Stellar Populations with Adaptive Optics: Four Test Cases

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1. Introduction

Several beautiful photographs of galaxies greet visitors in the foyer at ESO Headquarters in Garching. Some of these photos, in particular those of NGC 5128 (Cen A) and IC 5152, contain prominent foreground stars. Some may think that these bright over-exposed stars (and their diffraction spikes) spoil the beauty and usefulness of the photographs. However, on the basis that one astronomer's noise is another one's signal, we describe a project that aims to take advantage of these fortuitously placed stars to make adaptive optics images of the galaxies behind them.

The goal of this project, first described by Minniti & Bedding (1995), is to resolve distant galaxies into their component stars. This would allow studies of the sort that are currently only possible for galaxies in the Local Group. By constructing colour-magnitude diagrams, we could measure the ages and metallicities of the stellar populations making up the galaxy. There are several advantages to performing these studies in the infrared:

• The spectral energy distributions of red giant stars peak in the infrared, increasing the contrast relative to the underlying fainter and bluer stars.

• Extinction and reddening from dust are less than in the visible ($A_K = 0.1\ A_V$).

• The degeneracy in the optical colours of the red giant branch is avoided. This degeneracy makes it difficult to determine ages or metallicities from optical photometry, especially for the more metal-rich populations that dominate bulges and ellipticals.

• The transformation between the photometric observations and theory (M_{bol}, T_{eff}) is easier in the infrared than in the visible: the $J - K$ colour is directly related to T_{eff} and the H and K magnitudes are directly related to M_{bol}. The H filter is particularly useful for constructing deep luminosity functions because the bolometric correction is essentially independent of colour for late-type stars.

Adaptive optics (AO), which is currently only available in the infrared, gives two further benefits:

• It allows a substantial gain in sensitivity for point-source photometry by reducing the diameter of stellar images, thus increasing the signal relative to the background sky.

• The increased resolution reduces confusion in crowded regions.

One important limitation is that, until laser beacons become available, AO is restricted to fields which lie near a bright foreground star.

In this article we describe a first attempt to apply adaptive optics to the study of resolved stellar populations in galaxies (full details are given in Bedding et al., 1997). We have selected four widely different targets for this study which together provide excellent test cases and allow us to evaluate the potential of the VLT.

2. Observations

Observations were made in March and August 1995 with the ESO 3.6-m telescope using ADONIS (ADaptive Optics Near Infrared System; Rousset et al., 1994; Beuzit et al., 1994). The ADONIS instrument is the successor to COME ON+. Wavefront sensing is done at visi-

Figure 1: Image of NGC 5128, taken from the Digital Sky Survey. The image is 30′ × 30′, with north up and east to the left. All stellar images are foreground stars within our galaxy. The two brightest stars, used for wavefront sensing, are just below the centre and near the left-hand edge.

Figure 2: Photograph of IC 5152 taken at the prime focus of the ESO 3.6-m. The image is about 4′ wide. On deeper exposures, it is clear that the body of IC 5152 extends well beyond the bright (V = 7.9) foreground star.

ble wavelengths and the science detector operates in the near infrared. For the latter we used the SHARP II camera, which contains a 256 × 256 NICMOS 3 array with 0.″05 pixels, giving a field of 12.″5 × 12.″5.

An adjustable mirror in ADONIS allowed us to make offsets of a few arcseconds within a field, which we found useful in constructing a local flat field. It also allowed us to ensure that neither the bright reference star nor its diffraction spikes fell on the science detector. For each field we obtained a sequence of exposures offset by 2″ from the field centre in each of four orthogonal directions. The median of these frames was used for sky subtraction. After dark-subtraction, flatfielding and interpolation over hot pixels, the images were aligned and added to produce a single mosaic. Due to the sub-stepping process, the central 8″ × 8″ of the mosaic has the greatest effective exposure time and hence the highest signal-to-noise ratio.

3. Results

3.1 The giant elliptical galaxy NGC 5128

The S0/E pec. galaxy NGC 5128 (Cen A) is of interest both as the closest radio galaxy and because it shows evidence of having undergone a recent interaction. Fortuitously, two foreground stars are superimposed on the body of the galaxy, at distances of 4.′5 and 10.′9 from the nucleus and away from the central dust lane (see Fig. 1).

We observed fields next to both reference stars with ADONIS, but seeing conditions were poor and fast variations prevented good correction. The first star was bright ($K \simeq 5$) and produced too much scattered light on the science detector, preventing accurate sky subtraction. From a total integration time of 1 hour near the second star we failed to detect any individual stars in NGC 5128, down to an estimated magnitude limit of $K = 19.5$. Assuming the presence of old giant stars reaching $M_K = -5$, this allows us to place a lower limit on the distance to the galaxy of about 3 Mpc.

Since these observations, Soria et al. (1996) have published the first optical colour-magnitude diagram of the NGC 5128 halo, obtained with HST/WFPC2. They resolved this galaxy into stars and convincingly detected the tip of the old RGB at $I = 24.1$, deriving a distance of 3.6 ± 0.2 Mpc, consistent with our lower limit. These RGB stars would have $K \approx 22.5$, beyond our magnitude limit. Soria et al. also detected a handful of AGB stars, extending to $I = 22.6$, equivalent to $K \approx 20.5$. These stars would be at the limit of our detection and their absence is explained by the small field covered here, although we speculate that a few would have been detected with better seeing.

3.2 The halo of IC 5152

IC 5152 is a typical dwarf irregular (dIrr) galaxy on the outer fringe of the Local Group, at a distance of about 1.6 Mpc (van den Bergh, 1994). The galaxy is gas-rich and has on-going star formation, despite the fact that its isolated position appears to rule out a recent major interaction. It would be valuable to search this galaxy for an underlying old

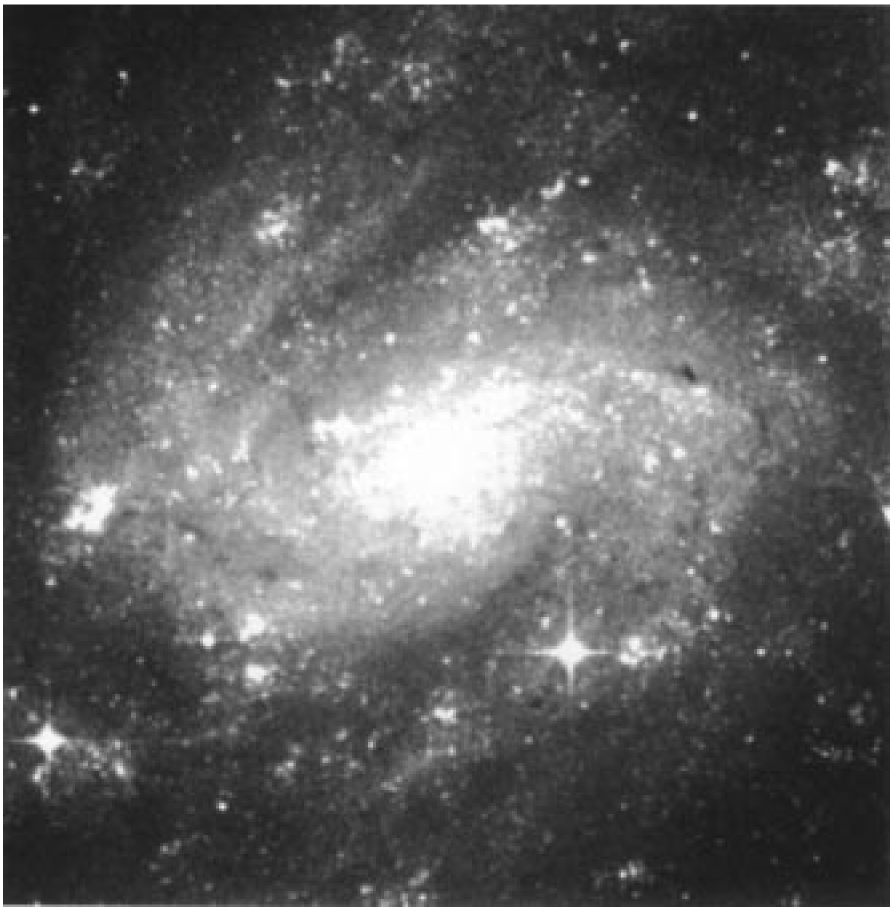
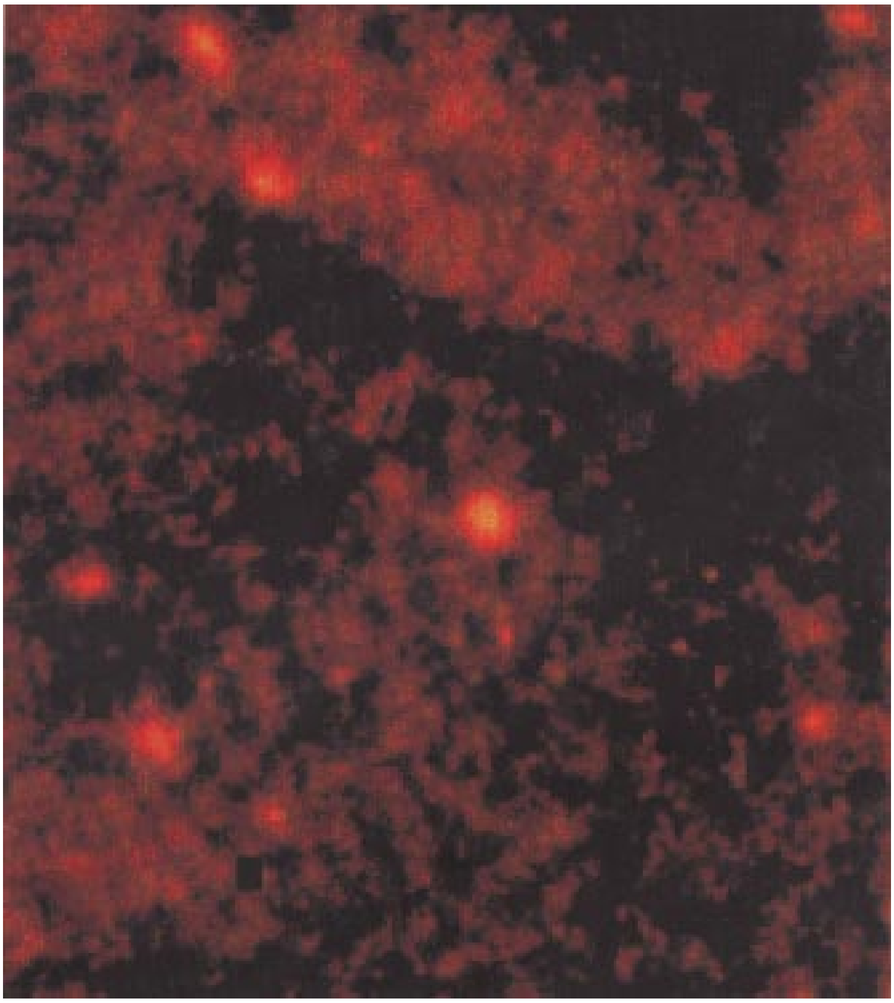


Figure 3: Image of the central 10′ × 10′ of NGC 300, taken from the Digital Sky Survey. North is up and east is to the left. The bright star 2′ SW of the nucleus was used for wavefront sensing.

Figure 4: ADONIS images of the NGC 300 disk field in K′. North is up and east is to the left. The bright elongated feature in the northern third of the image is caused by a reflection in the optical system. The image is 8″ × 8″.



population (age ~ 15 Gyr and [Fe/H] ≤ –1) which would indicate an initial large burst of star formation. There are, however, no detailed colour-magnitude diagrams of IC 5152 at any wavelength, partly due to a very bright foreground star located next to the main body of this galaxy (Fig. 2).

We observed a field in the outer part of IC 5152 next to this bright foreground star. The seeing was 0.″6–1.″0. From a 40-minute integration at *H* we detected three very faint stellar sources but low counts prevented us from deriving accurate magnitudes.

The failure to detect more stars could indicate that IC 5152 is more distant than 1.6 Mpc, or that its halo does not extend this far from the nucleus. On the basis of these marginal detections and the results obtained on NGC 300 (discussed below), we believe that useful results would have been possible on IC 5152 under excellent seeing conditions.

3.3 The disk of NGC 300

NGC 300 is a spiral galaxy in the Sculptor Group and lies at a distance of about 2 Mpc (Freedman et al., 1992; Walker, 1995). We used a bright star superimposed on the disk, about 2′ SW of the nucleus in the prominent SW spiral arm (Fig. 3). In the future, with improved AO systems, it may be possible to use the compact nucleus of NGC 300 itself as a reference to study the central regions.

A *K′* image taken during particularly good seeing (0.″6 at the seeing monitor) revealed about twelve sources with FWHM 0.″3–0.″4. However, reliable photometry was prevented by a bright strip across the image that was probably caused by reflected or scattered light from the reference star. For comparison, a deep (30-minute) NTT frame taken in I band in 0.″6 seeing as part of a separate programme (Zijlstra et al., 1996) shows the same stars, confirming the sensitivity of adaptive optics. Note that photometry of the NTT image in this region is impossible because the reference star is saturated.

Our *H*-band ADONIS image was not compromised by scattered light and is shown in Figure 4. It is the result of a 40-minute exposure taken in moderately good seeing (1″ at the seeing monitor). However, the slow variation of the see-

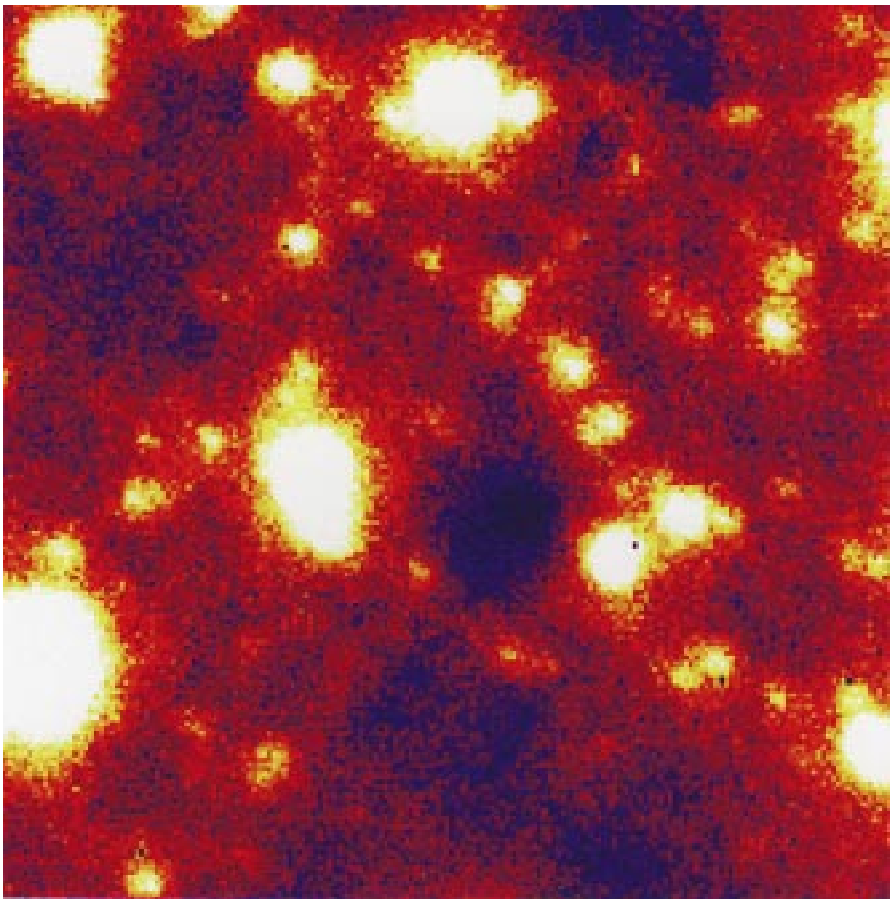


Figure 5: ADONIS K′ image of the Sgr window. The image is 8″ × 8″.

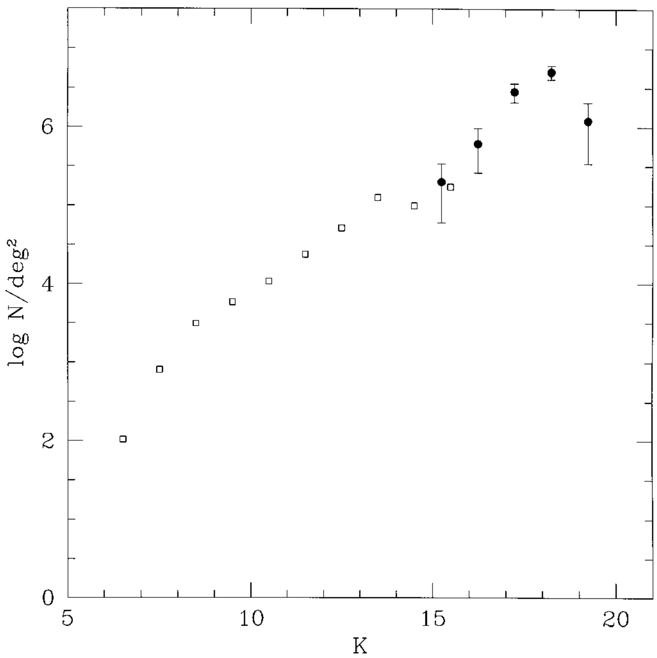


Figure 6: K luminosity function for the Sgr window. The squares are from Minniti (1995) and the filled circles are from the ADONIS observations. The lower counts in the faintest bin indicate incompleteness.

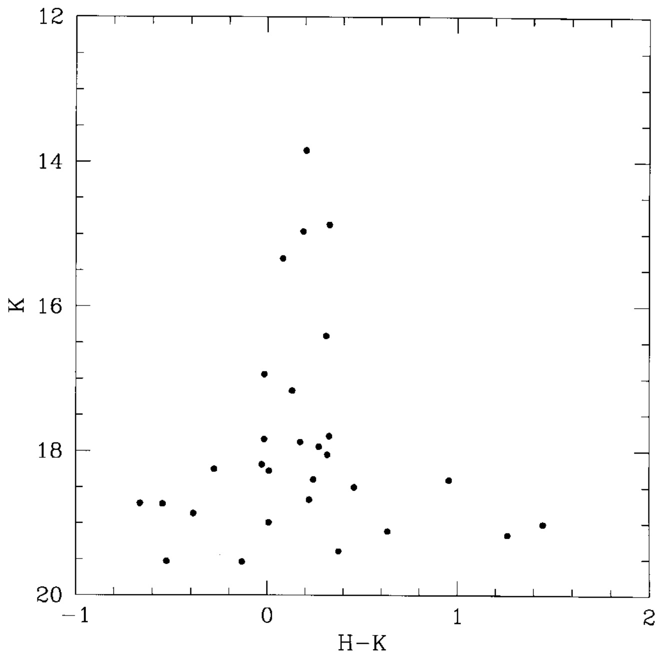


Figure 7: Infrared colour-magnitude diagram for the Sgr window. The main sequence turn-off of the bulge is at K ≈ 18, and the brightest stars in this figure lie on the sub-giant branch.

ing allowed good correction by the AO system. The stars observed here correspond to the bright supergiants with $I \approx$ 20.5 seen in the optical colour-magnitude diagrams of the disk of NGC 300 (Richer et al., 1985; Zijlstra et al., 1996). We did not go deep enough to detect the tip of the RGB of an old population, which would be at H = 20.5 at the distance of NGC 300.

3.4 The faintest stars in the Galactic bulge

We selected a field in the direction of the Galactic bulge, which should yield information about the structure of the inner Milky Way. We observed the Sgr field, which is located at (l, b) = (0°, –3°), at a projected distance of 0.4 kpc from the Galactic centre (assuming R_0 = 8 kpc). This is a crowded field, with sources covering a wide range of magnitudes. The reference star had estimated magnitudes of K = 8 and V = 9.5.

Figure 5 shows a 40-minute exposure in K' taken on August 24, 1995 during particularly good seeing. The FWHM of stellar sources is 0.″35. This image is much deeper than a combined exposure of 160 minutes taken the previous night in poorer seeing. We have found 70 stars in this image and obtained aperture photometry with DAOPHOT. Because of the variation of the PSF across the image, the aperture corrections for both the programme stars and the photometric standard are large (~ 0.6 mag) and are therefore an important source of error in the final photometry.

Note that the accuracy of photometry and of transformation to the standard system is limited for AO observations. This is because the AO corrections differ for the programme stars, the AO reference star and the photometric standards, due to sky and seeing variations. All images were taken in a close temporal sequence to minimise these errors, but we conclude that our zero point is good to only ~ 0.2 mag.

Figure 6 shows a K luminosity function for the Sgr window. As well as the ADONIS data, we have included the measurements of Soria et al. (1996), which cover the brighter magnitudes from K = 6 to 16. This infrared luminosity function represents the deepest measured for the Galactic bulge from the ground, reaching beyond the bulge turn-off, which is located at K ≈ 18.

Figure 7 shows a deep infrared colour-magnitude diagram from our ADONIS data. The internal errors in the K magnitudes for $K < 16$ are small (a few hundredths of a magnitude), and for $K > 18$ are much larger ($>$ 0.5 mag). The H photometry has larger errors because of poorer seeing, and the limiting H magnitude is about one magnitude brighter than at K.

4. Conclusions

We have made a first attempt to apply adaptive optics to the study of stellar populations in our galaxy and beyond. In the cases of NGC 5128 and IC 5152, we failed to detect individual stars. We believe that these targets should be feasible with ADONIS in excellent seeing. For NGC 300 we resolved a small number of K supergiants in the disk. For the Sgr bulge window our colour-magnitude diagram and luminosity function are the deepest yet obtained, reaching the turnoff of the bulge population for the first time in the infrared. These results demonstrate the feasibility of the method. Four factors are important in determining potential results:

Seeing. The quality of adaptive correction depends critically on the temporal frequency of the seeing variations. Obtaining CMDs of distant galaxies is only feasible under excellent seeing conditions (≤ 0.″8 and slow variations). Good seeing, and hence good adaptive correction, also helps to reduce the problems of field crowding.

Availability of reference stars. We require a bright star to be conveniently located for wavefront sensing. We found it best to use reference stars of $V \simeq$ 10. Brighter stars produce stray light contamination, making it difficult to flat-field and background-subtract, and fainter stars do not allow good correction. Using a laser beacon will increase sky coverage and also eliminate the problem of scattered light from the bright reference star, an important advantage.

Field of view. Adaptive optics correction is presently restricted to a small field around the reference star. This makes it time consuming to cover large regions of sky, which is necessary to improve the statistics.

With ADONIS on the ESO 3.6-m telescope we reached a 3-sigma limiting magnitude of H = 20.0 in one hour on point sources. Based on the limiting magnitude obtained in the NGC 300 field under good seeing conditions (FWHM ≤ 0.″8), we estimate that ADONIS can detect the brightest stars in bulges and ellipticals out to a distance modulus of $m – M \approx$ 27.5 (~ 3 Mpc). These figures are based on an absolute magnitude of M_H = –8 for the brightest giants in spheroidal populations of Local

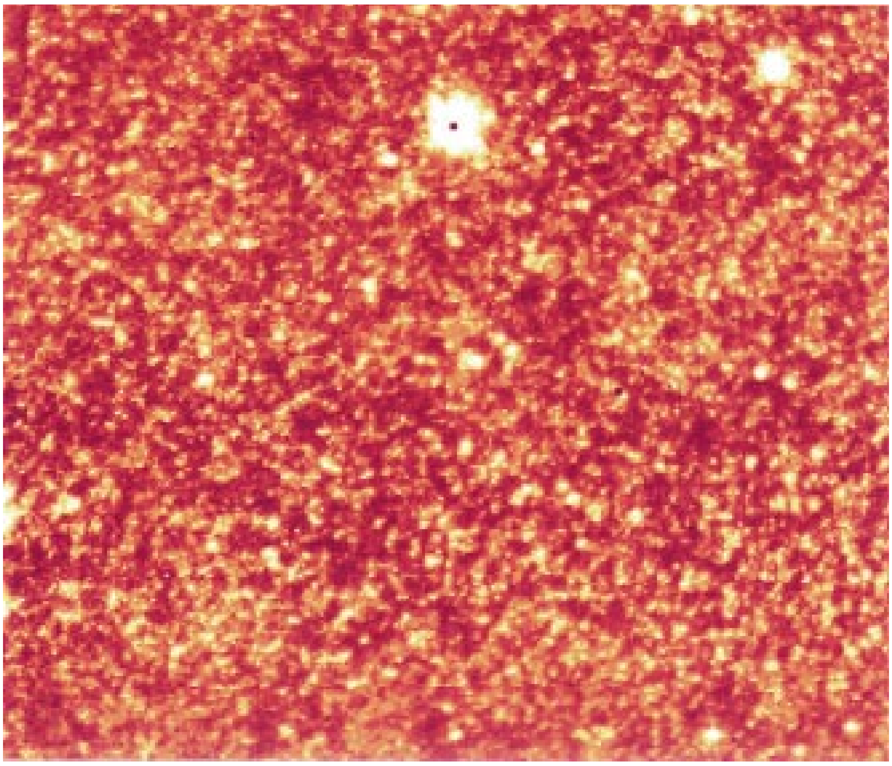


Figure 8: HST image of a halo field in NGC 5128 taken with NICMOS (Camera 3). The image is about 50″ by 45″ (the lower portion was discarded because of vignetting), centred at $\alpha_{2000} = 13^h\ 24^m\ 57^s$, $\delta_{2000} = -43°\ 02'\ 57''$. It is the mean of several 512-s integrations taken with filter F160W (H band). The two brightest objects (top) are probably foreground stars. Image courtesy of Pat McCarthy (OCIW).

Group galaxies (neglecting reddening). For comparison, the Centaurus group has $m - M = 27.8$ (Soria et al., 1996).

The results presented here should be surpassed by HST/NICMOS. Figure 8 shows an HST image of a halo field in NGC 5128 taken with NICMOS. It is one of the first images taken in the public access parallel programme. The halo of NGC 5128 is clearly resolved into thousands of red giants down to about $H = 22$.

Observations using adaptive optics on the VLT, while restricted to small fields of view, should be competitive with the HST/NICMOS image shown here because of the larger aperture and higher spatial resolution. New deconvolution and co-addition codes (e.g., Magain et al., 1997) should further improve the performance of adaptive optics. Thus, the VLT has the potential to transform extragalactic astronomy into stellar astronomy. There will be no need to rely on models and observations of the integrated light to find the physical properties of distant galaxies and their star-formation histories. Instead, we will be able to directly determine ages, metallicities and distances for the stellar populations of very distant galaxies. We might also be able to put important constraints on galaxy formation and decide on the history of mergers for a particular galaxy, just by looking at its shells and shreds.

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The Luminosity Function of Clusters of Galaxies: A 496

NEW CLUES TO CLUSTER FORMATION AND EVOLUTION

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1. Observations and Data

In 1993 we started, using the 1.5-m Danish telescope at La Silla, a large project aimed at a detailed investigation of the population and Luminosity Function, down to the faintest dwarf population, of the brightest clusters of the southern sample of clusters detected by ROSAT. Such sample is described in detail by Molinari et al. (1998).

All observations were carried out using Gunn *g, r* and *i* filters. In Figure 1, we display the observed mosaic for the cluster A 496. For each cluster we observed 4 fields of about 500 × 500 arcsec moving from the central region toward the outskirts up to a distance of about 20 arcmin. We were able in this way to correct for background contamination.

Assuming a King's approximation for the density distribution and a core radius of 0.25 Mpc (this corresponds, for A 496,