Texas. Wdst is the 0.8-m telescope of Wendelstein Observatory operated is the Hobby-Eberly Telescope, both of McDonald Observatory, Austin, Alto Observatory, respectively. McD27 is the 2.7-m telescope and HET CA22 and CA35 are the 2.2-m telescope and the 3.5-m telescope of Calar (1) Re-imaging of fields with poor data quality.

(1) Monet et al. 1996 were selected in each frame. The celestial coordinates of these stars were matched against the pixel position using IRAF.

The typical scatter is less than 0.4 arcsec rms. The scatter in the determined solutions within IRAF task CCXYMATCH, and the plate solution was computed using CCMAP. The typical scatter is less than 0.4 arcsec rms.

The \( K' \)-band images of one of our mosaic fields (S6 f5–f8). The number of false detections was determined by looking for positive detections in an inverted (multiplied by \( -1 \)) version of the image, after convincing ourselves that the background noise was sufficiently well approximated by a Gaussian. Fig. 5 shows the results of these tests.

At the depth of our data we detect roughly 1000 objects per mosaic field. Accepting 1 per cent contamination by false detections, i.e. roughly 10 false objects per mosaic field we fixed the detection threshold at \( t = 3 \sigma \) and the minimum number of consecutive pixels at 1.4 times the seeing disk area, \( N_{pix} = 1.4 \pi (FWHM/2)^2 \), (10 pixels at 1" , 16 pixels at 1.5"seeing for the near-IR frames) and performed object detection using these parameters on all \( K' \)-band images.

4.4 Completeness

To estimate the completeness limits of the MUNICS \( K' \)-selected catalogues, Monte–Carlo simulations were carried out to determine the detection completeness as a function of magnitude in each \( K' \)-band image.

### Table 2. MUNICS observing runs

| Date       | Tel. | Instrument | Remarks       |
|------------|------|------------|---------------|
| 1996 24-27.10 | CA35 | \( \Omega' \) | Quasar fields |
| 1997 15-19.5 | CA35 | \( \Omega' \) | Quasar fields |
| 1998 8-14.4 | CA35 | \( \Omega' \) | Quasar fields |
| 1998 12-17.5 | CA35 | \( \Omega' \) | Quasar fields |
| 1998 28.5-1.6 | CA22 | CAOS       |               |
| 1998 16-18.11 | McD27 | IG1       | Quasar fields |
| 1998 16-20.12 | CA22 | CAOS       |               |
| 1998 23-30.12 | CA35 | \( \Omega' \) |               |
| 1999 18.3 | Wdst | MONICA     | Calibrations  |
| 1999 27.5-3.6 | CA35 | \( \Omega' \) |               |
| 1999 9.18.6 | CA22 | CAOS       |               |
| 2000 26-31.5 | CA35 | MOSCA      | Spectroscopy  |
| 2000 27-28.5 | HET  | LRS        | Spectroscopy  |
| 2000 16.7 | CA35 | \( \Omega' \) | (1)           |
| 2000 20-22.11 | ESO-VLT | FORS1/2 | Spectroscopy  |
| 2000 24-28.11 | CA35 | MOSCA      | Spectroscopy  |
| 2000 5.12 | CA22 | CAOS       | (1)           |
| 2000 17-18.12 | CA22 | CAOS       | (1)           |
| 2000 19.12 | CA35 | \( \Omega' \) | (1)           |
| 2001 17-21.1 | CA35 | MOSCA      | Spectroscopy  |
| 2001 11-13.2 | CA35 | \( \Omega' \) | (1)           |

(1) Re-imaging of fields with poor data quality.

CA22 and CA35 are the 2.2-m telescope and the 3.5-m telescope of Calar Alto Observatory, respectively. McD27 is the 2.7-m telescope and HET is the Hobby-Eberly Telescope, both of McDonald Observatory, Austin, Texas. Wdst is the 0.8-m telescope of Wendelstein Observatory operated by the Universitats-Sternwarte München.

### 3.3 Astrometry

Astrometric solutions were computed for all \( K' \)-band images to translate pixel coordinates into celestial coordinates. For this purpose, astrometric standards from the USNO-SA1.0 catalogue (Monet et al. 1996) were selected in each frame. The celestial coordinates of these stars were matched against the pixel position using IRAF task CCXYMATCH, and the plate solution was computed using CCMAP. The typical scatter is less than 0.4 arcsec rms.

The \( V \), \( R \), \( I \), and \( J \) images of each field were registered against the \( K' \)-band image by matching the positions of \( \sim 200 \) bright homogeneously distributed objects in the frames and determining the coordinate transform from the \( K' \)-band system to each image in the other four pass-bands using the tasks XYXYMATCH and GEOMAP within IRAF. The scatter in the determined solutions is less than 0.1 pixels rms in the transformation from \( K' \) to \( J \), and less than 0.2 pixels rms from \( K' \) to the optical frames. Note that the frames themselves are not transformed. We only determine accurate transformations and apply these later to the apertures in the photometry process.

### 3.4 Spectroscopy

A spectroscopic follow-up programme is currently being conducted at the Calar-Alto 3.5-m telescope, the Hobby-Eberly Telescope, and the VLT, aiming ultimately at a magnitude-limited redshift survey of the \( K' \)-band selected catalogue. The results of these observations will be discussed in a future paper. In the mean time, the spectroscopic redshifts are used to calibrate photometric redshifts.
mosaic field), again as a function of π threshold Figure 5. (solid line), 3.0

N. Drory et al. For this purpose the PSF having the same FWHM as stars in the frames were added to the MUNICS images. For this purpose the centroid coordinates of the sources detected in the other frames using the full astrometric transformations as determined in Sect. 3.3. The shape of the apertures were transformed using only the linear terms of the transformation.

The photometric accuracy for the 5′′ apertures is shown in Fig. 7. At the 50 per cent completeness limit in the K′ band (19.59), the signal-to-noise ratio is \( \sim 10 \). For such an object having an \( R - K' \) colour of 6, the signal-to-noise ratio in the \( R \) band is roughly 3.



4.3 Photometry

Photometry was performed in elliptical apertures the shape of which were determined from the first and second moments of the light distribution in the \( K' \)-band image, as described in Drory (2001), and additionally in fixed size circular apertures of 5 and 7 arc seconds diameter. To ensure measurement at equal physical scales in every pass-band, the individual frames were convolved to the same seeing FWHM, namely that of the image with the worst seeing in each field. The signal-to-noise ratio as a function of magnitude for the 5′′ apertures is shown in Fig. 7. At the 50 per cent completeness limit in the \( K' \) band (19.59), the signal-to-noise ratio is \( \sim 10 \).

Aperture fluxes and magnitudes were computed for each object present in the \( K' \)-band catalogue irrespective of a detection in any other band. For this purpose the centroid coordinates of the sources detected in the \( K' \)-band images were transformed to the other frames using the full astrometric transformations as determined in Sect. 3.3. The shape of the apertures were transformed using only the linear terms of the transformation.

The photometric accuracy for the 5′′ aperture magnitudes is roughly 0.1 mag at \( K' = 19 \) mag. This error estimate includes the effects of photon noise and uncertainty in background determination and subtraction, but does not include (systematic) errors due to

Figure 5. The behaviour of the 50 per cent completeness limit for point-like sources and the number of spurious source detections as a function of the detection threshold \( t \) in units of the local background rms \( \sigma \) and the required number \( N_{\text{pix}} \) of consecutive pixels above the threshold in units of the seeing disk area \( \pi(\text{FWHM}/2)^2 \). The left panel shows the change in limiting magnitude at 50 per cent completeness as a function of \( N_{\text{pix}} \) for detection thresholds of 2.0\( \sigma \) (solid line), 3.0\( \sigma \) (dashed line), and 4.0\( \sigma \) (dotted line). The right panel shows the number of spurious sources integrated over all magnitudes per image (one mosaic field), again as a function of \( N_{\text{pix}} \) and the detection threshold \( t \). Line styles as in the left panel.

Table 3. Completeness limits for the MUNICS mosaic fields

| Band | S2 f1–f4 | S4 f1–f4 | S5 f1–f4 | S6 f1–f4 | S6 f5–f8 | S7 f5–f8 |
|------|----------|----------|----------|----------|----------|----------|
|      | 90%      | 50%      | 90%      | 50%      | 90%      | 50%      | 90%      | 50%      |
| K    | 19.05    | 19.45    | 18.69    | 19.18    | 19.42    | 19.80    | 18.26    | 18.56    | 19.53    | 19.92    | 19.23    | 19.83    |
| J    | 20.29    | 20.68    | 20.62    | 21.04    | 20.53    | 20.93    | 20.06    | 20.44    | 20.69    | 21.06    | 20.84    | 21.39    |
| I    | 21.86    | 22.29    | 22.18    | 22.60    | 21.72    | 22.07    | 22.35    | 22.72    | 22.70    | 22.08    | 21.94    | 22.34    |
| R    | 22.78    | 23.21    | 23.18    | 23.50    | 22.94    | 23.32    | 23.25    | 23.58    | 22.95    | 23.37    | 22.88    | 23.28    |
| V    | 23.13    | 23.51    | 23.62    | 23.94    | 23.36    | 23.72    | 23.36    | 23.68    | 23.50    | 23.89    | 22.96    | 23.28    |

In these simulations, 250 artificial objects with a Moffat-type PSF having the same FWHM as stars in the frames were added to the MUNICS images. For this purpose the IRAF package ARTDATA was used. A constant distribution of apparent magnitudes of the artificial objects was applied. Then the object detection algorithm was run on these frames, and the number of re-detected objects was recorded as a function of magnitude. This procedure was repeated 250 times in order to decrease statistical errors.

Fig. 8 shows the results of these simulations for 6 of the mosaic fields where imaging data in all five colours are available. The 50 per cent and 90 per cent completeness limits of the \( K' \)-band images are listed in Table 3. From these simulations we conclude that the mosaic fields comprise a reasonably homogeneous data set, with field-to-field variations in 50 per cent completeness of order \( \sim 0.4 \) mag, with the exception of S6 f1–f4 which is considerably shallower. The quasar fields, which are not shown here, have completeness levels in the same range as the shown mosaic fields.

Simulations with extended objects having de Vaucouleurs and exponential surface brightness profiles have also been performed. In general they yield 50 per cent completeness limits between 0.5 and 1 magnitude brighter than those determined for stellar sources, depending mostly on the adopted profile scale-length. The full results of these simulations will be extensively discussed in a future paper in the context of surface-brightness selection effects.
the photometric calibration. Fig. 8 shows plots of the magnitude error vs. object magnitude for one mosaic field in all five pass-bands.

Figure 6. Completeness fraction of point-like sources as a function of magnitude in the K’-band mosaic fields as determined by adding Moffat-type objects to the images and recording the fraction of such objects that was recovered by the detection process.

Figure 7. Signal-to-noise ratio in K’ (left panel) and R (right panel) as a function of magnitude in circular apertures of 5″ diameter for objects taken from the K’-selected catalogue of the field S6 f5–f8. The signal-to-noise ratio is defined here as the signal-to-noise ratio of the aperture photometry, i.e. total (sky-subtracted) flux within the aperture divided by the total noise within the aperture, with contributions to the latter coming from Poisson fluctuations in the object as well as the background, and the error in the determination of the background.

most do not scatter out of the stellar locus in parameter space (except in the presence of crowding). Rather, images of faint galaxies as they become smaller at larger distances, move onto the locus of point-like sources.

Using the multi-pass-band information available in MUNICS allows us to push the limit of reliable classification by using for each object the classification information in those pass-bands where the signal-to-noise ratio is highest. Therefore, in the mosaic fields where 5 colours are available, we classify as stellar every source that is classified as stellar by YODA in the three pass-bands with highest signal-to-noise. In the quasar fields, where less colour information is available, we rely on the two images with highest signal-to-noise.

As can be seen in Fig. 8, objects classified as stars occupy the clearly defined stellar sequence in the R–J vs. J–K′ colour–colour plane, with only very few objects classified as stellar having a J–K′ colour redder than ~ 1. These are either misclassified faint and compact galaxies or very late-type stars or brown dwarfs, the latter is a possibility for those objects having also red R–J colour. The objects lying on the stellar sequence at R – J > 2 and which are classified as galaxies were found to be faint and barely resolved objects failing the classification as a star only due to their appearance in one filter. In many cases an obvious reason – like a second close object – could be identified. We conclude that most of these objects are, in fact, misclassified stars. The total fraction of point-like sources in the catalogues is ~ 10 per cent.

As can be seen in Fig. 10, objects classified as stars occupy the clearly defined stellar sequence in the R–J vs. J–K′ colour–colour plane, with only very few objects classified as stellar having a J–K′ colour redder than ~ 1. These are either misclassified faint and compact galaxies or very late-type stars or brown dwarfs, the latter is a possibility for those objects having also red R–J colour. The objects lying on the stellar sequence at R – J > 2 and which are classified as galaxies were found to be faint and barely resolved objects failing the classification as a star only due to their appearance in one filter. In many cases an obvious reason – like a second close object – could be identified. We conclude that most of these objects are, in fact, misclassified stars. The total fraction of point-like sources in the catalogues is ~ 10 per cent.

We have also checked the results of the image-based classification against spectral classification for those objects where spectroscopy was already available, namely 45 galaxies and 53 stars having R < 20.5. All these objects were correctly classified.
4.5 Galactic extinction

We use the Galactic reddening maps provided by Schlegel, Finkbeiner, & Davis (1998) using a value of $R_V = 3.1$ to calculate $A_X = R_A E(B-V)$ to correct the measured magnitudes for Galactic foreground extinction. The values of $E(B-V)$ for our fields are given in Table 1.

4.6 Galaxy number counts

In Table 1 we present number counts of galaxies in the MUNICS mosaic fields in all five filters $K'$, $J$, $I$, $R$, and $V$. These counts are also shown in Fig. 8 together with a compilation of number counts from the literature. Object catalogues were generated independently for each pass-band for this purpose, and star–galaxy separation is based on the PSF classification as described above, using only single pass-band information. The data were not transformed into the standard magnitude system for this comparison. Completeness corrections were not applied to these galaxy number counts, but corrected counts will be presented in the context of a more detailed completeness analysis in a future paper. The counts are average counts from all the available MUNICS mosaic fields, with field-to-field variations in the number counts being on the level of 0.1 dex. The errors given in Table 1 only include Poissonian errors.

The number counts are compared to the following literature values: Gardner, Cowie, & Wainscoat 1993; Cowie et al. 1994; Glazebrook et al. 1994; Djorgovski et al. 1994; Gardner et al. 1996 for the $K$ band, Saracco et al. 1995; Teplz, McLean, & Malkan 1999 for the $J$ band, Tyson 1988; Lilly, Cowie, & Gardner 1991; Casertano et al. 1990; Gardner et al. 1994; Williams et al. 1996; Hogg et al. 1998; Steidel & Hamilton 1993; Steidel et al. 1994; Driver et al. 1994; Metcalfe et al. 1995.

We generally find good agreement with previously published number counts in all pass-bands, again as a consistency check confirming the quality of our photometry.

4.7 Colour distributions and objects at $z \geq 1$

In Fig. 10 we show the $J-K'$ vs. $K'$ colour–magnitude diagramme and the $R-J$ vs. $J-K'$, $V-I$ vs. $J-K'$, and $V-I$ vs. $V-R$ colour–colour diagrammes for MUNICS data from three mosaic fields. The total number of objects shown is 2977, of which 286 are classified as point-like. These plots also contain the tracks defined by the stellar population synthesis models described in detail in Sect. 2.2. Briefly, the models are an SSP, and three exponential star formation histories with e-folding times of 1, 3, and 10 Gyr forming at $z = 4$. The models have been normalised such that they represent typical $L^*$ objects at $z = 0$, with $L^*$ chosen according to their 'photometric' Hubble type. The cosmology adopted is again $H_0 = 65$, $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$.

These models reasonably envelope the region in the colour–magnitude $J-K'$ vs. $K'$ plane occupied by the data, with the SSP model following the outline of the data points along the bright and red edge as might be expected since any further star formation or a later formation epoch would render the object bluer relative to the SSP.

It is also worth noting that the models constitute a continuous sequence with the duration of the star formation as the parameter in the $R-J$ vs. $J-K'$ plane, closely following the SSP track up to a redshift of $\sim 1$, then rapidly turning bluer in $R-J$ while still getting redder in $J-K'$. A significant fraction of objects between the SSP and the 1 Gyr track is compatible with being well evolved objects at a redshift $z \gtrsim 1$. How many objects exactly populate this region is an important question which will be addressed in a future paper.

We finally conclude from these diagrammes that the quality of our data meets the requirements expressed in Sect. 3 and that we are in a position to construct a catalogue containing a large number of massive field galaxies in the redshift range $0.5 \lesssim z \lesssim 1.5$ to study their evolution in detail.

5 SUMMARY

The Munich Near-IR Cluster Survey (MUNICS) is a wide-area, medium-deep, photometric survey selected in the $K'$ band. It covers an area of roughly one square degree in the $K'$ and $J$ near-IR pass-bands with additional complementary optical imaging in the $V, R, and I$ bands.

MUNICS has been undertaken to study the evolution of both field galaxies and galaxy clusters out to redshifts around unity, and to investigate the nature of extremely red objects and their connection to the population of massive field spheroidal galaxies.

The survey area consists of $16 \times 6'$ fields targeted at QSOs with redshifts $0.5 < z < 2$ and $728 \times 13'$ stripes targeted at 'random' high Galactic latitude fields. Ten of the QSO fields were additionally imaged in $R$ and $J$, and $0.6$ deg$^2$ of the randomly selected fields were imaged in the $V, R, and I$ bands. The resulting object catalogues were strictly selected in $K'$, having a limiting magnitude (50 per cent completeness) of $K' \sim 19.5$ mag and
Table 4. $K'$, $J$, $I$, $R$, and $V$-band galaxy number counts for the MUNICS mosaic fields. The counts as a function magnitude and the error of the counts are given in logarithmic units. The values have not been corrected for incompleteness. The errors are Poissonian errors only.

| $J$ | $K'$ | $I$ | $R$ | $V$ |
|-----|------|-----|-----|-----|
| 14.25 | 1.19 | 0.47 | 1.37 |  |
| 14.75 | 2.11 | 1.38 | 2.32 |  |
| 15.25 | 2.44 | 2.20 | 2.59 |  |
| 15.75 | 2.83 | 2.70 | 2.93 |  |
| 16.25 | 2.99 | 2.89 | 3.07 |  |
| 16.75 | 3.25 | 3.18 | 3.32 |  |
| 17.25 | 3.41 | 3.35 | 3.46 |  |
| 17.75 | 3.56 | 3.51 | 3.61 |  |
| 18.25 | 3.70 | 3.66 | 3.74 |  |
| 18.75 | 3.79 | 3.75 | 3.82 |  |
| 19.25 | 3.83 | 3.79 | 3.86 |  |
| 19.75 | 3.73 | 3.69 | 3.77 |  |
| 20.25 | 3.10 | 2.98 | 3.18 |  |
| 20.75 | 3.87 | 3.84 | 3.91 |  |
| 21.25 | 3.86 | 3.82 | 3.89 |  |
| 21.75 | 3.41 | 3.34 | 3.47 |  |
| 22.25 | 3.99 | 3.96 | 4.02 |  |
| 22.75 | 3.97 | 3.94 | 4.00 |  |
| 23.25 | 3.86 | 3.83 | 3.90 |  |
| 23.75 | 3.62 | 3.57 | 3.66 |  |
| 24.25 | 3.36 | 3.29 | 3.41 |  |
| 24.75 | 2.75 | 2.58 | 2.86 |  |
| 25.25 | 3.42 | 3.36 | 3.47 |  |
| 25.75 | 3.03 | 2.93 | 3.11 |  |

$J \sim 21$ mag, sufficiently deep to detect passively evolving early-type systems up to a redshift of $z \lesssim 1.5$ and luminosity of $0.5L^\ast$. The optical data reach a depth of roughly $R \sim 23.5$ mag. The project’s main scientific aims are the identification of galaxy clusters at redshifts around unity and the selection of a large sample of field early-type galaxies at $0 < z < 1.5$ for evolutionary studies.

In this paper we describe the selection of survey fields as well as the observations and the reduction of the near-infrared and optical data. We define our photometric system and show it to be internally consistent by checking it against synthetic photometry of stars from stellar libraries. The construction of the $K'$-selected object catalogue is described in detail, particularly the choice of parameters for object detection, which ensures completeness to as faint magnitudes as possible while keeping the rate of false detections in our strictly $K'$-selected catalogue small. Photometry of the objects in the catalogue is performed in elliptical apertures on frames convolved to the same PSF in all filters, in order to guarantee measurements of the flux in equal physical areas. Stars and galaxies in the fields are classified using a Bayesian analysis of the light distribution in the images.

The quality of the survey data in terms of signal-to-noise ratio and limiting magnitude is discussed, with the completeness of the survey fields being characterised by Monte–Carlo simulations of point sources in the MUNICS frames. Also, galaxy number counts are presented in the five filters $K'$, $J$, $I$, $R$, and $V$ and compared to counts published by other authors.

Finally, we show the $J - K'$ vs. $K'$ colour–magnitude diagramme and the $R - J$ vs. $J - K'$, $V - I$ vs. $J - K'$, and $V - R$ colour–colour diagrammes for MUNICS objects, together with stellar population-synthesis models for different star-formation histories and conclude that the data set presented is suitable for extracting a catalogue of massive field galaxies in the redshift range $0.5 \lesssim z \lesssim 1.5$ for evolutionary studies and follow-up observations.

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REFERENCES

Arnouts S., D’Odorico S., Cristiani S., Zaggia S., Fontana A., Giallongo E., 1999, A&A, 341, 641
Bahcall N. A., Fan X., 1998, ApJ, 504, 1
Bahcall N. A., Fan X., Cen R., 1997, ApJ, 485, L53
Baum W. A., 1962, in IAU Symp. 15: Problems of Extra-Galactic Research, Vol. 15, p. 390
Benitez N., 2000, ApJ, 536, 571
Bertin E., Duranfled M., 1997, A&A, 317, 43
Figure 10. Colour–magnitude and colour–colour diagrammes for MUNICS objects taken from 3 mosaic fields (S2 f1–f4, S6 f5–f8, and S7 f5–f8) containing 2977 sources. Objects classified as stellar are marked with filled squares, extended objects are marked with open squares. Also shown are stellar population synthesis models for different star-formation histories. The model parameters are the same as in Fig. 1. Redshift along the model tracks is marked by circles at a $z$ spacing of 0.5, with $z = 1$ and $z = 2$ being accentuated by filled circles. The lines of constant redshift at $z = 1$ and $z = 2$ are drawn as thin solid lines.

Bizenberger P., McCaughrean M. J., Birk C., Thompson D., Storz C., 1998, Proceedings of SPIE, 3354, 825
Brinchmann J., Ellis R. S., 2000, ApJ, 536, L77
Broadhurst T. J., Ellis R. S., Shanks T., 1988, MNRAS, 235, 827
Bruzual G. A., Charlot S., 1993, ApJ, 405, 538
Casali M. M., Hawarden T., 1992, JCMT UKIRT Newsletter, 4, 33
Casertano S., Ratnatunga K. U., Griffiths R. E., Im M., Neuschaefer L. W., Ostrander E. J., Windhorst R. A., 1995, ApJ, 453, 599
Christian C. A., Adams M., Barnes J. V., Butcher H., Hayes D. S., Mould J. R., Siegel M., 1985, PASP, 97, 363
Cimatti A. et al., 1999, A&A, 352, L45
Colless M., Ellis R. S., Taylor K., Hook R. N., 1990, MNRAS, 244, 408
Couch W. J., Jurevic J. S., Boyle B. J., 1993, MNRAS, 260, 241
Couch W. J., Newell E. B., 1984, ApJS, 56, 143
Cowie L. L., Gardner J. P., Hu E. M., Songaila A., Hodapp K.-W., Wainscoat R. J., 1994, ApJ, 434, 114
de Propris R., Stanford S. A., Eisenhardt P. R., Dickinson M., Elston R., 1999, AJ, 118, 719
Djorgovski S. et al., 1995, ApJ, 438, 1
Driver S. P., Phillipps S., Davies J. I., Morgan I., Disney M. J., 1994, MNRAS, 268, 949
