BEYOND 31 mag arcsec$^{-2}$: THE FRONTIER OF LOW SURFACE BRIGHTNESS IMAGING WITH THE LARGEST OPTICAL TELESCOPES

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ABSTRACT

The detection of structures in the sky with optical surface brightness fainter than 30 mag arcsec$^{-2}$ (3σ in 10 × 10 arcsec boxes; r-band) has remained elusive in current photometric deep surveys. Here we show how present-day telescopes of 10 m class can provide broadband imaging 1.5–2 mag deeper than most previous results within a reasonable amount of time (i.e., <10 hr on-source integration). In particular, we illustrate the ability of the 10.4 m Gran Telescopio Canarias telescope to produce imaging with a limiting surface brightness of 31.5 mag arcsec$^{-2}$ (3σ in 10 × 10 arcsec boxes; r-band) using 8.1 hr on source. We apply this power to explore the stellar halo of the galaxy UGC 00180, a galaxy analogous to M31 located at ∼150 Mpc, by obtaining a radial profile of surface brightness down to μr ∼ 33 mag arcsec$^{-2}$. This depth is similar to that obtained using the star-counts techniques for Local Group galaxies, but is achieved at a distance where this technique is unfeasible. We find that the mass of the stellar halo of this galaxy is ∼4 × 10$^9$ $M_\odot$, i.e., (3 ± 1)% of the total stellar mass of the whole system. This amount of mass in the stellar halo is in agreement with current theoretical expectations for galaxies of this kind.

Key words: galaxies: evolution – galaxies: formation – galaxies: halos – galaxies: photometry – galaxies: spiral

1. INTRODUCTION

Ongoing technological advances are enabling the observation of deeper data every day, allowing us to discover objects that were hidden to previous generations of astronomers. Nowadays, the deepest optical data set, the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006), is able to detect point-like objects as faint as 29 mag (10σ; using 0′′/2 apertures). While our ability to detect compact structures in deep optical surveys is impressive, when the photons spread over extended areas, the lack of contrast against the foreground sky hampers our capacity to identify large objects.

Exploring astronomical objects with low surface brightness is extremely challenging from an observational point of view. It is not enough to have very deep data: a careful reduction and treatment of the sky is essential. In fact, it is common to find in the literature very deep data where the handling of the sky (although optimized for the detection of the faintest point-like sources) is inappropriate for the characterization of structures with the faintest surface brightness. In this sense, for instance, it is easy to find “holes” around the brightest extended galaxies in very deep surveys like the Canada–France–Hawaii Legacy Survey (CFHTLS; Goranova et al. 2009) or the Hubble Space Telescope (HST) eXtreme Deep Field (Illingworth et al. 2013). These are examples where the reduction pipeline has been probably very aggressive in subtracting the sky. This is very likely due to real signal, coming from features of low surface brightness around the objects, being confused with the background of the image and, consequently, oversubtracted.

The treatment of the sky is not the only actor playing a major role in the ability to detect and characterize astronomical structures of low surface brightness. In fact, there are many artifacts that affect the quality of the images: fringing, scattered light, ghosts, etc. All these phenomena generate gradients in surface brightness on the images that enormously complicate the study of the faintest components. To overcome all these problems, there have been an increasingly large number of works addressing these observational difficulties (e.g., Ferrarese et al. 2012; Duc et al. 2015; Fliri & Trujillo 2016). All these studies have pointed out the need for a careful preparation of the observational strategy and the reduction of the data. As the result of these efforts, state-of-the-art deep surveys aiming to explore the structures with the faintest surface brightness are currently reaching ∼29–30 mag arcsec$^{-2}$ (3σ, 10 × 10 arcsec boxes; r-band) using 8.1 hr on source. We apply this power to explore the stellar halo of the galaxy UGC 00180, a galaxy analogous to M31 located at ∼150 Mpc, by obtaining a radial profile of surface brightness down to μr ∼ 33 mag arcsec$^{-2}$. This depth is similar to that obtained using the star-counts techniques for Local Group galaxies, but is achieved at a distance where this technique is unfeasible. We find that the mass of the stellar halo of this galaxy is ∼4 × 10$^9$ $M_\odot$, i.e., (3 ± 1)% of the total stellar mass of the whole system. This amount of mass in the stellar halo is in agreement with current theoretical expectations for galaxies of this kind.

The study of the stellar halos surrounding nearby galaxies is one of many reasons to conduct very deep imaging. Probing the stellar halos in a large number of galaxies is a strong test of the current ΛCDM scenario of galaxy formation (e.g., Bullock & Johnston 2005; Abadi et al. 2006; Johnston et al. 2008). In fact, state-of-the-art cosmological simulations suggest that virtually all present-day galaxies will show several streams and a prominent extended stellar halo if they are observed down to μν > 31 mag arcsec$^{-2}$ (e.g., Cooper et al. 2010). This prediction remains untested except for a very limited number of galaxies in the Local Group (Ibata et al. 2009, 2014; McConnachie et al. 2009; Tanaka et al. 2011; Peacock et al. 2015) where the resolved star-counts technique has been used. In fact, with this technique, these studies have revealed features with equivalent surface brightness of ∼31–32 mag arcsec$^{-2}$. However, the technique of resolved star counts cannot be applied very far away. Using the HST, Zackrisson et al. (2012) have estimated a maximum distance of 16 Mpc for this strategy. This considerably limits the volume, the number, and the type of galaxies that can be studied. For this reason, we need to explore how deep we can go, in terms of surface brightness, with integrated
photometry. In fact, considering the intrinsic stochasticity of the formation process of stellar halos, the need for a larger sample of galaxies is clear if we want to probe the LCDM scenario of galaxy formation in depth. The current paper is designed as a pilot project to explore whether integrated photometry can produce images as deep as the star-counting technique. We will show that this is indeed feasible, opening the possibility of exploring stellar halos to a much larger volume than the Local Group of galaxies.

This paper is structured as follows. In Section 2, we describe our data, the target selection criteria, the observational strategy, and the data processing. Section 3 shows the results of our observation, and how the depth of our image compares with other previous surveys. In Section 4, we explore the distribution of the scattered light in our field of view (FOV). The characteristics of the stellar halo of our targeted galaxy, UGC 00180, as well as the effect of the point-spread function (PSF) are described in Section 5. Section 6 discusses the main results of this paper and, finally, our work is summarized in Section 7. Hereafter, we assume a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA

Ultra-deep observations of the galaxy UGC 00180 and its surrounding region were carried out with the Gran Telescopio de Canarias (GTC) using the OSIRIS (Optical System for Imaging and low–intermediate-Resolution Integrated Spectroscopy) camera. OSIRIS has a total FOV of $7.8 \times 8.5$, of which $7.8 \times 7.8$ are unvignetted. The OSIRIS camera is composed of two CCDs with a gap of $9.4$ between them. The pixel scale of the camera is $0.06254$. The images were obtained using the Sloan r′ filter during six (nonconsecutive) nights. Images were taken under good seeing conditions, producing a final image with a full width at half-maximum (FWHM) seeing of $\sim0.79$.

2.1. Target Selection

The selection of the galaxy, UGC 00180, was done to ensure 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 is a galaxy positioned at R.A.(2000) = $00^h19^m08.2$ and Decl. (2000) = $+15^d44^m57.6$. Its redshift is 0.0369. This locates the object at a distance of 151.3 Mpc, giving a scale of 0.733 kpc arcsec$^{-1}$. Consequently, a single shot of the OSIRIS camera covers $343 \times 343$ kpc$^2$ at the distance of the galaxy. In addition, we decided to take this 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 (Paturel et al. 2003), UGC 00180 is a Sab massive galaxy ($M_B = -21.76$, $V_{rot} = 267.6 \pm 18.4$ km s$^{-1}$). In this sense, this galaxy is comparable with M31, a massive Sb galaxy ($M_B = -21.2$, $V_{rot} = 256.7 \pm 6.1$ km s$^{-1}$). UGC 00180 has $R_{25}$(B band) = 32.0 ± 3′′ (i.e., 23.5 ± 2.2 kpc). This, together with its rotational velocity, translates into a dynamical mass of $M_{dyn} = (3.9 \pm 0.9) \times 10^{11} M_\odot$ inside its optical radius. Its global (Petrosian) color, according to the NASA/IPAC Extragalactic Database, is $g - r = 0.78$ (after correction for Galactic extinction). Following Bell et al. (2003), this color is equivalent to a $(M/L)_r = 2.51$ (Kroupa initial mass function (IMF); Kroupa 2001). Consequently, the stellar mass of UGC 00180 is $M_\star \sim 1.3 \times 10^{11}$ $M_\odot$.

2.2. Observational Strategy

The objective of our observation is to reach the theoretical surface brightness limit of GTC within the total amount of time allocated for this exercise (i.e., $\sim$8.1 hr on source as we describe below). To achieve this goal, we need to deal with several observational biases that affect very deep observations: fringing, scattered light, saturation, ghosts, etc. For this reason, we have designed an observational strategy that aims to obtain a background as flat as possible around our galaxy target. To do that, in addition to conducting the usual dithering scheme, we have pursued a rotation pattern to remove as far as possible effects due to contamination by scattered (residual) light. With the rotation pattern, we avoid the possibility that potential reflected residual light (from the telescope dome, telescope structure, etc.) might affect the camera at the same position angle (P.A.) during the full set of pointings. Moreover, the large number (243) of images we get in the end allow us to build a very flat sky to achieve our purpose.

The strategy that we have conducted is as follows. We have carried out nine observing blocks, each composed of three steps:

- Step A: The P.A. of the camera is fixed at a given angle and we make a dithering pattern of nine positions.
- Step B: The P.A. is rotated 120° with respect to the previous angle and we repeat the dithering pattern of nine positions.
- Step C: The P.A. is rotated again another 120° and we repeat the dithering pattern of nine positions.

The offsets of the dithering sequence, both in R.A. and in decl. are of $1′$. This offset is more than enough to derive a proper background map considering the brightness and size of the astronomical objects in the FOV of our final image. Moreover, this guarantees that our target of interest, the galaxy UGC 00180, is observed 100% of the time. At the end of each observing block we have 27 images. The observing blocks are identical to each other but start from a different set of orientation angles. These are:

- 0–120–240
- 10–130–250
- 20–140–260
- 30–150–270
- 40–160–280
- 50–170–290
- 60–180–300
- 70–190–310
- 80–200–320

The observational strategy is illustrated in Figure 1. Each pointing of the sequence has an exposure time of 120 s. That corresponds to a total amount of time on source of 8.1 hr. It must be noted that shorter exposure times than those conducted here, although desirable to avoid large sky variation during each exposure, would prohibitively increase the amount of time allocated to overheads (the camera readout time is 21 s). Consequently, a balance between the two quantities is necessary. In addition to the previous set of images, there

1. It is worth noting that the optical sky brightness at the Roque de los Muchachos observatory is extremely stable during the night. Measured variations are consistent with zero, $0.03 \pm 0.07$ mag arcsec$^{-2}$, within the precision error (see a report at http://www.ing.iac.es/astronomy/observing/conditions/skyyr/skybr.html).
were also a number of images with shorter exposure times (six pointings of 5 s each and two of 10 s) to avoid saturation of the central parts of UGC 00180.

As we have mentioned before, each OSIRIS pointing covers an unvignetted region of 7/8 × 7/8. The dithering and rotation sequence that we have conducted produces a final image covering a larger FOV (12/7 × 12/7). Figure 2 shows the weight map resulting from the stacking process that we describe in the following sections. Within the central four arcminutes of the image, the amount of observing time per pixel is quite homogenous, with a standard deviation per pixel of ∼2%. Our observing pattern allows the galaxy to never occupy exactly the same physical area of the CCD across the 243 exposures, helping in the building of an accurate background map. The observation pattern also helps to remove the gaps between the OSIRIS CCDs.

2.3. Flat-field Correction

An accurate estimation of the flat-field correction is key for the purpose of this work. Dome flats are not useful for our goals due to inhomogeneities in the illumination of the GTC Dome. Consequently, our flat-field correction should be based on sky imaging. Twilight flats, although better, are still insufficient for our purposes as variations between the night sky and the twilight spectrum may result in subtle flat-fielding differences. For this reason, we have decided to use our own set of science images to create a masterflat.

Masterflats are created for each observing night using a median of the normalized science images of that night. Ideally, one would like to use the full set of science images to obtain a much better masterflat, but slight differences in the focus and vignetting correction from night to night prevent such an approach. As mentioned before, the total number of nights used to complete our data set was six. The amount of data is such that there are at least 15 science images every night to combine and create the masterflat of that night. An independent masterflat is created for each CCD of the OSIRIS camera. The building of the masterflats is done as follows:

- For each individual 120 s science image, we create an object mask using SExtractor (Bertin & Arnouts 1996). The object masks are expanded to ensure that the outer light of the objects is also masked. Only those pixels outside the masks are used to create the final masterflat.
- Every individual science image of a given night is normalized to one. The determination of the number of counts to normalize each image is done in the same CCD position (close to the optical axis of the camera). This counting is done within a box of 50 × 50 arcsec².
- The normalized and masked individual science images are combined in a single masterflat using the median.

Figure 1. Dithering and rotation sequence followed to get the final image. The background image is a color composite of the UGC 00180 region obtained from the Sloan Digital Sky Survey (SDSS). The total field of view of the SDSS image corresponds to 13/5 × 13/5. The field of view of each pointing by the OSIRIS camera (7/8 × 7/8) is overplotted with a violet contour. The position of the orange crosses indicates the dithering pattern followed in each block of observations, whereas the green arrow indicates the position angle of the camera in each set of observations. In total, the final image is composed of 3 × 9 × 9 pointings. A full description of the procedure is given in the text.
The masterflats have a typical rms of 0.055%. Finally, the individual sciences images of each night are divided by their corresponding masterflats.

2.4. Removal of Bad Pixels

Before the combination of the full data set of science images, it is necessary to identify those regions of each OSIRIS CCD where the quality of the image is degraded. To do that we have created a mask image (based on the normalized masterflat) identifying: (a) bad columns, (b) hot pixels, and (c) vignetted regions of the camera (normally areas where the count rate is less than 65% of the peak). We have expanded our masked region slightly (to be conservative) to include also the pixels nearest those identified as bad ones. While doing the following reduction steps, our individual science frames are masked with these masks.

2.5. Astrometric Calibration

To avoid misalignments during the combination of our individual science images into a final mosaic, we need to ensure that the astrometry of all the individual images is the same. To conduct that task we use SCAMP (Bertin 2006). SCAMP is used to put all our science images into a common astrometric solution. SCAMP reads SExtractor catalogs and computes astrometric and photometric solutions for any arbitrary sequence of FITS images in a completely automatic way. Our astrometric solution takes as a reference the astrometry of the stars of the SDSS DR7 catalog (Abazajian et al. 2009) in our FOV. The number of stars used in each science image for our astrometric solution is typically around a couple of dozen.

2.6. Photometric Calibration

The photometric calibration of our science images is based on the photometry of SDSS DR7. We use the (unsaturated) stars in the SDSS DR7 catalog (Abazajian et al. 2009) within our FOV. The magnitudes of the stars in the SDSS DR7 catalog that we have used are those from the PSF photometry. We matched the SDSS DR7 photometric catalog to ours, after which we multiplied our images, making the photometry in both catalogs equal. The multiplicative factor is chosen such that our images are calibrated to a common zero point of 32 mag. The typical number of stars that are within each of our individual science images to conduct this photometric calibration task is ~30.

2.7. Sky Determination

The sky determination and subtraction are done for each of our science images individually before the final coaddition. The determination of the sky is done using only those pixels of the images that are not identified as objects by SExtractor. We place $10^5$ apertures randomly located through the images and we determine the resistant mean value of the counts in these apertures. We subtract that value from the calibrated images.

2.8. Image Coaddition

Once the astrometry of every individual science image is recalculated to a common astrometric solution and the images
are calibrated as well as sky-subtracted, we use SWarp (Bertin et al. 2002) to put all our data into a common grid. SWarp is a program that resamples and coadds together FITS images using any arbitrary astrometric projection defined in the WCS standard. The combination uses the median of those images. The common FOV is illustrated in Figure 2. The image resampling method that was used is LANCZOS3. The final coadded image (see Figure 3) is significantly deeper than the individual exposures, and features with low surface brightness, hidden in the individual exposures, emerge in the final stacking. These features (extended dust emission, halos of bright stars, etc.) affect the sky determination of our individual science images. For this reason, it is necessary to mask these regions and repeat the process of the sky determination in the individual exposures. The result of this repetition is our final image, which we explore in detail in the next sections.

3. RESULTS

Our final image is shown in Figure 3. Before discussing in detail the extended emission around our main target, the nearby galaxy UGC 00180, we briefly discuss here other structures visible in the FOV around this object. The most conspicuous feature is the extended and filamentary emission observed in the bottom part of the image that we have tentatively tagged as Galactic Cirrus. Without having color information, it is complicated to identify the origin of this extended emission. We have used the Planck satellite to see whether it is possible to see this feature in the 857 GHz (350 μm) channel (Planck Collaboration et al. 2014). At this wavelength, the dust of our own Galaxy is particularly visible. The spatial resolution in the far-infrared image (1.7 arcmin pixel$^{-1}$) is so poor compared to the size of our image that we cannot make any clear statement on this. However, the position of the maximum emission of the dust in the 857 GHz channel seems to coincide with the spatial location of the extended emission in the optical (see Figure 4), suggesting a dust origin for this feature.

We have also tagged three other regions in the image to illustrate the level of detail that can be explored in our data. These regions are called A, B, and C and have been shown in detail in Figure 5. Panel A shows a galaxy cluster located at $z = 0.389$. The region shown corresponds to $200 \times 200$ kpc$^2$ at the cluster redshift. The presence of intracluster light (observed in the $g'$-band rest frame) at distances as far as 150 kpc is very remarkable (at this redshift the cosmological dimming is 1.43 mag) and illustrates the depth of this image. We will quantify this depth in the following subsection. Panels B and C show galaxies undergoing mergers at different redshifts. In the particular case of panel C, two galaxies of similar brightness at $z = 0.287$ seem to have extended stellar halos that are connected by a bridge of stars. The distance between these two galaxies is larger than 100 kpc.

3.1. Surface Brightness Limit and Comparison with Other Surveys

To provide the limiting surface brightness of a given image, it is first necessary to define an area where a given fluctuation is considered to be a detection or not. For instance, for the SDSS survey, Kniazev et al. (2004), using circular apertures of $R = 12''$, found that a $3\sigma$ fluctuation in the surface brightness

![Figure 3. Field of view of 12/7 × 12/7 around UGC 00180. In addition to our main target, there are a number of interesting astronomical objects that are highlighted. A zoom-in to the objects tagged as A, B, and C is shown in Figure 5. The presence of an extended and filamentary emission in the bottom part of the image is also tentatively identified as a Galactic Cirrus of our own Galaxy.](image-url)
distribution of the image corresponds to an object with $\mu_{\text{lim}} = 26.4 \text{ mag arcsec}^{-2}$ ($g'$ band). Alternatively, another way to explore the limiting surface brightness of an image is to determine the limiting surface brightness down to which a galaxy profile can be confidently explored. Pohlen & Trujillo (2006), also using SDSS, were able to extract reliable (3$\sigma$) surface brightness profiles down to $\sim 27 \text{ mag arcsec}^{-2}$ at $R = 150''$ ($g'$, $r'$ bands). For the SDSS images, the number of pixels explored along a circular longitude of that radius is equivalent to the number of pixels inside a circular aperture of $R \sim 11''$. To put these numbers into context, it is worth noting that this depth was obtained with a 2.5 m telescope using an exposure time of $\sim 1$ minute.

There have been increasing efforts in recent years to obtain very deep imaging of nearby galaxies. Duc et al. (2015) have summarized the depth of different projects and we refer the reader to that reference for an exhaustive summary of the current status in the literature. A large number of previous works, including Duc et al. (2015), have been conducted using the Canada–France–Hawaii Telescope (CFHT). Those works (e.g., Ferrarese et al. 2012; Duc et al. 2015) typically reach a depth of $28.5–29 \text{ mag arcsec}^{-2}$ ($g'$ band) using 40–60 minutes.
on a 3.6 m telescope. Bridge et al. (2010), also using the same telescope but with integration of 5–10 hr, claim detections of features with a surface brightness of \( \sim 30 \) mag arcsec\(^{-2} \) (\( g' \) band). Using the SDSS Stripe82 data obtained by the SDSS 2.5 m telescope during \( \sim 1 \) hr, Flirij & Trujillo (2016) estimate a 3\( \sigma \) detection (\( r' \) band) at 28.5 mag arcsec\(^{-2} \). Watkins et al. (2014) claim a surface brightness limit of 29.5 mag arcsec\(^{-2} \) (\( V \) band) with 10.25 hr on source using the 0.6/0.9 CWRU Burrell Schmidt telescope. Finally, Jablonka et al. (2010), using the VLT telescope in a 6 hr exposure, obtained surface brightness profiles down to a limit of \( \mu_R \sim 30.6 \) mag arcsec\(^{-2} \) for the nearby galaxy NGC 3957.

Other works (i.e., Martínez-Delgado et al. 2010), using more modest apertures (\( D \sim 0.5 \) m), have reached 28–29 mag arcsec\(^{-2} \) (\( V \) band) using 10–15 hr on source. Finally, using an array of lenses equivalent to a 0.4 m diameter telescope (the Dragonfly telescope; Abrahm & van Dokkum 2014), Merritt et al. (2014) claim the detection of features with \( \mu_V \sim 29.5 \) mag arcsec\(^{-2} \) and \( \mu_r \sim 29.8 \) mag arcsec\(^{-2} \) on scales of \( \sim 10 \) arcsec for a total of 35 hr.

In this work, we have decided to obtain the limiting surface brightness of the image as the equivalent to a 3\( \sigma \) fluctuation (compared to the sky noise) in square boxes of \( 10'' \times 10'' \). The reason behind using boxes of this size is given by the typical size of the components we are interested in exploring in the stellar halo of UGC 00180 (see Figure 6). At the redshift of UGC 00180, this aperture is appropriate to probe features of \( 7.3 \times 7.3 \) kpc\(^2 \). Values like that are typical of the FWHM of streams of nearby galaxies (e.g., Martínez-Delgado et al. 2008). Using square boxes of \( 10'' \times 10'' \), we obtain a surface brightness limit of 31.5 mag arcsec\(^{-2} \) (3\( \sigma \), \( r'-\)band). This surface brightness limit refers only to the innermost \( 4 \times 4 \) arcmin\(^2 \) of the image, where the effective amount of time on source is \( 8.1 \) hr.

In order to compare our observations with other deep surveys, in Figure 6 we show how our galaxy would be seen at the depth of SDSS, Stripe82, and deep CFHT surveys. To mimic the depth of the different surveys, we have used our original GTC data and we have added noise to the image until we get a limiting surface brightness depth like the one reported in the literature for the different surveys. The limiting surface brightness (in the \( r' \)-band) is estimated as a fluctuation of 3\( \sigma \) using \( 10'' \times 10'' \) boxes. We use the following limiting values: 26.5 mag arcsec\(^{-2} \) (SDSS), 28.5 mag arcsec\(^{-2} \) (Stripe82), and 29 mag arcsec\(^{-2} \) (Deep CFHT). We have checked that our noise simulations were conducted properly by comparing our simulation of the SDSS depth with data from the same galaxy obtained directly by the SDSS. Based on these noise tests, it is worth noting how, for UGC 00180, the stellar halo is visible only when the GTC depth is reached.

To further test the depth of our data set, we explore the repeatability of the faintest features we can distinguish in our final image. The images of our galaxy were collected in two different observing sets with different sky and seeing conditions. Consequently, those features that are visible in both blocks of observations determine the actual surface brightness limit of our data in our set with the shortest exposure. The first set of data was taken during 2013 November 1, 4, 7, 8, 10, and 11 and it has a total of \( 6 \) hr on source. The second set of data was collected during 2013 November 25 and 26 for a total of \( 2.1 \) hr on source. A zoom-in around UGC 00180 for the two sets of data is shown in Figure 7. Overplotted in this figure are the surface brightness contours corresponding to \( 25, 28, \) and 30 mag arcsec\(^{-2} \). The vast majority of the faint features are identical in both independent data sets. There is a small difference in the bottom right part of the two images where the 30 mag arcsec\(^{-2} \) extends a little bit farther away in the shallow (2.1 hr) image than in the deeper block. This bottom part of the image was slightly overexposed (in the shallow block) with respect to the rest of the image of the galaxy due to our observational strategy. This produces a slightly higher signal-to-noise ratio in this part of the image, producing the observed differences.

4. SCATTERED LIGHT AROUND UGC 00180

As explained in Section 2, the reduction of the image has assumed a constant value for the sky. This value has been determined after carefully masking all the individually detected objects and the extended features of low surface brightness as dust emission, halos of bright stars, etc. However, the scattered light produced by the convolution of the sources in the field with the PSF constitutes a complex background that needs to be explored to test whether the features of low surface brightness around UGC 00180 have an origin external to the source. Slater et al. (2009) have conducted a detailed analysis of the scattered light produced by the bright stars in a given field. They show that in fields like the center of the Virgo Cluster (which contains three very bright stars of eighth magnitude to the west of M87) the convolution of the PSF with the bright stars of the images implies that every single pixel of the image beyond 29 mag arcsec\(^{-2} \) (\( V \) band) is dominated by the scattered light of one or more stars. If the contribution of scattered light is homogeneous over spatial scales similar to the size of the object of interest, in our case UGC 00180, then this scattered light is equivalent to having a second sky level (the first one being produced by the atmosphere at \( \sim 22 \) mag arcsec\(^{-2} \)) superimposed on the galaxy.

To construct the field of scattered light around UGC 00180 produced by the bright stars we need to accurately characterize the PSF of the image over as large an extent as possible. In practice, this means characterizing the PSF in this image at least down to \( 5 \) arcmin, which is the average separation of the brightest sources in our field. Ideally, one would like to create such a PSF using stars taken directly from the image and processed similarly. In practice, this is extremely complicated because the presence of bright stars in the field is avoided to keep simple the analysis of the object under study. For this reason, we conducted a campaign for observing the star \( \gamma \) Dra (\( V = 2.36 \) mag) with GTC (using the same rotation and dithering pattern as for the main object). The total amount of time on source was \( 13.5 \) s (27 pointings of 0.5 s each using a dithering pattern of nine pointings and three position angles: 0°, 120°, and 240°). Such a bright star allow us to explore the PSF of the GTC telescope down to a radial distance of \( \sim 5 \) arcmin. However, despite the very short integration times we are using, the GTC PSF appears saturated in its innermost region (<10 arcsec). For this reason, we combine that PSF with a PSF built using the unsaturated PSFs of the UGC 00180 field. The two PSFs are matched to cover the entire brightness and

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5 This GTC PSF is available to the astronomical community at the following webpage: http://www.gtc.iac.es/instruments/osiris/osiris.php#BroadBand_Imaging. The data were collected on 2014 December 23.
radial range. Figure 8 shows $\gamma$ Dra as seen by the GTC telescope.

With the PSF extremely well characterized down to large radial distances (error less than 0.07%, 0.11%, and 0.28% at 1 arcmin, 3 arcmin, and 5 arcmin respectively) we construct the field of scattered light produced by the brightest ($R < 17$ mag) stars of the image. It is worth noting that (except for UGC 00180), all the sources of our image brighter than $R = 17$ mag are point-like sources. The selection of the bright stars in our FOV is done using the USNO catalog. In particular, we have used the information provided by the UCAC 3 catalog (Zacharias et al. 2009), which contains the magnitude of the stars in $R$. We have used all the stars brighter than the above magnitude within a radial distance of 7 arcmin of UGC 00180. Once the catalog of bright stars is constructed, we build the scattered light field, locating the GTC PSF (normalized to the flux provided by the USNO catalog) at each position where the bright stars are. The results of doing this are illustrated in Figure 9. UGC 00180 is placed in a region of the image where the contribution of the scattered light from the nearby brightest sources is rather homogeneous and around 29.2 mag arcsec$^{-2}$. In fact, after subtracting the scattered light distribution (and adding back a constant value to the sky to recover the zero value from the sky) there is no effect on the structure of the stellar halo around UGC 00180.

The field of scattered light created above is based on the assumption that the shape of the PSF (particularly its wings) does not vary over the entire field. However, it is worth noting that the GTC PSF was created to represent the effect of the PSF on the center of the image. A future study of the stability of the GTC PSF mimicking the position of stars in different positions of the final image would be desirable to explore whether the above assumption is correct or not.

5. THE STELLAR HALO OF UGC 00180

The surface brightness profile of UGC 00180 has been obtained through elliptical apertures with ellipticity changing with radial distance to reflect better the disk and the outer (more roundish) component of the galaxy. Nearby contaminant sources like foreground stars and background galaxies were identified with SExtractor (Bertin & Arnouts 1996) and

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Figure 6. UGC 00180 as it would be observed by different surveys: SDSS, SDSS Stripe82, Deep data with CFHT (i.e., Ferrarese et al. 2012; Duc et al. 2015), and the present work. Each limiting magnitude of surface brightness has been estimated as a 3-sigma surface brightness fluctuation in boxes of $10'' \times 10''$. Note how, for this galaxy, the emergence of a stellar halo requires reaching a limiting surface brightness fainter than 30 mag arcsec$^{-2}$ in the $r$-band.
Figure 7. This figure displays two independently observed data sets of the galaxy UGC 00180 taken with GTC on different dates. The figure shows the repeatability of the faintest features of the stellar halo of this galaxy. Overplotted in this figure are the surface brightness contours corresponding to 25, 28, and 30 mag arcsec$^{-2}$.

masked. In those cases where SExtractor was unable to identify a source, we masked the object manually. In addition, the Galactic Cirrus feature found in the southeast part of the image was also masked to avoid its influence in the outer region of UGC 00180. The resulting surface brightness profile of UGC 00180 is shown in Figure 10.

The depth of the GTC observations allow us to explore a range of $\sim$14 mag in the galaxy profile, from around 19 mag arcsec$^{-2}$ in the center down to $\sim$33 mag arcsec$^{-2}$ in the outskirts. We have also overplotted the profile of the galaxy obtained using the SDSS image with the same elliptical apertures. The GTC surface brightness profile is 5 mag deeper than the SDSS one. This is in excellent agreement with the theoretical expectation taking into account the difference in size of the telescopes (10.4 m GTC versus 2.5 m SDSS) and the amount of time on source on the object (8.1 hr GTC versus 1 minute SDSS). Note that the seeing in the two data sets is comparable ($\sim$1$''$).

We have divided our profile into five different spatial regions to illustrate the different structures of the galaxy. The innermost region corresponds to the bulge of UGC 00180. From 4 to 18 kpc we see a gentle exponential decline that we identify with the inner disk of the object. After a break, the surface brightness profile continues to decline exponentially out to 37 kpc (the outer disk). This kind of behavior (broken exponential) has been identified many times in the literature using SDSS data (see, e.g., Pohlen & Trujillo 2006). In fact, the SDSS data for this galaxy also show the break feature. Close to the end of the outer disk we have a hint of a new downward-bending “break” feature. We tentatively identify this as the truncation of the disk. The faint surface brightness of the truncation ($>26$ mag arcsec$^{-2}$) makes it quite complicated to identify in galaxies that are not completely edge-on using surveys like SDSS (see a discussion about this in Martin-Navarro et al. 2014). The region beyond 37 kpc is dominated by a roundish component around the galaxy that is declining exponentially. We call this region the stellar halo of the galaxy. There is a soft bump around 60 kpc and 30 mag arcsec$^{-2}$ that corresponds to the regions where the light distribution around the galaxy is more filamentary. In fact, this feature can be identified with the tails of light we see in the northeast and southwest of the galaxy. The excess of light in the southeast region is probably Galactic dust and consequently it has been masked during the analysis. We use this radial position to identify two regions of the stellar halo: the inner part and the outer part.

The stellar halo of UGC 00180 is full of small clumps. These clumps could potentially have different origins: background galaxies, foreground faint stars, satellites of UGC 00180, or even regions of star formation. Not having color information at this extremely low surface brightness level, we cannot add much to distinguish among the different scenarios. Future works, including more bands, should be able to explore this issue and also the conjecture raised in the appendix by Bland-Hawthorn et al. (2005) where they show that even at low metallicities ($\text{Fe/H} = -1$), there may be “gegenschein” from dust scatter.

5.1. The Effect of the PSF on the Surface Brightness Profile

There is growing evidence in the literature showing that the effect of the PSF can alter significantly the amount of stellar light located in the periphery of galaxies (see, e.g., de Jong 2008; Trujillo & Bakos 2013). This effect has now been studied in detail by Sandin (2014, 2015). The results of these works indicate that the effect of the PSF can mimic artificial stellar halos around galaxies. Consequently, it is necessary to carefully account for the effects of the PSF (Capaccioli & de Vaucouleurs 1983) before any conclusion is drawn about the surface brightness distribution of our galaxy UGC 00180.

To correct for the effect of the PSF, it is required to have a detailed description of the PSF of the image. In particular, to be
able to explore the effect of the PSF, it is mandatory to have an accurate characterization of the PSF to radial distances as far as at least 1.5 times the radius of the galaxy (Sandin 2014). In our case, this means having a PSF well described up to a radial distance of ~3 arcmin. As we have explained before, we have the PSF of the GTC telescope characterized accurately down to a radial distance of 5 arcmin. This is ~10 times larger than the optical size ($R_{25}$) of the galaxy.

We simulate the effect of the PSF on the surface brightness distribution of our galaxy using the IMFIT code (Erwin 2015). IMFIT is an image-fitting program specially designed for describing the surface brightness distribution of galaxies. We select the following functions to fit the light distribution of our galaxy: a Sérsic (1968) bulge, a broken disk exponential (Erwin et al. 2008), and an exponential stellar halo. We convolve these functions with the PSF of the image and fit the galaxy’s light distribution. The convolved model is later subtracted from the image to get the residuals of the fit. These residuals include the spiral arm structure and other asymmetric features that the model cannot fit. After that, we sum the residuals to the deconvolved IMFIT model to create an image of the galaxy with the effect of the PSF removed. We show the difference between the original image and the deconvolved one in Figure 11.

The effect of the PSF on the distribution of light from the galaxy is particularly relevant beyond 25 mag arcsec$^{-2}$ ($r$-band). In fact, Figure 11 shows that after correcting for the effect of the PSF, the 28 mag arcsec$^{-2}$ isophotal contour has a disk-like shape. This is strikingly different from the roundish shape this contour has when exploring the original (i.e., PSF-affected) image. The filamentary structure of the extra light surrounding UGC 00180 is also more evident once its light distribution is corrected for the effect of the PSF. The effect of the PSF on the surface brightness profile of the galaxy is illustrated in Figure 12. The PSF affects both the central part, decreasing the central surface brightness of the bulge by ~1 mag arcsec$^{-2}$, and the very outer region of the galaxy where the effect is the opposite. Beyond 25 mag arcsec$^{-2}$ the deconvolved profile starts to deviate from the original profile. At radial distances greater than 50 arcsec, the difference between the original and the PSF-corrected profile is around 1 mag arcsec$^{-2}$. This has important consequences for the analysis of the galaxy: the stellar halo region is much fainter (a factor of ~2.5) than what could be guessed initially using the original image of the galaxy. We quantify this more precisely in the next section.

5.2. The Amount of Stellar Mass in the Stellar Halo

Motivated by the shape of the light distribution in Figure 12, we model the light distribution of the stellar halo by assuming an exponential profile. The use of an exponential law for describing stellar halos has also been followed in the past (e.g., Irwin et al. 2005; Ibata et al. 2007). The use of an exponential model assumes that the amount of light in the stellar halo continues to rise toward the center of the galaxy. In this sense, the exponential behavior of the light distribution of the stellar halo in the inner region is a hypothesis we have to assume here. However, this growing contribution of the stellar halo toward the innermost region is motivated by numerical works exploring the distribution of accreted material in galaxies (see, e.g., Cooper et al. 2010; Font et al. 2011).

We have measured the difference in the amount of light in the stellar halo that one would have estimated using the observed profile (i.e., that affected by the PSF) and the amount.
of light in the deconvolved model. The results of an exponential profile fitting to the light distribution in the halo are as follows. For the observed surface brightness profile, affected by the PSF: central surface brightness $\mu_r(0) = 24.7 \pm 0.2$ mag arcsec$^{-2}$ and scale-length $h = 18.6 \pm 0.2$ arcsec (13.6 $\pm$ 0.1 kpc). For the stellar halo corrected by the PSF:
$$\mu_r(0) = 26.6 \pm 0.3 \text{ mag arcsec}^{-2} \text{ and } h = 23.5 \pm 0.2 \text{ arcsec (17.2 \pm 0.2 kpc).}$$

The stellar halos estimated in this way correspond to the following fraction of light ($r$-band) compared to the total galaxy light: 0.11 (original profile) and 0.03 (stellar halo corrected for the effect of the PSF). To allow a comparison of the stellar halo of UGC 00180 with other stellar halos reported in the literature, we assume that the proportion of light contained in the stellar halo in the $r$-band is similar to the
Figure 12. The effect of the PSF on the surface brightness profile of UGC 00180. The original profile is shown using blue points whereas the profile obtained after accounting for the effect of the PSF is plotted using black points. The green dashed line shows the surface brightness profile of the GTC PSF.

proportion of stellar mass. This assumption is reasonable, taking into account that the global color of the galaxy \((g-r)\sim 0.8\) is rather red (see Section 2), suggesting low star formation activity, similar to what one would expect in the stellar halo region.

Figure 13 shows the stellar halo of UGC 00180 in comparison with other stellar halos measured in the literature: the Milky Way (MW, Carollo et al. 2010), M31 (Courteau et al. 2011), M33 (McConnachie et al. 2010), NGC 2403 (Barker et al. 2012), and M101 (van Dokkum et al. 2014). The mass fraction of UGC 00180 in the stellar halo is quite comparable to that measured in M31 (a galaxy with similar stellar mass). It is worth noting that this result is only achievable when the effect of the PSF is taken into account. The amount of stellar mass contained in the stellar halo of UGC 00180 is around \(4 \times 10^9 M_\odot\). We will discuss this in the next section.

6. DISCUSSION

Under the assumption of a Kroupa IMF and solar metallicity, the global color \((g-r = 0.78)\) of UGC 00180 suggests an average age for the stellar population of the galaxy of \(\sim 8\) Gyr (Vazdekis et al. 2010). This implies a relatively quiet life for this galaxy and an assembly epoch at \(z \gtrsim 1\). It is theoretically expected that the formation of stellar halos takes place mostly at \(z > 1\) (e.g., Cooper et al. 2010; Font et al. 2011; Tissera et al. 2012, 2014). Observational evidence for this has been reported by Trujillo & Bakos (2013). Assuming that the assembly history of UGC 00180 is typical of disk galaxies of its mass, it is worth comparing the structure of its stellar halo (size, shape, and amount of stellar mass) with the most recent cosmological simulations to explore this external component.

Comparison with the simulations is not straightforward because there is no unique way to characterize which stars correspond to the stellar halo and which ones to other components of the galaxy (see, e.g., Pillepich et al. 2014). In this paper we have used an exponential law (Patterson 1940) motivated by the shape of the profile of the galaxy in its outer region. In addition to the exponential shape, other model profiles in the literature have been used to fit the observed stellar halo distribution, such as a Sérsic law, a Hernquist model, or a power law (see, e.g., Gilbert et al. 2012). In Figure 14 we show our observed (circularized) profile versus the results from the simulations by Cooper et al. (2013) for galaxies with virial masses of a dark halo within the range \(12 < \log_{10} M_{200}/M_\odot < 12.5\). We have chosen this mass of dark matter halo because it is what is expected for galaxies like the MW and M31 (e.g., Watkins et al. 2010). Taking into account the stellar mass and morphological type of UGC 00180, it is expected that this object also inhabits a dark matter halo with similar properties.

Figure 14 shows two different renditions of Cooper et al. (2013) of the distribution of light from the galaxy depending on the “most-bound fraction” \(f_{\text{mb}}\) used to model the location of stars within the dark matter halos. For instance, quoting Cooper et al. (2013), \(f_{\text{mb}} = 0.01\) means that only the 1% most-bound particles of the simulations are used to describe the stellar distribution. Comparing the models with the light distribution of UGC 00180, we can infer that the profile of the real galaxy fits rather well with the expectation of the model with \(f_{\text{mb}} = 0.05\). The agreement is remarkably good (i.e., the observed profile is within the scatter of the model prediction) down to \(\log \rho_c(M_\odot \, \text{kpc}^{-2}) \approx 3\) or, equivalently, \(R \approx 80\) kpc. Moreover, the models correctly predict an increasing relevance of the accreted stellar component at radial distances beyond \(25\) kpc and \(\log \rho_c(M_\odot \, \text{kpc}^{-2}) < 5\). This transition region
corresponds to an equivalent surface brightness of \( \mu_r \sim 29 \text{ mag arcsec}^{-2} \). Beyond a radial distance of 80 kpc (\( \mu_r \gtrsim 32 \text{ mag arcsec}^{-2} \)) the observed profile is quite uncertain, preventing us from concluding whether the stellar halo of UGC 00180 is “truncated” or whether the sudden drop in the stellar profile at those distances is the result of an over-subtraction of the sky at such faint levels.

Independently of the shape of the profiles, it is worth comparing the model predictions about the amount of stellar mass contained in the stellar halo of the galaxies. We have

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**Figure 13.** Mass fraction of the stellar halo vs. total stellar mass of the galaxy. The figure shows the location of the stellar halos of galaxies compiled from the literature (green points) as well as the stellar halo of UGC 00180 (black solid point). In addition, we have overplotted the model predictions from Purcell et al. (2007) (red area) and Cooper et al. (2013) (blue and orange) for galaxies inhabiting dark matter halos with \( 12 < \log_{10}(M_{200}/M_\odot) < 12.5 \). The gray dashed lines correspond to the positions on this plane of stellar halos with fixed stellar mass (10^7, 10^8, 10^9, and 10^10 M_\odot).

**Figure 14.** Median profiles of circularly averaged stellar mass surface density, \( \rho_* \), for accreted stars (dashed lines) and in situ stars (dotted lines) taken from the model of Cooper et al. (2013) with \( f_{\text{mb}} = 1\% \) (left panel) and \( f_{\text{mb}} = 5\% \) (right panel). A solid line shows the median profile combining accreted and in situ components. The light blue and orange regions indicate the 10\%–90\% scatter of the median profiles. The black points correspond to the circularized (PSF deconvolved) profile of stellar mass surface density of UGC 00180 assuming a constant \( M_*/L_r = 2.51 \) (see the text for details).
overplotted in Figure 13 the predictions from Purcell et al. (2007) (red area) and Cooper et al. (2013) (blue and orange) for galaxies inhabiting dark matter halos with $12 < \log_{10} M_{200}/M_\odot < 12.5$. The position of the models from Cooper et al. (2013) with $f_{\text{mb}} = 0.01$ and $f_{\text{mb}} = 0.05$ are indicated respectively with blue and orange colors. Both the MW and M31 are in perfect agreement with all model predictions. However, M33 and NGC 2403 are significantly outside the theoretical regions. The reason why these galaxies are not described by the models is easy to understand. We have only shown the model predictions for dark matter halos with mass $12 < \log_{10} M_{200}/M_\odot < 12.5$. However, M33 and NGC 2403 inhabit dark matter halos a factor of 10 less massive (see, e.g., Seigar 2011). The location of M101 is not well described by the models of Cooper et al. (2013), although it is statistically compatible with predictions of Purcell et al. (2007). In any case, this galaxy seems to have a very small stellar halo for its total stellar mass. Could M101 be incorrectly described by the models because the mass of its dark matter halo is not within $12 < \log_{10} M_{200}/M_\odot < 12.5$? According to Hyperleda, the maximum rotation velocity corrected for the inclination of M101 is $V_{\text{rot}} = 274 \pm 10 \text{ km s}^{-1}$. This is suggestive of a dark matter halo with mass similar to that of M31. However, taking into account that M101 seems to be clearly in interaction, associating a large dark matter halo mass to its rotational velocity is perhaps premature. Finally, UGC 00180 is slightly offset (although compatible within the error bars) from the predictions of the theoretical models. The large stellar mass and rotational velocity of UGC 00180 could imply that this galaxy inhabits a dark matter halo with mass $\log_{10} M_{200}/M_\odot > 12.5$. If this were the case, the agreement with the models of Purcell et al. (2007) and Cooper et al. (2013) could be better.

According to Figure 13, MW, M31, and UGC 00180 have stellar halos with mass ranging between $10^9$ and $4 \times 10^9 M_\odot$. The models of both Purcell et al. (2007) and Cooper et al. (2013) predict that the progenitors of the stellar halos of these galaxies will be satellites with $M_\ast \sim 3 \times 10^8 M_\odot$. Consequently, on average, we expect the number of merging events with these types of satellites to range from $\sim3$ (for galaxies like MW) to $\sim12$ (for M31 and UGC 00180). Nowadays, the number of satellite galaxies that both the MW and M31 have with $M_\ast \sim 3 \times 10^8 M_\odot$ and within $R < 300$ kpc is $\sim1$ (McConnachie 2012). If this number is representative of the population of satellites of these galaxies in the past, we can infer that the average merging timescale for these satellites is $\sim1$–$3$ Gyr (assuming that MW and M31 have basically been formed since $z \sim 2$).

Finally, we can focus our attention on the general prediction of models of galaxy formation that states that all present-day galaxies will show several streams and a prominent stellar halo if they are observed down to $\mu_V > 31$ mag arcsec$^{-2}$ (e.g., Cooper et al. 2010). In MW, M31, and UGC 00180, where the observations have gone deep enough to explore this prediction, this is indeed the case. This question remains open for M101, a galaxy with similar stellar mass to those above, whereas the deepest current observation (e.g., Mihos et al. 2013; van Dokkum et al. 2014) are at the limit ($\sim30$ mag arcsec$^{-2}$; $3\sigma$ $10 \times 10$ arcsec boxes) for exploring this issue.

7. SUMMARY AND CONCLUSIONS

In this paper we have addressed the following question: what is the surface brightness limit that the current largest optical telescopes ($\sim10$ m) can achieve within a reasonable amount of time (i.e., $<10$ hr on source)? Using the 10.4 m GTC telescope, during a total of 8.1 hr on source, we have found that it is feasible to reach 31.5 mag arcsec$^{-2}$ ($3\sigma$; $10 \times 10$ arcsec boxes in the $r$-band). This is a surface brightness limit around $1.5$–$2$ mag deeper than most current surveys dedicated to exploring the faintest extended astronomical structures using integrated photometry.

Using this ultra-deep observation, we have explored the stellar halo of UGC 00180, a galaxy with similar mass and morphology to M31. After addressing the effect of the PSF on the surface brightness distribution of this galaxy, we have been able to probe its surface brightness profile down to $\mu_V \sim 33$ mag arcsec$^{-2}$. This is equivalent to the depth reached when using the star-counting technique to measure the light profiles of galaxies, but this time for a galaxy located at $150$ Mpc, where that technique is unfeasible. The fraction of light contained in the stellar halo of UGC 00180 is $(3 \pm 1\%)$, in agreement with state-of-the-art models of galaxy formation. Our pilot project shows that current technology will allow us to study the stellar halos of many hundreds of galaxies. This opens the possibility to exploring the expected large variety of shapes and morphologies of this faint component around galaxies. Reproducing, quantitatively, the characteristics of stellar halos in a large number of objects will be one of the most demanding tests of the ΛCDM scenario of galaxy formation in the future.

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