Introducing the LBT Imaging of Galactic Halos and Tidal Structures (LIGHTS) survey

A preview of the low surface brightness Universe to be unveiled by LSST*

Ignacio Trujillo1,2, Mauro D’Onofrio5, Dennis Zaritsky4, Alberto Madrigal-Aguado1,2, Nushkia Chamba3, Giulia Golini3, Mohammad Akhlaghi1,2, Zahra Sharbarf6, Raúl Infante-Sainz1,2, Javier Román1,2,7, Carlos Morales-Socorro5, David J. Sand4, and Garreth Martin1,9

1 Instituto de Astrofísica de Canarias, C/ Vía Láctea s/n, 38205 La Laguna, Tenerife, Spain
e-mail: trujillo@iac.es
2 Departamento de Astrofísica, Universidad de La Laguna, 38205 La Laguna, Tenerife, Spain
3 Department of Physics and Astronomy, University of Padova, Vicolo Osservatorio 3, 35122 Padova, Italy
4 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721-0065, USA
5 The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova 10691 Stockholm, Sweden
6 School of Astronomy, Institute for Research in Fundamental Sciences (IPM), PO Box 1956836613, Tehran, Iran
7 Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía, 18008 Granada, Spain
8 Universidad Internacional de Valencia, C/ Pintor Sorolla, 21, 46002 Valencia, Spain
9 Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Korea

Received 18 June 2021 / Accepted 11 August 2021

ABSTRACT

We present the first results of the LBT Imaging of Galaxy Haloes and Tidal Structures (LIGHTS) survey. LIGHTS is an ongoing observational campaign with the 2 × 8.4 m Large Binocular Telescope (LBT) aiming to explore the stellar haloes and the low surface brightness population of satellites down to a depth of \( \mu_v \sim 31 \text{ mag arcsec}^{-2} \) (3σ in 10′′ × 10′′ boxes) of nearby galaxies. We simultaneously collected deep imaging in the \( g \) and \( r \) Sloan filters using the Large Binocular Cameras. The resulting images are 60 times (i.e., \( \sim 4.5 \text{ mag} \)) deeper than those from the Sloan Digital Sky Survey, and they have characteristics comparable (in depth and spatial resolution) to the ones expected from the future Legacy Survey of Space and Time (LSST). Here we show the first results of our pilot programme targeting NGC 1042 (an M 33 analogue at a distance of 13.5 Mpc) and its surroundings. The depth of the images allowed us to detect an asymmetric stellar halo in the outskirts of this galaxy whose mass \((1.4 \pm 0.4 \times 10^9 \, M_\odot)\) is in agreement with the ΛCDM expectations. Additionally, we show that deep imaging from the LBT reveals low mass satellites (a few times \(10^5 \, M_\odot\)) with very faint central surface brightness \(\mu_v(0) \sim 27 \text{ mag arcsec}^{-2}\) (i.e., similar to Local Group dwarf spheroidals, such as Andromeda XIV or Sextans, but at distances well beyond the local volume). The depth and spatial resolution provided by the LIGHTS survey open up a unique opportunity to explore the ‘missing satellites’ problem in a large variety of galaxies beyond our Local Group down to masses where the difference between the theory and observation (if any) should be significant.

Key words. galaxies: evolution – galaxies: formation – galaxies: halos – galaxies: photometry – galaxies: structure – dark matter

1. Introduction

The imminent arrival of new large-aperture, wide-field of view telescopes covering a significant fraction of the night sky is set to revolutionise many facets of present-day astronomy. Deep imaging is certainly no exception. The possibility of deep imaging of large areas of the sky will allow us to make statistical studies in many astrophysical branches. While this becomes a reality, there are a number of astrophysical problems requiring deep imaging with high spatial resolution where current large telescopes can provide significant insights ten years in advance. With this goal in mind, we present the first results of the LBT Imaging of Galaxy Haloes and Tidal Structures (LIGHTS) survey. The main objectives of the LIGHTS survey are to address two problems closely related to the nature of dark matter: the properties of stellar haloes of galaxies and the population of faint satellites around them. The lessons to be learned from LIGHTS will pave the way for the massive statistical analysis we expect from the Vera C. Rubin observatory by the end of the Legacy Survey of Space and Time (LSST) survey.

The presence of a low surface brightness stellar halo around galaxies is an unavoidable consequence of the galaxy formation mechanism within the \( \Lambda \) cold dark matter (ΛCDM) cosmological paradigm. Dark matter haloes are built through multiple mergers White & Rees (1978), and during this process, they get disrupted together with their stellar component. This results in a low surface brightness stellar halo associated with the surviving galaxy, a record of the accretion history of the object (Bullock & Johnston 2005; Abadi et al. 2006; Johnston et al. 2008). The star counting technique (either with space- or ground-based telescopes) has been used to explore the stellar properties of haloes belonging to the closest galaxies to a high level of detail (see e.g. Rejkuba et al. 2005; Harris et al. 2007;
Ibata et al. 2009, 2014; McConnachie et al. 2009; Durrell et al. 2010; Tanaka et al. 2011; Monachesi et al. 2013; Okamoto et al. 2015; Crnojević et al. 2016; Harmsen et al. 2017; Carlin et al. 2019; Smercina et al. 2020). However, this technique remains mostly limited to galaxies where individual stars can be resolved (i.e. up to 16 Mpc using current technology; see e.g. Zackrisson et al. 2012). Therefore, if we want to significantly increase the number of explored galaxies, we need to rely on deep broad-band imaging of unresolved stellar populations. Although there are marvellous examples of bright streams surrounding galaxies (e.g. Martínez-Delgado et al. 2010; Morales et al. 2018), a comprehensive analysis of the stellar halos of galaxies (showing its intricate structure) requires images deeper than \( \mu_V = 30 \text{ mag arcsec}^{-2} \) (see e.g. Johnston et al. 2008; Cooper et al. 2010). This depth is around a factor of 2.5 to ten times (i.e. 1 to 2.5 mag) deeper than current deep broad-band imaging (see e.g. Ferrarese et al. 2012; Mihos et al. 2013; Duc et al. 2015; Capaccioli et al. 2015; Fliri & Trujillo 2016; Merritt et al. 2016; Huang et al. 2018; Hood et al. 2018; Rich et al. 2019). In fact, there is only a handful of galaxies observed at such depth (i.e. \( \mu_V \approx 30 \text{ mag arcsec}^{-2} ; 3 \sigma \text{ in } 10^\circ \times 10^\circ \)) with broad-band imaging (e.g. Jablonka et al. 2010; Trujillo & Fliri 2016). This surface brightness regime is, however, well within the reach of large telescopes using a modest improvement on the statistical determination of which fraction of faint galaxies are real satellites promises to significantly extend our capabilities to explore the ‘missing satellites’ problem well beyond the Local Volume (i.e. at distances beyond 12 Mpc).

The LIGHTS survey aims to systematically detect stellar halos and ‘missing satellites’ galaxies (if any) of a representative sample of nearby (\( D \sim 20 \text{ Mpc} \)) galaxies by obtaining ultra-deep imaging (i.e. \( \mu_V \gtrsim 50 \text{ mag arcsec}^{-2} ; 3 \sigma \text{ in } 10^\circ \times 10^\circ \)). These observations are performed using the Large Binocular Cameras (LBCs) of the LBT telescope in the Sloan bands \( g \) and \( r \). In this paper, we present the first results of one galaxy in the LIGHTS sample, NGC 1042.

This paper is structured as follows: in Sect. 2, we describe the properties of NGC 1042 and its surroundings. We present the data used in Sect. 3. Section 4 is dedicated to the analysis of the results. Finally we discuss and summarise our results in Sect. 5. All the magnitudes are provided in the AB system.

2. NGC 1042 and its surroundings

NGC 1042 is a Sc galaxy (Sandage & Tammann 1981) located at \( RA(2000) = 02^h 40^m 23.0^s \) and \( Dec(2000) = -08^\circ 26'01'' \). The galaxy distance \( D = 13.5 \pm 2.6 \text{ Mpc} \) has been recently measured using the Tully–Fisher relationship (Monelli & Trujillo 2019). That distance agrees very nicely with the one estimated by Theureau et al. (2007; 13.2 Mpc) using the Large Scale Reconstruction of the region. At such a distance, 1\( ^\circ \) corresponds to 0.064 kpc.

The galaxy is located in the sky of a region with relatively low dust contamination (\( A_k = 0.095 \) and \( A_r = 0.065 \text{ mag} \); Schlegel et al. 1998; Schlafly & Finkbeiner 2011, according to NASA/IPAC Extragalactic Database, NED). Using Sloan Digital Sky Survey (SDSS), Monelli & Trujillo (2019) measured the following apparent magnitudes for NGC 1042: 11.24 \( \pm 0.05 \) (\( g \text{-band} \)) and 10.80 \( \pm 0.05 \) (\( r \text{-band} \)), which after correction for Galactic extinction implies a global colour of \( g - r = 0.41 \text{ mag} \). The absolute magnitude in the \( r \text{-band} \) is \( -19.9 \text{ mag} \). Using Rodigher & Courteau (2015), we estimate a (\( M/L \)), for the galaxy of \(-0.75 \text{ T}_\odot \). Consequently, the stellar mass is estimated to be \( 5 \times 10^9 \text{ M}_\odot \). This is around 1/10th of the stellar mass of the Milky Way (see e.g. Licquia & Newman 2015).

The H\( i \) mass can be obtained from its integrated, self-absorption-corrected, H\( i \) line flux: \( S_{HI} = 58.12 \pm 5.90 \text{ Jy km s}^{-1} \) (Springob et al. 2005). We apply the following equation to get the H\( i \) mass \( M_{HI} = 2.36 \times 10^5 \times D^2 \times S_{HI} = 2.5 \pm 0.4 \times 10^9 \text{ M}_\odot \) (see e.g. Filho et al. 2013). The dynamical mass within the region dominated by the baryonic disc can be roughly measured by using the size of the galaxy and its rotational velocity \( (M_{dyn}(M_r) = 2.326 \times 10^7 R_s \sigma_r^2) \) (see e.g. Pohlen & Trujillo 2006). The radial distance corresponding to the 25 mag arcsec\(^{-2} \) (\( B \text{-band} \)) isophote is \( R_{25} = 1.95 \text{ arcmin} \) (HyperLeda; Makarov et al. 2014), or 7.5 kpc. Its maximum rotational velocity corrected for inclination is 128 km s\(^{-1} \) (Fig. 14 in van Gorkom et al. 1986) where we have used an inclination of 34.4\(^\circ \) (Monelli & Trujillo 2019). Consequently, the dynamical mass of NGC 1042 in its innermost \( \sim 8 \text{ kpc} \) is \( M_{dyn} = 2.9 \times 10^{10} \text{ M}_\odot \). Therefore, the galaxy has properties (stellar mass, dynamical mass, etc.) similar to M33 (see e.g. Corbelli & Salucci 2000).

The environment around NGC 1042 has recently attracted a lot of attention (see e.g. Müller et al. 2019b) due to the claim that this region contains two galaxies ‘lacking dark matter’...
Ultra-deep observations of the galaxy NGC 1042 and its surrounding region were carried out with the Large Binocular Telescope using the Large Binocular Cameras (Blue and Red simultaneously; Galllongo et al. 2008). The images were taken using Director Discretionary Time (DDT; PI D’Onofrio) during the night of 14th October 2020 in dark conditions. The total amount of time provided was 2 h. LBC cameras are composed of 4 CCDs with a pixel scale of 0.225′′. Each CCD covers approximately 7.8′ × 17.6′, with gaps between the chips of ~18′′. The final field of view of the LBC cameras is approximately 23′ × 25′. The LBC Blue camera is blue optimised for observations from around 3500 to 6500 Å, while the LBC Red camera is red optimised for observations from approximately 5500 Å to 1 μm. We use the g-SLOAN filter in the LBC Blue and the r-SLOAN filter in the LBC red. Images were taken under good seeing conditions, producing a final (stacked) image with a full width at half-maximum (FWHM) seeing of ~0.9′′ in both bands.

3.1. Observational strategy
To obtain a background as flat as possible, we follow an observational strategy similar to the one conducted in Trujillo & Fliri (2016). This consists of obtaining a flat-field from the data itself. To do this with enough accuracy, it is necessary to follow a dithering pattern with a step size similar to or larger than the size of the main object under study. Considering that the diameter of NGC 1042 is D25 ∼ 4′, we used steps of 5′.

The total amount of time granted (2 h) was split into 30 different pointings with an exposure time of 180 s each. Taking into account the overheads, the total time on-source was 1.5 h in each pointing.

3.2. Flat-field correction
Using the bias images, we create a masterbias by combining all the bias frames with a sigma clipping median using Gnuastro’s Arithmetic. This is done for each CCD of the LBC. This masterbias is later subtracted from all science images. Masterflats are created for each filter using the science (already bias corrected) images themselves. This is performed in two steps. First, the science images are normalised as follows. The pixel (1176,3027) of the central CCD of the LBC (CCD 2) is used as the centre of a normalisation ring. That ring has an inner radius of 2305 pixels and a width of 200 pixels. That ring crosses the four CCDs. For each CCD and within the corresponding ring region, we calculate the resistant (to the outliers) median value of the pixels. That value is used to normalise the flux of the CCD for each science image. Then, we combine all the normalised and bias subtracted science images using a sigma clipping median stacking. We get four preliminary masterflats this way, one per CCD. Science images are divided by these first step masterflats. This action allows us to better highlight the sources in the science images. To get an improved masterflat, we consequently mask all the detected sources using NoiseChisel (Akhlaghi & Ichikawa 2015; Akhlaghi 2019), also part of Gnuastro, and we median combine all the re-normalised and masked images once again to create a final masterflat (one per CCD). Finally, the individual science images of each filter are divided by their corresponding CCD masterflats.

3.3. Astrometry, sky determination, and image co-addition
To determine the astrometry of our individual science images we conduct the following steps. We start by calculating an astrometric solution using Astrometry.net (v0.85; Lang et al. 2010). We use Gaia EDR3 (Gaia Collaboration 2021) as our astrometric reference catalogue. This produces a first astrometric solution that we consequently improve using SCAMP (v.2.10.0; Bertin 2006). SCAMP reads catalogues that we generate using SExtractor (v.2.25.2; Bertin & Arnouts 1996) and calculates the distortion coefficient of the images. As each CCD of the LBC has its own distortions, we run this using the entire block of science images of each CCD. After this step, we run SWarp (2.42.5; Bertin et al. 2002) on each individual image to put them into a common grid of 9501 × 9501 pixels. The image resampling method is LANCZOS3.

Before co-adding all our science images, we subtract the sky of our individual CCD exposures by masking the signal of each image using NoiseChisel. For each CCD, we calculate the median of the Sky image produced by NoiseChisel and we remove that value from the image. This very conservative way of subtracting the sky, avoiding any polynomial fits, is done to avoid removing any potential large-scale low surface brightness feature in our data. To stack all our images we use a median combination using Gnuastro’s Arithmetic program (0.13.12-f50c; Akhlaghi & Ichikawa 2015). The co-added image is significantly deeper than any individual image, and therefore, a large number of very low surface brightness features emerge from the noise. These features, which include the extended wings on the stars, the stellar haloes around galaxies, and Galactic cirri, 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.

---

3 The ring radius is chosen to cover, for all CCDs on the focal plane, a region that has a similar illumination. The width of the ring is selected such that the total number of pixels in it (~3 × 10⁵) is large enough to have a statistically robust way of measuring the median (at the 0.05% level).

4 The values of the main NoiseChisel parameters used for this task are: -tilerize = 50,50 –minskyfrac = 0.9 –meannedmddiff = 0.01 –sntresh = 5.2 –detgrowquant = 0.7 –detgrowsmaxholesize = 1000.

---

References:
- Galllongo et al. 2008
- Galllongo et al. (2008)
- Jensen et al. 2003
- van Dokkum et al. 2018, 2019
- Montes et al. 2020
- Cohen et al. 2018
- Trujillo & Fliri (2016)
- Bertin et al. 2002
- Bertin 2006
- Lang et al. 2010
- Gaia Collaboration 2021
- Bertin & Arnouts 1996
- SCAMP
- Bertin & Arnouts 1996
- Astrometry.net (v0.85)
- Gnuastro
3.4. Photometric calibration

The photometric calibration of our science images is based on the photometry of SDSS DR12 images (Alam et al. 2015). Due to the final size of our FOV (>30′ × 30′), we use the SDSS tool ‘mosaics’\(^5\). We create both SDSS $g$ and $r$-band imaging. The zeropoint of those images is 22.5 mag. We use around 600 (unsaturated) stars in both SDSS and LBT within our FOV to calibrate the LBT image photometrically. The stars used range between 18 and 22 mag for both filters. We do not find any need to add a colour term between the SDSS filters and Sloan LBT filters.

The flux of the stars in the SDSS and LBT images that we have used are obtained using Petrosian magnitudes obtained by SExtractor. As the SDSS images are photometrically calibrated, we matched the photometric catalogue of the stars in SDSS to the LBT catalogue, resulting in the following zeropoints for the LBT images: $ZP_g = 34.527 ± 0.006 ± 0.01$ and $ZP_r = 34.111 ± 0.006 ± 0.01$ mag (the first error bar corresponds to the statistical error and the second error bar is the typical photometrical zeropoint calibration error reported by the SDSS team for these filters; Ivezić et al. 2004). Therefore, in practice the ultimate photometric precision in the LIGHTS survey is given by the SDSS photometric accuracy. The final combination is shown in Fig. 2. The final images for each filter separately are shown in Fig. 3. The limiting surface brightness (3$\sigma$; 10′′ × 10′′; i.e. equivalent to a $3\sigma$ fluctuation with respect to the background of the image in an area of 10′′ × 10′′) of the LBT images are: 31.2 mag arcsec$^{-2}$ ($g$-band) and 30.5 mag arcsec$^{-2}$ ($r$-band). These values correspond to the central ($R < 11.3′$) region of the images where 24 or more pointings overlap.

3.5. Other datasets

Until the arrival of the next generation of very wide and deep surveys such as the LSST (Ivezić et al. 2019), SDSS continues to be the reference survey to compare with in terms of imaging due to its excellent sky background quality. On the other hand, images from the Dragonfly telescope array (Abraham & van Dokkum 2014) are commonly cited as representative of high quality imaging for exploring the low surface brightness Universe. For this reason, to illustrate the depth and quality of our LBT deep imaging, we compare some of the galaxies present in our LBT data with their counterparts on SDSS and Dragonfly imaging\(^6\).

SDSS $g$ and $r$ band imaging data were retrieved from the DR14 SDSS (Abolfathi et al. 2018) Sky Server. The magnitude zero-point for all the data is the same: 22.5 mag. The exposure time of the images is 53.9 s and the pixel size 0.396″. The observations were taken in drift scanning mode, providing accurate photometry down to $\mu_r \sim 26.5–27$ mag arcsec$^{-2}$ along the surface brightness profiles ($r$-band; Pohlen & Trujillo 2006). Using the following metric ($3\sigma$; 10′′ × 10′′) for measuring the limiting surface brightness, we achieve the following SDSS depths for this region of the sky: 27.5 mag arcsec$^{-2}$ ($g$-band) and 26.9 mag arcsec$^{-2}$ ($r$-band).

Dragonfly images of the NGC 1052 field (Merritt et al. 2016) were retrieved from the Dragonfly archive (v0.9\(^7\)). Images were collected in $g$ and $r$ filters. The number of lenses on the Dragonfly array was 8 at the time the data were taken. Typical exposures for this galaxy were between 15 and 20 h. The pixel scale of the Dragonfly images used here is 2″. The field of view of the Dragonfly images is ~2 × 3′. Therefore, we crop these images to cover the same area as that of our LBT dataset. To remove the sky, we masked the Dragonfly images and we subtract a constant value. Later, we calibrate them to the SDSS photometry finding the following zeropoints: $ZP_g = 16.02$ and $ZP_r = 15.86$ mag.

The limiting surface brightness (3$\sigma$; 10′′ × 10′′) of the Dragonfly images in the field of NGC 1042 are 28.7 mag arcsec$^{-2}$ ($g$-band) and 29 mag arcsec$^{-2}$ ($r$-band). It is worth noticing the existence of the DESI Legacy Imaging Surveys (Dey et al. 2019) covering also this region of the sky. Martínez-Delgado et al. (2021) has estimated a limiting surface brightness for this dataset of ~29 mag arcsec$^{-2}$ (3$\sigma$; 10′′×10′′). Unfortunately, the public available images of this survey are affected by a severe background oversustraction around the brightest galaxies which prevents its use for a direct comparison with our results.

\(^5\) https://dr12.sdss.org/mosaics

\(^6\) It is worth noticing the existence of the DESI Legacy Imaging Surveys (Dey et al. 2019) covering also this region of the sky. Martínez-Delgado et al. (2021) has estimated a limiting surface brightness for this dataset of ~29 mag arcsec$^{-2}$ (3$\sigma$; 10′′×10′′). Unfortunately, the public available images of this survey are affected by a severe background oversustraction around the brightest galaxies which prevents its use for a direct comparison with our results.

\(^7\) https://www.dragonflytelescope.org/data-access.html
and 28.0 mag arcsec$^{-2}$ ($r$-band)$^8$. In other words, they are around 1 mag deeper than SDSS images.

Figure 2 shows a large number of low surface brightness features surrounding NGC 1042. Many of these features were discussed at length in Müller et al. (2019b). For example, one such feature is the stellar bridge between NGC 1047 and NGC 1052 that indicates their interaction. Another example is the narrow stellar stream on the eastern part of the image, which is likely associated with merging activity in NGC 1052. Of most relevance here is the apparent plume of stars between NGC 1042 and

4. Analysis

4.1. The low surface brightness features surrounding NGC 1042
NGC 1052. Visual inspection at various contrast levels shows that the plume consists of at least two loops of stars belonging to NGC 1052 (see also Müller et al. 2019b) and so is not a connecting structure between NGC 1052 and NGC 1042 (Fig. 3). This lack of interaction between these two galaxies is also supported by the absence of a clear distortion in the disc of NGC 1042 and excluded given the large measured line-of-sight distance difference: \( D = 13.5 \text{ Mpc} \) for NGC 1042 (see e.g. Theureau et al. 2007; Monelli & Trujillo 2019) and \( D = 19 \text{ Mpc} \) for NGC 1052 (see e.g. Tonry et al. 2001; Jensen et al. 2003).

There is also some light excess towards the bottom right part of the image that is not directly linked to any bright source on the image. For that reason, we have explored whether such brightness excess can be associated with faint Galactic cirrus emission. In Fig. 4, we show the optical and the radio maps of this region of the sky. We have used the 350 μm map produced by the Planck satellite to indicate the location of the Galactic cirrus (Planck Collaboration I 2014). There is a qualitative agreement between the location of very extended low surface brightness features in our optical LBT image and the Planck dust map. However, the optical brightness in the bottom right corner is a bit larger than expected according to the dust intensity in this region. For this reason, although we think that part of the excess of light in that corner is real we cannot fully reject the possibility that part of that light results from an artefact of the data reduction.

### 4.2. A non-symmetric stellar halo around NGC 1042

We now focus on the galaxy NGC 1042 itself (Fig. 5). The object is shown using three different datasets with different depths. As the limiting surface brightness of the data becomes fainter than 30 mag arcsec\(^{-2}\) (3σ; 10′′ × 10′′), an excess of light in the outer part of the disc is observed in the eastern region (see Fig. 3). Considering the modest stellar mass of this galaxy (\( \sim 5 \times 10^9 M_\odot \)), similar to M 33, the figure shows the importance of reaching very faint limits to observe the stellar haloes of relatively low mass disc galaxies.

To quantify the amount of stellar mass in the outer part of NGC 1042, we have explored the stellar mass density distribution of the galaxy. To do that, we have first extracted the \( g \) and \( r \) surface brightness profiles (see Fig. 6). This was done after masking all the surrounding sources using NoiseChisel (we also initially test our masks using the sources detected by Max-Tree Objects finding similar results Teeninga et al. 2016; Haigh et al. 2021). This mask is based on the LBT imaging and it is later also applied to the SDSS and Dragonfly datasets. We used elliptical apertures with the following properties: axis ratio 0.83 and position angle 15° (measured clockwise from the north axis). These values are the ones provided in Monelli & Trujillo (2019). In all the data used here, we observe a sudden decrease in the surface brightness profiles of NGC 1042 at around 200″. In the images shown in Fig. 5, this corresponds to the end of the visible disc in SDSS (re-binned) and Dragonfly datasets. The colour radial profile is also shown in Fig. 6. The shape of the radial colour profile has the characteristic U-shape (see e.g. Azzollini et al. 2008; Bakos et al. 2008; Pranger et al. 2017) of Type II disc galaxies (Erwin et al. 2005; Pohlen & Trujillo 2006). Interestingly, the end of the U-shape is connected with the sudden drop in the brightness observed in the surface brightness profiles at \( R \sim 200″ \). We identify this drop as a truncation (van der Kruit 1979). We expand on the meaning of this truncation feature later on. Beyond 220″ (i.e. \( \sim 14 \text{kpc} \)) the light distribution of NGC 1042 no longer follows the symmetry of its disc. This asymmetric excess of light in the outer part of NGC 1042 has a surface brightness of \( \sim 29 \text{ mag arcsec}^{-2} \) (\( g \)-band). Finally, the LBT surface brightness profiles show a second drop at \( R \sim 310″ \). For both \( g \) and \( r \) filters, this radial distance corresponds to a surface brightness of \( \sim 30 \text{ mag arcsec}^{-2} \). The reason for this sudden drop in surface brightness in the outer part of the galaxy is connected to the visible end of the asymmetric light around the NGC 1042 (see the LBT stamp in Fig. 5).

Using the surface brightness and radial colour profiles, we calculate the stellar mass to light ratio radial profile using Roediger & Courteau (2015) following the prescription provided in Bakos et al. (2008). We use the parameters given in Roediger & Courteau (2015) for a Bruzual & Charlot (2003, BC03) model and a Chabrier initial mass function (IMF; Chabrier 2003). The resulting stellar mass density profile of NGC 1042 is also shown in Fig. 6. A sudden decrease at \( R = 194″ \) is also visible in this profile (which we have identified as a truncation above) which corresponds to a stellar mass density of \( \sim 1 M_\odot \text{ pc}^{-2} \). This density value is in strong agreement with the suggestion by Trujillo et al. (2020) of using the radial location of this density value as an indicator of galaxy size. In fact, the truncation agrees with the idea that this radial location represents the current location of the star formation threshold of this galaxy. Inside this feature we see a region of active star formation while, beyond this radial position, the stellar light we correspond to the sum of stars that have migrated from the internal disc and/or have been accreted across the history of the galaxy (i.e. its stellar halo). For this last reason, beyond this radial location the light distribution of the galaxy is no longer symmetric. In what follows, we refer to that radial position as \( R_{\text{edge}} \). Consequently, we measured the amount of stellar mass in the stellar halo as the stellar mass beyond \( R_{\text{edge}} \).

To estimate the total stellar mass of NGC 1042, we have integrated its stellar mass density profile down to the radial location where the profile remains reliable (i.e. where the colour profile errors are lower than 0.2 mag). We find the following values: 6.3 ± 1.6 \( \times 10^8 M_\odot \) (SDSS), 6.2 ± 1.6 \( \times 10^8 M_\odot \) (Dragonfly) and 6.5 ± 1.6 \( \times 10^8 M_\odot \) (LBT). This is in good agreement with the raw estimation done in Sect. 2, using the global galaxy colours provided by Monelli & Trujillo (2019). Beyond \( R_{\text{edge}} \), the amount of stellar mass we measure (in the stellar halo) is: 1.2 ± 0.3 \( \times 10^8 M_\odot \) (Dragonfly) and 1.4 ± 0.4 \( \times 10^8 M_\odot \) (LBT). Note that for SDSS it is not possible to estimate a stellar halo using our definition as the profile never reaches \( 1 M_\odot \text{ pc}^{-2} \) due to its limited depth. Therefore, the fraction of stellar mass in the halo of this galaxy (defined as the fraction of stellar mass beyond \( R_{\text{edge}} \)) is: 2.0 ± 0.5% (Dragonfly) and 2.1 ± 0.5% (LBT).

To end the discussion on the stellar halo of NGC 1042, it is worth noticing that this galaxy was previously identified as a candidate for having a stellar halo (if any) whose stellar mass is below the expectation from the ΛCDM galaxy formation model (Merritt et al. 2016, 2020). The measurement of the amount of mass in the stellar halo is not a straightforward task. For this reason, in the past, many different approaches have been conducted to make this measurement (e.g. the mass beyond a given number of effective radii, the mass beyond a given radial physical distance, interpolating the outer shape of the stellar mass density profile towards the inner region, the amount of mass below a given stellar mass density, etc.). In Merritt et al. (2020), three different ways of estimating the stellar halo mass of NGC1042 were used. In all three cases, the stellar halo mass
Fig. 3. Sloan g (upper panel) and r band (lower panel) images of the NGC 1042 region taken with the LBT. The images have been rebinned to a pixel size of 4.5′ (i.e. 20 × 20 the original pixel scale) to facilitate the observation of the low surface brightness features. The pink arrow on the upper panel points to the extended emission of NGC 1042 to the east region. The pink arrows on the bottom panel indicate the location of stream and shell structures of NGC 1052. Towards the edges of these images the number of exposures drop significantly (see Fig. 1) and the depth and quality decreases.
of the galaxy lies at the bottom edge of the prediction of cosmological simulations (see their Fig. 8). Upon performing a direct comparison with their work, we note the following important difference: the adopted value of the distance to NGC 1042. Here we have used a more recent measurement of 13.5 Mpc (Monelli & Trujillo 2019), while Merritt et al. (2016) used a previous value of 17.3 Mpc (Tully et al. 2009). Merritt et al. (2016) found a total stellar mass of NGC 1042 of $(1.53 \pm 0.48 \times 10^{10}) M_\odot$ (at 17.3 Mpc). At 13.5 Mpc, that total stellar mass for NGC 1042 corresponds to $(9.3 \pm 2.9 \times 10^{9}) M_\odot$ (i.e. this value is above the value we measured here using the Dragonfly data but in agreement within the error bars with our mass estimate for this object).

We can also make a direct comparison of the stellar mass in the halo by measuring the amount of stellar mass at stellar mass densities below $1 M_\odot$ pc$^{-2}$ (see Fig. 8 in Merritt et al. 2020). With this definition, as mentioned above, we find a stellar mass in the stellar halo of $1.2 \pm 0.3 \times 10^{7} M_\odot$ using the Dragonfly dataset. While Merritt et al. (2020) find (after the distance correction we have discussed above) $9.6 \pm 2.5 \times 10^{7} M_\odot$. We find, therefore a 25% larger value (although still within the error bars). However, when using the LBT dataset, we obtain a stellar halo mass for NGC 1042 which is nearly 50% larger (i.e. $1.4 \pm 0.4 \times 10^{7} M_\odot$) than the one measured in Merritt et al. (2020). The most likely reason for the discrepancy the way the stellar mass density of this galaxy is determined. Both in this work and in Merritt et al. (2016), the stellar mass density is based on the surface brightness profile and the $g-r$ colour radial profile. For that reason, having an accurate colour estimation of the outermost part of the galaxy (in particular in its halo region) is key getting a reliable estimation of the stellar mass in that region. To address this issue, as the Dragonfly S/N is low in that region of the galaxy, Merritt et al. (2016) extrapolate outwards the $g-r$ colour they measure in the disc region ($R < 160''$; see their Fig. 2). In other words, their outer part of NGC 1042 ($R > 160''$) is characterised with a $g-r$ colour that ranges from 0.3 to 0.4 mag. Note that this colour is even bluer than the colour measured in the star forming region of the galaxy. Such a blue $g-r$ colour is in contradiction with the observed colour profile in the Dragonfly dataset (both here and in Merritt et al. 2016) in the region between 160 and 200'', which shows the well known U-shape up to $R = 200''$. Looking now at the LBT colour profile, we see that beyond $R = 200''$ the colour of the stellar halo remains red ($g-r \sim 0.55$ mag). The difference between using a colour of $g-r = 0.35$ mag (i.e. (M/L)$_g = 0.60$) instead of $g-r = 0.55$ mag (i.e. (M/L)$_g = 1.27$) is a factor of ~2.1 in stellar mass. Therefore, if Merritt et al. (2016) had used a similar colour as the one we measure with the LBT, they would have found a stellar halo mass larger than the value reported. In doing so, the stellar halo mass of NGC 1042 will be in better agreement with the expectation from ΛCDM for this type of galaxy (Merritt et al. 2020). The present work shows that, to measure the halo stellar masses to better than a factor of two, colours are essential. Colours can only be obtained well into the halo with observations whose depth allows the exploration of features fainter than 30 mag arcsec$^{-2}$ ($3\sigma; 10'' \times 10''$). To end this section, it is worth mentioning that the effect of the Point Spread Function (PSF) has not yet been accounted for in the current analysis. Addressing the PSF effect produced by the galaxy itself is key to have an accurate characterisation of the amount of stellar mass in the stellar halo region. To measure the effect of the PSF it is necessary to have a detailed characterisation of the PSF over spatial scales of at least 1.5 times larger than the object under study (Sandin 2014). This will be done in a future work following the prescriptions developed in Infante-Sainz et al. (2020). Having said that, the low inclination of NGC 1042, the fact that both Dragonfly and LBT (with different PSFs) show similar amount of mass (once the colour in the outer part is measured accurately) in the stellar halo region and the detection of an asymmetric.
Fig. 5. Emergence of the stellar halo of NGC 1042 as the depth of images increases. The panel shows the galaxy NGC 1042 at three different surface brightness limiting depths (3σ; 10′′ × 10′′): SDSS 26.9 mag arcsec$^{-2}$ (r-band), Dragonfly 28.0 mag arcsec$^{-2}$ (r-band) and LBT 30.5 mag arcsec$^{-2}$ (r-band). In the case of SDSS, we show the visual aspect of the galaxy in two different ways: (a) when the original SDSS pixel scale is used (i.e. 0.396′′) and (b) when the SDSS data is rebinned to the pixel size of Dragonfly in these images (i.e. 2′′). A non-symmetric stellar halo (with surface brightness $\mu_g > 29$ mag arcsec$^{-2}$) is observed in the LBT image. In all the stamps, the background in white and black is built by summing $g$ and $r$ filters to enhance the detection of low surface brightness features. North is up and east to the left.

excess of light in the outer part of the galaxy suggest that the effect of the PSF will not be dominant in this particular case.

4.3. A sample of faint galaxies in the field of view of NGC 1042

In the previous section, we have illustrated the extraordinary capacity of LBT to uncover the stellar halo around galaxies, using NGC 1042 as a relatively low mass example. In this section, we show the high potential of the LIGHTS survey to find and explore very low surface brightness (satellite) galaxies. As the aim of this work is only to illustrate the capabilities of LBT for low surface brightness studies, what follows is by no means a comprehensive list of all the low surface brightness objects in this image. In fact, the criteria followed to explore some of these objects are: (a) an example of an object being relatively bright but not discussed in the literature as is the case of SDSS J024007.01–081344.4, (b) the faintest low surface brightness galaxy in the field discussed in Cohen et al. (2018): NGC 1052-DF1, (c) two low surface brightness galaxies found in deep surveys of the region: T20-12000 (Tanoglidis et al. 2021) and LSB21 (Román et al., in prep.), and finally (d) a galaxy not previously reported that we have dubbed as LBT1. The summary of the properties of these galaxies are given in Table 1 and their images are shown in Fig. 7.

With the exception of the new object detected here (LBT1) whose size (as measured using the 30 mag arcsec$^{-2}$ isophote in the $g$-band) is $R_{30} \sim 10''$ and whose central surface brightness is $\mu_g(0) \sim 27$ mag arcsec$^{-2}$, the rest of the faint galaxies are visible in the shallower surveys, SDSS and Dragonfly, used here. However, it is only the combination of depth and spatial resolution of LBT that allows us to explore the detailed nature of these galaxies. In fact, for most of these galaxies distinguishing the presence of faint foreground and background objects contaminating the light of these galaxies is only possible with the LBT data. This is key to accurately measuring the structural properties of
Fig. 6. Surface brightness, colour and stellar mass density profiles of NGC 1042 using LBT, Dragonfly and SDSS which have different depths. The surface brightness profiles shown here correspond to the observed values while the radial colour and stellar mass density profiles are shown after being corrected by Galactic extinction and the inclination of NGC 1042. In the case of the surface brightness profiles, only values above $3\sigma$ the sky noise of the image are shown.

Table 1. Some examples of low surface brightness (satellite) galaxies surrounding NGC 1042 explored in this work.

| Name                 | RA (2000)    | Dec (2000)    | $m_g$ (mag) | $m_r$ (mag) | $\mu_g(0)$ (mag/arcsec$^2$) | $\mu_r(0)$ (mag/arcsec$^2$) | $R_{e,g}$ (arcsec) | $R_{e,r}$ (arcsec) | Reference |
|----------------------|--------------|---------------|-------------|-------------|-----------------------------|-----------------------------|-------------------|-------------------|-----------|
| SDSS J024007.01–081344.4 | 02:40:07.0   | −08:13:44.4   | 17.17       | 16.70       | 23.81                       | 23.30                       | 11.1              | 10.9             | (1)       |
| NGC 1052-DF1         | 02:40:04.6   | −08:26:48.3   | 19.52       | 18.95       | 26.69                       | 26.03                       | 15.2              | 15.1             | (2)       |
| T20-12000            | 02:39:39.3   | −08:13:42.3   | 19.23       | 18.47       | 24.40                       | 23.85                       | 6.9               | 8.9              | (3)       |
| LSB21                | 02:40:28.8   | −08:14:36.5   | 19.98       | 19.56       | 24.12                       | 23.72                       | 10.9              | 11.2             | (4)       |
| LBT1                 | 02:40:40.6   | −08:23:08.9   | 22.70       | 22.06       | 27.11                       | 26.41                       | 4.2               | 4.9              | (5)       |

Notes. The structural properties provided correspond to those found in this work. This table includes the name of the galaxies, their spatial location, their apparent magnitudes in the $g$ and $r$ bands, their central surface brightness, and their effective radii in arcsec. To the best of our knowledge the above galaxies were first found/discussed in the following references: (1) Abazajian et al. (2003), (2) Cohen et al. (2018), (3) Tanoglidakis et al. (2021); object also known as SDSS J023939.36–081342.0, (4) Román et al. (in prep.); object also known as SDSS J024028.61–081436.7, (5) this work. The apparent magnitudes and surface brightness have been corrected by the following Galactic extinction: $A_g = 0.095$ and $A_r = 0.065$ mag. The quantities are given showing only the significant figures up to which the values can be regarded as reliable.

these objects (see e.g. Bennet et al. 2017). The surface brightness profiles of these faint galaxies and their radial colour profiles obtained with the LBT data are shown in Fig. 8.

A brief discussion of the properties of these faint galaxies in the field of NGC 1042 follows.

SDSS J024007.01–081344.4. This is a galaxy with spheroidal appearance and with a central excess of light that is potentially a star cluster. The central surface brightness in the $g$-band is close to 24 mag arcsec$^{-2}$. Its $g - r$ colour is very homogeneous and around 0.5 mag. Only in its very outer region there is a red trend visible, which is likely contamination by other nearby sources.

NGC 1052-DF1. This galaxy has a very low central surface brightness $\mu_g(0) \sim 26.7$ mag arcsec$^{-2}$. This object is visible in the SDSS image after re-binning it to the Dragonfly pixel scale. However, its very low surface brightness prevented it from being
catalogued in the SDSS archive. The depth of LBT imaging allow us to trace the structure of this faint galaxy to more than 3 times its effective radius. The colour of NGC 1052-DF1 is very homogeneous $g - r \sim 0.55$ mag. There are no signatures of tidal distortions down to the explored radial range ($R = 50''$) and surface brightness of $\sim 31$ mag arcsec$^{-2}$.

**T20-12000.** This galaxy has an elongated spheroidal appearance. Its vicinity to a brighter star makes it difficult to explore its outer part. In fact, we observe a large difference in the shape of the surface brightness profiles between the $g$ and $r$ bands. Therefore, the profiles remain unreliable even at surface brightness levels as bright as 26.5 mag arcsec$^{-2}$.

**LSB21.** This galaxy has an elongated spheroidal shape. Its central surface brightness is faint $\mu_g(0) = 26.12$ mag arcsec$^{-2}$ and it has a rather flat radial colour profile $g - r = 0.4$ mag. The surface brightness profiles of the galaxy show a change in the slope at around $16''$, potentially indicating that this galaxy has two structural components with the latter resembling an exponential disc.

**LBT1.** This is the faintest galaxy in the sample discussed in the paper. It has a spheroidal morphology. It is invisible in the SDSS and Dragonfly datasets. Its central surface brightness is extremely low $\mu_g(0) = 27.11$ mag arcsec$^{-2}$ and it has a rather flat radial colour profile $g - r \sim 0.65$ mag.
To conclude this section, we expand further on the galaxy LBT1. This object is invisible in SDSS and Dragonfly, and therefore highlights the potential of spatial resolution, when combined with depth, for studying the low surface brightness universe. In this sense, the LIGHTS survey allows us to explore very faint and small galaxies around nearby (but well beyond the Local Group) galaxies such as NGC 1042. In what follows, we assume LBT1 is at the distance of NGC 1042 (i.e. 13.5 Mpc or, equivalently, a distance modulus $m_0 = 30.65$ mag). However, for completeness, we also present its physical properties if the object is located at the distance of NGC 1052 (i.e. 19 Mpc or $m_0 = 31.39$ mag). Nonetheless, we would like to point out the following. The distance between LBT1 and NGC 1042 is $300''$ (i.e. 19.2 kpc at 13.5 Mpc) and $590''$ with respect to NGC 1052 (i.e. 54.3 kpc at 19 Mpc). Considering the dynamical mass of NGC 1042 ($2.9 \times 10^{10}$ $M_\odot$) and NGC 1052 ($1.7 \times 10^{12}$ $M_\odot$; Pierce et al. 2005), it is possible to estimate the instantaneous tidal radius ($r_{\text{tidal,inst}}$) of LBT1 (Johnston et al. 2002). To do such an estimation, it is necessary to assume a dynamical mass for LBT1. Here we use a range for the dynamical mass to light ratio between 10 and 100. This implies the following tidal radius for LBT1: $15'' < r_{\text{tidal,inst}} < 32''$ (caused by NGC 1042) or $9'' < r_{\text{tidal,inst}} < 20''$ (caused by NGC 1052). The absence of tidal distortions in LBT1 (at least in the inner $10''$) favours, although not conclusively, the idea that this object is associated with NGC 1042 rather than with NGC 1052.

If LBT1 is at the distance of NGC 1042, then its absolute magnitudes are: $M_g = -7.95 \pm 0.02$ and $M_r = -8.59 \pm 0.02$ mag ($M_v = -8.69 \pm 0.02$ and $M_r = -9.33 \pm 0.02$ mag at 19 Mpc). Considering its global colour ($g - r = 0.64 \pm 0.03$ mag), its (M/L) would be $1.78 \pm 0.44T_\odot$ (assuming a Chabrier IMF) and therefore its total stellar mass is $3.5 \pm 0.9 \times 10^7 M_\odot$ ($7.0 \pm 1.8 \times 10^5 M_\odot$ at 19 Mpc) and its effective radii are $R_{e,g} = 290 \pm 30$ and $R_{e,r} = 338 \pm 30$ pc ($R_{e,g} = 386 \pm 40$ and $R_{e,r} = 451 \pm 40$ pc at 19 Mpc). In Fig. 9, we show the location of this galaxy in comparison to other dwarf galaxies in the Local Group (McConnachie 2012). To estimate both $R_e$ (in the V-band) and $\mu_V(0)$ for LBT1 we have interpolated between the values we have retrieved in the $g$ and $r$ bands. Examples of Local Group galaxies that are similar in stellar mass, effective radius and central surface brightness to LBT1 are the Andromeda XIV (Majewski et al. 2007) dwarf spheroidal (if LBT1 is at 13.5 Mpc) or the Sextans (Irwin et al. 1990) dwarf spheroidal (if LBT1 is located at 19 Mpc). Both at 13.5 and 19 Mpc, LBT1 falls on top of the local scaling relationships. Therefore, we cannot favour either of these two distances with this photometric data alone.

As shown in Fig. 9, LBT1 has an effective radius that is comparable to those satellites in the Local Group with similar stellar mass. However, the central surface brightness of LBT1 ($\mu_V(0) \sim 26.8$ mag arcsec$^{-2}$) is among the faintest for its stellar mass. In fact, the object is around 10 times fainter than the average satellite galaxy with the same stellar mass in the Local Group. This highlights the power of LBT imaging for detecting even the faintest satellites beyond the Local Volume ($D > 12$ Mpc).

### 5. Discussion and conclusions

In this paper we present the first results of the LIGHTS survey conducted with the LBT. This work shows the potential of LBT to conduct low surface brightness studies at extremely faint levels ($\mu_V \sim 31$ mag arcsec$^{-2}$; $3\sigma$ in $10'' \times 10''$). The relatively large FOV of the LBC instrument ($23' \times 25'$), the large collecting area of the LBT ($2 \times 8.4$ m) and the possibility of conducting simultaneous observations in two different filters make LBT extremely competitive for these types of studies. Here we have shown that with only 1.5 h on source, the telescope is capable of providing images that have comparable depths to those expected once the LSST survey is completed (i.e. $\mu_V \sim 31.1$ mag arcsec$^{-2}$ and $\mu_V \sim 30.6$ mag arcsec$^{-2}$; $3\sigma$ in $10'' \times 10''$ Laine et al. 2018). Not only the depth, but also the pixel scale of the future LSST and LBT images is approximately the same (i.e. $\sim 0.2''$). Together with the good quality seeing of both observatories, this allows exquisite spatial ground-based resolution. This superb spatial resolution is an enormous advantage for low surface brightness studies because the high spatial resolution allows one to detect, characterise and remove the many compact foreground (i.e. stars) and background (i.e. high-z galaxies) sources that plague such deep images.

These similarities allow us to preview what kind of low surface brightness studies the future LSST will be capable of. In this paper, we have focused on two important issues in extragalactic...
Fig. 9. Structural properties of the galaxy LBT1 in relation to low mass galaxies in the Local Group (McConnachie 2012). For its stellar mass, LBT1 has an effective radius which is common within the Local Group satellite population. However, its central surface brightness ($\mu_V(0) \sim 26.8 \text{ mag arcsec}^{-2}$) is among the faintest for its stellar mass. If LBT1 were in the Local Group it would resemble properties similar to the dwarf spheroidals Andromeda XIV or Sextans.

We acknowledge financial support from the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No 721463 to the SUNDIAL ITN network, and the European Regional Development Fund (FEDER), from IAC project P/300624, financed by the Ministry of Science, Innovation and Universities, through the State Budget and by the Canary Islands Department of Economy, Knowledge and Employment, through the Regional Budget of the Autonomous Community. DZ acknowledges financial support from NSF AST-2006785. NC acknowledges support from the research project grant “Understanding the Dynamic Universe” funded by the Knut and Alice Wallenberg Foundation under Dnr KAW 2018.0067 and Chris Usher for interesting comments. DJS acknowledges support from NSF grants AST-1821967 and 1813708. JR acknowledges funding from the State Agency for Research of the Spanish MCIU through the ‘Center of Excellence Severo Ochoa’ award to the Instituto de Astrofísica de Andalucía (SEV-2017-0709), financial support from the grants AYA2015-65973-C3-1-R and RTI2018-096228-B-C31 (MINECO/FEDER, UE) as well as support from the State Research Agency (AEI-MCINN) of the Spanish Ministry of Science and Innovation under the grant ‘The structure and evolution of galaxies and their central regions’ with reference PID2019-105602GB-I00/10.13039/501100011033. The LBT is an international collaboration among institutions in the United States, Italy and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona Board of Regents; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, The Leibniz Institute for Astrophysics Potsdam, and Heidelberg University; The Ohio State University, representing OSU, University of Notre Dame, University of Minnesota and University of Virginia. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is funded by the National Aeronautics and Space Administration and operated by the California Institute of Technology. This work was partly done using GNU Astronomy Utilities (Gnuastro, ascl.net/1801.009) version 0.13.12-50c. Work on Gnuastro has been supported by the European Union’s Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No 721463 to the SUNDIAL ITN network, and the European Regional Development Fund (FEDER), from IAC project P/300624, financed by the Ministry of Science, Innovation and Universities, through the State Budget and by the Canary Islands Department of Economy, Knowledge and Employment, through the Regional Budget of the Autonomous Community. DZ acknowledges financial support from NSF AST-2006785. NC acknowledges support from the research project grant “Understanding the Dynamic Universe” funded by the...
