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Chronicling the histories of galaxies at distances of 1 to 20 Mpc: simulated performance of 30, 50, and 100m telescopes

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Abstract. A key science driver for future ELTs is to chronicle the complete formation and evolutionary histories of a meaningful number of nearby galaxies through their resolved stars. The goal will be to measure the entire star formation and chemical enrichment histories of a sample of galaxies that includes all Hubble types and covers all of their components, demanding photometry of stars in regions with high surface brightness at distances of up to 20Mpc. We present simulations that compare the abilities of 20, 30, 50, and 100m telescopes to recover the correct stellar population mix represented in field star color-magnitude diagrams observed with J, H, and K filters. As input, our simulations use scenes containing stars drawn from a mix of model isochrones with differing ages and metallicities, with surface densities set to match that found in the M31 bulge and at the effective radius of NGC 3379. We convolve these scenes with PSFs corresponding to the projected performance of MCAO systems containing two deformable mirrors, including the effect of realistic variations in the atmospheric turbulence profile over the span of the observations. These simulations provide a way to evaluate the scientific advances enabled by ELTs of differing apertures in the area of extragalactic stellar populations.

Keywords. Instrumentation: adaptive optics, Techniques: photometric, Galaxies: stellar content, Hertzsprung-Russell diagram

1. Introduction

The problem of galaxy formation occupies a central role in astrophysics, as it connects the study of cosmology to that of star formation and the dispersal of chemical elements. The framework of hierarchical structure formation (e.g. White & Rees 1978) has been remarkably successful in reproducing the basic distribution of galaxies in the Universe. Galaxy formation depends, however, on complex processes occurring on a huge range of scales, such that it is unreasonable to expect a cosmological model to contain all of the necessary ingredients needed to explain the properties of galaxies over time. Ideas need to be guided by observations that demonstrate how the physics of e.g. gas cooling, star formation, feedback from stars, and mergers operate in all kinds of galaxies. To provide a concrete example, two recent simulations of forming disk galaxies, differing mainly in their treatment of stellar feedback, produced wildly different star formation histories. In Abadi *et al.* (2003), the galaxy has a massive old spheroid and a ∼4Gyr-old disk, while Robertson *et al.* (2004) simulated a disk galaxy dominated by ∼10Gyr-old solar metallicity stars, with little or no spheroidal component.

Clearly, measurements of the star formation and chemical enrichment histories derived from resolved star photometry in nearby spiral disks, bulges, and elliptical galaxies can powerfully illuminate how galaxies formed. Such measurements have been made or are

underway in many of the nearest galaxies, but their accuracy is generally limited by the crowding from the extreme numbers of stars found in high surface brightness spiral bulges and disks as well as in elliptical galaxies. Future ground-based ELTs will provide dramatic improvement in our ability to study spirals and ellipticals out to distances of ∼20 Mpc *mainly* through their higher spatial resolution (Olsen, Blum, & Rigaut 2003). These gains come at the costs, however, of limiting observations to wavelengths at which adaptive optics (AO) correction is possible (generally agreed to be the near-infrared and beyond) and of the extra effort needed to extract precise ($\lesssim$2%) photometry from AO-corrected images. The technical issues concern the accuracy with which ages and metallicities of stellar populations can be measured with near-infrared photometry alone, the accuracy of absolute photometric calibration in crowded fields in which the PSF has a significant fraction of the light distributed in broad wings, and the effect of temporal and spatial variations in the AO correction on the photometry. For evaluating the impact of ELTs on the study of the formation of nearby galaxies, there are additional issues that must be addressed, such as the sample size, field of view, and filter complement needed for the observations. In this contribution, we describe our progress on simulations aimed at addressing all of the above issues for realistic 20, 30, 50, and 100m telescopes. Our simulations are guided by a desire to answer two questions:
1) When did spiral disks form with respect to bulges?, and
2) When did elliptical galaxies form the bulk of their stars?

2. Multi-conjugate adaptive optics PSF simulations

Our MCAO PSFs were calculated to simulate the spatial and temporal Strehl ratio variations that might be seen in a typical ELT observation. To this end, we selected an hour-long segment of atmospheric turbulence profile data obtained with the TMT MASS/DIMM (Tokovinin 2003) in northern Chile, kindly provided to us by Richard Clare. We broke this segment into five 12-minutes intervals, within which we averaged the values of $C_{\rm n}^2$ for the ground layer and six higher altitude layers, r_0, and θ_0. We used these average values to calculate five sets of PSFs for each telescope (20, 30, 50, and 100m) and for each filter (I, J, H, K), with each set representing different atmospheric conditions. Each set of PSFs span a $20'' \times 20''$ field of view and were calculated on a 7×7 regular grid, for adequate sampling of the spatial variability. The error sources used in the AO PSF calculation include the errors due to the finite number of guide stars and two deformable mirrors, as well as the finite spatial resolution of the wavefront sensors and the two deformable mirrors. Other error sources should be significantly smaller than these.

3. Procedure for creating simulated images

For the work reported here, we simulated two scenes, one corresponding to the bulge of M31 (d ∼780 kpc), the other to one effective radius of the giant elliptical galaxy NGC 3379 (d ∼10 Mpc). We used the star formation and chemical enrichment history of the disk galaxy simulated by Robertson *et al.* (2004) to guide the population mix for the M31 scene, and that of the $2{\times}10^{11} M_\odot$ elliptical galaxy in the simulation by Chiosi & Carraro (2002) for the NGC 3379 scene. Using these input population mixes, we selected an appropriate number of stars from the Girardi *et al.* (2002) set of isochrones, being sure to include stars several magnitudes fainter than the analytically calculated crowding limits. We then placed these stars in distinct JHK images and convolved them separately with the 5 sets of PSFs for each of the 4 telescopes; for the 20 and 30m

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telescopes we assumed 20″ fields of view, for the 50m we used a 10″ field of view, and for the 100m a 5″ field of view. We then averaged the 5 image sets representing different atmospheric conditions together, so as to simulate a single hour-long observation. After adding sky background and noise, we calculated PSF-fitting photometry for the images using DAOPHOT/ALLSTAR, fitting only to the diffraction-limited core of the PSF. Because these images are far too crowded to allow accounting for the broad PSF wings using standard aperture corrections, we corrected the photometry using 1) the spatial Strehl profile from the first 12-minute interval of atmospheric data, as if we had made a PSF observation immediately preceding the hour-long integration, and 2) using the spatial Strehl profile from the average of the first and last 12-minute intervals, as if we had made PSF observations both before and after the hour-long integration. This procedure allowed us to investigate the degree to which we can realistically correct for spatial and temporal variations in the AO PSFs.

4. Results and conclusions

In Figure 1, we show the $J-K$, K color-magnitude diagrams obtained through photometry of the 20, 30, 50, and 100m images, including the results of different stages of correction for the Strehl ratio variation in the images. As seen in the Figure, when left uncorrected, the Strehl variations introduce a scatter of up to tenths of magnitudes in the photometry, with a lesser effect for the larger telescopes because of their smaller fields of view and intrinsically shallower spatial Strehl variations. Using a single PSF observation provided improvement, but scatter of a few hundredths of magnitudes remained. Using two PSF observations provided photometry of quality nearly identical to that obtained using "perfect" knowledge of the correction for the broad PSF wings. Thus, we have provided a demonstration that high-quality photometry of crowded fields with ELTs will realistically be possible.

Our next step will be to derive the population mixes from these simulated color-magnitude diagrams using an automated maximum likelihood technique. This step will allow us to connect the delivered accuracies of near-infrared photometry from ELTs with errors in age and metallicity, and allow investigation of the fields of view and filters needed to achieve a given accuracy in the star formation histories. Given the depths of our simulated CMDs and our past experience with such simulations, we expect the 30m telescope to deliver star formation histories accurate to 1-2Gyr in the M31 bulge, while 50 to 100m telescopes will be needed to usefully investigate the high surface brightness regions of giant elliptical galaxies such as NGC 3379.

Acknowledgements

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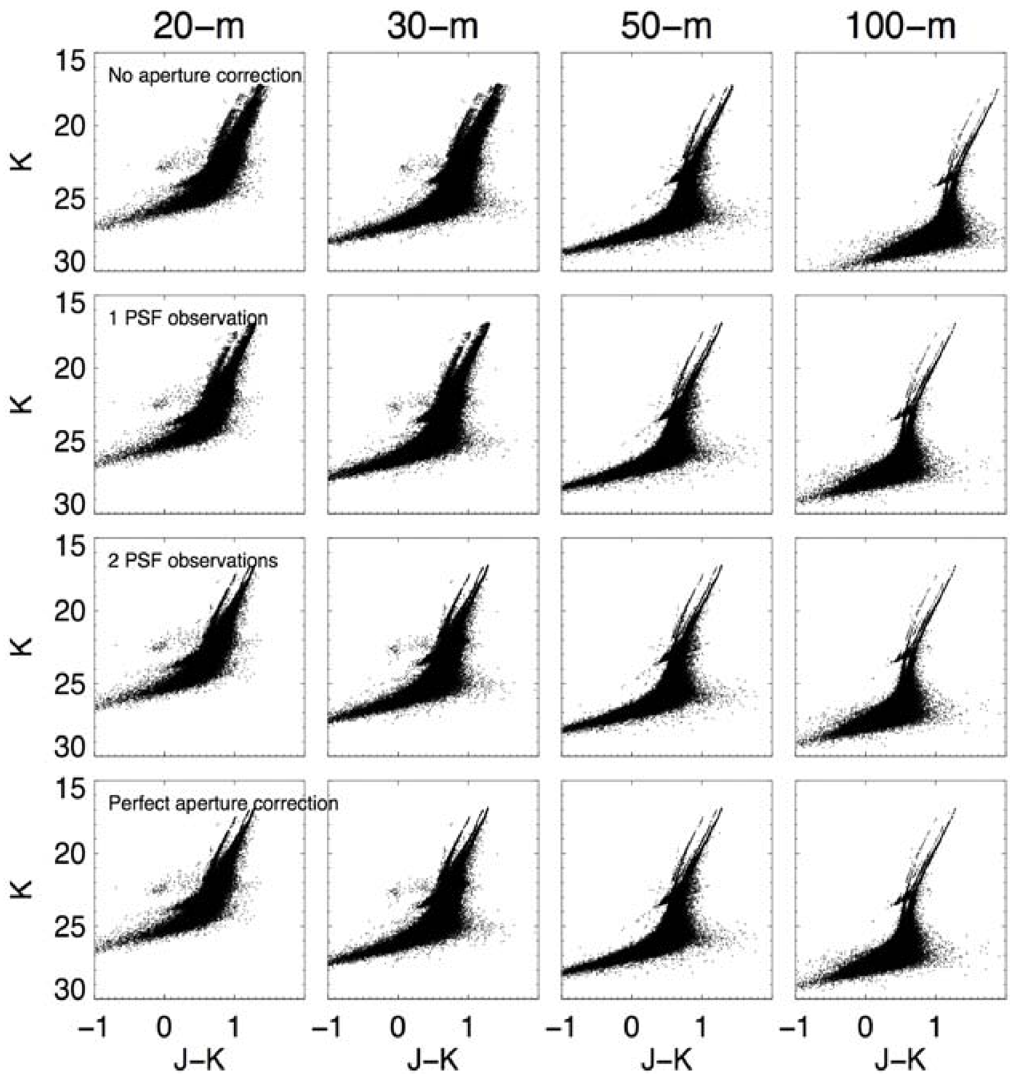

Figure 1. Simulated photometry of the M31 bulge with ELTs. Top row shows photometry with no aperture correction, second row photometry with aperture correction derived from the first turbulence profile, third row photometry with aperture correction derived from the average of the first and last turbulence profiles, and bottom row photometry with perfect aperture correction.

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Discussion

Ellerbroek: Several stellar populations speakers have commented that resolution is more important than integration time for most crowding-limited observations. Does this mean that an under-filled aperture might be an option for some applications?

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Olsen: Yes, this would be an option for the most crowded regions in which the confusion limit is reached in short exposure times.

Mould: Please explain what you based your different Strehl ratios on, for the 3 classes of telescopes.

Olsen: Brent Ellerbroek explains that it is in part because of the increased impact of the cone effect on the larger aperture telescopes and, for the 100m telescope, the limitation of the PSF simulation to a 100×100 actuator system rather than a 200×200 system.

Ardeberg: Could you give us an estimate of the accuracy in age and in abundance that we can get at the distances and with the tools described? In addition, how far could they take us with reasonably similar results?

Olsen: Our simulations show that we can discriminate populations with roughly 1Gyr accuracy in age and 0.3 dex accuracy in metallicity in the M31 bulge with a 30m telescope. The cheat here, though, is that the same isochrone set used to create the simulation was used to compute the best fit population mix. However, we have been able to qualitatively reproduce the LMC's star formation history with 2MASS near-infrared photometry of only the bright evolved stars, leading us to believe that simulation results aren't totally outlandish.

Ardeberg: It is easy to agree on the importance of spatial resolution. In this respect, where do you feel that our assumptions are most shaky?

Olsen: I'm not an AO expert, but according to Brent Ellerbroek, an AO system producing reasonably high Strehl at 550nm would require at minimum several 200W lasers, given 10cm sub-apertures. Industry is currently struggling to produce 50W lasers. The deformable mirrors for an optical AO system also appear to be a serious technical challenge.

Kucinskas: A technical question: which methods/tools did you use for the derivation of ages and metallicities in M31 and M32?

Olsen: I produced basis functions from the library of Padova isochrones by turning the isochrones into Hess diagrams, convolving them with photometric errors and completeness, and restricting the analysis to the area of the CMDs that are 100% complete. I then used a downhill simplex method to find the best-fit linear combination of basis functions.