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The hidden Universe

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Abstract

Mapping the low surface brightness ($\mu > 28\,\mathrm{mag\,arcsec^{-2}}$) structures of the galaxies opens the possibility of testing our current ΛCDM galaxy formation model. At these surface brightness values the accretion history of the galaxies should clearly reveal. We present here two undergoing projects conducted at the IAC whose aim is to explore the lowest surface brightness regions of nearby galaxies using ultra-deep imaging. The first one is the Stripe82 IAC Legacy Project, 270 square degrees based on the SDSS Stripe82 data reaching down to $28.5\,\mathrm{mag\,arcsec^{-2}}$. The second is an overwhelmingly deep imaging of a nearby galaxy, UGC 00180, taken with the 10.4m GTC telescope and showing galaxy details down to $31.5\,\mathrm{mag\,arcsec^{-2}}$.

1 Introduction

There is a huge amount of astrophysical phenomena that remain still barely studied due to the lack of large (several hundreds of square degrees), multiwavelength and deep ($\mu_V > 28\,\mathrm{mag\,arcsec^{-2}}$) optical surveys. These unexplored astrophysical events are those which are very subtle and extent over large areas of the sky. For instance, little is known about the connection of the so-called "optical cirrus" or diffuse galactic light of our Galaxy [6, 19] and the dust filamentary structure observed in the far infrared full sky surveys (i.e. [13]). Also, only a relative small number of nearby galaxies have been probed with enough depth (i.e. [8, 17, 15, 18, 14, 22, 3]) to explore the cosmological predictions (e.g. [5, 10, 25]) about the formation of the faint stellar haloes, tidal streams and ultra-faint satellites surrounding these objects. Similarly, only a handful of nearby galaxy clusters (e.g. [23, 11]) have been observed with enough depth to start understanding the intra-cluster light (ICL) expected from a hierarchical assembly (e.g. [4]) of these cosmic structures.

Today, there are few dedicated surveys designed to explore some of the above astronomical questions. To name a few, we have The Pan-Andromeda Archaeological Survey (PAndAS; [16]) conducted by the 3.6 m Canada-France-Hawaii Telescope (CFHT) whose main aim is the exploration of the stellar halo surrounding our neighbour Andromeda galaxy. Using the same telescope, another deep and large survey is the Next Generation Virgo Cluster Survey (NGVS; [9]). Among its observational goals is the exploration of the ICL in our closest galaxy cluster. However, there has not been yet a plan for a general multi-purpose deep survey expanding over a large area of the sky that allows a systematic analysis of the phenomena stated in the previous paragraph. Nonetheless, many of the above issues could be addressed with a proper reduction of the data collected along the celestial equator in the Southern Galactic Cap of the Sloan Digital Sky Survey (SDSS; [26]) known popularly as the "Stripe 82" survey [12, 1]. In this contribution, we describe our current efforts at the IAC to provide such data to the community, together with a particular project whose aims is to push the 10 m class telescopes to the limit and reach $\mu_V > 30\,\mathrm{mag\,arcsec^{-2}}$.

2 The IAC Stripe82 Legacy Project

The Stripe 82 survey is a 2.5 deg wide region along the celestial equator ($-50\,\mathrm{deg} < \mathrm{RA} < 60\,\mathrm{deg}$, $-1.25 < \mathrm{Dec} < 1.25$ for a total of $275\,\mathrm{deg}^2$). This region of the sky has been imaged repeatedly approximately 80 times in all the five SDSS filters: u, g, r, i, and z. The Stripe82 area is a perfect piece of the sky for exploring many of the astrophysical phenomena described above. First, it is accessible for the vast majority of ground-based facilities, helping to create ancillary spectroscopic and photometric observations if needed. Second, for analysing the optical emission of the dust of our own Galaxy, it covers regions from low to high Galactic extinction at its RA ends [24].

Around a third of all the available SDSS data in the Stripe 82 area (123 of 303 runs[1]) were originally combined by [2]. The goal of that coaddition was "to use this deep survey to understand the single pass data at its limits and to do science at fainter magnitudes or correspondingly higher redshifts" [2]. However, the real treasure of the Stripe82 survey is not only related to the detection of "point-like" sources but in a different unique aspect: the exquisite surface brightness depth that a proper combination of this data can reach along a wide area. In fact, one of the particular aspects of the SDSS survey is that it has been conducted using drift-scan mode. This observational technique has proved to be very efficient avoiding many of the artefacts affecting the quality of the imaging. Thanks to this mode of observation, the sky background of the images is flatter and can be subtracted with great accuracy. Consequently, the single pass SDSS imaging is superb for studies of low surface brightness features (reaching down to $\sim 25\,\mathrm{mag\,arcsec^{-2}}$ through direct detection and $\sim 27\,\mathrm{mag\,arcsec^{-2}}$ through profile averaging techniques; [21]). These are remarkable figures taking into account that the SDSS survey has been obtained with exposure integrations of 53.9 s using a 2.5 m telescope. Considering that, on average, any region of the sky in the Stripe82 area has been observed 80 times, a simple calculation shows that an optimal combination (i.e. assuming all singles passes were of the same quality) of the Stripe82 would be able to reach ~ 2.4 mag deeper than the regular SDSS. In practise, only around 2/3 of the full available Stripe82 data is useful (i.e. reasonable seeing and darkness) for our purposes

[1] A SDSS run is a single continuous drift scan obtained on a single night.

and the real increase in depth of Stripe82 compared to the regular SDSS is closer to 2 mag.

To show the depth of our new coaddition of the Stripe82 data, in Fig. 1 we compare the depth of the single pass SDSS imaging (upper left panel) versus the Stripe82 r-band (upper right panel), the Stripe82 deep r-band obtained from the stacking of the g, r and i Stripe82 bands (bottom left panel) and this same image but smoothed with a boxcar average of $3''$ (bottom right panel). The surface brightness depth of the images has been estimated using the r.m.s. of the images on boxes of $3 \times 3\,\mathrm{arcsec}^2$ (i.e.around $3 \times$ FWHM) and corresponds to $3\,\sigma$ detections.

The ΛCDM model predicts an increasing amount of substructure (stellar streams, shells, filaments) within the stellar halos of galaxies when lowering the surface brightness threshold to values below $30\,\mathrm{mag\,arcsec}^{-2}$ ([5, 10, 25]). Consequently, the brightest streams will be in the reach of the surface brightness limits of $\mu_r \sim 29\,\mathrm{mag\,arcsec}^{-2}$ we acquire in our Stripe82 coadds. Figure 1 shows an exciting example of the possibilities and new discoveries Stripe82 offers in this regard, an extended faint ($\mu_r \sim 28\,\mathrm{mag\,arcsec}^{-2}$) stellar stream around NGC 0936 (also known as the 'Darth Vader'galaxy).

3 Crossing the last frontier: $\mu > 30\,\mathrm{mag\,arcsec}^{-2}$

Despite the enormous depth of the previous surveys, we are lacking broadband data able to explore the structure of the galaxies below $\mu > 30\,\mathrm{mag\,arcsec}^{-2}$. Here we present how current 10 meter class telescopes can provide imaging with fainter limits in a reasonable amount of time. In particular, we show the ability of the 10.4 m GTC telescope to provide imaging with a limiting surface brightness of $31.5\,\mathrm{mag\,arcsec}^{-2}$ ($3\,\sigma$ detections in $10 \times 10\,\mathrm{arcsec}^2$; r-band) in 8 hours on source.

We point the GTC telescope to the galaxy UGC 00180 using the OSIRIS camera. The selection of the galaxy was done to assure that the OSIRIS FOV was able to cover a significant region of sky around the galaxy plus the possibility of exploring very extended stellar features surrounding the object. UGC 00180 redshift is 0.0369. This locates the object at a distance of 151.3 Mpc, providing a scale of $0.733\,\mathrm{kpc\,arcsec}^{-1}$. Consequently, a single shot of the OSIRIS camera covers $343 \times 343\,\mathrm{kpc}^2$ at the galaxy distance. In addition, we decided to take a galaxy with characteristics similar to the well explored massive galaxies in our vicinity, so we can have a reference to compare with. According to Hyperleda [20], UGC 00180 is a Sab massive galaxy ($M_B = -21.76$, $V_{\mathrm{rot}} = 267.6 \pm 18.4\,\mathrm{km\,s}^{-1}$). In this sense, this galaxy is comparable with M31, a massive Sb galaxy ($M_B = -21.2$, $V_{\mathrm{rot}} = 256.7 \pm 6.1\,\mathrm{km\,s}^{-1}$).

The result of our observations are shown in Fig.2. The figure shows how the UGC 00180 galaxy will be seen depending on the depth of different surveys. The stellar halo of our galaxy is clearly seen in our deep data. Note that for this galaxy is necessary to go beyond $\mu > 30\,\mathrm{mag\,arcsec}^{-2}$ to see the stellar halo emerging from the noise.

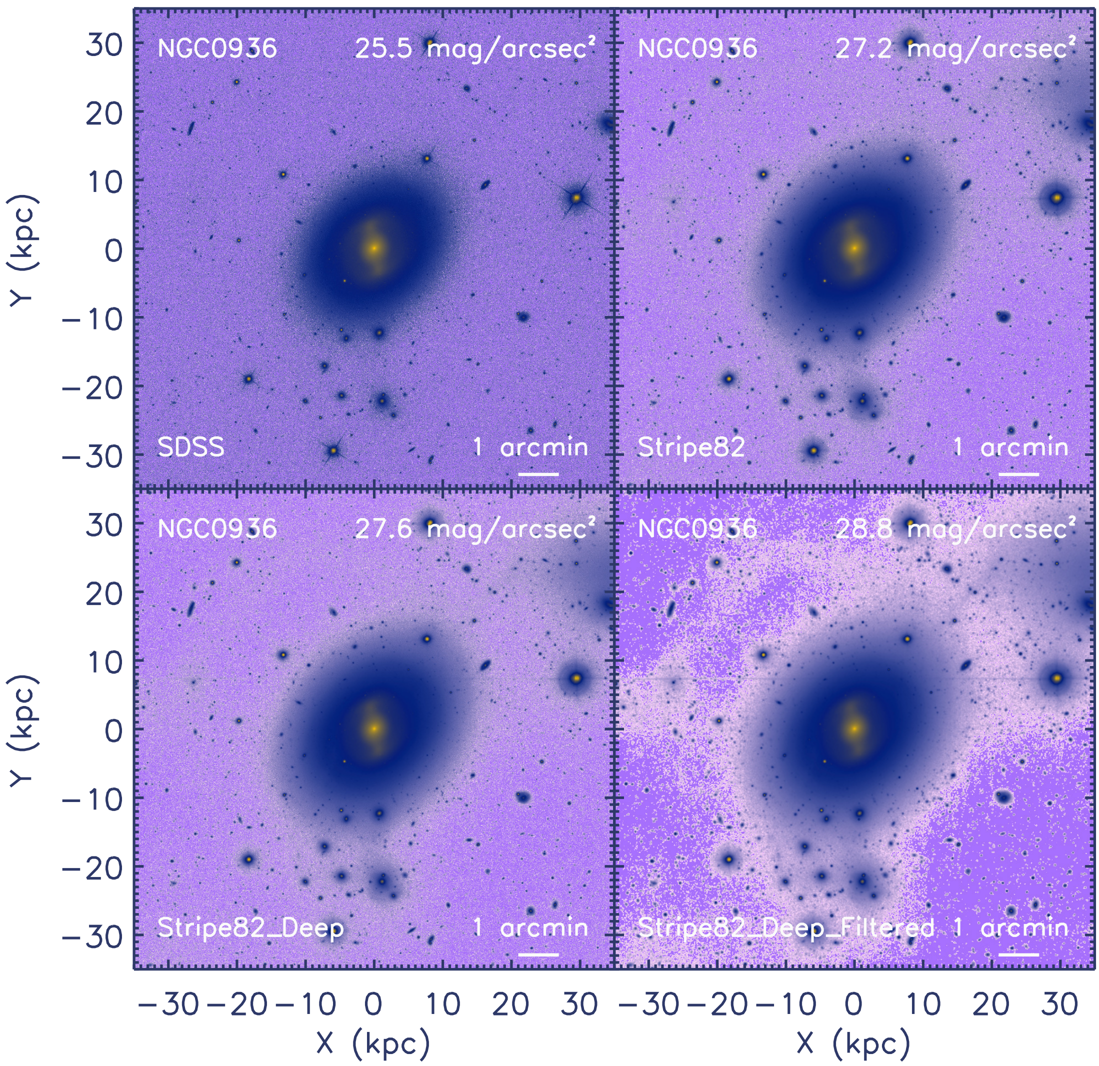

Figure 1: The effect of increasing the depth at observing nearby galaxies. The figure shows the galaxy NGC 0936 in the r'-band (the so-called Darth Vader's galaxy) at four different surface brightness limiting depths: $\mu_r(3\,\sigma;9\,\mathrm{arcsec}^2) = 25.5, 27.2, 27.6$ and $28.8\,\mathrm{mag\,arcsec}^{-2}$. The emergence of a faint tidal stream ($\mu_r \sim 28\,\mathrm{mag\,arcsec}^{-2}$) around this galaxy (*bottom right* panel) exemplifies the need of ultra-deep observations to explore the substructure prediction by the ΛCDM model.

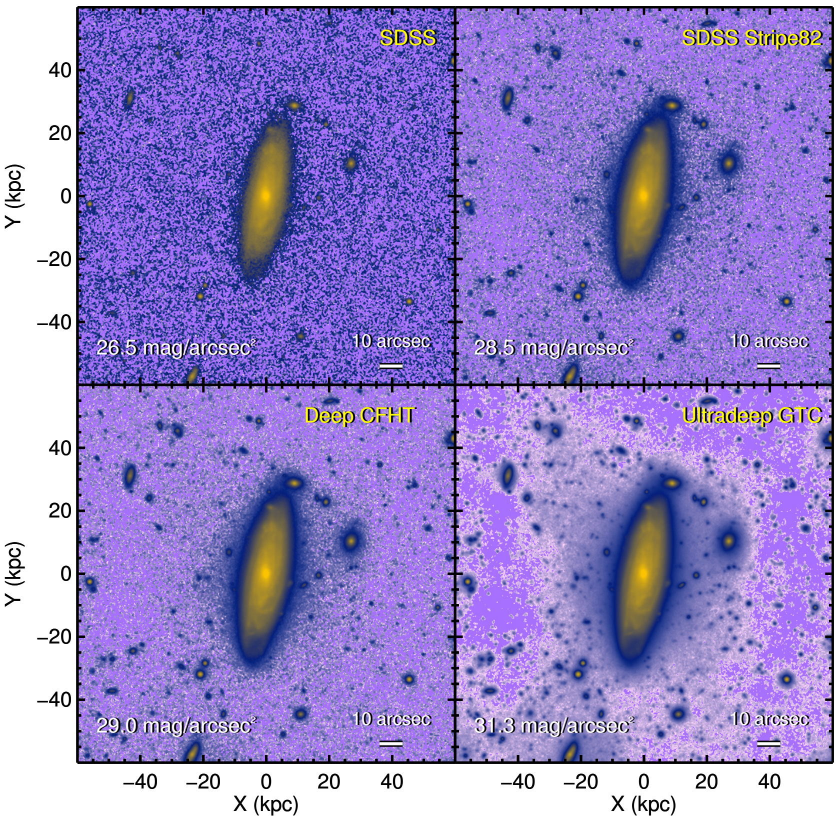

Figure 2: UGC 00180 as it would be observed by different surveys (SDSS, SDSS Stripe82, Deep data with CFHT (i.e. [9, 7]) and the present work). Each limiting magnitude has been estimated as a $3\,\sigma$ fluctuation in boxes of $10 \times 10\,\mathrm{arcsec}^2$. Note how, for this galaxy, the emergence of a stellar halo requires reaching surface brightness fainter than $30\,\mathrm{mag\,arcsec}^{-2}$.

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