Resolved Stellar Populations with MAD: Preparing for the Era of Extremely Large Telescopes

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Deep images in *J*, *H* and K_s filters using the Multi-conjugate Adaptive optics Demonstrator (MAD) on the VLT have been made of a region of the Large Magellanic Cloud near the globular cluster NGC 1928. Our aim was to assess if accurate photometry could be carried out down to faint limits over the whole MAD field of view. In addition we tested how accurate a basic analysis of the properties of the stellar population could be made using the near-infrared MAD photometry, compared to the Hubble Space Telescope optical photometry. This study has implications for understanding the issues involved in Extremely Large Telescope imaging of resolved stellar populations.

Archaeological evidence about the properties of individual stars over a large range of ages can tell us much about galaxy formation and evolution processes from the present day back to the early Universe. Low-mass stars have very long and passive lives and their photospheres hold time capsules of the gas from the interstellar medium out of which they formed. Thus populations of individual stars of a range of ages provide uniquely detailed information about the changing properties of galaxies: how the rate of star formation and chemical composition varied from its formation to the present day. Such studies can provide a link between the local Universe, high redshift surveys and theoretical simulations of galaxy formation and evolution.

A classical observational approach uses accurate multi-colour photometry of resolved stellar populations to create detailed colour–magnitude diagrams (CMDs), which can be interpreted using sophisticated statistical techniques. However this approach requires wide-field images with high, stable spatial resolution. In this respect the Hubble Space Telescope (HST) has revolutionised the photometric study of resolved stellar populations. However it remains a relatively small telescope, with a diffraction limit at optical wavelengths that is approached by the image quality of adaptive optics (AO) imagers working in the infrared on 8-metre-class ground-based telescopes. An AO imager on an Extremely Large Telescope (ELT) will of course lead to dramatic improvements in spatial resolution in the infrared.

At the moment most ground-based AO imagers are single guide star systems, which have very small fields of view with a strong variation in the point spread function (PSF) over this field. In order to be able to expand the field size and uniformity of the PSF, a technique called multi-conjugate adaptive optics (MCAO) is required. Here we describe an experiment with the prototype MCAO imager, MAD, at ESO's Very Large Telescope (VLT; see Marchetti et al. [2007] for details). It is anticipated that ELT imaging will be carried out with MCAO-fed imagers. ELTs are likely to be infrared (IR) optimised, using AO-based instrumentation (Gilmozzi & Spyromilio, 2007). This means that sensitive high-resolution ground-based imaging will only be possible at wavelengths starting from (perhaps) optical *I*-band, with a peak efficiency in the near-IR (NIR). Both sensitivity and spatial resolution are important for the study of resolved stellar populations, especially for compact galaxies and also for more distant galaxies beyond the Local Group. Hence it is valuable to carry out pilot studies in this wavelength range with the AO instruments available today.

NIR photometry does have several advantages: it can limit the effects of high and/or spatially variable extinction towards or inside a stellar field and it can also provide enhanced temperature sensitivity in a CMD, in particular when combined with optical bands. From theoretical evolutionary tracks we know that in an optical–IR CMD the features will be stretched out due to the long colour baseline. There exist robust techniques to make detailed analyses of observed CMDs by comparing them to theoretical models (e.g., Cignoni & Tosi, 2010). Whilst in the optical domain the theoretical stellar evolution models are well calibrated, in the NIR they still have to be fully verified for a range of stellar evolutionary phases. Moreover this aspect needs to be confirmed from an observational point of view using the actual photometric accuracies.

AO currently only works effectively at NIR wavelengths and this is likely to remain the case for the foreseeable future. This implies adapting current CMD analysis techniques, which are almost exclusively carried out at optical wavelengths. These changes bring several challenges to interpreting the images and the first step is to obtain useful *training* datasets.

Our MAD experiment

The Multi-conjugate Adaptive optics Demonstrator on the VLT has been employed to obtain deep images in *J*, *H* and K_s filters in a region of the Large Magellanic Cloud near the globular cluster NGC 1928. This field has previously been imaged at optical wavelengths by the Advanced Camera for Surveys (ACS) on HST. MAD, was mounted as visitor instrument on Unit Telescope 3 (UT3) at the VLT for three observing runs in 2007 and 2008. MAD is a demonstrator instrument built to prove the MCAO concept on the sky and is able to measure the atmospheric turbulence using three natural guide stars located, ideally, at the vertices of an equilateral triangle within a field of view of 2 arcminutes in diameter. This approach allows the turbulence to be corrected over the whole field of view (see Marchetti et al., 2006; 2007). The 2048 by 2048 pixel NIR detector available in MAD covered only a 1-arcminute square region of the full field of view, with 0.028-arcsecond square pixels. We used all three broadband filters available: *J*, *H* and K_s with total exposure times of 60 minutes in K_s, and 42 minutes in the *J* and *H* filters.

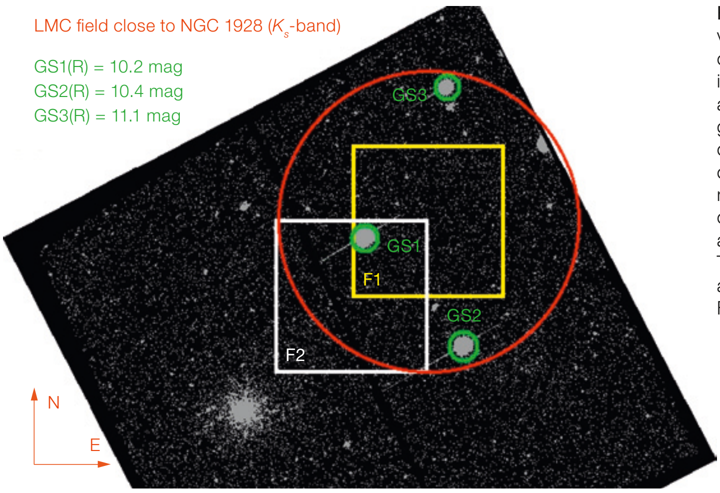


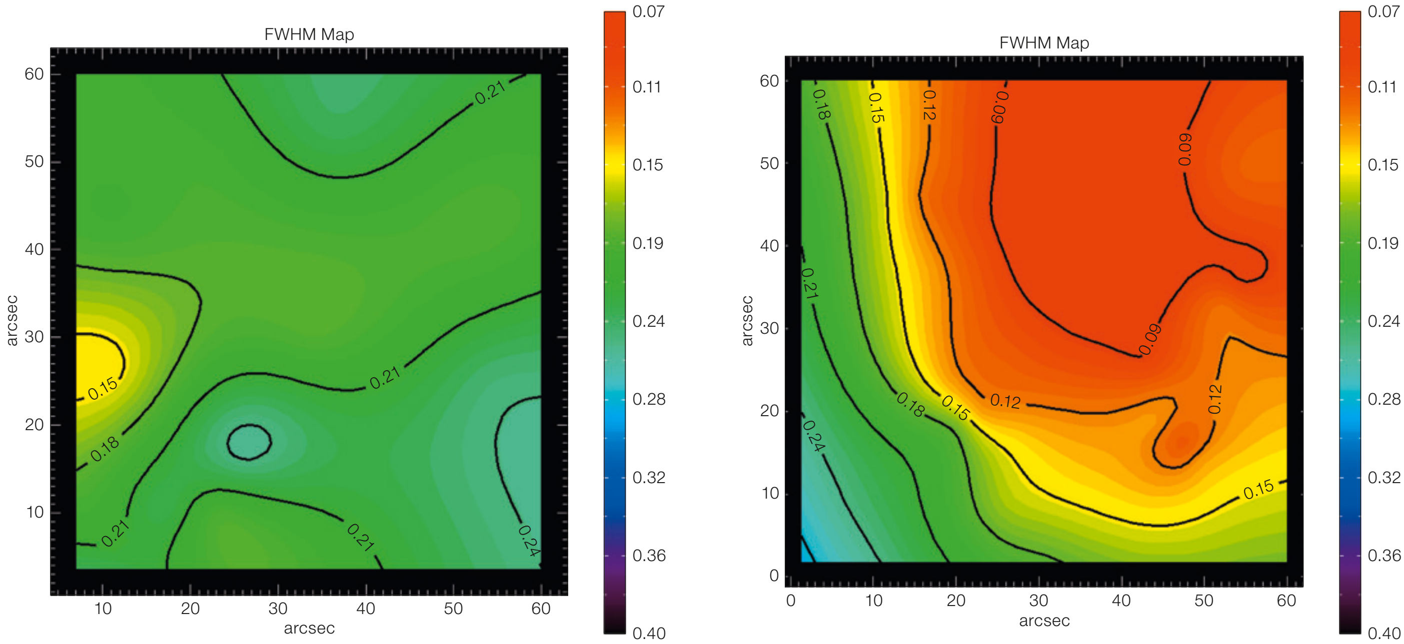
Figure 1. MAD field of view (yellow and white) on top of an ACS/HST image (from Mackey et al., 2004). The natural guide stars (green circles) are within a circle of diameter 2 arcminutes. The asterism is centred at RA = 05:21:11 and DEC = –69:27:32. The two pointings F1 and F2 are shown. From Fiorentino et al. (2011).

The MAD requirement of three bright natural guide stars within a circle of two arcminutes in diameter combined with our desire to image a region for which HST optical photometry was already available, limited the possible sky coverage. We found a suitable asterism in a region close to the Large Magellanic Cloud (LMC) globular cluster NGC 1928 (Figure 1). The area mapped by MAD observations is completely covered by ACS images (Mackey et al., 2004).

For our MAD images we estimated the stability of both the full width at half maximum (FWHM, see Figure 2) and the Strehl ratio of the PSF across the observed fields, using an IDL program provided by E. Marchetti. Despite the strong variation over the field, the best FWHM was achieved in field F2 (0.08 arcseconds) and it is close to the *H* filter diffraction limit (0.05 arcseconds). In contrast, the uniform PSF in field F1 only reaches a FWHM of 0.14 arcseconds, which is twice the K_s diffraction limit (0.07 arcseconds). The mean FWHM is 0.12 arcseconds for *H*-band and 0.20 arcseconds for the K_s-band. The Strehl ratio shows a similar spatial behaviour to the FWHM. The Strehl ratio in field F1 is quite uniform with values ranging from 5 to 15 % (in K_s-band), whereas this distribution varies rapidly in field F2 from 5 to 25 % (in *H*-band). The maximum Strehl ratios obtained in both fields reach, or even slightly exceed, the performance expected for MAD in "star-oriented" reference wavefront mode. As an example, the maximum Strehl ratio in K_s-band was predicted to be between 11 % and 24 % for seeing decreasing from 1.0 to 0.7 arcseconds.

MAD has been able to reach a FWHM of twice the diffraction limit in *H*- and K_s-bands at the large zenith distances typical of the LMC. The maximum Strehl ratio we have obtained in K_s-band is larger than 30 %, which is better than the expected performance (24 %) for MAD in "star-oriented" mode in our seeing conditions (seeing larger than 0.7 arcseconds). The uniformity and the stability of the correction varied not only with the position from the guide star asterism, but also with airmass and seeing conditions. The complex dependency of these factors prevented us from making a direct comparison between our results and other MAD studies. However, in other experiments MAD was successfully able to reach the diffraction limit in K_s-band (e.g., Falomo et al., 2009).

Figure 2. The FWHM variation (in arcseconds) measured across the field F1 (see Figure 1) in the K_s-band filter (left) and across the field F2 in the *H*-band filter (right). From Fiorentino et al. (2011).



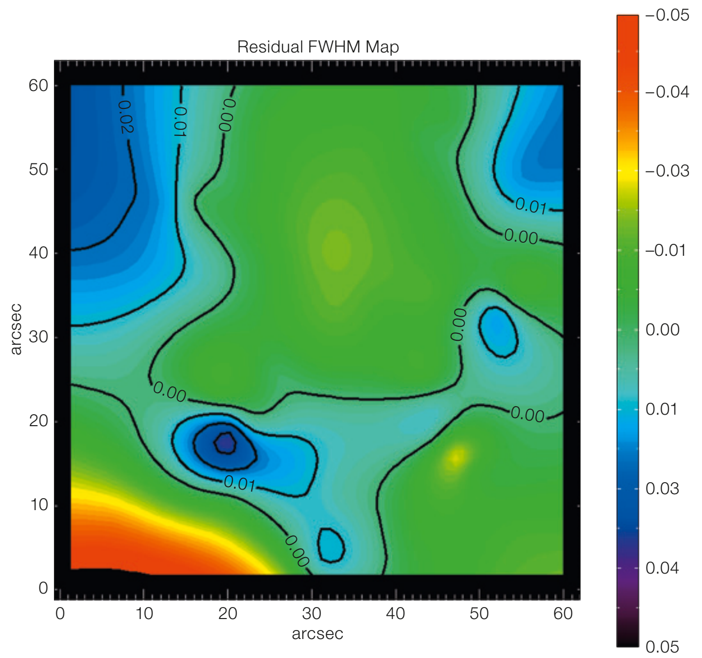


Figure 3. Residual map of the observed PSF *vs.* the model (in arcseconds) created with DAOPHOT for the challenging case of field F2 in *H*-band. From Fiorentino et al. (2011).

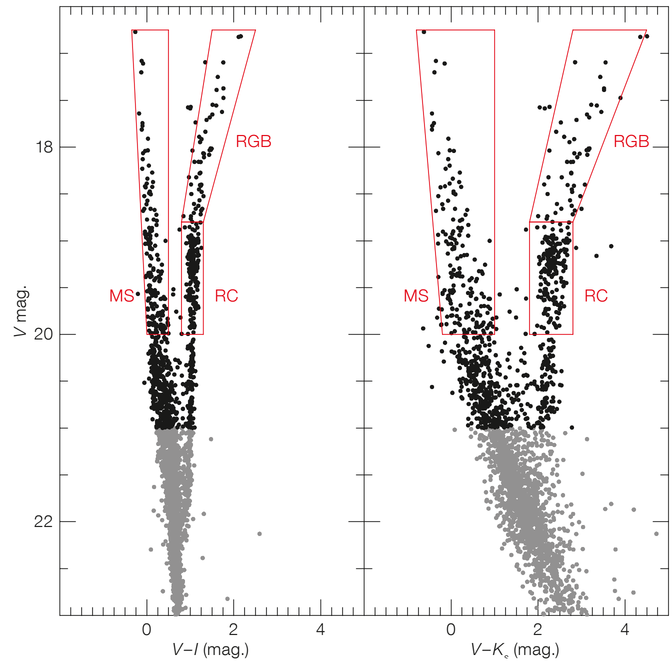


Figure 4. Colour–magnitude diagrams obtained combining purely optical *V*, *I* (from HST/ACS) and optical and near-infrared *V*, K_s (from HST/ACS and MAD) filters are shown at left and right (from Fiorentino et al., 2011). Red boxes are used to highlight the evolutionary phases considered in the CMD analysis, i.e. the Main Sequence (MS), the Red Clump (RC) and the Red Giant Branch (RGB).

The AO performance was so good that we were able to perform photometry using standard photometric packages, as DAOPHOT/ALLSTAR (Stetson, 1987; 1994). The approach is to model the PSF as the sum of a symmetric analytic bivariate function (typically a Lorentzian) and an empirical look-up table representing corrections to this analytic function computed from the observed brightness values within the average profile of several bright stars in the image. This hybrid PSF seems to offer adequate flexibility in modelling the complex PSFs that we found. Furthermore, the empirical look-up table makes it possible to account for the PSF variations (linear or quadratic) across the chip. We have compared the observed PSFs, and their variation over the field, with the PSF models created using DAOPHOT; an example is shown in Figure 3. Our experience in dealing with quite a large dataset of real MAD images (see Fiorentino et al. [2011] for details) suggests that a uniform correction is preferred to a very high, but non-uniform, Strehl ratio.

The colour–magnitude diagrams

The combination of optical and IR photometry is shown in Figure 4, (see Fiorentino et al. [2011] for all the filter combinations). The longest colour baseline to K_s-band stretches out the main CMD features (right panel) the most, hence allowing an easier and more precise separation of different stellar populations in all evolutionary phases. In Fiorentino et al. (2011), we performed a basic application of the well-established CMD synthesis methods to interpret our optical/IR CMDs in terms of a likely star formation history (SFH). The HST/ACS photometry is very deep (at least 4 mag below the Main Sequence Turn Off (MSTO), i.e. *V*, *I* ~ 26 mag) and the completeness is 100 % at the level of our faintest NIR observations. The set of synthetic populations (each with ~ 50 000 stars) that have been compared with our final catalogue have been simulated using the package IAC-STAR (Aparicio & Gallart, 2004), which generates synthetic CMDs for a given SFH and metallicity function. Composite stellar populations are calculated on a star-by-star basis, by computing the luminosity, effective temperature and gravity of each star by interpolation in the metallicity and age grid of a library of stellar evolution tracks.

Using our final optical/IR catalogue (*VIJHK*$_s$), where the optical observations come from ACS/HST, we could determine how well stellar evolution models in the different filter combinations match our data for the most likely SFH, derived by Holtzman et al. (1999) for a nearby field in the LMC. Given the uncertainties in the IR stellar evolution tracks, we pay special attention to comparing optical *vs.* infrared or purely infrared CMDs. We conclude that it is possible to apply the same techniques for determining SFHs in *V*- and *I*-bands to IR datasets, even if optical filters are clearly more accurate in this case. The optical/IR and purely IR analyses show the same trends, suggesting that the IR analysis could be improved, when deeper more accurate photometry will be available. Another key role for the IR analysis will be played by the theoretical calibration of IR stellar evolution tracks.

As by product of our analysis we could estimate the distance to the LMC by means of the infrared red clump method and we obtained 18.50 ± 0.06 (random error) ± 0.09 (systematic error), which is in very good agreement with distances measured with other independent methods.

Future prospects

We, among others (Bono et al., 2009; Ferraro et al., 2009; Campbell et al., 2010; Sana et al., 2010; and Fiorentino et al., 2011), have shown that the accurate and deep wide-field stellar photometry required to make detailed colour–magnitude diagrams is possible with MAD. Although MAD was a demonstrator instrument with a small engineering grade detector, the experiment worked very well. A future ELT will sample the atmospheric turbulence more accurately, which means that the peak correction achievable with MAD is smaller than that expected from an ELT. This means that future ELT MCAO instrumentation will be much more stable in terms of uniformity and performance (e.g., Deep et al., 2011).

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Colour image of the young open star cluster NGC 2100 situated in Large Magellanic Cloud taken with the EMMI instrument on the ESO New Technology Telescope (NTT) at the La Silla Observatory. Exposures in broad *B*-, *V*- and *R*-bands were combined with narrowband images centred on the emission lines of Hα, [N II] 6583 Å and [S II] 6716,6731 Å. Data for this image were selected by David Roma as part of the ESO Hidden Treasures competition. More details can be found in Release eso1133.