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Precise and deep photometry from the ground: on-sky science performance of MCAO

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ABSTRACT

Multi-conjugate adaptive optics is a central technology for the Extremely Large Telescopes (NFIRAOS on TMT and MAORY on E-ELT). GeMS on the 8-m Gemini South telescope is the first facility-class MCAO and the first to use laser guide stars. We have observed the Galactic globular cluster NGC 1851 (and 5 other targets) and here we present the results of the profile-fitting photometry in the near-infrared. This is the most precise photometry to date of a cluster taken from the ground, confirmed by our ability to detect the double subgiant branch, previously observed only from space. The high Strehl ratio of the images pushes the depth of the stellar detections well below the main sequence knee of the colour-magnitude diagram, making this also the deepest near-infrared CMD yet obtained from ground. The large number of stars allows to evaluate the performance of the instrument in terms of position-dependent PSF. We demonstrate how the analysis of the spatial and temporal PSF variations allows us to develop effective photometric techniques for MCAO to be used for the next generation of large telescopes.

1. INTRODUCTION

In multi-conjugate adaptive optics (MCAO) multiple guide stars are used to measure the atmospheric distortion in different directions around the observing direction in order to reconstruct the turbulence above the telescope within the covered field of view. By using multiple deformable mirrors (DMs) optically conjugated at different altitudes, MCAO can deliver a corrected field of view much larger than in the case of classical adaptive optics where the main limitation is the isoplanatic angle.

The Gemini Multi-Conjugate Adaptive Optics System (GeMS)[1,2] at the Gemini South telescope is the first facility-class MCAO instrument that uses laser guide stars (LGSs). Because it's the precursor to a new generation of MCAO systems on Extremely Large Telescopes (NFIRAOS[3] on TMT and MAORY[4] on E-ELT), it is of extreme importance to understand its performance and scientific capabilities as well to develop an accurate method to measure the photometry. Galactic globular clusters (GGCs) represent the best target for this purpose because they extend over a field of view of arcminutes, they are rich in point-like sources to probe the image quality and they provide many bright natural guide stars (NGSs) used by the instrument to measure their tip-tilt aberration.

Here we present the photometric results of our observations with GeMS of the GGC NGC 1851 in the near-infrared (NIR) band K_s (2.15 μm). By matching our results with an HST/ACS catalogue in the visible of the same object,[5] we create a deep and precise colour-magnitude diagram (CMD) that demonstrates the potential for MCAO. One of the interesting interesting features of this globular cluster is the presence of two distinct subgiant branches, already seen on HST/ACS images by Milone et al.[6] and interpreted as evidence of a second generation of star that formed $\sim$ 1 Gyr after than the first. A different interpretation by Cassisi et al.[7] suggests that the the two populations are coeval, with one a factor two more enhanced in CNO than the other. Another characteristic of NIR CMDs of globular clusters is the presence of a bend towards the faint end of the main sequence. This large deviation of faint stars from a black-body radiation is caused by the collisionally

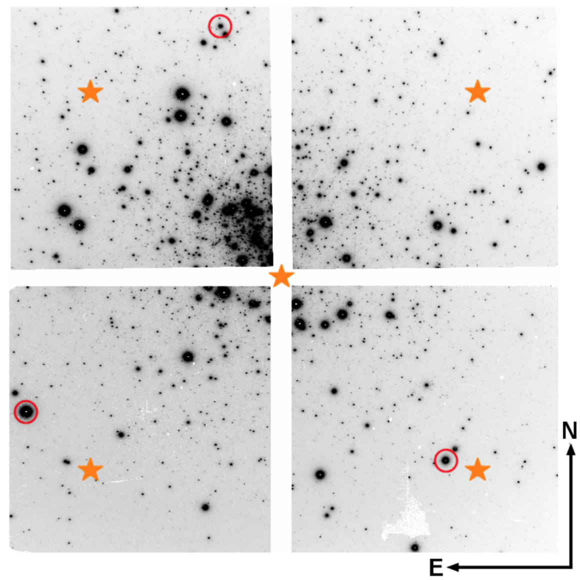

Figure 1: Mosaic of a 160 s exposure of NGC 1851 taken by GeMS/GSAOI with the K_s filter. The red circles highlight the three NGSs and the orange star symbols the position of the five LGSs.

induced absorption of molecular hydrogen in their cold atmospheres. The position of the main sequence knee (MSK) in the CMD is independent of the cluster's age and can therefore be used to determine it by measuring the relative distance of the MSK from a time-dependent feature like the main sequence turnoff.[8] This method has the advantage over others of being independent of distance and reddening, avoiding the uncertainty on those.

2. OBSERVATIONS AND IMAGE REDUCTION

GeMS is the MCAO module at the Gemini South telescope on Cerro Pachón (Chile) that uses five LGSs with a power of 10 W each to generate on the atmospheric sodium layer a constellation 60 arcseconds wide. Because LGSs cannot be used to determine the tip-tilt and defocus aberrations,[9,10] the instrument requires three additional NGSs in the field of view to measure. Two DMs, conjugated to the ground and at 9 km of altitude, deliver the correction to the instrument's camera, the Gemini South Adaptive Optics Imager (GSAOI), a 2x2 HAWAII-2RG mosaic with an 83" FOV and a pixel scale of 0.0196"/px.

The images of NGC 1851 in K_s band were taken at the end of 2012 during the GeMS/GSAOI science verification phase. The average FWHM seeing at 0.5 μm was 0.75" at the zenith, measured by RoboDIMM on Cerro Tololo, and the airmass was between 1.018 and 1.075 with low wind speeds between 0.6 and 3.5 m/s. The observation was divided into 12 exposures of 160 s each in order to reduce the saturation of the detector caused by the many bright stars in the cluster. Another advantage of taking multiple exposures is the ability to reject cosmic rays from the analysis and the application of a dithering pattern to the telescope to reduce the impact of bad areas of the detector like the gaps between the chips or clusters of dead pixels. To include in the catalogue also the bright stars, two shorter images were taken with 41 and 90 seconds of exposure.

The detectors are read non-destructively before and after the integration using Fowler sampling[11] and therefore there is no need to remove a bias level from the images. A dark frame subtraction is not necessary too, because of the very low dark current in this kind of NIR chips.[12] A problem common to these detectors is the non-linearity of the response; this behaviour is fixed by applying a third order polynomial correction with the coefficients provided by Gemini. The flat fielding of the exposures was done by combining the dome with the the twilight median flat fields to take advantage of the high S/N of the first and of the correct spectral signature of the sky in the second. We don't subtract a sky frame from our exposures because are targets are only stellar sources and their background can be considered constant over the size of the PSF.

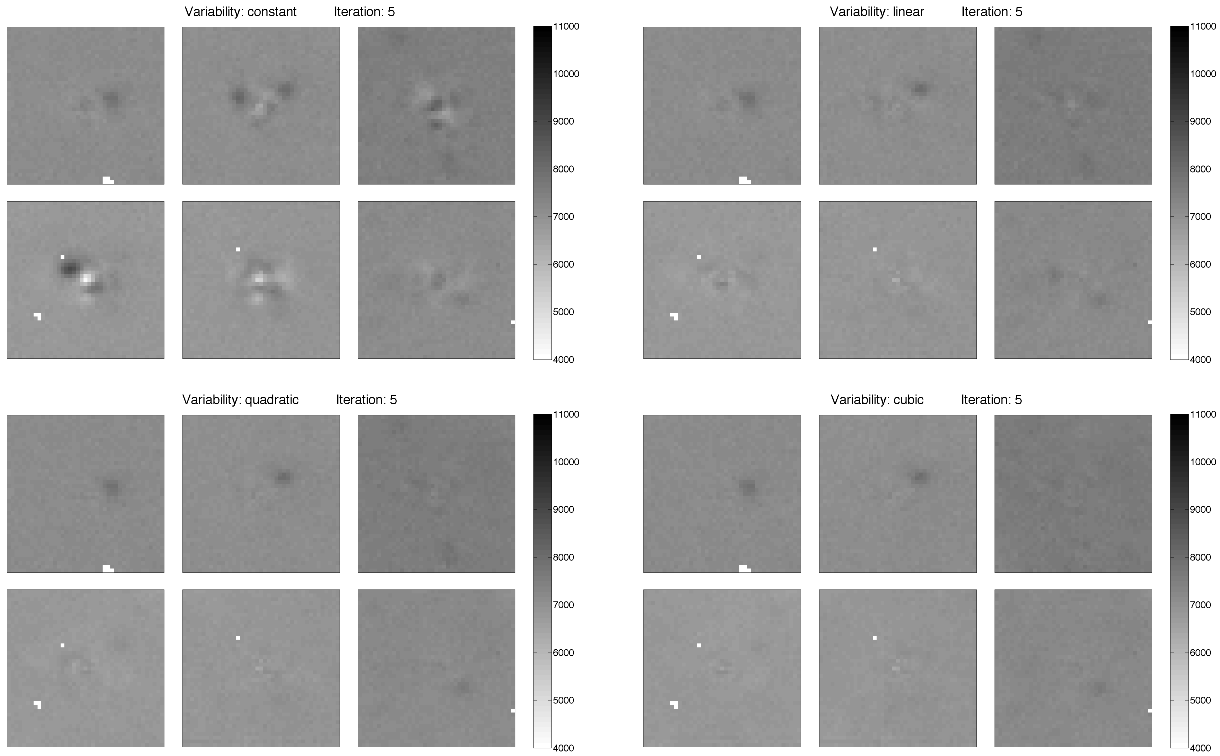

Figure 2: Residual of the profile-fitting photometry using different degrees of PSF spatial variability.

3. PHOTOMETRIC REDUCTION

For the photometric reduction we used the DAOPHOT package[13–15] that has already been proven to work with MCAO data.[8,16,17] Stars are identified by the FIND task and only those that are found in at least three of the twelve exposures are kept for the PSF fitting photometry. In crowded fields like globular clusters, aperture photometry doesn't provide results as good as profile-fitting photometry and to achieve precision we need then an accurate estimation of the PSF model. The size of our PSF model is of 1.8 arcseconds, very large compared to the typical FWHM of 0.1 arcseconds delivered by GeMS during our observations. The need for a wide diameter is caused by the persistence in the profile of the seeing-limited halo caused by the high spatial frequencies in the turbulent wavefront, not corrected by the relatively low number of actuators of the DMs.

By looking at the spatial and temporal variability of the PSF shape, simplified in Fig. 6 by its ellipticity, it's easy to conclude that each exposure needs to be treated independently and that within the same exposure the PSF has to be allowed a certain degree of spatial variability. DAOPHOT defines the PSF model on a grid where the value of each element is a polynomial function up to the third order of the coordinates on the image. For the analysis of this globular cluster, the coefficients of the polynomials are found using 400 bright and isolated stars selected by hand within the full field of view of the observations.

We have tested the four degrees of PSF variability available in DAOPHOT (constant, linear, quadratic and cubic) by looking at the residuals of the profile-fitting of six test stars in one of the exposures. The results in Fig. 2 show that a higher variability provides a more uniform background after the subtraction of the star and for this reason we have chosen to use the cubic polynomials.

Because the system produces for each exposure a different PSF that has a different systematic error, the same stars appear to have different instrumental magnitudes between one observation ad the next. The catalogues produced using profile-fitting on each chip of each exposure are then matched to the 2MASS Point Source Catalog for the photometric calibration; but because 2MASS is not deep enough to share many stars with our catalogue, we use an intermediate one generated from seeing-limited archival images taken with CTIO/NEWFIRM. The

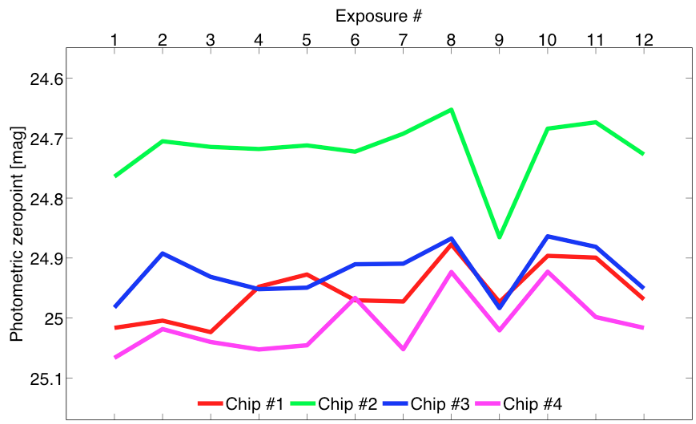

Figure 3: Photometric zero points in K_s of the four chips in the twelve exposures.

photometric calibration offsets are plotted in Fig. 3 and they show that an independent calibration of the exposures is necessary to avoid an additional scatter of the magnitudes. The reddening effect of interstellar dust is not corrected because for NGC 1851 the value is extremely small[18] (E(B-V)=0.02). After the profile-fitting photometry and the zero point calibration, the magnitudes of the stars in the cluster are found combining the measurements from the individual exposures using artificial skepticism.[19]

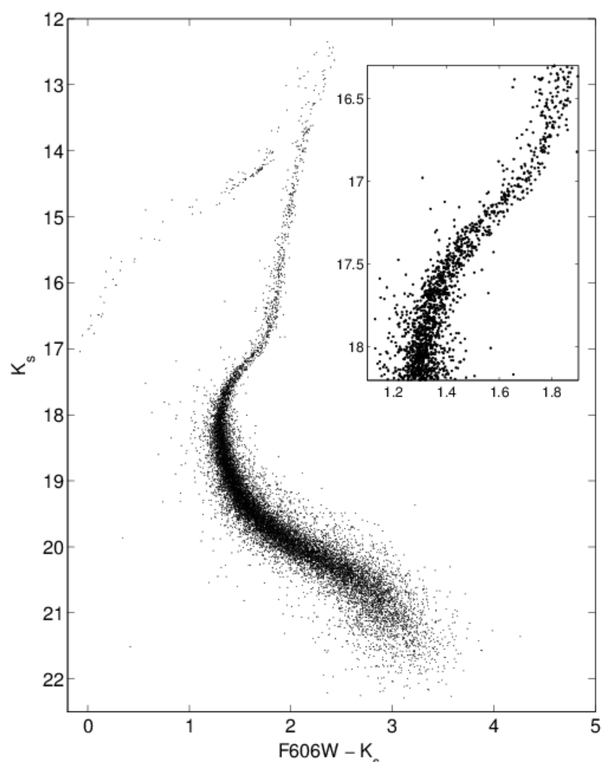

Figure 4: NIR-optical colour-magnitude diagram of NGC 1851 obtained from our K_s images taken with GeMS and from the F606W observations by HST/ACS. In the inset, a zoom in of the double subgiant branch.

4. SCIENTIFIC RESULTS AND INSTRUMENTAL PERFORMANCE

In Fig. 4 is shown the colour-magnitude diagram of the globular cluster obtained by matching the K_s photometry from GeMS with the F606W magnitudes measured by HST/ACS.[5] The MCAO reduction of the size of the PSF core respect to seeing-limited observations has increased the S/N enough to measure the faint stars in the lower main sequence. The limiting magnitude of K_s=22 makes this one of the deepest NIR photometry ever obtained from the ground and the distinct detection of the main sequence knee at K_s=20.5 will allow for a clear estimation of the cluster's age. The optimization of the MCAO PSF model has improved also the photometry of the bright stars. This is visible in the subgiant branch where the precise measurements of the NIR brightness can separate two distinct sequences that represent two separate stellar populations in the cluster. The ratio of stars between the faint and the bright branch is 0.47, consistent with the findings of Milone et al.[20]

The same stars used for determining the PSF models can also probe the quality of the MCAO correction on every exposure; their images are oversampled and the contours at half the peak value are fitted with ellipses. The maps of the geometric FWHM and ellipticity $(a - b)/a$ are plotted in Fig. 5 and 6. For the measurement of the Strehl ratio (SR), the peak value is taken from the brightest pixel of the oversampled image and the flux value from the DAOPHOT photometry. The performance of GeMS measured by the FWHM and SR have the expected spatial variability, with a better result in the center slowly degrading towards the edge of the field of view but with an overall correction much more uniform than in the case of single-conjugated AO. To the opposite, the ellipticity of the PSF varies both in magnitude and angle across the frame without following a symmetric pattern. And contrary to the FWHM ans SR maps that appear stable during our observations, the ellipticity maps change suddenly between exposures.

5. CONCLUSIONS

Using GeMS we have obtained precise photometry in the K_s band of the globular cluster NGC 1851, as proved by the detection of both the main sequence knee and the split in the subgiant branch. GeMS proves the capacity for MCAO to provide photometric measurements of scientific quality, an important step towards the use of this kind of instruments for the future Extremely Large Telescopes. We have also shown that the delivered PSF is extremely complex in both spatial and temporal variability and that a careful definition of the PSF model is necessary to achieve the best profile-fitting photometry. In 2014 the GeMS/Gemini team has identified the cause of the problem in the misalignments of the five field stops of the LGSs in the WFS respect to the rest of the optical train and by realigning the WFS CCDs, the problem seems to have been resolved. The photometric techniques used to deal with the problematic images of the science verification phase could be nevertheless useful also the future, when the MCAO systems on ELTs will deliver a much higher Strehl ratio, possibly exposing smaller asymmetries in the PSFs' cores.

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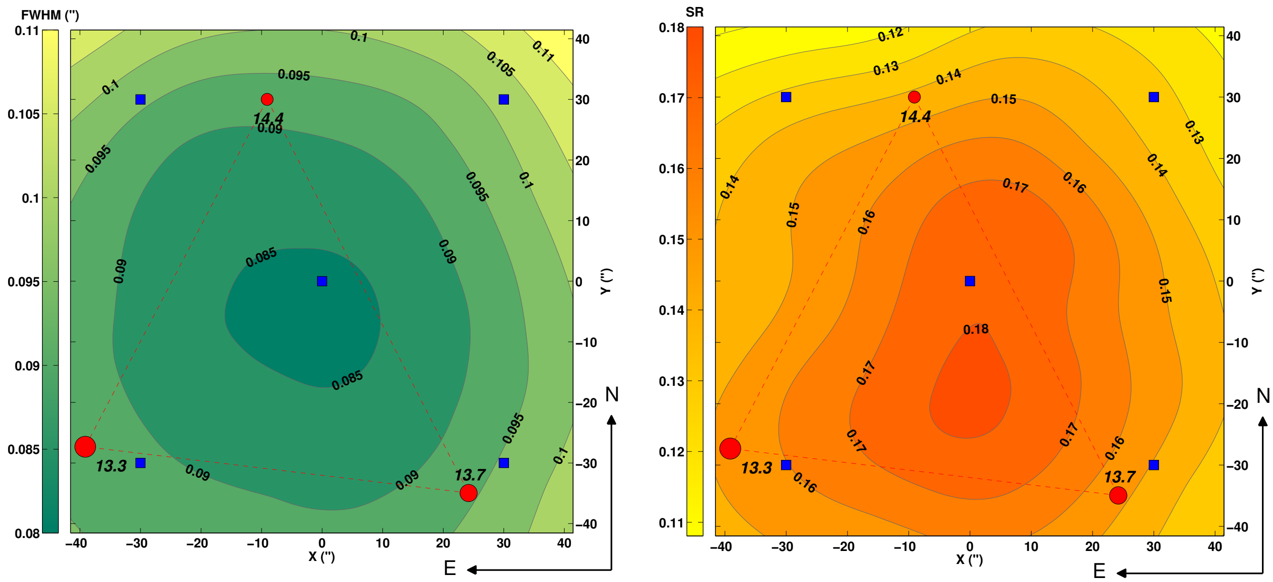

Figure 5: Maps of the FWHM *(left)* and Strehl ratio *(right)* of the first exposure.

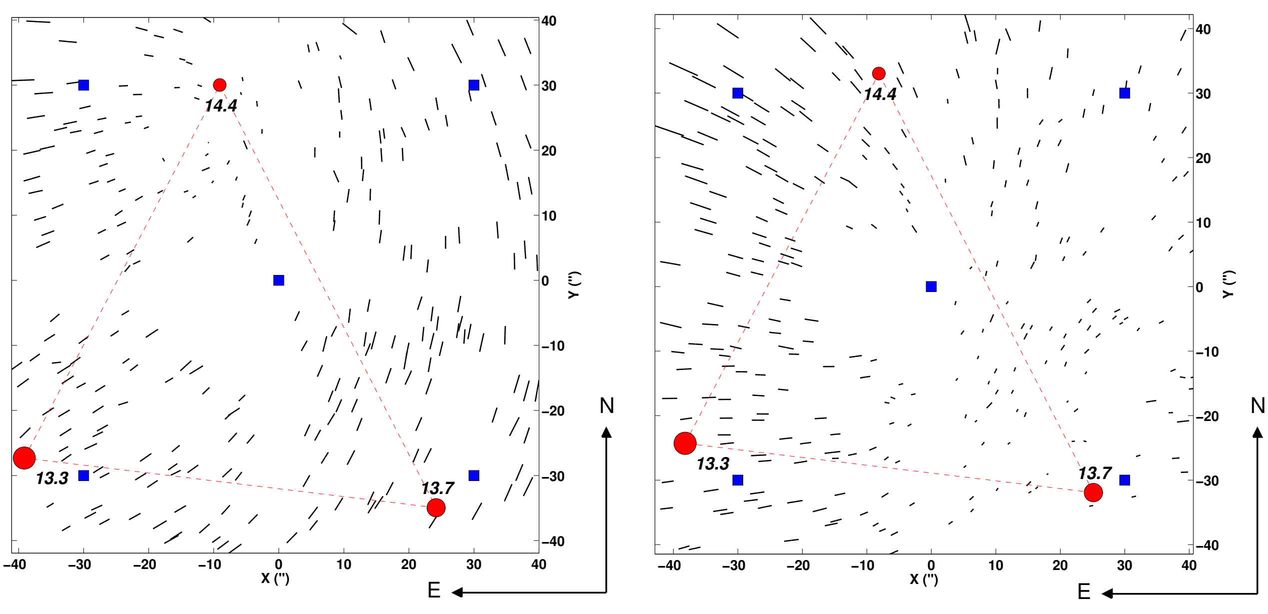

Figure 6: Maps of stars' ellipticities in the first two exposures. The length of the lines is proportional to the ellipticity value.

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