Deep Large Binocular Camera r-band Observations of the GOODS-N Field

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Abstract

We obtained 838 Sloan r-band images (~28 hr) of the GOODS-North field with the Large Binocular Camera (LBC) on the Large Binocular Telescope in order to study the presence of extended, low surface brightness features in galaxies and investigate the trade-off between image depth and resolution. The individual images were sorted by effective seeing, which allowed for optimal resolution and optimal depth mosaics to be created with all images with seeing FWHM < 0′9 and FWHM < 2′0, respectively. Examining bright galaxies and their substructure as well as accurately deblending overlapping objects requires the optimal resolution mosaic, while detecting the faintest objects possible (to a limiting magnitude of mAB ∼ 29.2 mag) requires the optimal depth mosaic. The better surface brightness sensitivity resulting from the larger LBC pixels, compared to those of extant WFC3/UVIS and ACS/WFC cameras aboard the Hubble Space Telescope allows for unambiguous detection of both diffuse flux and very faint tidal tails. Azimuthally-averaged radial surface brightness profiles were created for the 360 brightest galaxies in each of the two mosaics. On average, these profiles showed minimal difference between the optimal resolution and optimal depth surface brightness profiles. However, < 15% of the profiles show excess flux in the galaxy outskirts down to surface brightness levels of μ′ AB ∼ 31 mag arcsec−2. This is relevant to Extragalactic Background Light (EBL) studies as diffuse light in the outer regions of galaxies are thought to be a major contribution to the EBL. While some additional diffuse light exists in the optimal depth profiles compared to the shallower, optimal resolution profiles, we find that diffuse light in galaxy outskirts is a minor contribution to the EBL overall in the r-band.

Unified Astronomy Thesaurus concepts: Astronomical techniques (1684); Extragalactic astronomy (506)

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1. Introduction

Galaxy mergers and interactions play a critical role in galaxy evolution and are observed across cosmic time (Barnes 1992; Bundy et al. 2005; Lotz et al. 2008, 2011). In the nearby Universe, mergers and interactions are able to be observed with high resolution using the Hubble Space Telescope (HST). These observations have shown that as redshift increases, galaxies appear more irregular, have closer neighbors, exhibit features of recent interactions, or appear to be in the process of merging (Burkey et al. 1994; Duncan et al. 2019, and references therein). Various studies have visually identified and classified these merging systems based upon appearance (Darg et al. 2010) and features such as tidal tails, streams, and other diffuse/extended flux regions (Elmegreen et al. 2007; Mohamed & Reshetnikov 2011; Elmegreen et al. 2021).
However, these features can be missed by high-resolution HST imaging due to their intrinsically low surface brightness.

Tidal tails and bridges of matter between galaxies are clear signatures of past or on-going interactions (Toomre & Toomre 1972). These interactions are known to trigger star formation and play a critical role in galaxy evolution throughout the Universe (Hernquist 1989; Conselice 2014, and references therein). A few studies have looked for interacting systems within various extragalactic deep fields. For example Elmegreen et al. (2007) examined the Galaxy Evolution from Morphologies and SEDs (GEMS) survey (Rix et al. 2004) and the Great Observatories Origins Deep Survey (GOODS) South field (Giavalisco et al. 2004) for mergers and galaxy interactions to z ≈ 1.4. They defined a sample of 100 objects, and measured properties of the galaxies and star-forming clumps within the interacting galaxies. Similarly, Wen & Zheng (2016) identified a sample of 461 merging galaxies with long tidal tails in the COSMOS field (Scoville et al. 2007) using HST/ACS F814W (I-band). They only included galaxies in 0.2 ≤ z ≤ 1 which corresponds to rest frame optical light sampled by the F814W filter with a surface brightness limit of ∼25.1 mag arcsec^{-2}. However, most of their sample have intrinsic surface brightness ≥ 23.1 mag arcsec^{-2}.

Straughn et al. (2006) and Straughn et al. (2015) identified “tadpole” galaxies, based on their asymmetric knot-plus-tail morphologies visible in HST/ACS F775W at intermediate redshifts (0.3 ≤ z ≤ 3.2) in the Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006). Using multi-wavelength data, they studied rest frame UV/optical properties of these galaxies in comparison with other field galaxies. They measured the star formation histories and ages of these galaxies and concluded that “tadpole” galaxies are still actively assembling either through late-stage merging or cold gas accretion.

The Large Binocular Telescope (LBT) is able to obtain imaging for 4 of the 5 CANDELS (Grogin et al. 2011; Koekemoer et al. 2011) fields that are in the northern hemisphere or around the celestial equator (Ashcraft et al. 2018; Otteson et al. 2021; Redshaw et al. 2022, T. McCabe et al. 2023, in preparation). Ashcraft et al. (2018) presented ultra deep U-band imaging of GOODS-N (Giavalisco et al. 2004) and created optimal resolution and optimal depth mosaics, which represent the best U-band imaging that can be achieved from the ground. Each mirror of the LBT is equipped with a Large Binocular Camera (LBC), which allowed for parallel U-band and Sloan r-band imaging. With the large field of view (FOV) of the LBC, our GOODS-N observations encompass the HST footprint, which makes the complementary, very deep r-band data especially useful for larger survey volumes.

Deep imaging of the CANDELS fields also allows for investigations into the amount to which galaxies contribute to the Extragalactic Background Light (EBL) (McVittie & Wyatt 1959; Driver et al. 2016; Windhorst et al. 2022a; Carleton et al. 2022, and references therein). Currently, a discrepancy exists between EBL predictions from integrated galaxy counts (Driver et al. 2011, 2016; Andrews et al. 2018) and from direct measurements (Puget et al. 1996; Hauser et al. 1998; Matsumoto et al. 2005, 2011, 2018; Lauer et al. 2021; Komgut et al. 2022; Lauer et al. 2022). Ultra-Diffuse Galaxies, diffuse intragroup or intracluster light, as well as faint light in the outskirts of galaxies have all been proposed as sources that would be capable of closing the discrepancy between galaxy counts and direct EBL measurements.

Using the capabilities of the LBT/LBC for deep r-band imaging allows the detection of faint flux in galaxy outskirts in the form of star-forming clumps, tidal tails/mergers, and diffuse light. This paper builds upon the previous U-band work of Ashcraft et al. (2018), Otteson et al. (2021), Redshaw et al. (2022) and T. McCabe et al. (2023, in preparation) by utilizing the seeing sorted stacking procedure to create optimal depth and optimal resolution mosaics of GOODS-N for the r-band obtained simultaneously. Using these mosaics, we attempt to address the level to which faint, extended light in the outer regions of galaxies can contribute to the total observed EBL.

This paper is organized as follows. In Section 2, we describe the acquired data and the creation of optimal depth/resolution mosaics and corresponding object catalogs. Section 3 describes the surface brightness profiles for the 360 brightest galaxies in the mosaic FOV and the implications for any excess diffuse flux. Section 4 describes a collection of galaxies with signatures of interactions out to redshifts of z ≤ 0.9. Lastly, Section 5 summarizes and discusses these results. Unless stated otherwise, all magnitudes presented in this paper are in the AB system (Oke & Gunn 1983).

2. Observations

The LBCs are two wide field, prime focus cameras, one for each of the 8.4 m primary mirrors of the LBT. The LBCs are unique as one camera is red optimized (LBC-Red; LBCR), while the other is blue optimized (LBC-Blue; LBCB). We utilized the LBCR camera along with the Sloan r-band filter, which has a central wavelength of λ_c = 6195 Å, a bandwidth of 1300 Å (full width at half maximum; FWHM), and a peak CCD quantum efficiency of ~96% within the r-band filter. The LBC focal planes are composed of 4 EEV42-90 CCD detectors each, which have an average plate scale of ~0.″225 (Giallongo et al. 2008).

2.1. Sloan r-band Observations of the GOODS-N Field

Using binocular imaging mode, LBC observations of the GOODS-N field were carried out in dark time from 2013 January through 2014 March. This mode allowed for U-band observations to be collected with the LBCB camera simultaneously with r-band observations with the LBCR camera. The U-band data were presented in Ashcraft et al. (2018), where the
seeing sorted stacking technique and the associated trade off between optimal resolution and optimal depth mosaics were discussed. Utilizing a combination of US and Italian partner institutions, 838 r-band total exposures were collected using the LBC with a total integration time of \( \sim 28 \) hr (100,727 s). The individual exposures in this data set each had an exposure time of 120.2 s.

We utilized a dither pattern around a common center position for all images taken over many nights, which included a minimal shift to fill in the gaps between detectors and for removal of detector defects and cosmic ray rejection. The HST GOODS-N field covers an area of \( \sim 0.021 \) deg \(^2\), which was easily contained inside the LBC’s large FOV of \( \sim 0.16 \) deg\(^2\). Calibration data, bias frames, and twilight sky-flats were taken on most nights, and were used with the LBC pipeline for the standard data reduction steps (see Giallongo et al. 2008, for details).

### 2.2. Creating r-band Mosaics

For each of the 838 individual exposures, the Gaussian FWHM was measured for unsaturated stars in the FOV, with the median value corresponding to the seeing of the entire exposure. As described in Ashcraft et al. (2018), Otteson et al. (2021) and Redshaw et al. (2022), this allows for a seeing distribution to be created for the entire data set as shown in Figure 1. The median FWHM for all images is \( \sim 1\arcsec 07\), which is marginally larger than the typical seeing conditions on Mt. Graham for r-band of \( 0\arcsec 97 \pm 0\arcsec 06 \) (Taylor et al. 2004).

Following the prescription from Ashcraft et al. (2018), the optimal depth r-band stack was created with all exposures with FWHM \( \lesssim 2\arcsec 0\), which excludes only the 33 images with the worst seeing (\( \sim 4\% \) of the data set). The optimal resolution r-band stack was created using all images with FWHM \( \lesssim 0\arcsec 9\), which corresponds to the best 150 exposures (\( \sim 18\% \) of the data).

Prior to creating the mosaics, the relative transparency was calculated for each of the 838 exposures following the prescription in Otteson et al. (2021), Redshaw et al. (2022) and McCabe et al. (2022; in preparation). In order to account for the night to night differences in relative atmospheric transparency, the flux ratio between \( \sim 100 \) unsaturated stars was taken with respect to the flux values from the Sloan Digital Sky Survey (SDSS) Data Release 16 (Blanton et al. 2017; Ahumada et al. 2020) in the r-band. In this case, a relative transparency value of 1.0 indicates that the median flux from the \( \sim 100 \) matched SDSS stars in the r-band is equal to the flux from the same stars in the individual exposure. Relative transparency values less than 1.0 indicate that there is less flux received from these stars than expected based upon SDSS r-band values. Figure 2 shows the relative transparency for the night of 2013 January 17, where the median transparency varied from \( \sim 0.94 \) to \( \sim 0.98 \) (the remaining 14 nights are

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**Figure 1.** A histogram of the FWHM measured from unsaturated stars for the 838 individual r-band exposures taken in the GOODS-N field with the LBCRed camera. The dotted-dashed line represents the largest FWHM (0\arcsec 97) included in the optimal resolution mosaic. The vertical dashed line represents the cut-off of FWHM = 2\arcsec 0 used for the optimal depth mosaic, which includes 805 exposures. The median value of the FWHM distribution, FWHM = 1\arcsec 07, is highlighted by the red, dotted line.

**Figure 2.** Relative transparency values for the first 59 exposures in the sample from 2013 January 17. The color of each data point represents the median seeing value of \( \sim 100 \) unsaturated stars identified in the FOV. The conditions on this particular night allowed for particularly high transparency. On average, across the entire data set, the relative transparency is \( \sim 80\% \) with some nights between 40\% and 60\%. The flux across each image was scaled so that the relative transparency values were equal to unity and uniform from image to image and therefore, night to night. The complete figure set (15 images) showing the relative transparency for each of our LBT observing nights is available in the online journal. (The complete figure set (15 images) is available.)
available in the online journal). We corrected for these night-by-night transparency differences by simply scaling images by the median transparency offset to achieve a transparency of 1.0 in the affected images.

The optimal resolution and optimal depth mosaics were created by combining individual exposures with SWARP (Bertin et al. 2002; Bertin & Amorisco 2010). Table 1 summarizes some of the key SWARP parameters used for creating these mosaics. The choice of parameters is almost identical to those used previously in Ashcraft et al. (2018), except for using a “BACK_SIZE” parameter of 280 pixels for the mesh size, and a “BACK_FILTERSIZE” of 7. The background parameters were increased to compensate for the increased number of bright saturated stars in individual images compared to the U-band data of Ashcraft et al. (2018).

| Keyword                  | Value         |
|--------------------------|---------------|
| COMBINE_TYPE             | CLIPPED       |
| WEIGHT_TYPE              | MAP_WEIGHT    |
| PIXELSCALE_TYPE          | Median        |
| CENTER (J2000)           | 12:36:54.5, +62:15:41.1 |
| IMAGE_SIZE (pix)         | 6351, 6751    |
| RESAMPLING_TYPE          | LANCZOS3      |
| CLIP_SIGMA               | 5.0           |
| CLIP_AMFRAC              | 0.5           |
| BACK_SIZE                | 280           |
| BACK_FILTERSIZE          | 7             |

A mask image was generated to discard any bright stars and their surrounding corrupted areas during the r-band object detection process. The mask was created from the optimal depth image, which had the largest Gaussian wings resulting from the larger FWHM of included exposures. For consistency, the same mask was used for both mosaics. The final object catalogs excluded all objects with the SExtractor FLAGS value larger than 3, and magnitude errors greater than \( \sigma_{AB} > 0.4 \) mag. Lastly, photometric zero-points were determined by identifying unsaturated stars with AB magnitudes between \( r_{AB} \approx 18 \) and \( r_{AB} \approx 22 \) mag and matching them to SDSS r-band magnitudes. Approximately 170 stars within this magnitude range were verified in the LBC images. Stars with nearby neighboring objects were excluded in order to prevent potentially biased flux measurements. We measured photometric zero-points of 28.06 and 28.05 mag for the optimal resolution and optimal depth mosaics, respectively.

### 2.3. LBC r-band Catalogs

SEXTRACTOR (Bertin & Arnouts 1996) was used to identify objects and create photometric catalogs. We developed a SExtractor parameter set which adequately balanced the unique source separation without removing extended, low surface brightness features from their host galaxies. Beginning with the SExtractor parameters used in the Ashcraft et al. (2018) analysis, various parameters were tweaked to optimize object detection and deblending. For the r-band catalogs, the deblending parameters “DEBLEND_NTHRESH” and “DEBLEND_MINCONT” were adjusted to more accurately separate objects, especially in the more densely populated regions of the field. For object detection, a Gaussian filter was used to smooth the image with a convolving kernel (FWHM 2.0 pixels) and a convolution image size of 5 × 5 pixels. It was found that changing the deblending parameters affected the number of objects detected, but the choice of the smoothing filter did not have a significant impact on the number of extracted objects by SExtractor. However, failure to use a smoothing filter resulted in a large amount of spurious detections. The major SEXTRACTOR parameters used to create the final r-band catalogs are listed in Table 2.

### Table 2

| Keyword                  | Optimized Resolution | Optimized Depth |
|--------------------------|----------------------|-----------------|
| DETECT_MINAREA           | 6                    | 6               |
| DETECT_THRESH            | 1.0                  | 1.0             |
| ANALYSIS_THRESH          | 1.0                  | 1.0             |
| DEBLEND_NTHRESH          | 64                   | 64              |
| DEBLEND_MINCONT          | 0.004                | 0.004           |
| WEIGHT_TYPE              | MAP_RMS              | MAP_RMS         |

3. Analysis

The trade off between the optimal resolution and optimal depth mosaics is clear when looking at the larger and brighter galaxies in the LBT/LBC mosaics. When lower resolution images (FWHM \( \geq 1.0^\prime \)) are included, the light from galaxies smooths out and substructures are lost within larger/brighter galaxies (see Figures 3 and 4). This phenomena is most apparent when comparing bright face-on spiral galaxies (\( r_{AB} \approx 17.5–19.5 \) mag) from the r-band optimal resolution (0.9 FWHM) and optimal depth (2.0 FWHM) mosaics and the U-band optimal depth mosaic (1.9 FWHM; Ashcraft et al. (2018)) to HST-ACS V606 images of Giavalisco et al. (2004).

Figure 3 clearly illustrates the power of having both ground based optimal resolution and optimal depth images in addition to high resolution HST imaging. In the top panel, a bar is clearly present in the HST image and the r-band optimal resolution mosaic, but is much less discernible in the optimal depth mosaic. This feature is also discernible in the LBT mosaics, especially in the optimal resolution r-band mosaic. Of the detectable features in the LBT mosaics, the smallest scale galaxy features are easier to identify in the optimal resolution mosaic. Most notably, extended low-surface brightness flux in the outer parts of the galaxy is present in the deeper LBT...
r-band mosaics; however, this flux is not always apparent in the HST images.

Figure 4 shows two additional bright galaxies that fall outside of the HST footprint. However, these galaxies exhibit signatures of star-forming clumps within their spiral arms, which are particularly prominent in the optimal depth images. While clumps are observed to be more prevalent at higher redshifts, these optimal depth and resolution mosaics may be

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**Figure 3.** Four bright face-on spiral galaxies in the GOODS-N field, which are also observed in HST CANDELS. The top galaxy has $U_{AB} = 20.8$ mag and $r_{AB} = 19.5$ mag, the second galaxy has $U_{AB} = 18.0$ mag and $r_{AB} = 17.5$ mag, the third galaxy has $U_{AB} = 19.9$ mag and $r_{AB} = 18.5$ mag, and the bottom galaxy has $U_{AB} = 19.5$ mag and $r_{AB} = 18.5$ mag. The LBC optimal depth $U$-band image, LBT $r$-band optimal resolution image, LBT $r$-band optimal depth image, and the HST ACS $V$-band ($F606W$; Giavalisco et al. 2004) image are shown from the left columns to the right columns, respectively.
useful in determining the origin and ages of the clumps in addition to serving as analogs for high redshift galaxies (Elmegreen et al. 2009a, 2009b; Overzier et al. 2009; Fisher et al. 2014; Adams et al. 2022, and references therein).

The lower-resolution images also make it more difficult to deblend neighboring objects (see Figure 5). Example Region 2 in Figure 5 shows a large region, which is detected as one object by SExtractor in the optimal depth, yet lower-resolution mosaic, indicated by a dashed circle, while SExtractor is able to separate the objects within the dashed circle in the higher-resolution mosaic, indicated by solid circles. All magnitudes presented in Figure 5 are measured in the optimal depth LBT r-band, except for the objects within the example 2 dashed circle, which come from the optimal resolution r-band catalog. Objects 3, 4, and 6 in Figure 5 are examples of faint objects detected in the optimal depth LBT image $r_{AB} \gtrsim 28.4$ mag. Only object 6 was detected in the optimal resolution catalog, which is near its limit for reliable detections, and all three regions show almost no measurable flux above the background levels in the HST F606W filter.

Figure 5 shows a low-surface brightness region in the example of circle 1, which is barely detectable in the HST F606W mosaic. In contrast, the compact object in the example of circle 5 is fainter ($m_{AB} \simeq 27.7$ mag) than the low-surface brightness region of example 1 ($m_{AB} \simeq 26.3$ mag), yet its small size and higher-surface brightness makes it easy to detect in the high-resolution HST images.

### 3.1. Optimal Resolution versus Optimal Depth LBT r-band Mosaics

In order to compare the optimal resolution and optimal depth mosaics, the catalogs described in Section 2.3 were used to look at object magnitude as a function of FWHM (Figure 6). The solid lines represent the FWHM limits of $\sim 0.65$ and $\sim 0.90$ for the optimal resolution and optimal depth mosaics, respectively. Objects with $m_{AB} \gtrsim 29$ mag generally have sizes “smaller” than the FWHM limit of the Point-Spread Function (PSF), and therefore are not reliable detections. The black dashed and dotted–dashed lines represent the effective surface

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Note that within region 2, the galaxy farthest to the right does not appear in the LBT U-band image, as it has been redshifted beyond detection ($z_{\text{spec}} = 3.52$).
brightness limits for the optimal resolution and optimal depth mosaics, respectively, while the red dashed line denotes the star/galaxy separation.

The SExtractor half-light radii were compared to the equivalent HST $V$-band catalog of the GOODS-N field from Giavalisco et al. (2004). For this analysis, only galaxies with magnitudes between $18 \leq m_{AB} \leq 27$ mag as measured in the HST $V$-band were selected. Figure 7 shows that the half-light radii measured in the optimal resolution image are in better agreement with the HST size measurements with less scatter than those in the lower resolution image. This comparison is represented by a median offset of $0\farcs127 \pm 0\farcs095$ for the optimal resolution radii while the optimal depth radii are offset from the HST values by $0\farcs181 \pm 0\farcs131$. In order to accurately represent intrinsic object sizes, we subtracted the PSF FWHM-values of of $0\farcs74$ and, $1\farcs00$ in quadrature from the optimal resolution and depth measurements, respectively ($r_{\text{corr}} = \sqrt{r^2 - (\text{FWHM}/2)^2}$). For consistency, the PSF-size was subtracted in quadrature for the $V$-band HST images as well, but since the HST/ACS PSF is so narrow ($0\farcs08$ FWHM; see Figure 10(a) of Windhorst et al. (2011)), this correction had almost no effect except for the very smallest and most faint objects. Additionally, the right panel of Figure 7 shows that the half-light radii measured from the optimal resolution mosaic are systematically smaller than those measured from the optimal depth mosaic.
4. Results

4.1. Tidal Tails and Merging Galaxies

We visually inspected the LBT GOODS-N $r$-band mosaics for signs of galaxy interactions such as tidal tails, diffuse plumes, and bridges. Approximately, 60 galaxies were found that were candidates for interactions, the 30 most obvious galaxies were selected for the sample of interacting galaxies. These galaxies are listed in Table 3 along with their classification, redshift, and position. Interacting systems can resemble multiple types, especially when looking at both the HST and LBT images of the same systems. Each of these classifications is defined as follows, following Elmegreen et al. (2007):

1. Diffuse: interactions are defined by diffuse plumes with small, star-forming regions.

2. Antennae: antennae type interactions resemble the local Antennae system with long tidal tails and signs of possible double nuclei.

3. M51: M51 interactions consist of a main spiral galaxy with a tidal arm that forms a bridge toward a companion.

4. Assembly: Assembly types are irregular galaxies that appear to be merging and are made up of small pieces.

5. Equal mass: Equal mass types appear as though two similar sized galaxies are in the process of merging.

6. “Shrimp”: “Shrimp” types are characterized by a single prominent arm and uniformly distributed star-forming clumps without signs of a central nucleus or core.

7. Tidal tail: tidal tail interactions exist when both interacting galaxies still resemble their pre-merger shape, but have an extended tidal tail which indicates a recent interaction.

Since this sample of interacting galaxies was selected with the goal of observing extended flux in the outer regions of the galaxies, it is inherently not a complete sample of interacting galaxies in the GOODS-N field. After the galaxies were selected, HST imaging was examined if available. For a complete sample, deeper HST imaging and spectroscopic redshifts would be required to confidently confirm galaxy morphology and interacting systems. However, since the $r$-band mosaics are $\gtrsim 90\%$ complete to surface brightness (SB) levels of $m_{AB} \lesssim 31\text{ mag arcsec}^{-2}$, these 30 galaxies constitute a representative sample to this SB limit. While HST imaging is not available for each galaxy in our sample, the Appendix shows the $r$-band and $U$-band optimal depth images and HST (F275W, F336W, F435W, F606W, F775W, F814W, F850LP, F105W, F125W, F160W, which correspond to the NUV, u, b, v, i, z, Y, J, H filters) images when available. Our sample covers objects with tidal features and redshifts in the range of $z \approx 0.03–1.0$.

Below we briefly comment on a small subset of three representative galaxies out of the 30 interacting galaxies from Table 3. Full discussion and LBT/HST imaging of all 30 interacting galaxies can be found in the Appendix.

1. Galaxy 1: this galaxy appears to have both a plume and a tidal tail in the LBT $r$-band (Figure 11). The plume appears above the galaxy, while the tidal tail extends toward the lower left. These features are not easily identifiable in HST imaging, but become apparent after smoothing the F160W data. When looking at high resolution imaging with HST F336W and F275W, this galaxy appears to be composed of multiple clumps.

2. Galaxy 3: this galaxy has a diffuse tail above the galaxy that is present in both the LBT and HST imaging (Figure 12). However, the LBT $r$-band image also shows a second tidal tail below the galaxy that is not present in the HST imaging.
3. Galaxy 6: LBT r-band imaging of this galaxy shows diffuse, tidal debris to the right side of the galaxy, which is not easily identifiable in the HST imaging (Figure 13).

The tidal debris appears to make a loop around the galaxy in the deep r-band image.

These examples show that deep r-band imaging with the LBT/LBC is critical for finding low surface brightness regions such as tidal tails, plumes, and streams that are not otherwise identifiable with HST imaging. These data, along with multiwavelength HST imaging and the U-band data from Ashcraft et al. (2018) should be used in future studies to study the ages, colors, and properties of these galaxy interactions.

4.2. Implications for the Extragalactic Background Light

The powerful ability of the optimal depth mosaics to highlight extended, low SB features in the outskirts of galaxies can be...
utilized to investigate the contribution of diffuse galaxy light to the EBL. For galaxies brighter than $m_{AB} \approx 21.5$ mag, the azimuthally averaged radial surface brightness (SB) profiles were measured using the custom IDL program galprof\textsuperscript{14} for both the optimal resolution and optimal depth $r$-band mosaics. This left a sample of 360 galaxies suitable for the surface brightness analysis after eliminating galaxies in close proximity to bright stars or the edge of the FOV. The 360 galaxy profiles were analyzed and the excess light in the optimal depth profile was ranked as “confident”, “potential”, or “identical.” Surface brightness profiles ranked as “confident” exhibited a $\sim 1.0$ mag arcsec$^{-2}$ difference in the two profiles over multiple radial points or had multiple data points between the two profiles that were separated by more than the 1σ uncertainty ranges plotted. Profiles ranked as “potential” were classified by a $\sim 0.5$ mag arcsec$^{-2}$ difference between the two profiles. However, typically the uncertainty ranges in the optimal depth and resolution data points encompassed the corresponding data point, which did not allow for as confident of a classification. The majority of the surface brightness profiles were identified as “identical”, where there was no apparent difference between the optimal depth and optimal resolution profiles.

Prior to analyzing the surface brightness profiles, we measured the surface brightness sky limits at which the two mosaics began to significantly differ. In order to accomplish this, model galaxies with pure exponential disk profiles matching the size of actual galaxies with $m_{AB} \approx 19$–21.5 mag were created. Approximately 250 non-saturated stars were used to create a model PSF-star for both the optimal resolution and optimal depth mosaics. The model galaxies were then convolved with the corresponding PSF and random background pixels were sampled to create a background map. Then, galprof was run to create surface brightness profiles of the model galaxies. In this analysis, we find the optimal resolution and depth profiles deviated at surface brightness levels of $\mu_{r}^{AB} \sim 31$ mag arcsec$^{-2}$.

Figure 8 shows a representative selection of 20 out of 360 surface brightness profiles for galaxies in the optimal resolution (blue) and optimal depth (red) mosaics. 16/20 do not exhibit any distinguishable difference between the two profiles to $\mu_{r}^{AB} \lesssim 31$ mag arcsec$^{-2}$ between the profiles and were categorized as “identical.” Galaxies A, B, C, and D are four examples of galaxies that were ranked as “confident” or “potential” candidates for having significant additional light in the optimal depth surface brightness profiles. Galaxies A and D were categorized as “potential” since they exhibited $\sim 0.5$ mag arcsec$^{-2}$ differences in surface brightness with both profiles being within the uncertainty ranges of the other. However, galaxies B and C show larger, more robust differences between the optimal depth and resolution profiles.\textsuperscript{15}

\textsuperscript{14} http://www.public.asu.edu/~rjansen/idl/galprof1.0/galprof.pro

\textsuperscript{15} The bottom right profiles in Figure 8 were not labeled as “potential” or “confident” as the optimal depth profile was not consistently brighter than the optimal depth.

Driver et al. (2016, Figure 2) showed that the number density of galaxies in the $r$-band peaks at $m_{AB} \approx 19$–24 mag. Thus, this subset of galaxies constitutes a representative sample of galaxies which significantly contributes to the EBL, to surface brightness levels of $\mu_{r}^{AB} \lesssim 31$ mag arcsec$^{-2}$, where the background levels of the optimal depth and optimal resolution mosaics begin to differ. Of the 360 galaxies with surface brightness profiles, only 19 were labeled as “confident” and 32 galaxies were labeled as “potential.” Therefore, 5%–14% of galaxies in this sample have excess flux in their outskirts out to surface brightness levels of $\mu_{r}^{AB} \lesssim 31$ mag arcsec$^{-2}$, which could contribute to missing, diffuse EBL light as summarized by Driver & Robotham (2010), Driver et al. (2016) and Windhorst et al. (2018). However, the possibility of more uniform, missing flux from all galaxies cannot be ruled out as it would be diffuse enough across the LBT FOV where it would be removed during the SWARP background subtraction process. This excess $r$-band light could be the result of an older population of stars in the galaxy outskirts, star formation being traced by Hα out to redshifts of $z \approx 0.2$, or tidal tails from galaxy interactions.

Additional light in the outskirts of galaxies is also observed though a slight offset in the magnitude difference between the optimal resolution and depth catalogs. This is shown in Figure 9, where for all galaxies between 18 and 28 mag, the median magnitude difference is $0.023 \pm 0.143$ mag. This positive magnitude offset indicates that on average, there exists additional light in the outskirts of the optimal depth galaxies. With regards to galaxies brighter than 21.5 mag, which correspond to the magnitude range for the 360 galaxies with surface brightness profiles, Figure 10 shows that additional flux exists in the optimal depth images. The magnitude difference between the optimal resolution and optimal depth sources exhibit a positive offset ($0.024 \pm 0.014$ mag) from zero, which indicates that the same galaxies are brighter in the optimal depth mosaic. On average, median offset between the optimal resolution and optimal depth magnitudes for the full sample of galaxies between 18 and 28 mag is not robust given the uncertainties. However, when looking at the subset of galaxies brighter than 21.5 mag, there is clear evidence that additional flux exists. This additional flux is attributed to diffuse light in the galaxy outskirts that is visible through long periods of integration from the ground.

In addition to the surface brightness profile analysis, the total contribution of light in galaxy outskirts to the EBL was calculated by integrating the normalized galaxy counts up to the optimal resolution and optimal depth completion limits of $\sim 27$ mag following the methods in Driver et al. (2016), Carleton et al. (2022) and Windhorst et al. (2022a). Beginning with the differential number counts from the optimal resolution and optimal depth mosaics, the number counts began to become incomplete after $\sim 27$ mag. As stated in Driver et al. (2016), Carleton et al. (2022) and Windhorst et al. (2022a), the
Figure 8. Radial surface brightness profiles for 20 of the 360 brightest objects with $r_{AB} \leq 21.5$ mag. The blue data points show the surface brightness profile for the optimal resolution image, while the red points show the corresponding profile for the optimal depth image. The total integrated $r_{AB}$ magnitudes from the profiles are listed in the lower left corner. The blue arrow represents the half-light radius measured with SEXTRACTOR. The galaxy inset images show the optimal resolution (left) and optimal depth (right) images. Galaxies A, B, C, and D clearly show excess flux in the outskirts of the optimal depth surface brightness profiles at levels brighter than $r_{AB} \leq 31$ mag. The complete figure set showing all 360 surface brightness profiles is available in the online journal. (The complete figure set (18 images) is available.)
The majority of the EBL is comprised of light from galaxies between 18 and 24 mag. As a result, by integrating the galaxy counts up to the completeness limit of 27 mag provides an accurate measure of the integrated EBL. Therefore, the contribution to the EBL which is from any additional light in the outskirts of galaxies in the optimal depth mosaic would be represented by the difference between the total energy \(\text{EBL}\) from the integrated galaxy counts for each of the two mosaics. This analysis showed that the EBL contribution from the optimal depth and optimal resolution mosaics are 3.52 and 3.33 nW m\(^{-2}\) sr\(^{-1}\), respectively. Therefore, the difference between these values represents the expected EBL contribution from the diffuse flux in the outskirts of galaxies in the optimal depth mosaic. This corresponds to 0.1 nW m\(^{-2}\) sr\(^{-1}\), which amounts to \(\sim 5\%\) of the total EBL in the Sloan \(r\)-band (see Figure 1 in Windhorst et al. (2022a)). Since these independent methods of searching for additional light in the outskirts of galaxies provide similar results, it can confidently be stated that only a small fraction (\(\sim 5\%–14\%\)) of extra light in galaxy outskirts is available to contribute toward missing EBL light.

5. Summary and Conclusions

838 \(r\)-band exposures (\(\sim 28\) hr) were obtained between 2012 December and 2014 January of GOODS-N in order to examine the trade-off between optimal image resolution and depth. Following the seeing sorted stacking method detailed in Ashcraft et al. (2018), the best seeing images were stacked to create optimal depth and optimal resolution mosaics. The optimal depth mosaic was found to be necessary for the study of low surface brightness regions presented in this work. The sacrifice in resolution was complemented by increased surface brightness sensitivity down to \(m_{AB} \sim 31\) mag arcsec\(^{-2}\).

The main challenge for photometric measurements was to overcome the natural confusion limit for separating objects, which occurs once faint objects are closer than \(\sim 1\arcsec\) in ground based images (Windhorst et al. 2011). In order to accurately deblend sources in the mosaics, SExtractor in dual image mode was utilized in order to deblend and detect objects using the optimal resolution mosaic. Within the optimal depth and optimal resolution mosaics, objects can be detected to \(m_{AB} \sim 29\) and \(m_{AB} \sim 28.5\) magnitudes, respectively.

A collection of 30 candidate interacting galaxies were investigated along with their low-surface brightness features. For the majority of these systems, the galaxies were not
resolved sufficiently for detailed morphological classification. For the sample galaxies that did fall within the HST footprint, the higher resolution images were used for interaction classification following the methods of Elmegreen et al. (2007) and the diffuse flux/tidal tails were described. Future studies can utilize the LBT U-band and r-band mosaics along with additional filters to continue to study the properties of these 30 interacting galaxies. Specifically, the colors of the diffuse plumes and tidal tails can be measured to gain more insight into the age and properties of these stellar populations.

Lastly, surface brightness profiles were measured for the 360 brightest galaxies with $r_{AB} < 21.5$ mag in both the optimal resolution and optimal depth mosaics. Galaxies with magnitudes $m_{AB} < 21.5$ provide a representative sample of galaxies that could contribute significantly to the Extragalactic Background Light in the r-band (Driver et al. 2016). These surface brightness profiles show marginal differences between the optimal resolution and optimal depth mosaics to surface brightnesses of $\mu_r^{AB} \sim 31$ mag arcsec$^{-2}$. Only 19/360 galaxies confidently exhibited excess flux in the optimal depth radial profiles, while another 32/360 galaxies were categorized as “potentially” having excess flux in the outskirts.

As a result, on average, we conclude that only $\sim 5\%-14\%$ of extra light in the outskirts of galaxies are likely to contribute to the Extragalactic Background Light out to surface brightness levels of $\sim 31$ mag arcsec$^{-2}$. The EBL contribution from the outskirts of galaxies was found to be $\sim 5\%$ of the EBL determined from the integrated galaxy counts. We find that while there is some contribution to the EBL from diffuse light in galaxy outskirts, there is not enough of a contribution in the r-band to close the discrepancy between direct EBL measurements (Puget et al. 1996; Hauser et al. 1998; Matsumoto et al. 2005, 2018; Lauer et al. 2021; Korngut et al. 2022) and predicted values (Driver et al. 2011, 2016; Andrews et al. 2018).

In the era of JWST, the detection of interacting galaxies and tidal tails out to $z \sim 1$ in addition to diffuse light in the outskirts of galaxies is of particular significance. As shown in early JWST results from Finkelstein et al. (2023), Windhorst et al. (2022b) and references therein, tidal tails and diffuse light is commonly observed. This observed diffuse light is evidence that the $\sim 5\%-14\%$ additional light discovered in this paper and Ashcraft et al. (2018) in the U-band appears to be commonplace, especially at $z > 1$. As a result, future studies may be able to refine the limits for the contribution from tidal tails and diffuse light toward the EBL that are presented in this paper.

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Appendix

Tidal Tails and Mergers

Below, we briefly describe the full sample of different tidal tail and merging galaxy candidates. Galaxies which reside within the HST FOV are shown first.

1. In the r-band, there is a diffuse plume above the galaxy and a long tidal tail downward to the left in the image (top galaxy in Figure 11). This galaxy is inside the HST FOV, but the tidal debris is not clearly visible without smoothing the data, and is most prominent in the F160W. It has a clear dust lane through the center perpendicular to the tidal tails visible in the HST optical wavelengths. In the F160W image, the dust lane disappears, so that two distinct cores become visible. Multiple brighter clumps of this galaxy are seen in the HST F336W and F275W images. Since it is detected in both x-ray (Wang et al. 2016) and radio (Biggs & Ivison 2006), it may have outflows or cooling flows associated with an AGN. Other studies have classified this galaxy as a starburst, high-excitation narrow-line radio galaxy, and merging, and measured a redshift of $z_{\text{spec}} = 0.457$ (Wirth et al. 2004).

2. Galaxy 2 shows a clear recent interaction with at least two galaxies, possibly a third, with measured redshifts, $z \approx 0.375$ (bottom images in Figure 11). There is a tidal tail between the two galaxies in the bottom right, which is also visible in the LBT U-band. Another tidal tail in the
Figure 11. Galaxy 1 (top): A galaxy with long extended tidal tail and diffuse flux seen in LBT $r$-band and has a $z_{\text{spec}} = 0.457$. The galaxy is visible in HST images from F275W-F160W, with only a double lobe being visible in the UV. The diffuse flux and tidal tail is visible in the NIR wavelengths, especially bright in the F105W. Galaxy 2 (bottom): Multiple spiral galaxies interacting with two long tidal tails visible linking the galaxies. The galaxies all have either spectroscopic or photometric $z \sim 0.375$. This system is only partially visible in HST imaging with best views being in the $J$ and $H$-bands. Only one of the tidal streams is clearly visible in the $U$-band.
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opposite direction probably links the central galaxy to a third spiral galaxy in the upper left. This tidal tail barely is detectable in the U-band mosaic, which could be due to multiple reasons including an older stellar population in the interaction. Unfortunately, this system of galaxies is on the edge of the HST FOV and only the less dominant tidal tail is visible in the HST WFC3 IR images.

3. An elliptical galaxy with a diffuse debris tail visible in the r-band and partly in the U-band mosaic (top galaxy in Figure 12). It has a $z_{\text{spec}} = 0.530$ (Moran et al. 2007). The diffuse flux above the main galaxy has a similar photometric redshift to the main galaxy, and can been seen in the HST V to H-bands. There appears to be a tail of debris coming from the bottom of the main elliptical galaxy, and the brightest clump in the stream has a $z_{\text{spec}} = 0.533$ (Moran et al. 2007).

4. Reminiscent of the nearby system, Stephan’s Quintet, there are at least three similar size spiral galaxies involved with this interaction (bottom set of images in Figure 12). Two of the galaxies are already merging, while a third appears to be gravitationally influencing one of the tidal tails. In the HST imaging, the tidal arms are visible in all bands, and the system has $z_{\text{spec}} = 0.299$ (Wirth et al. 2004).

5. Similar to M51, galaxy 5 (top galaxy in Figure 13) has a diffuse tidal stream on the bottom right linking it to a smaller companion galaxy and with a $z_{\text{spec}} = 0.253$ (Wirth et al. 2004). The HST images show a dust lane through the center of the galaxy and parallel to the diffuse stream. In the centers of both the main and the companion galaxies, no detectable flux is present in both the F336W and F275W filters.

6. There is smooth diffuse tidal debris visible in the LBT r-band to the right of the galaxy that appears to make a loop around the galaxy, but is not detectable in the LBT U-band (bottom galaxy in Figure 13). From the HST imaging, it appears as a face on disk galaxy with a very bright center and possible bar. The tidal debris is only marginally seen without smoothing. It has been classified as a broad-line AGN and a measured $z_{\text{spec}} = 0.306$ (Wirth et al. 2004).

7. An edge-on disk galaxy, which has been identified as an AGN (top galaxy in Figure 14). It has extra diffuse flux upward and to the left, which is seen in both r-band and U-band. In addition, it has a possible approximately equal size grazing companion. The main galaxy has $z_{\text{spec}} = 0.637$ (Barger et al. 2008), but the potential companion galaxy to the right is not spectroscopically confirmed to be at the same redshift. However, the small galaxies to the left have $z_{\text{spec}} = 0.632$ (Barger et al. 2008).

8. There is smooth, diffuse debris to the left of the central galaxy seen in the LBT r-band, while the U-band only shows background objects (bottom galaxy in Figure 14).

The galaxy has $z_{\text{spec}} = 0.440$ (Wirth et al. 2004). It has also been categorized as a S0/spheroid galaxy, which is confirmed by the HST images, as well as a high-excitation narrow-line radio galaxy (Wirth et al. 2004). The redder HST filters also show the diffuse flux in the same location as the LBT r-band.

9. Appearing as an elliptical galaxy, but it clearly has rings with recent star-forming clumps visible in the HST images (top galaxy in Figure 15). The small bright object to its lower left has the same redshift $z_{\text{spec}} = 0.377$ (Wirth et al. 2004). It appears to be a smaller galaxy being tidally disrupted and absorbed by the larger galaxy. In the LBT r-band, there appears to be even more diffuse tidal arms that are not easily visible in the HST imaging. Auxiliary data includes a detection in the radio by the VLA (Morrison et al. 2010). The bright galaxy to the upper left is a foreground interloper.

10. At least two merging galaxies with the central regions of each galaxy still visible, but distorted (bottom galaxy in Figure 15). From the LBT observations, there appears to be a tail coming from top and curving around to the right. From the Elmegreen et al. (2007) designations, this galaxy could be categorized as a shrimp type based on its shape and features visible in the different imaging. There is no available redshift for this galaxy.

11. This system appears to have 3 elliptical galaxies with a long diffuse stream toward the upper left corner linking to a possible 4th galaxy in the system (top system of galaxies in Figure 16). With redshifts of $z = 0.798$ (Treu et al. 2005), these red galaxies are almost not detectable in the LBT U-band. The redder HST filters show the same diffuse stream visible in the LBT r-band at low surface brightness levels.

12. An elliptical galaxy surrounded by diffuse plumes with the most prominent plume to the lower left (bottom galaxy in Figure 16). It is on the edge of HST FOV, and does not have any redshift information. Only the HST I-band (F814) image shows the entire region around the galaxy and there does appear to be diffuse flux around the galaxy in this filter. However, it would be easy to miss without re-binning or smoothing the HST data.

13. This is a good example of where HST imaging was critical to confirm that it is an interacting system (Figure 17). Also, it is the highest redshift galaxy in our sample with $z_{\text{spec}} = 0.937$ (Barger et al. 2008). The HST image shows a second possible distinct core at the top of the galaxy, or a starburst clump. The core near the center is not visible in the bluer filters, which indicates a dusty galaxy. There are multiple clumpy objects around the main galaxy, which could be associated with the main merging system.

The following objects are completely outside the HST FOV. In Figures 18–25 only the optimal depth LBT
images in the $U$-band on the left and the $r$-band on the right are shown. Some of the objects are in the footprint for other surveys including Herschel, Spitzer, VLA, and Chandra.

14. A galaxy with long tidal streams reminiscent of the Antennae galaxy, but the central region is unresolved (top galaxy in Figure 18). The diffuse tidal streams are not seen in the $U$-band, except for a few faint spots.
along the tails. At a redshift of $z_{\text{spec}} = 0.277$ (Casey et al. 2012), the $U$-band corresponds to NUV flux, which means there is little evidence of recent star formation in these tidal streams. The galaxy was detected by both Herschel (infrared; Casey et al. 2012) and VLA (radio; Biggs & Ivison 2006).

15. Two galaxies with extended flux in tidal tails seen in the LBT $r$-band, but only the brightest clumps are in the tails are detectable in the $U$-band (middle system of galaxies in Figure 18). The system was detected in the infrared by Herschel and Spitzer, and the top galaxy is associated with a radio source (VLA; Morrison et al. 2010)). The bottom large galaxy is interacting with the smaller galaxy to the left, while the top galaxy has $z_{\text{spec}} = 0.456$ (Casey et al. 2012).
16. A very red galaxy, probably elliptical/S0 type galaxy, which is only barely visible in the LBT U-band. This galaxy is surrounded by diffuse plumes and has a stream to the upper left (bottom galaxy in Figure 18). From the literature, it has a photometric redshift of $z_{\text{phot}} = 0.48$ (Rafferty et al. 2011).

17. Two large irregular galaxies just outside the HST FOV (top galaxy system in Figure 19). There are multiple star-forming clumps around the two galaxies, which are most likely physically associated based on their colors. The larger galaxy on the right side appears to have a M51 like bridge with the small galaxy to its right. They are at a low redshift of $z_{\text{spec}} = 0.0366$ (Wirth et al. 2004).

18. In the $r$-band there is a large extended shell of diffuse light around the galaxy (middle galaxy in Figure 19), which is not seen in the $U$-band. This galaxy has $z_{\text{spec}} = 0.560$ (Albareti et al. 2017). The diffuse shell could be a signature of a recent merger.

19. A galaxy with long extended diffuse plumes and loops around the galaxy that is only seen in the LBT $r$-band (bottom galaxy in Figure 19). There is one tidal stream in the bottom left, which has detectable flux in the corresponding $U$-band area.

20. Another galaxy with rings of diffuse light surrounding it (top galaxy in Figure 20). The outer most ring is only seen in the LBT $r$-band, and could be a sign of a recent merger.
merger. There is no indication of interaction with any other galaxies nearby it, and no available redshift information.

21. An elliptical galaxy with one stream interacting with a much smaller nearby galaxy, and a large diffuse plume above the galaxy (bottom galaxy in Figure 20). This extended diffuse light is not detected in the $U$-band, except for discreet clumps along the tidal arm, which are most likely associated with recent star formation.

22. Diffuse plumes surround the galaxy in the center of the image, as well as a couple of bubbles, or loop features at the bottom (Figure 21). In the $U$-band, the majority of the diffuse flux is not detected with only the brighter bubble feature visible. For galaxies within this field, there is no redshift information. The main galaxy could be interacting with multiple galaxies around it, including the similar size elliptical below it, and a galaxy farther to the right following one of the tidal streams.

23. An interesting system with potentially multiple galaxies interacting (top system of galaxies in Figure 22). There is a larger elliptical at the bottom of the image with a bridge to a galaxy above it, and a tidal stream extending...
even farther above it. Without redshift information, it is unknown if the various objects along the tidal tail are gravitationally associated with the interaction.

24. A face-on disk galaxy with multiple star-forming clumps and an extended flux feature on the top and left side of galaxy (bottom galaxy in Figure 22). While most
noticeable in the $r$-band, there are a few brighter spots visible in $U$-band. Another galaxy without any redshift information.

25. An assembly type with two diffuse bridges linking two brighter clump cores (top galaxy in Figure 23). The left bridge connecting the cores is much fainter in the $U$-band compared to the rest of the components of the system. There is no redshift information available for this system.

26. An edge-on spiral galaxy with extended flux on the left side, which is only detected in the $r$-band (bottom galaxy in Figure 23). There are other galaxies in the image with irregular shapes, and signatures of recent interactions or mergers, including a galaxy consisting of clumps at the bottom of the image. There is no redshift information available for any of the objects in the image.

27. A dense area of galaxies with multiple possible interactions (top system of galaxies in Figure 24). The most obvious one is a bridge between two galaxies near the center and is visible in both the $r$-band and the $U$-band. There is also a known QSO in the field with a $z_{\text{spec}} = 0.334$ (Albareti et al. 2017). The remainder of the objects in the field do not have known redshifts.

28. A potential double nuclei merging system with diffuse flux above the galaxy in $r$-band (bottom galaxy in Figure 24). While most of the galaxy is detected in $U$-band, remarkably, the bright core in the center not visible in the $U$-band. Visually there appears to be links to nearby objects, but there is no redshift information to confirm.

29. An elliptical galaxy with diffuse plumes seen in the $r$-band, but in the $U$-band the plumes are less distinct (top galaxy in Figure 25). There is no redshift information for this galaxy.

30. An angled spiral galaxy with diffuse flux extending down toward the smaller galaxy below it (bottom galaxy in Figure 25). The possible diffuse bridge linking the two galaxies is only detected in the $r$-band. However, without redshift information, it is not possible to know for sure if these objects are truly interacting.
Figure 18. Galaxy 14 (top): a merging system with a long extended tidal tail to the right and a smaller tail with diffuse flux to the left. It is only significantly detected in the LBT r-band and has $z_{\text{spec}} = 0.277$ (Casey et al. 2012). Galaxy 15 (middle): two galaxies of equal size with multiple extended streams, including a bridge between the galaxies, and a redshift of $z_{\text{spec}} = 0.456$ (Casey et al. 2012) is measured for the top galaxy. The diffuse light in the streams is not easily visible in the U-band, but there appears to be potential star-forming clumps. Galaxy 16 (bottom): a red galaxy with diffuse debris to the upper left only detected in r-band and a possible redshift of $z_{\text{phot}} = 0.48$ (Rafferty et al. 2011).
Figure 19. Galaxy 17 (top): two large distorted galaxies with antenna like main regions and $z_{\text{spec}} = 0.0336$ (Wirth et al. 2004). Both look similar in the $r$-band and $U$-band, and the galaxy on the right is also interacting with a smaller galaxy to the lower right. Galaxy 18 (middle): a large diffuse shell of flux is seen only in the $r$-band and as $z_{\text{spec}} = 0.560$ (Albareti et al. 2017). Galaxy 19 (bottom): A galaxy with long extended diffuse plumes and loops around the galaxy, distinctly visible in $r$-band, with one stream of flux partially detectable in $U$-band.
Figure 20. Galaxy 20 (top): a galaxy with rings of diffuse light around it, with the outermost ring only noticeable in the LBT r-band. Galaxy 21 (bottom): an elliptical galaxy with one stream interacting with a much smaller nearby galaxy, and a large diffuse plume above the galaxy. Only potential star-forming clumps along the tidal stream are visible in the U-band.
Figure 21. Galaxy 22: in the r-band, there is a diffuse plume surrounding the central galaxy, along with a couple of bubble like features at the bottom of the galaxy toward another similar size galaxy. Only the main bubble feature is detected in the U-band.
Figure 22. Galaxy 23 (top): a long diffuse stream is running from the bright galaxy at the bottom to the top of the image, which is not as clearly defined in the $U$-band. There is a bridge visible in both the $r$-band and the $U$-band linking the main galaxy to a slightly smaller one. Galaxy 24 (bottom): a galaxy with extended flux along the top and right portion seen in LBT $r$-band and partly visible in the $U$-band. It appears to be a face-on disk with multiple star-forming clumps and possibly interacting with galaxy above it.
Figure 23. Galaxy 25 (top): an assembly type system with two diffuse bridges linking two brighter clump cores. All except the bridge on the left connecting the two cores are detected in both $r$-band and $U$-band. Galaxy 26 (bottom): an edge-on spiral galaxy with extended flux toward the left seen in the $r$-band, but not in the $U$-band. At the bottom of the image, there is a galaxy consisting of several clumps.
Figure 24. Galaxy 27 (top): a dense area with multiple galaxies interacting and a clear tidal stream between two galaxies near center. Most of the galaxies and features within the field are detected in both $r$-band and $U$-band. The QSO in the system has a $z_{\text{spec}} = 0.334$. Galaxy 28 (bottom): a system in the process of merging with potential double nuclei and a diffuse stream toward the top of the image. In the $U$-band, the central nucleus is not visible.
Figure 25. Galaxy 29 (top): an interesting extended plume of diffuse light toward the bottom left seen only in the $r$-band. Galaxy 30 (bottom): an angled spiral galaxy, with a tidal bridge extending down toward the smaller galaxy below it, which is not detected in the $U$-band.
