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Conference Report

Resolving the Extended Stellar Halos of Nearby Galaxies: The Wide-Field PISCeS Survey

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Abstract: The wide-field Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS) investigates the resolved stellar halos of two nearby galaxies (the spiral NGC 253 and the elliptical Centaurus A, $D \sim 4$ Mpc) out to a galactocentric radius of 150 kpc. The survey to date has led to the discovery of 11 confirmed faint satellites and stunning streams/substructures in two environments substantially different from the Local Group; i.e., the loose Sculptor group of galaxies and the Centaurus A group dominated by an elliptical. The newly discovered satellites and substructures, with surface brightness limits as low as $\sim$32 mag/arcsec^2, are then followed-up with HST imaging and Keck/VLT spectroscopy to investigate their stellar populations. The PISCeS discoveries clearly testify the past and ongoing accretion processes shaping the halos of these nearby galaxies, and provide the first census of their satellite systems down to an unprecedented $M_V < -8$.

Keywords: galaxies: evolution; galaxies: groups; galaxies: halos; galaxies: photometry

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1. The Past, Present, and Future of Near-Field Cosmology

The past decade has seen a tremendous effort to study the properties of our Milky Way (MW) and its neighbouring Local Group (LG) galaxies in great detail. In particular, the wide-field surveys of the MW-analogue M31 (PAndAS, SPLASH; [1,2]) have highlighted significant differences in the halo properties, accretion history, and satellite populations of the two LG giant spirals. This is unsurprising, as theoretical simulations predict a large halo-to-halo scatter in the properties of MW-sized halos (e.g., [3]), but it certainly underlines the need for in-depth surveys of galaxies beyond the LG.

A variety of approaches can be adopted to refine our knowledge of galaxy halos and their inhabitants: for example, deep pencil-beam surveys of a select sample of nearby (<10–15 Mpc) galaxies can be performed from the space (the Galaxy Halos, Outer disks, Substructure, Thick disks, and Star clusters, or GHOSTS, survey; e.g., [4]); or a larger number of more distant (>15–20 Mpc), unresolved galaxies can be investigated in integrated light (e.g., [5–7]). However, it remains an observational challenge to produce wide and deep resolved stellar maps such as those available for LG galaxies. With the advent of ground-based wide-field imagers, the first PAndAS-like maps for nearby MW-analogues are finally starting to be obtained (e.g., [8,9]).

2. The PISCeS Survey

The Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS) was designed to help bridge the gap between our detailed knowledge of LG galaxies' properties and the integrated light information from unresolved galaxies at larger distances by targeting two resolved galaxies at $\sim$4 Mpc. To facilitate a comparison to the MW and M31, the PISCeS targets are $\sim$ MW-mass galaxies, a spiral (NGC 253, also known as Sculptor) and an elliptical (NGC 5128, or Centaurus A, Cen A). The former is part of a loose filament of galaxies, the latter of a rich group, thus giving us the opportunity to investigate halos and faint satellite populations evolving under different environmental conditions.

PISCeS ultimately aims at obtaining a deep, wide-field view of the extended halos of Sculptor and Cen A, by resolving individual stars out to a galactocentric radius of ∼150 kpc (i.e., comparable to the PAndAS survey). The survey is performed with the Magellan/Megacam imager [10] in the g and r filters, and its areal coverage is ∼95% and ∼80% complete for Cen A and Sculptor, respectively (the total area corresponds to ∼16 deg^2, or ∼95 Megacam pointings).

After performing point-spread-function photometry, we are able to resolve the uppermost ∼1.5 mag of the red giant branch (RGB) population in our targets, with a limiting magnitude of $r \sim 27$ mag. In the color–magnitude space, RGB stars have a clearly distinct sequence from those of unresolved background galaxies and foreground Galactic stars. These predominantly old populations are ideal tracers for the extended halo, and allow surface brightness values as faint as ∼32 mag/arcsec^2 to be reached without the complications inherent to intergrated light studies (e.g., sky subtraction, flat-fielding, Galactic cirrus, etc.).

3. Results

In Figure 1, we report the RGB stellar density map derived for Cen A (from [11]; the data do not include our latest observing run): overdensities in the number of RGB stars reveal a plethora of previously unknown faint satellites, streams, and substructures. To date, the PISCeS results can be summarized as follows:

- *satellites of Sculptor:* we search for previously unknown satellites by performing an initial visual inspection of the Magellan images, which is complemented by an identification of RGB stellar overdensities. To date, we have confirmed two new faint satellites around Sculptor ($M_V \sim -10$ and -12), of which one (Scl-MM-Dw2) is an intriguing tidally disrupting ultra-diffuse galaxy ([12,13]; i.e., a galaxy with an effective radius larger than ∼1.5 kpc and a low central surface brightness, in this case $\mu_{V,0} \sim 26$ mag arcsec^{-2}, following the definition by [14]). We are following-up Scl-MM-Dw2 with a novel coadded stellar spectroscopy technique ([15]) which will allow us to assess the possible presence of velocity and metallicity gradients along its extent;
- *satellites of Cen A:* within the PISCeS footprint we have discovered nine new satellites of Cen A, with luminosities in the range $M_V \sim -8/-14$, as confirmed by our HST follow-up imaging (GO-13856 and GO-14259; see also [11]). Of particular interest are: CenA-MM-Dw3, a disrupting dwarf at ∼90 kpc from Cen A with extended tidal tails (∼2 deg), which has the faint surface brightness of an ultra-diffuse galaxy, a prominent nuclear star cluster and a strong metallicity gradient along its tails; and CenA-MM-Dw1, another ultra-diffuse dwarf with a fainter candidate satellite of its own and a globular cluster system similar to the one of the Fornax dwarf in the LG. The properties of the new satellites are consistent with those of LG dwarfs of comparable luminosities; PISCeS extends the faint end of the satellite luminosity function in the Cen A group by two magnitudes. The preliminary Cen A galaxy luminosity function is steeper than the ones of the MW and M31, but similar to the one derived for the rich M81 group by [16];
- *halo substructures in Cen A:* as seen from Figure 1, Cen A appears to have had a rather active accretion/interaction history: many of the low surface brightness features highlighted by the PISCeS map resemble those previously identified in M31's halo, even though they appear to be less numerous; these features are being followed-up with HST imaging in order to derive their star formation histories and possibly characterize their progenitors' stellar content. Once the substructures are identified, they can be decoupled from the smooth stellar halo to more robustly derive the latter's profile and shape (e.g., [17]);
- *globular cluster population around Cen A:* the wide-field photometry of Cen A's halo has allowed us to identify ∼1000 globular cluster candidates and several ultra-compact dwarf galaxies, identified with a two aperture photometry technique. Some of these objects are spatially correlated with

stellar streams, similarly to what was found for M31 [18], and will guide our interpretation of past accretion events as well as provide valuable constraints to derive Cen A's total halo mass.

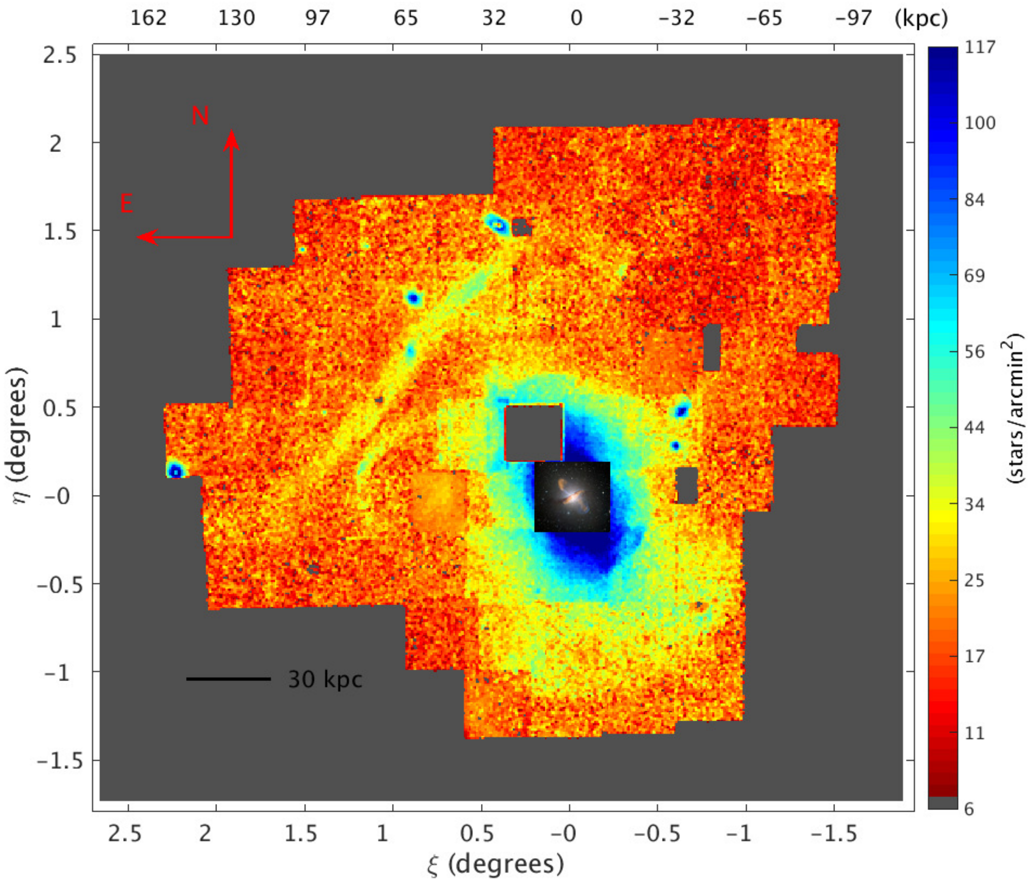

Figure 1. Stellar density map of old, metal-poor RGB stars in the extended halo of Cen A, from the Magellan/Megacam PISCeS survey (Figure 3 from [11]). PISCeS reaches significantly fainter surface brightness limits (down to $\mu_V \sim 32$ mag/arcsec^2) with respect to integrated light alone, thus allowing us to decode the past evolutionary history of Cen A. The density scale is shown on the right; the physical scale is reported on the upper axis. The central regions of the galaxy are replaced by a color image (the star-count map in this region suffers from incompleteness due to stellar crowding). The next generation of telescopes will allow us to obtain comparable maps for tens of galaxies in the Local Volume, thus revolutionizing our understanding of galaxy evolution.

4. Summary and Future Work

The PISCeS survey pushes the limits of near-field cosmology beyond the LG, and enables a comparison of external galaxies' resolved halos to the wide-field surveys of the MW companion M31. The detailed characterization of the extended stellar halos of Sculptor and Cen A will shed light onto their in situ vs. accreted halo components, their metallicity gradients, their faint satellite populations, their halo mass, and shape. These are among the first efforts to explore the properties of extended halos and faint satellite populations for a range of host galaxy morphologies and environments. Such efforts are also starting to be extended to isolated hosts with lower masses (e.g., the Magellanic Analog Dwarf Companions And Stellar Halos, MADCASH; [19]), in order to provide a much needed comparison to the recently discovered satellite system of the Large Magellanic Cloud (e.g., [20] and references therein).

In the next decade, the advent of ground-based and space-borne telescopes (e.g., LSST, JWST, Euclid, GMT, TMT, E-ELT, WFIRST) will open up a new window for near-field cosmology. The next generation of resolved wide-field surveys will be capable of reaching the horizontal branch magnitude level for ∼100 galaxies within ∼10 Mpc, thus delivering maps comparable to (and deeper than) the one shown in Figure 1 for Cen A (e.g., [21]). These upcoming efforts will ultimately provide crucial constraints to theoretical models of galaxy formation and evolution.

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