New and future observational perspectives

Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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Resolved stellar populations: the outlook for JWST and ELT

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Abstract. The study of the resolved stellar populations in nearby galaxies and star clusters through the analysis of colour-magnitude diagrams provides the most detailed and quantitative determination of the star formation histories of these systems. The properties of different age populations provide an insight into distinct physical processes taking place during the entire history of the stellar system. The detection of the oldest main sequence turn-offs is currently restricted to stellar systems within the Local Group due to the limitations in spatial resolution and flux sensitivity of available telescopes. Individual stars need to be detected and accurately distinguished from their neighbours. To improve this situation we need to build new telescopes with larger primary mirrors that can deliver a very stable image quality at the diffraction limit. Over the next decade we can look forward to new larger telescope in space: the *James Webb Space Telescope*, currently scheduled to be launched in 2021; and several large telescope projects, the largest of which is the 39m ESO extremely large telescope on Cerro Armazones in Chile, currently scheduled to start operations in 2024.

Keywords. stars: Hertzsprung-Russell diagram

1. Introduction

The detailed study of resolved stellar populations has a long history. One of the first things that Galileo pointed his telescope at in 1609 was the crowded stellar fields that make up the Milky Way. He showed for the first time that the diffuse light seen with the naked eye is made up of individual stars. In 1785 Caroline and William Herschel made the first estimate of the distribution of stars in the entire Milky Way, using the laborious approach of counting stars by eye. The advent of astronomical photography in the middle of the 19th century made it possible to record images and spectra in a repeatable and consistent way and keep them for later analyses with the facilities and comfort available in a laboratory. At the beginning of the 20th century photographic plates advanced our understanding of both the luminosity distribution and variations in stellar properties in and around the Milky Way, thus providing a dramatic revelation of the size of the Universe and our place in it.

Another major development took place in the 1980s: the advent of low-noise large-format CCD cameras which, unlike photographic plates, can have a linear response to incident light, maintained down to extremely low light levels. This improved the accuracy and repeatability of stellar photometry and allowed much deeper images to be made. An additional important development was adaptive optics, the ability to actively stabilise and dramatically improve image quality, by correcting the distortions coming from the passage of light through the Earth's atmosphere. This has lead to increasingly spectacular images (and resolved spectral data cubes) from ground-based telescopes. Of course the

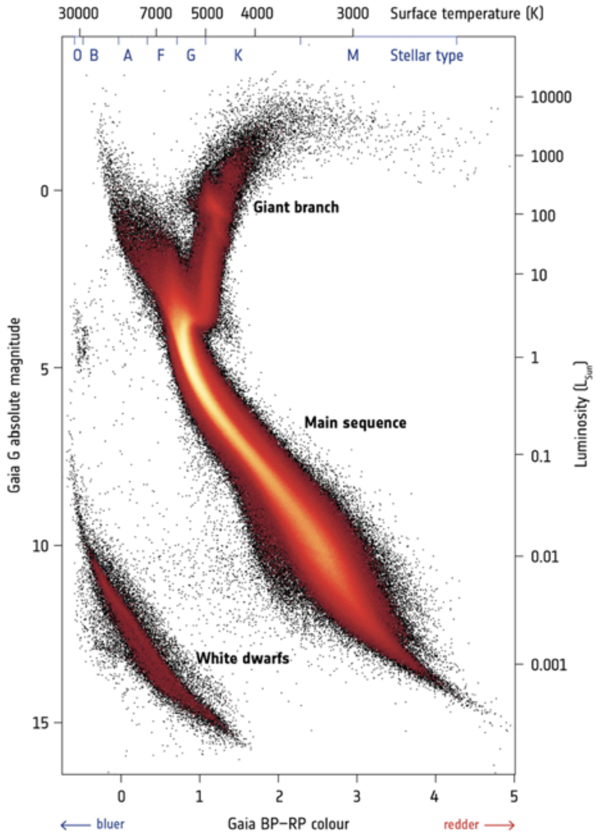

Figure 1. Gaia DR2 Hertzsprung-Russell Diagram of 4 276 690 sources with low extinction. The colour scale represents the square root of the density of stars. Approximate temperature and luminosity equivalents are provided on the top and right axes, to guide the eye. From Gaia Collaboration and Babusiaux *et al.* (2018).

most direct (if not the cheapest) way to remove the effects of the Earth's atmosphere is to move above it, as was shown, by sending a 2.4m diameter optical telescope into space in 1990: the NASA/ESA *Hubble Space Telescope* (HST), equipped with imagers and spectrographs, and for many years it could be refurbished and modernised by NASA/ESA astronauts.

A dramatic recent development is coming from the ESA/Gaia astrometric satellite. It is carrying out a ground-breaking all-sky survey of accurate magnitudes, colours, proper motions and parallaxes of more than 1.7 billion individual stars in and around the Milky Way, extending well out into the stellar halo, and including many nearby dwarf galaxies (Gaia Collaboration and Brown *et al.* 2018). The early results have already started to overturn what we thought we understood about our own Galaxy, and also the small dwarf galaxies orbiting around it. One of the most impressive results coming from the latest data release (DR2), that took place in April 2018, is the most detailed and extensive colour-magnitude diagram (CMD) ever made of the Milky Way (Gaia Collaboration and Babusiaux *et al.* 2018). The accurate distances provided by Gaia parallaxes allow every star to have correct luminosity, leading to the exquisitely detailed CMD shown in Fig. 1.

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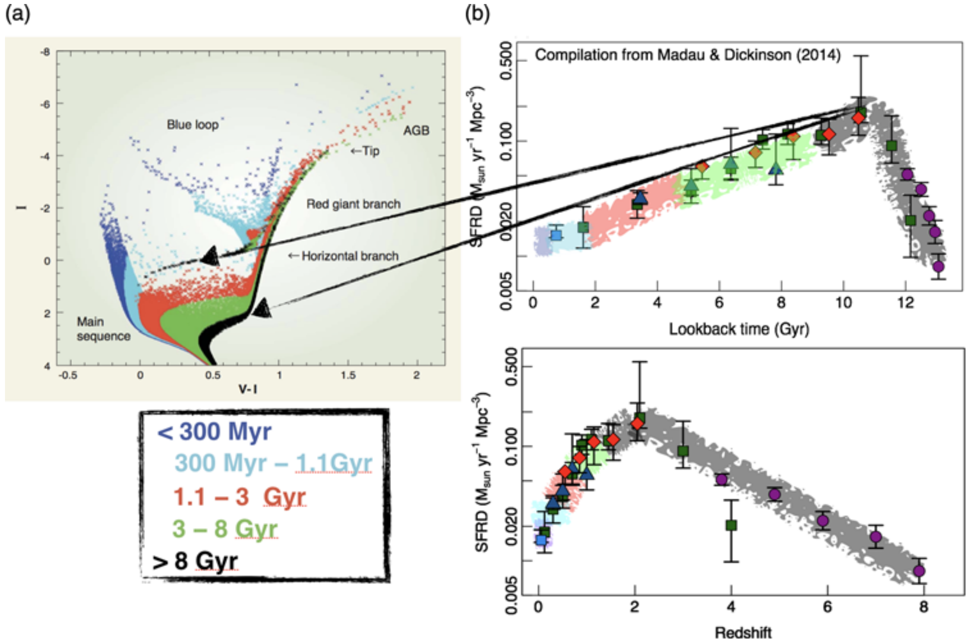

Figure 2. (a) a synthetic CMD for an artificial galaxy with a constant star-formation rate over time and a constant metallicity. The different stellar evolution phases are labelled. The age ranges of these different features are colour coded, as shown below the CMD. The oldest stars are in black and are to be found on the faintest main sequence turnoffs and on the Horizontal Branch, as indicated by black arrows. These stars have formed at look-back times of ∼8 Gyr and more (from Tolstoy 2011); (b) the corresponding regions in terms of the evolution of the cosmological star formation rate density (SFRD) are shown, using data taken from Madau & Dickinson (2014). The colour coding is that same as in the CMD. The SFRD is plotted both in terms of redshift and look-back time.

2. Star Formation Histories

Determining the star formation history (SFH) of a stellar system based on CMDs could begin once it was established how the distribution of stars related to the different phases of stellar evolution. The first studies were based on looking at the overall characteristics of the CMD and separating the different populations into two classes: Population I (young stars) and Population II (old stars). This was first applied to two newly discovered dwarf spheroidal galaxies (Sculptor and Fornax) by D. Baade in 1944. This terminology clearly became too simple, as it was realised that stellar populations in galaxies were always more complex than this, as ever deeper and more accurate CMDs were made, and the models of stellar evolution used to interpret them also became more sophisticated (see Fig. 2a).

In the 1990s for the first time model CMDs were created to compare directly to observed CMDs to obtain accurate and well motivated SFHs (e.g. Tosi *et al.* 1991; Greggio *et al.* 1993; Gallart *et al.* 1996; Tolstoy & Saha 1996; Dolphin 1997; Tolstoy *et al.* 1998). Fig. 2a shows an artificial CMD and the colour code shows how different age stellar populations distribute themselves in a CMD of constant star formation rate with time. In principle the interpretation is the straight forward counting of the number of stars in different parts of the diagram corresponding to the different ages. Of course reality isn't

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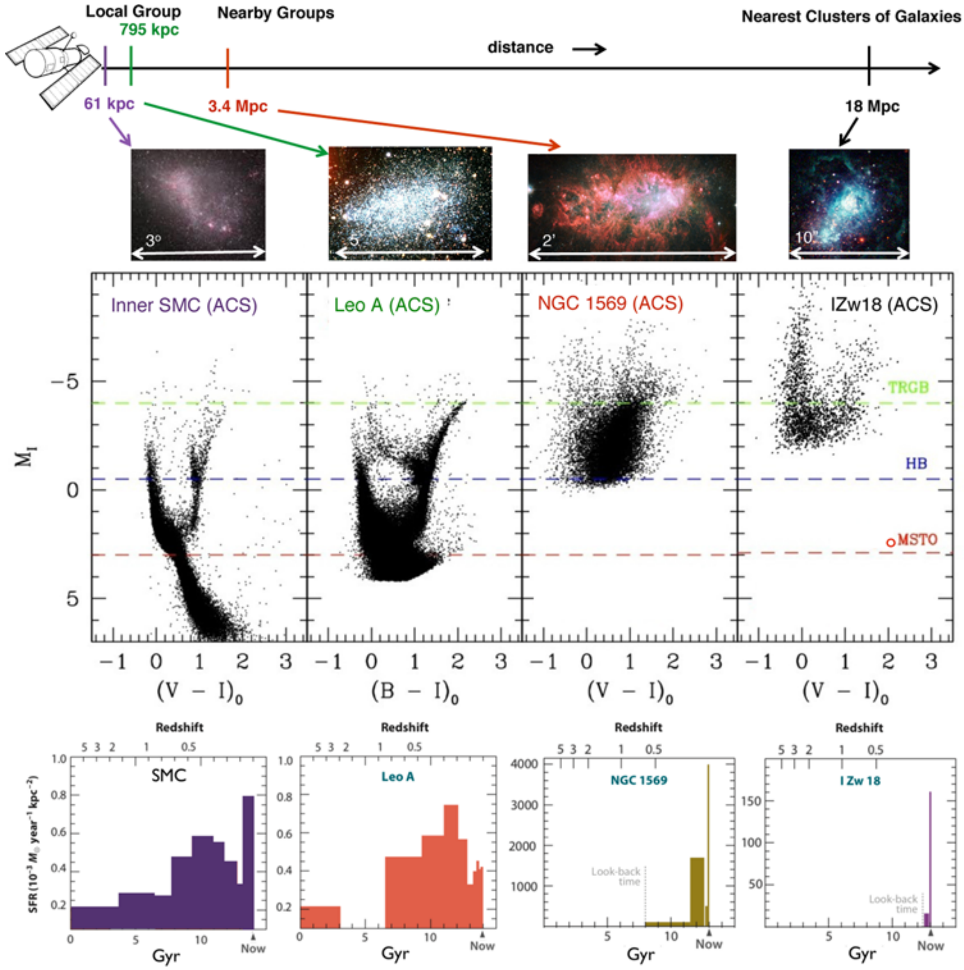

Figure 3. A collection of HST/ACS CMDs and below them the corresponding SFHs for 4 dwarf galaxies at increasing distance from us. The dashed lines show the position of the oldest MSTO, the Horizontal Branch (HB) and the Tip of the Red Giant Branch (TRGB). The photometry and SFH analysis are taken from Cignoni *et al.* 2012 (SMC); Cole *et al.* 2007 (Leo A); Grocholski *et al.* 2012 (NGC 1569) and Aloisi *et al.* 2007 (I Zw 18).

quite this simple, and issues like photometric errors and completeness need to be considered. In addition stellar models have been more reliable in some regions of the CMD than in others. Both the Horizontal Branch (HB) and the Asymptotic Giant Branch (AGB) have proved challenging to model in such away that they can be securely tied to a star formation rate with time. But this is changing rapidly with ever better models.

The most secure way to determine the age of the full range of different populations in a galaxy is to accurately measure the number of stars along the main sequence turnoff (MSTO) region, where the different age populations are clearly well separated by age, as seen in Fig. 2a. However, the oldest turnoffs are very faint, and they get thinner and thinner in luminosity range. It is thus only within the Local Group that it is possible (with often still a large amount of telescope time) to resolve stars going all the way down to the oldest MSTOs, as seen in Fig. 3.

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Fig. 3 shows some examples of HST CMDs, all the result of significant amounts of HST/ACS time, and the resulting SFHs coming from them, and how the detail that is possible decreases with increasing distance, as the older MSTOs are not detected. These are among the best CMDs that have come from HST at each of the distances and so this reflects current absolute limits. Thus Fig. 3 shows both the strengths of diffraction limited imaging in the Local Group (for the SMC at $\sim$ 60 kpc and even Leo A at nearly 800 kpc) and the limitations of a small telescope like HST in being able to extend the same detail beyond the Local Group (to NGC 1569 at 3.4 Mpc or I Zw 18 at 18 Mpc).

2.1. *Ancient Main Sequence Turnoffs*

There a number of excellent and detailed studies of large samples of (mostly) dwarf galaxies, determining star formation histories (SFHs) back to the oldest times (e.g. Cole *et al.* 2007; Monelli *et al.* 2010a,b; de Boer *et al.* 2012, 2015; Cignoni *et al.* 2012; Brown *et al.* 2014; Weisz *et al.* 2014; Gallart *et al.* 2015; Skillman *et al.* 2017; Rubele *et al.* 2018; see also Fig. 3). These are primarily with the HST, but for some very nearby galaxies, such as the Magellanic Clouds and dwarf spheroidal galaxies in the halo of the Milky Way, ground-based wide-field imagers with excellent image quality give a more complete overview. These are often complemented by HST zoom-in fields for more precise details of the most ancient populations.

The details with which resolved SFHs can be determined for large numbers of individual galaxies is making it possible to accurately tie the Local Group SFH to the cosmological star formation rate density (SFRD) that is measured in redshift surveys (e.g. Boylan-Kolchin *et al.* 2015) going up to very high redshifts (which correspond to ancient look-back times, see Fig. 2b). This is an important connection, especially for the study of the role of the most numerous low mass dwarf galaxies that redshift surveys will always struggle to detect.

2.2. *The Horizontal Branch & the Asymptotic Giant Branch*

One clear advantage for extending accurate SFHs beyond the Local Group is to be able to look at more luminous features in a CMD. For example the HB to trace ancient populations, and AGB stars to trace intermediate age populations.

More luminous stars have the obvious advantage that they can be detected at greater distances more easily. However they have the disadvantage that their direct relation to SFHs has often been rather rough. This is because both AGB and HB star evolution depend on uncertain and possibly hard to predict mass-loss events before and/or during their evolution. They are late-stages of stellar evolution, and thus are dependent on an understanding of all the stellar evolution processes that proceeded them, each with their own uncertainties, as John Lattanzio reminded us at this meeting.

HB stars offer a uniquely luminous insight into the most ancient stellar populations in a galaxy, and it has recently been shown that they can offer a more accurate look at how star formation rates and metallicity varied at the earliest times (Salaris *et al.* 2013; Savino *et al.* 2015, 2018). It is clear that the HBs in nearby galaxies all look different (see Fig. 4), revealing a variety of early SFHs even in the smallest dwarf galaxies, even more so than had previously been envisaged (Savino *et al.*, *in prep*).

At this conference it has been shown that our understanding of AGB stars is rapidly developing and they are important constituents of any intermediate age stellar population. Their very high luminosities in the infrared mean that they are clearly critical contributors to the total infrared flux of such galaxies.

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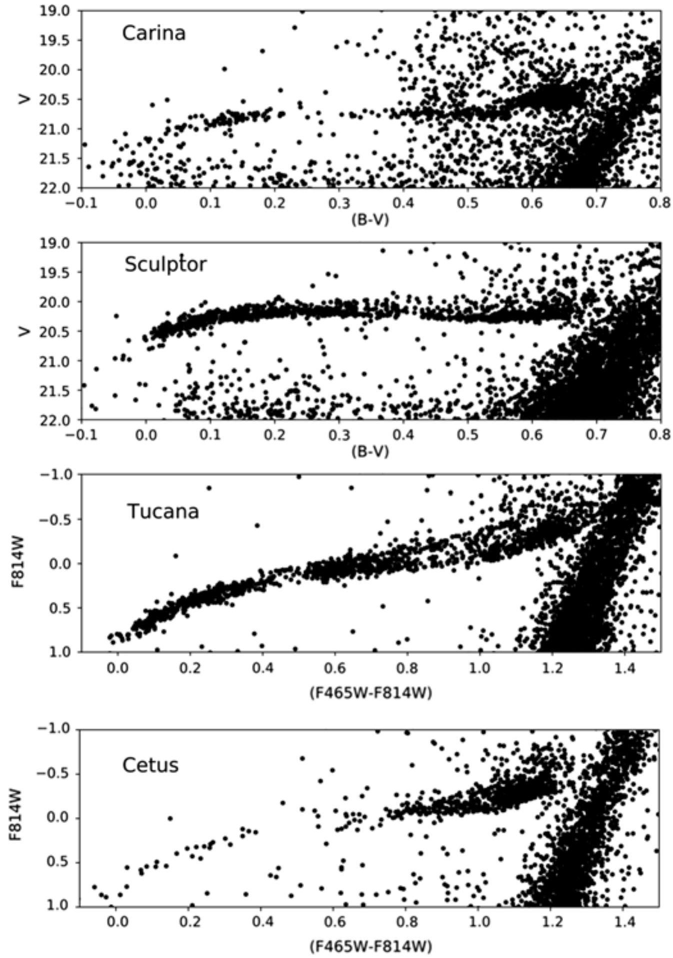

Figure 4. A compilation of the Horizontal Branches of 4 Local Group dwarf spheroidal galaxies. These data come from CTIO/MOSAIC: Carina (Bono *et al.* 2010); Sculptor (de Boer *et al.* 2012); and HST: Tucana (Monelli *et al.* 2010b); Cetus (Monelli *et al.* 2010a). Compilation by A. Savino.

3. Gaia: Proper Motions

Gaia allows uniquely accurate measurements of the positions and motions of resolved stellar populations in real time (Gaia collaboration and Helmi *et al.* 2018). The combination of Gaia's exquisite positions and the stability of HST gives a solid time baseline of many years and means we have the ability to determine both very accurate orbits of dwarf galaxies and globular clusters and also the internal proper motions of stars in these systems (e.g. Massari *et al.* 2018), see Fig. 5. This information is going to continue to increase in accuracy and sophistication over the next series of Gaia data releases.

This detailed information can be combined with metallicity and also SFHs to build up an accurate chemo-dynamical picture of the Milky Way and also some nearby galaxies and globular clusters. It also allows much more detailed CMDs as the proper motions provide a useful method to remove foreground stars, as they will move like the halo or disk of the Milky, and not like member stars in these systems (see Gaia collaboration and Helmi *et al.* 2018). This is clearly a fundamental issue in the study of ultra faint dwarf galaxies (e.g. Simon 2018; Fritz *et al.* 2018; Massari & Helmi 2018).

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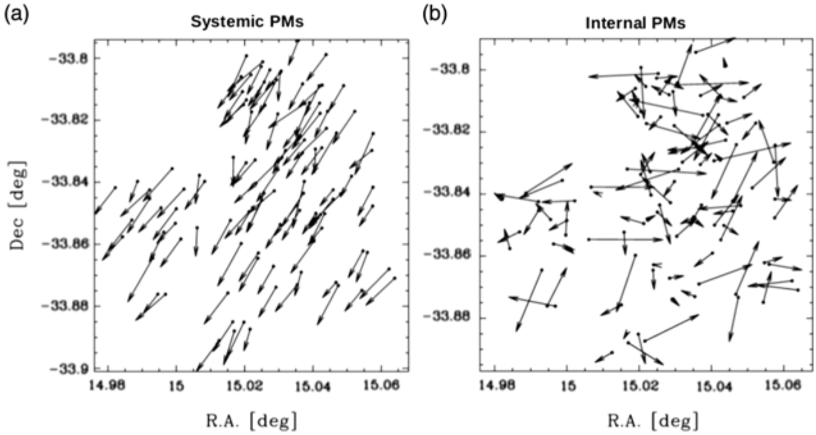

Figure 5. (a) the global (systemic) proper motion of the Sculptor dwarf spheroidal galaxy in an HST field of view, which shows ordered arrows, all of them pointing on average in the direction of the systemic motion; (b) the internal proper motions, after the subtraction of the absolute motion, magnified by a factor of 40. These show the disordered internal motions in the same system. From Massari *et al.* (2018).

4. Future Facilities: JWST & ELT

Making deep and accurate CMDs, tracing ancient populations, will be possible for more distant systems, extending beyond the Local Group, with the advent of future large more sensitive telescopes like the *James Webb Space Telescope* (JWST) in space and MICADO on the ESO Extremely Large Telescope (ELT). These studies benefit tremendously from the combination of extra flux sensitivity (allowing fainter stars to be detected) and spatial resolution coming from a larger primary mirror, allowing these faint stars to be separated and accurately measured in more crowded conditions that naturally arise as we look out to greater distances and into more compact regions, such as Elliptical galaxies and Bulges of Spiral galaxies.

As part of the ELT/MICADO project an image simulator was developed, called SimCADO (Leschinski *et al.* 2016). This simulator takes account of the properties of the source, the atmosphere, the telescope, the instrument and the detector to simulate a realistic MICADO image. This can be used to understand the crowding properties of dense stellar systems, for example, see Fig. 6. At the top a series of simulations are shown, using the dense Galactic globular cluster M4 as a template, which is placed at a range of different distances (from 200 kpc to 2 Mpc). This shows how the crowding increases as the spatial scale becomes increasingly compressed. The extraordinary resolving power of MICADO is critically important to be able to detect individual stars in the heart of Elliptical galaxies (see also Deep *et al.* 2011). This is shown in the lower part of Fig. 6, where the synergy between JWST/NIRCAM and ELT/MICADO is made clear. NIRCAM will have a larger field of view, but also larger pixels than MICADO. This is because JWST is a much smaller telescope than the ELT, and so the diffraction limit will result in a poorer spatial resolution. MICADO has a 6 times better spatial resolution than JWST, which makes a larger field of view very expensive in pixels of the size that properly sample the diffraction limit. The number of stars in the MICADO field is likely to be comparable if not much greater than in the JWST field for a galaxy at the distance of the Virgo cluster.

The superior angular resolution of MICADO images makes crowded field photometry and astrometric applications especially attractive. Exciting opportunities include mapping individual stellar orbits in external stellar systems and stellar orbits and flaring

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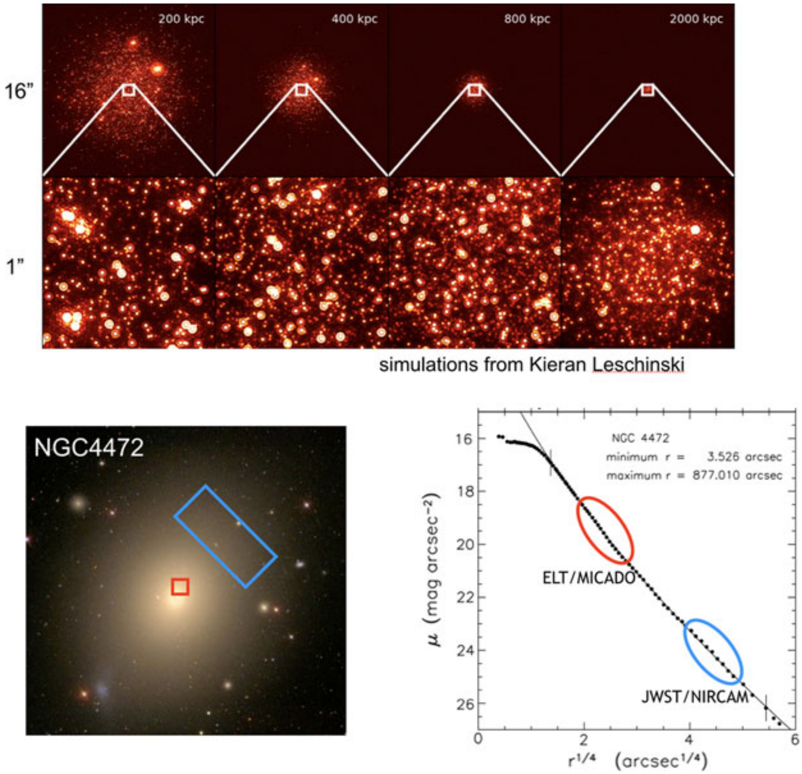

Figure 6. On top are the simulations made by SimCADO of what would be expected from an M4-like globular cluster observed at a range of different distances within the central CCD chip of MICADO, and the zoom-in of the central 1 arcsec. These simulations were carried out by Kieran Leschinski. Below is an image of NGC 4472 with the rough footprint of JWST-NIRCAM (in blue) and ELT-MICADO (in red), and next to this image we show the stellar surface brightness (or stellar density) range that these positions correspond to, which are close to the maximum that these instruments can hope to achieve.

gas fainter and closer to the event horizon of the central black hole in the Galaxy than ever before with direct imaging. Astrometry will be feasible within the central regions of globular clusters over a range of distances and can be extended to monitor black holes in other galaxies. Proper motions of numerous individual stars in resolved stellar systems will allow a more active view of how stellar systems move and change. This will, amongst many other things, enable us to trace the presence (or absence) of black holes in a range of environments, as well as making accurate mass models by combining these results with radial velocity measurements to obtain a 3D view of stellar motions. We will be able to map the dark matter distribution in a variety of environments and for a range of spatial and temporal scales, and set constraints on the physical nature of dark matter particles.

One of the major issues for most people working on interpreting the whole CMD in terms of a SFH is that this is best done in the optical, which better matches the peak of the spectral energy distribution of most stars. However both JWST and ELT will work best in the infra-red, and may not be able to produce anything comparable in the optical. Thus we have to get used to looking infra-red CMDs and adapting our techniques to this. Certain populations stand out very well in the infra-red, and AGB stars are a prime example of this. However main sequence stars and even red giant branch stars typically fall into a smaller region of an infrared CMD, compared to an optical CMD. This requires more accurate photometry to extract the same information as in an optical CMD.

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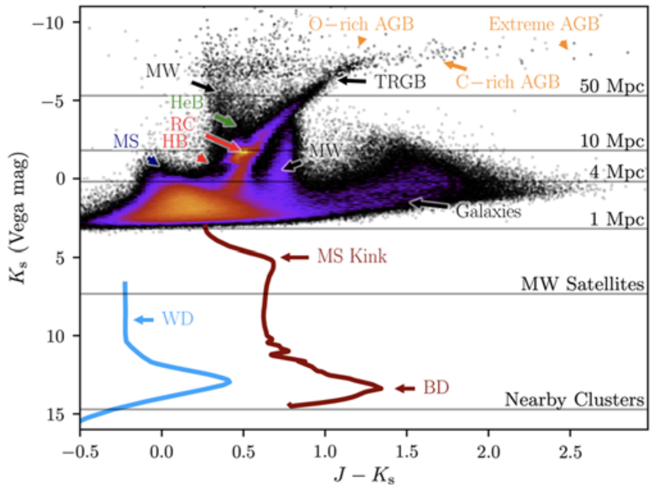


Figure 7. The underlying black open circles are the photometry from the VISTA Magellanic Clouds (VMC) infrared survey of a field in the Large Magellanic Cloud (from Cioni *et al.* 2011). This CMD includes foreground Milky Way stars and also faint background galaxies misidentified as stars. Over plotted are the expected sensitivity limits for similar observations with JWST at a range of different distances. This figure was made by D. Weisz.

In Fig. 7 we show an example of a ground based infrared CMD of the Large Magellanic Cloud, including foreground stellar contamination from the Milky Way and also faint background galaxies that are misidentified as stars. The horizontal lines compare the depths that can be reached with JWST for similar resolved stellar systems at different distances. It is clear that JWST will be a very powerful instrument pushing our understanding of resolved stellar populations far beyond the Local Group, but this will mostly be on the basis of the brighter components of the CMD. As stated above, this is also only possible where the images are not overly crowded. ELT/MICADO should achieve a comparable sensitivity in the best conditions, but with the ability to go into higher surface brightness regions, like the central regions of Elliptical galaxies (see Fig. 6).

So in summary ELT/MICADO and NIRCAM will work over the same infrared wavelength range, but MICADO will be able to resolve structures that NIRCAM cannot. In crowded fields, the MICADO resolution gives an effective sensitivity gain of $\sim$3 magnitudes with respect to NIRCAM, allowing MICADO to probe regions where JWST cannot reach. ELT/MICADO will also achieve astrometric measurements $\sim$6 times faster, or for objects $\sim$6 times more distant, than JWST/NIRCAM (Davies *et al.* 2018). However, as shown by Fig. 6, there will be great complementary between the two facilities and together they will provide us with, among many other things, the first detailed picture of the resolved stellar populations in an Elliptical galaxy.

References

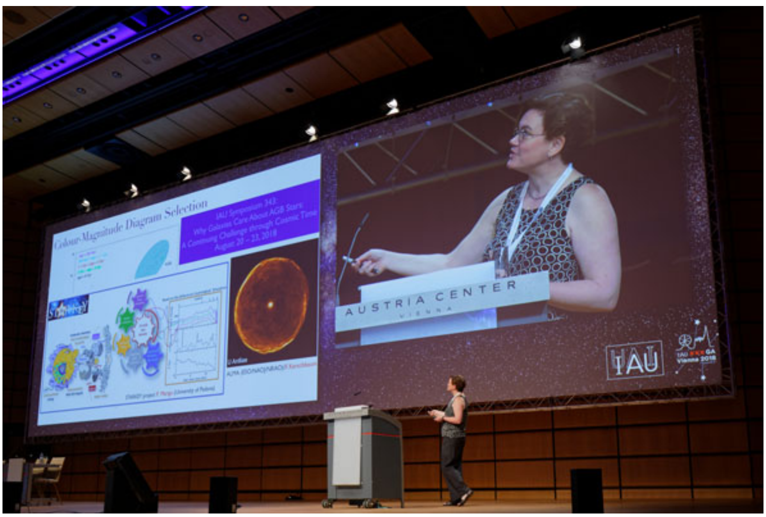
Aloisi, A., *et al.* 2007 *ApJ* (Letters), 667, L151
Gaia Collaboration and Babusiaux, C., *et al.* 2018, *A&A*, 616, A10
Boylan-Kolchin, M., *et al.* 2015, *MNRAS*, 453, 1503
Brown, T.M. *et al.* 2014, *ApJ*, 796, 91
Gaia Collaboration and Brown A.G.A *et al.* 2018, *A&A*, 616, A1
Bono G. *et al.* 2010, *PASP*, 122, 651
Cignoni, M. *et al.* 2012, *ApJ*, 754, 130
Cioni, M.R. *et al.* 2011, *A&A*, 527, A116
Cole, A.A., *et al.* 2007, *ApJ* (Letters), 659, L17

Davies, R., *et al.* 2018, *SPIE*, 10702, 1
Dolphin, A. 1997, *NewA*, 2, 397
de Boer, T.J.L., *et al.* 2012, *A&A*, 539, A103
de Boer, T.J.L, Belokurov, V. & Koposov, S. 2015, *MNRAS*, 451, 3489
Deep, A., *et al.* 2011, *A&A*, 531, A151
Fritz, T.K., *et al.* 2018, *A&A*, in press [arXiv:1805.00908]
Gallart, C., Aparicio, A., Bertelli, G., & Chiosi, C. 1996, *AJ*, 112, 1950
Gallart, C. *et al.* 2015, *ApJ* (Letters), 811, L18
Greggio, L., Marconi, G., Tosi, M., & Focardi, P. 1993, *AJ*, 105, 894
Grocholski, A.J. *et al.* 2012 *AJ*, 143, 117
Gaia Collaboration and Helmi, A., *et al.* 2018, *A&A*, 616, A12
Leschinski, K. *et al.* 2016, *SPIE*, 9911, 24
Madau, P. & Dickinson, M. 2014, *ARAA*, 52, 415
Massari, D. *et al.* 2018, *Nat. Astron.*, 2, 156
Massari, D. & Helmi, A. 2018, *A&A*, in press [arXiv:1805.01839]
Monelli, M., *et al.* 2010a, *ApJ*, 720, 1225
Monelli, M., *et al.* 2010b, *ApJ*, 722, 1864
Rubele, S., *et al.* 2018, *MNRAS*, 478, 5017
Salaris, M., *et al.* 2013, *A&A*, 559, A57
Savino, A., Salaris, M. & Tolstoy, E. 2015, *A&A*, 583, A126
Savino, A., *et al.* 2018, *MNRAS*, 480, 1587
Simon, J.D. 2018, *ApJ*, 863, 89
Skillman, E.D. *et al.* 2017, *ApJ*, 837, 102
Tosi, M., Greggio, L., Marconi, G., & Focardi, P. 1991, *AJ*, 102, 951
Tolstoy, E., & Saha, A. 1996, *ApJ*, 462, 672
Tolstoy, E., Gallagher, J. S., & Cole, A. A., *et al.* 1998, *AJ*, 116, 1244
Tolstoy, E. 2011, *Science*, 33, 176
Weisz, D.R. *et al.* 2014, *ApJ*, 789, 147

Discussion

Gennaro: What do you think the impact of loss of UV capabilities will be in the next decade on studies of stellar populations?

Tolstoy: We will certainly suffer from it, but we should stay positive and try to learn as much as we can from the new IR capabilities.



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