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What do galaxies look-like beyond 31 mag/arcsec^2?

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Abstract

Detection of optical surface brightness structures with magnitudes fainter than 30 mag arcsec^{-2} has remained elusive in current photometric deep surveys. We will show, for the first time outside the Local Group, ultra deep imaging (>31 mag arcsec^{-2}) of two galaxies: UGC00180, an analogous to M31 located at 150 Mpc and NGC0493, an analogous to Milky Way located at 25 Mpc. Using the 10.4 m Gran Telescopio de Canarias telescope, combined with an exquisite treatment of the sky subtraction and PSF effects, we reach similar depth as that obtained using star counts techniques in the Local Group. We find that the mass of the stellar halo of UGC00180 is (3±1) % of its total stellar mass, well in agreement with theoretical predictions for M31 or the Milky Way. On the other hand, data in two bands for NGC0493 gives us a clue on the kind of stellar populations we can expect at the lower surface brightness limits. This work opens new frontiers not only in the study of outskirts of galaxies but also in the theories of galaxy formation. We will present our current work with GTC detecting low surface brightness structures such as satellites and streams.

1 Introduction

Low surface brightness astronomy is the next frontier in imaging data and it is starting to change the way we see the Universe. Lambda Cold Dark Matter cosmology predicts a vast variety of substructures surrounding Milky Way-like galaxies [1, 2]: halos, streams, disrupted globular clusters... Although a fraction of these features have already been detected in previous works (e.g., [5, 4, 3]), most of them still remains unseen below the 30 mag arcsec^{-2} limit.

The low surface brightness features surrounding the galaxies contain precious information about the formation of these objects. In fact, the analysis of the low surface brightness structures around the galaxies are opening a large number of questions. From the "missing satellites problem" [6] to the apparent absence of stellar halo in some galaxies as M101 [8], the only way out of these challenges are to methodically study the low surface brightness features where the galaxies are wrapped in.

However, reaching such depths is not an easy task and requires a carefully designed observation strategy combined with a data treatment intended to preserve the extended structures. Most of present-day deep imaging surveys are perfect to study point sources or bright extended objects, but usually the low surface features have been removed during the reduction process.

There are three key points when dealing with very deep imaging:

- Internal reflections of the camera and the optics of the telescope. These reflections can generate ghosts, fringing or residual light, among other effects. This can be solved by designing a good observation strategy.
- Scattered light. This is the light spread in the detector from the objects of the image. We can overcome this problem carefully characterising the Point Spread Function (PSF) of the camera. Since the aim is to unveil extended low surface brightness structures, the PSF has to be characterised down to many arc minutes depending on the field of view under study.
- Sky treatment. Usually, sky subtraction is done via modelling and subtraction. However, depending on the scales of such modelling, this subtraction can add noise to the data and even remove real low surface brightness extended structures.

Our group is overcoming the above mentioned problems and developing the tools to exploit both archival and new data in order to obtain as much information as possible below 30 mag arcsec^{-2}. On one hand, we have the expertise with sky subtraction acquired during the re-reduction of the Stripe 82 data set (The Stripe 82 IAC Legacy Project, [10]) In this paper, we show our current work in the field of ultra-deep imaging and low surface-brightness science, as well as future prospects.

2 Data acquisition and processing

To avoid the aforementioned problems related to the low surface brightness regime, we have designed both a data acquisition strategy and a reduction process with four key elements: the observing strategy, the flat fielding, the sky subtraction and the PSF treatment.

The observing strategy combines a 9-point dithering pattern together with a rotation pattern. The aim is to obtain different images from the object in different positions of the CCD, so the same feature of the image never hits the same pixel in the CCD. This allows us to remove any internal reflection or effect that the camera or the telescope present by the co-adding process. In this sense, it is key to select a convenient exposure time: it has to be long enough not to increase the noise in the co-add, but short enough to allow a large number of different positions of the object.

In order to reach low surface brightness limits, the flat fielding has to be incredibly accurate (~1–2 %). This is impossible to obtain using dome flats, where the illumination and the dome of the telescope would introduce false structures in the images. Neither the sky flats are valid for our purposes, since the gradients in the sky and the differences with the night sky would also introduce errors in the data. This is the reason why we obtain our flat fields from the science images itself.

To do so, we take advantage of a dithering and rotation pattern. By thoroughly masking objects in the science images and combine images from one night, we obtain a very accurate flat field to correct our images from the response of the camera and the optical system.

Regarding the sky subtraction, we try to avoid any modelling, which would introduce noise in the data, presumably masking low surface brightness structures. Instead of modelling it, we extract a constant value in each of our images. This value is obtained by rejecting all the pixels associated with an object an placing random apertures in the image. The sky value will be the robust mean of the value of the sky in every aperture.

These kind of observations do not require a photometric night or very good seeing, but it is important that the conditions during the night are as stable as possible. We also take into account the effect of the PSF and build the map of scattered light that contaminates our images. The PSF of the telescope is obtained with separate observations of bright stars following the same observing strategy, which allows us to characterise the wings of the PSF down to many arcmin from the centre of the star.

3 Ultra-deep imaging with GTC: UGC00180 and NGC0439

We have conducted a pilot program with the 10-meter class telescope, the Gran Telescopio de Canarias, observing the galaxy UGC 00180 [7] during 8.1 hours (on source) in r-band. This galaxy is very similar to M31 in mass ($M_{\rm dyn}$ = (3.9±0.9) x 10^{11} $M_\odot$) and morphological type (Sb) and is located at a distance of 151 Mpc. Using the techniques described in Section 2, we obtained an image with a surface brightness limiting magnitude of 31.5 mag arcsec^{-2} (3–σ; 10 arcsec ×10 arcsec). This depth unveils the stellar halo of that galaxy, as well as new structures, probably galactic cirrus and mergers at intermediate redshifts (see Fig. 1).

We repeated the experiment with NGC 0493, a galaxy comparable to the Milky Way and located at a distance of 25 Mpc. In order to properly characterise the stellar populations composing the stellar halo of that galaxy, we observed the object in two bands: g and r. Using the strategy outlined in Section 2, we obtained a similar depth as with the previous galaxy (∼31 mag arcsec^{-2}). Preliminary images in both bands can be seen in Fig. 2.

4 Future work

Once our team manage the tools and the strategies to make the best of the data, the plan is to extend this techniques to other objects and telescopes. In this sense, 1-meter telescopes make are interesting candidate for these studies. Many of them have wide fields of view (∼ 1 degree), more time available to the community than the largest telescopes (this is very relevant for our survey, as even using the biggest telescopes our survey requires many hundreds of hours) and optimised acquisition systems. One example of this kind of facility is

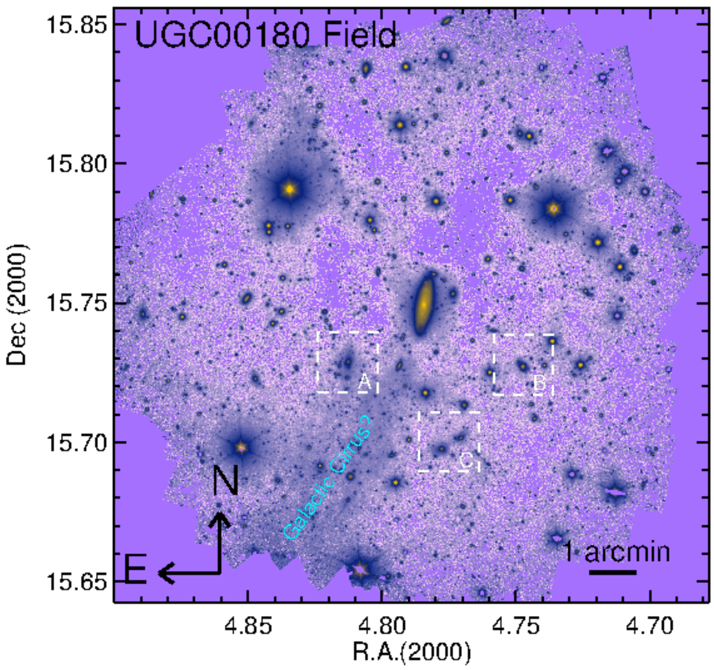

Figure 1: Field of view of the galaxy UGC00180 from GTC data down to 31.5 mag arcsec^{-2} (3–σ; 10 arcsec $\times$10 arcsec). Galactic cirrus and other science cases such as mergers (see boxes A, B and C) can be clearly seen in the image.

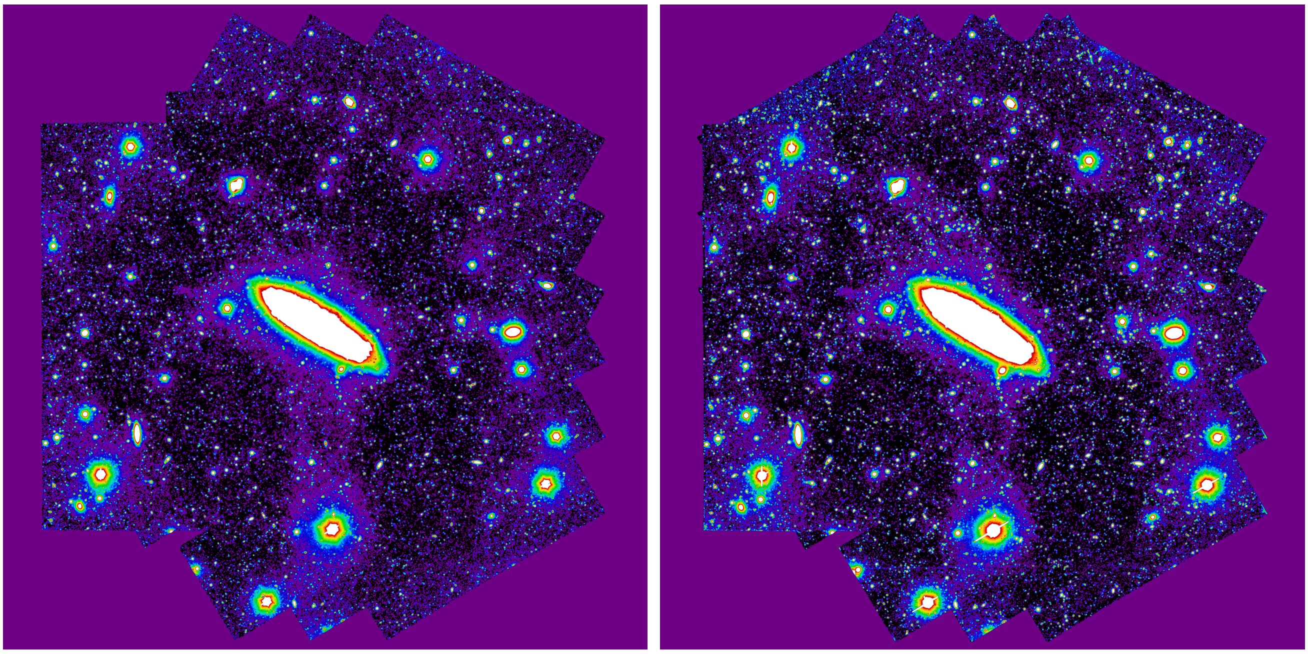

Figure 2: Field of view of the galaxy NGC493 from GTC data in g-band (left panel) and in r-band (right panel). Some streams and other interesting features start to emerge and requires further investigation.

Las Cumbres Observatory[1] [9], JAST/T80 telescope at Observatorio de Javalambre (Teruel) or Stella Robotic Telescopes and OGS telescope at the Observatorio del Teide.

Our group is exploring the best combination between instrumentation and data treatment to make the most of archival data and existing facilities. This will open the path to explore the low surface brightness Universe with future instruments and surveys, such as the Large Synoptic Survey Telescope (LSST) in a very systematic way, testing the theories of dark matter and galaxy formation with the faintest structures.

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