The Dragonfly Edge-on Galaxies Survey: Shaping the Outer disk of NGC 4565 via Accretion

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Abstract

We present deep g- and r-band imaging of the well-known edge-on galaxy NGC 4565 (the “Needle Galaxy”), observed as part of the Dragonfly Edge-on Galaxies Survey. The 3σ local surface brightness contrast limit on 10″ scales is 28.616 ± 0.005 mag arcsec−2 for the r-band image and 28.936 ± 0.005 mag arcsec−2 for the g-band image. We trace the galaxy’s starlight in narrow slice profiles spanning over 90 kpc along the major axis (with bin sizes ranging from 1.7 × 0.5 to 1.7 × 7.8 kpc) to surface brightnesses below 29 mag arcsec−2. We confirm the previously observed asymmetric disk truncation in NGC 4565. In addition, the sharp northwest truncation turns over to a shallower component that coincides with a fan-like feature seen to wrap around the northwest disk limb.

We propose that the fan may be a tidal ribbon and qualitatively replicate the fan with simple simulations, although alternative explanations of the fan and the disk’s asymmetry are shown to be possible. In any case, we conclude that there is strong evidence for accretion-based outer disk growth in NGC 4565.

Unified Astronomy Thesaurus concepts: Spiral galaxies (1560); Galaxy evolution (594); Disk galaxies (391)

1. Introduction

Our understanding of the formation and growth of spiral galaxies in a hierarchical, dark matter-dominated universe is constantly evolving. Fall & Efstathiou (1980) developed a model to describe the formation of thin, rotating disk galaxies by the collapse of slowly rotating gas within a massive dark matter halo. Stellar feedback was found to be crucial for the formation of realistic disks in simulations (White & Frenk 1991; Mo et al. 1998). Spiral galaxies were thought to have avoided any recent major mergers, as otherwise they would have been transformed into elliptical galaxies (Negroponte & White 1983 and many others).

Minor mergers initially did not fit comfortably into this picture. Dissipationless N-body simulations showed that minor mergers cause thin disks to spread, warp, and flare, coming to resemble thick disks or an S0/Sa galaxy (Quinn et al. 1993; Walker et al. 1996). Cosmological simulations and observations both showed minor mergers to be very common, which raised questions of how so many thin disks in spiral galaxies were able to survive to the present day (Hopkins et al. 2009 and references therein).

Improvements in simulations of mergers, particularly the inclusion of gas, resolved this tension. It was first shown that gas-rich major mergers can result in a disk-dominated remnant if star formation is suppressed during the interaction (by interstellar medium pressurization) such that the system is gas-dominated at the moment of coalescence (Springel & Hernquist 2005; Robertson et al. 2006). Such mergers could plausibly contribute to the assembly of today’s spirals at high redshift, where progenitors are more likely to have high gas fractions. When gas is available in a spiral galaxy, the degree of disk heating from minor mergers is greatly reduced and a recognizable thin disk survives the encounter (Hopkins et al. 2009; Scannapieco et al. 2009; Moster et al. 2010). More realistic orbits in improved dissipationless N-body simulations also led to decreased disk heating, showing that minor mergers are not catastrophic for spiral galaxies (Hopkins et al. 2008; Kazantzidis et al. 2008). Thin disks may be able to survive minor mergers, but is it also possible to grow these disks with accretion? The accretion of satellite galaxies is often thought of in terms of bulge growth and stellar halo assembly (Helmi & White 1999; Bullock & Johnston 2005; Abadi et al. 2006). However, recent work shows that minor mergers do lead to disk growth and indeed may be necessary to explain the growth of disks since z ~ 2 as star formation and stellar migration alone are likely insufficient (Bluck et al. 2012; Ownsworth et al. 2012; Sachdeva et al. 2015). These claims are supported by cosmological hydrodynamic simulations, where stars that formed in satellite galaxies (“ex situ”) are found throughout disks at the present day (Pillepich et al. 2015; Rodriguez-Gomez et al. 2016). Minor mergers are also an effective way to explain the size growth of early-type galaxies over this period as major mergers do not increase size efficiently (Bezanson et al. 2009; Naab et al. 2009).

If ongoing minor mergers play an important role in the growth of disks, there should be some hint of the origin of recently accreted material. The many streams surrounding the Milky Way plainly reveal its extensive and ongoing merger history (Belokurov et al. 2006; Helmi et al. 2017; Malhan et al. 2018). The age–velocity dispersion relation of stars in the solar neighborhood (Quinn & Garnett 2001) and disruptions in stellar phase-space (Gómez et al. 2012) may show the impact of these past mergers on the disk. These high-dimensional approaches are not feasible for galaxies other than our own.
For relatively nearby galaxies, resolved stellar photometry can be used to assess changes in the age or metallicity of stars across the disk (e.g., Radburn-Smith et al. 2012; Streich et al. 2016). Otherwise, one can examine the morphology and structure of galaxies in wide-field broadband imaging to search for signatures of recent minor mergers. It has been suggested that broken exponential profiles with a larger outer scalelength (Type III) arise due to minor mergers (Younger et al. 2007). However, there are many other possible explanations: smooth gas accretion combined with radial migration (Minchev et al. 2012), a superposition of thin and thick disks (Comerón et al. 2012), tidal interactions, galaxy harassment (Watkins et al. 2019), or simply the onset of the stellar halo-dominated regime. An upbending outer profile does not necessarily imply outer disk assembly via minor mergers.

Stellar streams near the disk plane, outer warps, or other disturbances in the outskirts of a disk are more convincing evidence of recent accretion events than profile inflections alone. Dedicated, deep integrated light observations are required in order to follow the outer disk to its farthest reaches to search for such clues. This approach is complicated or precluded by scattered light within conventional reflecting telescopes. The Dragonfly Telephoto Array has been specifically designed to minimize scattered light and has been successfully used to study a variety of very low surface brightness structures, including low surface brightness dwarfs (Merritt et al. 2014; van Dokkum et al. 2015), stellar halos (Merritt et al. 2016), and extended stellar disks (Zhang et al. 2018).

In this paper, we present deep observations of the edge-on galaxy NGC 4565 with Dragonfly. In Section 2 we describe our observations and data reduction procedure. Section 3 focuses on the important areas of point-spread function (PSF) characterization and source subtraction. Our analysis is presented in Section 4, and discussed in Section 5. We summarize this paper in Section 6.

Throughout, we adopt a distance of 12.7 Mpc to NGC 4565. This is the average of the two tip of the red-giant branch distances tabulated on the NASA/IPAC Extragalactic Database (11.9 and 13.5 Mpc; Radburn-Smith et al. 2011; Tully et al. 2013, respectively). Jupiter notebooks containing the code used to produce the profiles and the figures in this paper are available on GitHub.¹

2. Observations and Data Reduction

The Dragonfly Telephoto Array (Abraham & van Dokkum 2014) is a robotic mosaic telescope currently consisting of 48 Canon 400 mm /2.8L IS II USM telephoto lenses. State-of-the-art anti-reflective coatings on optical surfaces and the absence of obstructions in the optical path lead to significantly less scattered light than in typical reflecting telescopes. This makes Dragonfly well-suited for observations of low surface brightness objects and features. A generous field of view (2.6 × 1.9) avoids irregularities where individual pointings are stitched together and enables confident detection of faint features unhindered by image artifacts. In its current configuration, Dragonfly is equivalent to a 0.99 m f/0.4 refracting telescope.

The Dragonfly Edge-on Galaxies Survey (DEGS) is an imaging campaign targeting nearby edge-on spiral galaxies (C. Gilhuly et al. 2020, in preparation). Galaxies were selected using criteria of distance, absolute magnitude, inclination, and absence of Galactic cirrus. Dragonfly’s large field of view and excellent sensitivity to low surface brightness structures enables the exploration of galactic disk outskirts and stellar halos, and the edge-on orientation of the sample allows a cleaner separation of disk and halo components.

NGC 4565 was the first galaxy in the DEGS sample to be observed, and it was imaged for significantly longer than typical DEGS targets. A more “typical” DEGS galaxy observation is that of NGC 5907, presented in van Dokkum et al. (2019). We observed NGC 4565 over 64 nights from spring 2015 to summer 2017. The majority of our data originate from 42 nights in 2017, after Dragonfly was upgraded to a 48-lens configuration. In total, we collected 29,473 10 min exposures (equivalent to 102.3 hr with the entire array). This is Dragonfly’s deepest field to date. Half of the array is equipped with Sloan Digital Sky Survey (SDSS) g filters, and the other half with r filters. These filters are similar to SDSS filters; see Figure 2 of Abraham & van Dokkum (2014) for details. Dithers of 35' and slight misalignment of the lenses were used to improve control over sky systematics.

We produced coadded images of the NGC 4565 field using the Dragonfly reduction pipeline. A detailed description of this software can be found in Section 3 of Danieli et al. (2020). One key strength of the pipeline is the two-stage sky subtraction applied to individual frames. The sky is first modeled using source masks generated from each frame. The intermediate sky-subtracted frames are then median-combined to produce an intermediate mosaic. This mosaic is then used to define a more robust source mask due to its greater depth, enabling better sky models and ultimately a more uniform final image.

Another relevant strength of the pipeline is its ability to reject poor-quality frames obtained under conditions where very light cloud contamination or high atmosphere aerosols enhance the wings of the PSF. This subtle effect is not always visible to the eye, but we are able to exclude such data by rejecting deviant zero-points during photometric calibration. This data pruning technique allows Dragonfly to observe in all conditions, making use of brief photometric windows without contaminating the final images.

The final images of the NGC 4565 field contain 4448 r-band frames and 4416 g-band frames, equivalent to 30.8 hr with the entire array. A low conversion rate from raw exposure time to final images is expected given our data pruning technique described above. These images are available for download at https://www.dragonflytelescope.org/data-access.html.

3. PSF Management and Source Subtraction

Scattered light can lead to overestimations of thick disk and stellar halo components of galaxies, and great change in their outer color profiles (de Jong 2008; Sandin 2014, 2015). Therefore, when studying low surface brightness regions in galaxies, particularly edge-on galaxies, it is crucial to characterize the PSF to large radii. The ideal approach is to perform PSF deconvolution on an image, but this is a significant undertaking (Karabal et al. 2017). Often the more tractable approach is to fit the galaxy with a two-dimensional model, and then to compare model images produced with and without PSF convolution. This provides an estimate of the contribution by scattered light in all regions of the galaxy. This technique has been adopted in numerous recent low surface

¹ https://github.com/cgilhuly/papers/tree/master/2019/NGC4565_disc
brightness studies (Trujillo & Fliri 2016; Borlaff et al. 2017; Peters et al. 2017; Comerón et al. 2018; Martínez-Lombilla et al. 2019; Martínez-Lombilla & Knapen 2019), which themselves demonstrate the importance of wide-angle PSF characterization and correction.

While the unique design of Dragonfly reduces the amount of scattered light at large angles relative to traditional telescopes, it remains important to estimate the impact that scattered light may have on galaxies and other features in our images. 2D Bayesian modeling of scattered light was used to characterize the wide-angle PSF in our final coadded images (Q. Liu et al. 2020, in preparation). The inner 5'' of the PSF was modeled with a Moffat function and the outer PSF was fitted with multiple power laws to a radius of 20'', and extrapolated to a radius of 33'33''. The outer portions of our r-band PSF was well-modeled by two power laws \((n = 3.44 \text{ from } 5''-4'', n = 3.02 \text{ from } 4'' \text{ outward})\) while the g-band PSF required three \((n = 3.44 \text{ from } 5'' \text{ to } 64''/6, n = 2.89 \text{ from } 64''/6 \text{ to } 117''/5, \text{ and } n = 2.07 \text{ from } 117''/5 \text{ outward})\). We cannot rule out the possibility that low-amplitude variations in the sky on scales of \(\sim 10''\) may have affected our modeling efforts, and we are continuing to investigate. We refer the interested reader to Q. Liu et al. (2020, in preparation) for further details.

Scattered light from stars and compact sources was mitigated using a technique called “multi-resolution filtering” (MRF). We refer the interested reader to van Dokkum et al. (2020) for a detailed description of this technique. In brief, sources were identified and segmented by running Source Extractor (Bertin & Arnouts 1996) on a higher-resolution reference image. A model image of the detected sources was then convolved with a kernel constructed to approximately convert from the PSF of the high-resolution image to that of Dragonfly (Equation (4) of van Dokkum et al. 2020). The stellar aureoles of stars brighter than 16.5 mag were also modeled to a radius of 33'33'', using the parametric wide-angle PSF described above. The core PSF (constructed empirically from unsaturated stars) was flux-matched to the wide-angle PSF at a radius of 30''. Finally, the convolved model image was subtracted from the Dragonfly image.

For this purpose, we used archival MegaPipe (Gwyn 2008) Canada–Hawaii Telescope (CFHT) images accessed from the Canadian Astronomy Data Centre. The images are \(1''23 \times 1''18\), somewhat off-center relative to NGC 4565, and are sampled at 0''.186. The r'-band image combines nine individual 5 min MegaPrime exposures and has an image quality of 1''.09. The g'-band image combines five individual 5 min exposures and has an image quality of 1''.27.

The source subtraction software automatically masked the worst residuals at the core of bright objects. Additional masking was done by hand for extended emission surrounding background galaxies, sources that were not modeled and subtracted (due to low surface brightness or overlap with a much brighter source), and surrounding the brightest stars in the field. In addition to residuals from source subtraction, we masked regions contaminated by background galaxy clusters southeast of NGC 4565 (400 d J1236+2550, \(z = 0.175\); GMBCG J189.255931+25.84396, \(z = 0.308\); WHL J123647.1 +255131, \(z = 0.1823\)) to avoid contamination from the galaxies’ outskirts or any intracluster light.

We estimated the effective depth of the source-subtracted images using sbcontrast, a code bundled with MRF. The code binned the entire image to the desired scale, subtracted a local background from each binned pixel based on the surrounding 8 pixels, and calculated the variation among the binned and background-subtracted pixels. This technique was designed to measure the typical contrast of objects of a given size with their immediate surroundings. The 3\(\sigma\) surface brightness limit on 10'' scales is 28.616 \pm 0.005 mag arcsec\(^{-2}\) for the r-band image and 28.936 \pm 0.005 mag arcsec\(^{-2}\) for the g-band image. On scales from 1'' to 4'', these limits are somewhat fainter \((\sim 29.0 \text{ mag arcsec}^{-2}\text{ for r-band, } \sim 29.6 \text{ mag arcsec}^{-2}\text{ for g-band})\).

4. Analysis

4.1. Overview

In Figure 1, we present several different views of our reduced and processed images of NGC 4565. The upper left panel shows a large area of the NGC 4565 field in false color, spanning 2''4 \times 2''4. The upper right panel offers a closer look at the galaxy in the r-band mosaic. The bottom panels show the source-subtracted r-band cutout. Our source mask is included in the bottom right panel; the “raw” source-subtracted image (with automatic masking of core residuals only) is shown in the bottom left panel. For reference, we have replaced the bright regions of NGC 4565 with an SDSS gri color cutout in the lower right panel.

Dragonfly is poorly suited for imaging point sources to great depth due to its relatively large pixels, but it excels in revealing extended low surface brightness features. In the NGC 4565 field, structures with \(\mu_r = 27-28 \text{ mag arcsec}^{-2}\) are clearly visible without any binning or enhancement of the image. Some examples include a large tidal tail around a \(z = 0.02\) galaxy, tidal structures in a cluster at \(z = 0.175\) (as well as extended intracluster light), and features likely associated with the outer disk of NGC 4565 (discussed below; see also Figure 6). These examples are consistent with the estimated 3\(\sigma\) surface brightness contrast limit of 28.616 \pm 0.005 mag arcsec\(^{-2}\) for the r-band image (on scales of 10'').

4.2. Azimuthally Averaged Profiles

We explore the distribution of stellar light in the galaxy using azimuthally averaged surface brightness profiles. The profiles were extracted using the photutils.isophote package (Bradley et al. 2019). The isophote-fitting routine automatically imposed a fixed position angle and ellipticity for isophotes with semimajor axes greater than 780''. The r-band isophotal solution was imposed on the g-band to ensure consistency.

We measured the median sky inside a circular annulus centered on NGC 4565, with an inner radius of 1000'' and an outer radius of 1125'' (a width of 50 pixels). We considered the greatest difference between the median sky measured in annuli 50 pixels wide immediately inside and outside the sky annulus as a primary source of systematic uncertainty, as the position of the sky annulus is arbitrary and there are small variations in the background on scales of \(\sim 10''\) (with an amplitude of less than 0.2% of the mean sky value). We note that there is some
overlap between the major axis of our azimuthally averaged profiles and the sky annulus, but due to their ellipticity the galaxy isophotes have little overlap with the sky annulus. To mitigate large-scale, low-amplitude variations in the background, the image was divided into four quadrants defined by the major and minor axes of the galaxy. (In particular, the southern half of the image was seen to be noticeably brighter than the northern half.) The $r$-band isophotal solution was applied to each quadrant in turn, and the sky was measured in each individual quadrant. The four quadrant profiles were weighted according to the number of unmasked pixels at each radius and averaged. The resulting combined profiles are shown in Figure 2, with systematics introduced by sky subtraction shown as shaded regions.

We used IMFIT (Erwin 2015) to model the light distribution of NGC 4565, in order to assess the impact of the PSF on our profiles. The galaxy was fitted with a nearly edge-on broken exponential disk and a Sersic bulge. The darkest portions of the dust lane were initially masked during fitting to improve model convergence. The dust lane was then unmasked and the best-fit parameters from the first model were used as initial values for a second modeling run. For this second run, all parameters were held fixed except for intensities. Once the model parameters were finalized, model images were produced with and without PSF convolution. The $r$-band model image (produced with PSF convolution) and residuals are shown alongside the observed image in Figure 3.

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Figure 1. Four different views and visualizations of NGC 4565 as imaged by Dragonfly. The top left panel is a false-color composite combining Dragonfly $g$- and $r$-band images, showing a large portion of the final image. The top right panel is a central cutout of the $r$-band image shown with Gauss histogram equalization scaling. The lower left panel shows the source-subtracted $r$-band image and uses a four-cycle sawtooth color palette. The lower right panel shows the source-subtracted $r$-band image (with histogram equalization stretch) where high surface brightness inner regions of NGC 4565 have been replaced with a color image from the Sloan Digital Sky Survey. Our full source mask is shown in the lower right panel; in general, we show source-subtracted images without our full mask applied. The scale bar in the lower right panel applies to both lower panels.
Azimuthally averaged profiles were extracted from model images with and without PSF convolution, using the elliptical isophotes previously fitted to the r-band image. The resulting profiles are plotted alongside the r- and g-band profiles in Figure 2. Since the kink in the observed profiles near 650″ also appears in the model profiles but does not correspond to a model component or feature, this feature is at least partly explained by the isophote geometry. Indeed, there is a sudden drop in fitted ellipticity at this radius.

The profile of the PSF-convolved model image first becomes twice as bright as the non-PSF convolved model image at 472″ ± 12″ for g-band and 496″ ± 12″ for r-band. However, the observed profiles are much brighter than the model image profiles at these radii. If the difference between the PSF-convolved and non-PSF-convolved profiles is taken as an estimate of the scattered light present at a given isophotal contour, only 8.6% of the observed r-band profile and 13% of the observed g-band profile can be explained by scattered light at 472″ ± 12″. We repeated this test at an arbitrary position in the outer profile, 980″ ± 25″. Here the estimated contribution from scattered light is even less for the r-band profile (3.2%) and somewhat larger for the g-band profile (21%). The estimated contribution of scattered light from the bright regions of the galaxy is not negligible (and may be somewhat underestimated in the outer profile; see the caveats below) but is far from sufficient to explain all of the light in the outskirts of the galaxy.

There are some important caveats to our 2D model comparison. The wide-angle PSF was only fitted out to a radius of 1200″, and the PSF cutout images used for model fitting and convolution were only 1250 × 1250 arcsec (radial scale of 625″). The accepted rule of thumb for the minor axis of edge-on galaxies is to measure the PSF on scales 1.5 times larger than the largest radius of interest (Sandin 2014). This rule is relaxed to 1.1 times the largest radius of interest for early-type galaxies and face-on disks (Sandin 2015). We have not met this standard for the full extent of the area covered by our azimuthally averaged profiles, but the range of scales is sufficient for the scope of this paper. In the future, we will extend our PSF fitting range and increase the size of the PSF cutout images used for model fitting and convolution. This will be necessary for work measuring the stellar halo fraction of the galaxy. In the meantime we focus on the outskirts of the disk, which are less sensitive to the PSF and well-covered by our current PSF models.

Due to the ellipticity of our outer isophotes, the effective radial extent of the profile in Figure 2 is much smaller toward the minor axis. Furthermore, the galaxy is oriented at a 44° angle to the pixel grid, which gives a factor of ~1/2 increase to the effective radial coverage of the PSF cutout along the major and minor axes of the galaxy. The resulting effective coverage of 883″ is sufficient to estimate PSF contamination to a radius of ~800″ along the major axis and, conservatively, ~590″ along the minor axis (which would correspond to a semimajor axis length of ~1140″ in our azimuthally averaged profiles).

### 4.3. Disk Slice Profiles

Major axis profiles were extracted in thin slices extending from the center of NGC 4565 to the northeast (NW) and southeast (SE). The position angle adopted was 134° (east of north). We adopted a slice width of 11 pixels (27.5′ or 1.7 kpc) to increase the signal-to-noise ratio (S/N) in the faint outer regions while still focusing on the disk midplane in bright regions. The procedure for measuring the sky was the same as for the azimuthally averaged profiles, though the quadrants were rotated 45° with respect to the previous quadrants such that either disk limb fell in the center of a quadrant rather than lying at the boundary of two quadrants.

We show the NW and SE disk slice surface brightness and color profiles in Figure 4. On each side of the disk, the profile from the opposite side is shown in grayscale to highlight their differences. Below the profiles, a rotated image of NGC 4565 is included for reference. The NW (g-band) profile reaches a depth of 29.4.0.4 mag arcsec−2 (29.8.0.4 mag arcsec−2) at a radius of 761″ ± 12″, or 46.8 ± 0.7 kpc. The outer SE profiles are sparse due to heavy masking of background galaxy clusters, but do reach depths of 29.0.14 mag arcsec−2 and 29.5.0.13 mag arcsec−2 for the r- and g-band respectively at a radius of 811″ ± 12″ (or 49.9 ± 0.7 kpc). The impact of systematic sky uncertainty is generally large beyond this radius, and the point-to-point variation in the profiles becomes larger than the measurement errors.

We extracted major axis profiles from the model images with and without PSF convolution using the same technique as applied to the observed data. Figure 5 compares the resulting profiles to the NW r- and g-band profiles. The PSF-convolved profile first becomes twice as bright as the non-PSF-convolved profile at 636″ ± 12″ for g-band and 711″ ± 12″ for r-band. The estimated contribution of scattered light to the observed profiles at these respective positions is 25% and 34% for the g-band profile, and 3.6% and 4.4% for the r-band profile. As with the azimuthally averaged profiles, scattered light from the
bright inner regions of the galaxy is non-negligible in the outskirts but is not sufficient to account for most of the observed light. We reiterate that, due to the limited size of the PSF cutout used for model fitting and convolution, we cannot confidently estimate the contribution of scattered light along the major axis beyond 800″. This is not a great concern as the point-to-point variation becomes larger than the measurement error in this regime, effectively marking the end of the reliable portion of the profile.

We confirm the overall disk asymmetry previously observed by Näslund & Jörðó (1997) and Wu et al. (2002), and we find the asymmetry to be robust to changes in position angle of the NW and SE profile slices. This asymmetry is strongest near the disk truncation; the SE disk limb appears to truncate at a smaller radius, and much less sharply. The two sides become comparable again toward the end of the truncation regime, though there are large gaps in the SE profile in the post-truncation regime due to masking of background clusters and a star that was not deblended from NGC 4565 during source subtraction. The inner NW disk is somewhat dimmer than the inner SE disk. This may be a sign that material on the NW side has been redistributed toward the sharp truncation, or simply that there is more dust at the midplane on the NW side.

4.3.1. NW Disk Limb

We trace the NW disk truncation over 8 kpc to a surface brightness of ~27 mag arcsec$^{-2}$, and confirm the end of the sharp truncation regime as first probed by Wu et al. (2002). We find an extended excess of light in the post-truncation regime centered near 570″ (35 kpc) that to our knowledge has not been previously reported. We mark this radius in Figure 4 with a dotted vertical line. A fan-like structure surrounding the NW edge of the disk is visible at the position corresponding to the excess light in the profile. This feature is highlighted in Figure 6, and can also be seen in Figure 4. The estimated contribution of scattered light to the major axis profiles at a radius of 580″ ± 6″ is only 6.1% (g-band) and 1.1% (r-band). We also note that the fan does not have a counterpart above the midplane. Therefore, we do not expect this feature to be induced by the PSF.

A few concentric ridges are visible in the fan. We highlight these features in Figure 6. The ridges are visible in our images before and after source subtraction. It is unclear if these ridges are true features or the coincidental alignment of compact sources that lead the eye. Closer inspection of the CFHT MegaPipe image does show some low surface brightness objects below the detection threshold for MRF that line up with the ridges in the Dragonfly images.

Due to the depth of our imaging, we are able to measure major axis slice color profiles through and beyond the truncation. The profile takes on a distinct u-shape about the NW truncation radius, reaching a minimum of 0.22 ± 0.10 at a radius of 430″ ± 4″. Beyond the truncation the color reddens again, except in the vicinity of the fan. Instead the color becomes bluer, with a minimum lower than that reached about the truncation (0.17 ± 0.17) at a radius of 555″ ± 6″. This sharp decrease in $g - r$ occurs immediately before a small gap in the profiles due to automatically masked residuals from source subtraction, and therefore may be caused by contamination. Color measurements in eight patches across the fan, south of the major axis profile footprint (avoiding subtracted sources and the ridges), range from 0.42 to 0.58. These values are consistent with the color before and after the sharp blueward drop. Therefore, we do not consider this feature in the major axis $g - r$ profile to be representative of the fan’s color.

4.3.2. SE Disk Limb

The transition from bright inner regions to outer disk is much smoother on the SE side of the disk than on the NW side. Additionally, the break radius on the SE side is smaller than on the NW side (~360″ versus 430″ ± 4″, or 22 kpc versus 26.4 kpc). The outer SE color profile displays a u-shape similar to that in the NW color profile. The color remains relatively constant between 360″ and 430″ (reaching a minimum of 0.31 ± 0.05 at 422″ ± 4″) and does not begin to redden again until beyond the NW truncation radius. We note that the minimum $g - r$ color on the SE side of the disk is redder than that on the NW side (0.31 ± 0.05 versus 0.22 ± 0.10).

As discussed in Section 3, broad masking is required beyond ~500″ (31 kpc) due to background galaxy clusters and improperly subtracted stars. Some milder contamination may extend outside the masked region, so caution is required when considering the few unmasked data points in the outer SE profile.

4.3.3. Comparison with Literature Profiles

Figure 7 shows the major axis profiles produced in this work alongside previously published major axis profiles. There is good agreement across all work on the differing shapes of the NW and SE profiles and the position of the NW truncation.
Agreement remains excellent through the truncation regime, to
a radius of $\sim 600''$ (37 kpc). Beyond this radius, our NW profile
extends farther than other work with smaller error bars. Wu
et al. (2002) observed a shallow outer component (which they
modeled as a power-law stellar halo), but our profiles continue
to decrease more rapidly in this regime. The relative excess
observed by Wu et al. (2002) may be attributable to scattered
light; Sandin (2015) demonstrated that a similar upturn in
minor axis profiles of NGC 4565 can be explained by scattered
light, but did not repeat the same test for major axis profiles.
The sharp upturn toward the end of the Näslund & Jörsäter
(1997) SE profile could be contamination from previously
noted background clusters.

There is broad agreement between our NW profiles and the
GHOSTS NW major axis stellar density profile (Harmsen et al.
2017). The inflection point marking the end of the first
truncation is not discernible in their profile (see their Figure 6)
due to a gap between Hubble Space Telescope (HST) pointings
and larger radial bins, but their outer points are suggestive of an
outer component with a longer scale length.

Figure 4. Southeast (left) and northwest (right) major axis $g$- and $r$-band profiles and color profiles. On each side of this figure, the corresponding profiles from the opposite side of NGC 4565 are shown in faint gray for comparison. Error bars depict random errors in each bin and shaded error envelopes include systematic uncertainty in the measurement of the sky. The error bars in $g - r$ are relatively large for the inner regions due to the inclusion of two distinct populations of pixels within a bin (dusty and non-dusty) rather than low $S/N$ in this region. The radii marked with vertical dashed and dotted lines are the approximate positions of the truncation and a post-truncation excess in the northwest profiles, respectively. A rotated $r$-band image of NGC 4565 (with a sawtooth color palette and Gauss histogram equalization scaling) is shown below the profiles with a common horizontal scale. The positions of several relevant features and objects are noted. The slice in which the major axis profiles were extracted is indicated by the two horizontal black lines spanning the width of the galaxy image.
5. Discussion

In order to grow stellar disks of the appropriate mass and radius at the present date, the accretion of satellite galaxies must have played a part (Bluck et al. 2012; Ownsworth et al. 2012; Sachdeva et al. 2015). Karademir et al. (2019) demonstrated that it is possible to significantly increase the size of a disk without altering its scale height via mergers with small satellites (mass ratios of 1:50 or 1:100) when the satellite approaches at low inclination to the disk plane. Evidence of disk growth via accretion of externally formed stars can be found in cosmological hydrodynamic simulations (Pillepich et al. 2015; Rodriguez-Gomez et al. 2016) and can be inferred from the ages and motions of stars in our own Galaxy (Quillen & Garnett 2001; Gómez et al. 2012). However, observing such evidence in other galaxies is challenging.

Recently, Zhang et al. (2018) detected an extended low surface brightness disk surrounding NGC 2841 out to distances of 70 kpc. Radial migration and in situ star formation were both identified as likely contributors to the formation of the outer disk, but were unable to fully account for the disk’s present-day size and mass. A warp in the extended disk suggested accretion has also played an important role in the formation of this structure.

Below, we discuss distinct features of NGC 4565’s disk that suggest growth or evolution by accretion of satellite galaxies, namely, the galaxy’s strong disk asymmetry and the northwestern fan. We consider plausible scenarios that may explain these features.

5.1. Evidence for Accretion-based Growth

The disk of NGC 4565 is strongly asymmetric through the midplane, with the strongest asymmetry near the NW truncation radius. The new fan-like feature we have found on the NW side is another asymmetry between the two sides. Together with the one-sided H\textsc{i} warp, these asymmetries indicate that one or more events or processes have not had an equal influence across the disk. Such processes would likely have external causes rather than arising due to secular evolution. It is not immediately clear how the striking disk asymmetries of NGC 4565 were shaped. We do know that it is not unusual for galaxies to be at least weakly asymmetric, in stars as well as H\textsc{i} (Haynes et al. 1998; van Eymeren et al. 2011).

Roškar et al. (2008) demonstrated that down-bending disk breaks may arise due to the combination of a radially declining star formation rate and radial migration. A notable signature of such disk breaks is a u-shaped age gradient, where the minimum stellar age is reached at the break radius. We report a u-shaped $g - r$ gradient on the NW side of the disk, and a similar but weaker feature on the SE side. If we consider $g - r$ color as an indicator of average stellar age, our observations of the galaxy’s truncation and color profile resemble the scenario presented by Roškar et al. (2008). This would suggest that radial migration has built up the post-truncation disk. However, this process cannot account for the strong disk asymmetry, the fan, or the shallower post-truncation disk. Another (or, at least an additional) explanation is needed.

The fan’s well-defined shape (Figures 4 and 6) suggests a dynamically distinct structure. It seems to lie in the disk plane right at its visual edge, wrapping around the edge of the disk with minimal extent above the midplane. There is a hint of the fan visible in the density of old stars plotted in Figure 2 of Radburn-Smith et al. (2014). The optical warp that follows the H\textsc{i} warp is traced by younger ($\lesssim$1 Gyr) stars rather than older stars, and so the fan is not likely to be directly associated with the warp. While the fan does not appear in the Harmsen et al. (2017) major axis density profile of red giant branch stars, this is likely due to a combination of coarse binning and the gap at 35–45 kpc (see their Figure 6).

5.1.1. Identifying Progenitor Candidates in the Vicinity of the Disk

We note a low surface brightness object coincident with the warp. Its position is marked in Figure 4, and it can also be clearly seen in Figure 6. Previous HST imaging has resolved this object into stars, and it was deemed to be a massive star cluster (Radburn-Smith et al. 2014). An alternative interpretation is that this object may be the remnant of a recently accreted dwarf galaxy. If this is the case, it may be associated with the creation of the fan.

NGC 4565 hosts surviving satellites which may be interacting or may have recently passed through the disk plane. An obvious candidate is IC 3571, the dwarf irregular galaxy just north of the disk (noted in Figure 4). It has a projected separation of 348″ (21 kpc) from the center of NGC 4565 (240″ or about 15 kpc perpendicular to the disk plane). It is connected to NGC 4565 in H\textsc{i} (Zschaechner et al. 2012) and therefore is clearly interacting. Another candidate that stands out is NGC 4562 ($M_\star = 8.13 \times 10^8 M_\odot$; Sheth et al. 2010), a late spiral 800″ (49 kpc) southwest of the center of NGC 4565 (noted in Figure 1).

5.2. The Fan as a Tidal Ribbon

Recently, Dehnen & Hasanuddin (2018) showed that the dynamical conditions necessary for nearly one-dimensional...
stream formation can be strongly violated in the case of a satellite on a circular orbit sufficiently close to the disk plane. In this case the vertical oscillation frequency varies substantially between stars and so they are dispersed perpendicular to the satellite’s orbit as well as along the orbit, forming a band or “tidal ribbon.” We suggest that the NW fan may consist of ribbon-like debris from a dwarf satellite in the process of being disrupted by NGC 4565. This class of tidal debris has not, to our knowledge, been observed previously.

To investigate this possibility, we have produced numerical simulations of tidal ribbons that qualitatively match both the global properties of NGC 4565 and the appearance of its fan using the Lagrange-stripping method of Fardal et al. (2015), as implemented in the galactic dynamics package gala (Price-Whelan 2017). For a given progenitor orbit and mass in a particular host potential, test particles are released at each time step with positions and velocities consistent with those expected for stars being stripped by tides and then integrated forward to the present. This technique produces realistic models quickly and allows a substantive exploration of parameter space.

The potential used in our simulations was constructed to approximately match NGC 4565’s H I rotation curve. The disk was modeled with a triple Miyamoto–Nagai (MN) approximation to an exponential disk (Smith et al. 2015). The triple MN disk mass density deviates from exponential at large radii and eventually becomes negative, but our model has positive mass densities everywhere due to the dark matter halo. The total mass of the disk is $10^{11} M_\odot$ and the radial scale length is 5 kpc. The dark matter halo was represented by a $10^{12} M_\odot$ Navarro–Frenk–White profile (Navarro et al. 1996) with $r_s = 25$ kpc. A Hernquist bulge (Hernquist 1990) of mass $3 \times 10^{10} M_\odot$ with a scale radius of 0.5 kpc was included as well.

We generated many tidal ribbons with varying initial radius (30–36 kpc) and velocity in the plane (190–220 km s$^{-1}$), viewed from four distinct edge-on sightlines. After some experimentation, the initial vertical velocity and displacement were fixed at 20 km s$^{-1}$ and 4 kpc to match the apparent width of the fan. Two representative tidal ribbons are shown in Figure 8. We consider surface mass density “images” as a simple proxy for visible light images. Both mock images show excess mass contributed by the ribbon affecting the shape of the overall surface mass density distribution near the edge of the disk, but having minimal impact on the rest of the galaxy.

From our imaging, we estimate the surface mass density of the ribbon surrounding NGC 4565 at $10^3 M_\odot$ kpc$^{-2}$ near the NW disk limb. The simulated ribbons’ mass densities at the edge of the disk approximately matches this value.

We have shown the results of 1.5 Gyr of interaction, but we were able to achieve similar structures with 1 Gyr of interaction. For longer simulations, the debris becomes more and more evenly distributed perpendicular to the progenitor’s orbit (more “ribbon-like”). We have fixed the ribbon progenitor mass at $10^9 M_\odot$; we are able to produce similar ribbons for less and more massive progenitors, but the impact of the debris on mock galaxy images is most similar to NGC 4565 for this mass. Both mock images include at least one rounded lobe that seems to wrap around one edge of the disk. The first image has rounded lobes above and below the plane on the right side of the disk, while the second image shows a rounded lobe only above the plane on the left side of the disk. The low surface brightness disk outskirts north and east of NGC 4565’s NW disk limb appear to drop off faster than anywhere else around the galaxy (Figure 4), and so the latter tidal ribbon morphology/orientation is a better match to this galaxy.

The simulated tidal ribbons both introduce new features at either side of their host galaxy’s disk. So far, we have focused on the prominent features at the NW disk limb and have neglected the opposite side of the disk. There does seem to be a linear feature extending from the south side of the disk toward a bright (masked) star, noted in Figure 4. Similar linear features are seen in the contours of the mock images with tidal ribbons. The low surface brightness glow surrounding the disk also seems to be more puffy north of the SE disk limb.

5.3. Other Scenarios to Consider

The tidal ribbon explanation is not unique, and does not preclude other processes from growing or influencing the outer disk of NGC 4565. Minor mergers (Zaritsky & Rix 1997), tidal interactions (Kornreich et al. 2002), and accretion of gas from the intergalactic medium (Bournaud et al. 2005) have all been suggested as possible causes of asymmetry in spiral galaxies. Halo asymmetry or outer disk instabilities have also been identified as possible internal causes of asymmetry (Zaritsky et al. 2013). In the case of NGC 4565, an external origin would not be surprising given the galaxy’s asymmetric warp at large radii (present in young stars and in H I).

The stronger NW truncation can be viewed as an excess relative to the SE side of the disk. In this case, the bluer color
about the truncation could be indicative of a recent gas-rich accretion event that has deposited material primarily at the truncation radius. Qualitatively, the bluest regions of the NW color profile fall in the radial range where the NW surface brightness exceeds the SE surface brightness. Outside of this range, the colors of both sides of the disk are more similar. In this interpretation, the underlying disk of NGC 4565 is approximately symmetric in surface brightness and color and there is little change in outer disk color from 25 to 34 kpc.

The fan and disk truncation asymmetry may have been induced by a satellite flyby. Price-Whelan et al. (2015) demonstrated that a satellite galaxy passing vertically through the midplane at a large distance of 80 kpc can induce asymmetric rings in the disk around 20–40 kpc. These rings propagated outwards and oscillated above and below the midplane by a few kiloparsecs, similar to the amplitude of the fan (see their Figure 8).

While the optical warp and the fan appear to be separate features due to their differing stellar populations, they may share a common origin. The stellar content of the warp region implies a recent gas-rich accretion event (Radburn-Smith et al. 2014). The fan could consist of disk stars ejected or excited by this event. Similarly, the fan could be associated with the disk’s asymmetry if it may be explained by another accretion event or by a satellite flyby. The outermost H I contours in the right panel of Figure 6 are similar to the fan’s shape, suggesting that there may be a gaseous component to the fan and that both disk stars and gas were ejected by the perturbing event.

6. Summary

We have presented deep imaging of NGC 4565, one of the first galaxies from the DEGS to be observed and reduced. In major axis slice profiles targeting the disk, we have found an end to the sharp NW disk truncation, a fan-like feature in the post-truncation disk, and another outer inflection point in the NW profile. We identified a distinct u-shape in the color profiles about the radius of the NW truncation.

Several possible origins for the disk asymmetry and fan feature were identified. We gave particular attention to the tidal ribbon hypothesis and produced some simple simulations that qualitatively replicate the fan. All of the scenarios outlined that may have helped shape the features seen on the NW side of NGC 4565 require some interaction with a satellite galaxy. We identified what may be the remnant of a dwarf galaxy in the vicinity of the warp, and IC 3571 and NGC 4562 are also two candidate perturbers. There are several other dwarf galaxies with similar line-of-sight velocities to NGC 4565 that are likely satellites. Additionally, many low surface brightness satellite candidates have been identified in our imaging (S. Danieli et al. 2020, in preparation).

We drew a connection with the recently discovered extended low surface brightness disk surrounding NGC 2841 (Zhang et al. 2018) as another feature that appears to have at least a partially accreted origin. The existence of these structures may inform the distribution of satellite galaxies around their hosts (and similar systems) as some formation scenarios require specific orbit parameters and orientations. To form a tidal...
ribbon, the satellite must be accreted in the plane on a disk-like orbit (with vertical oscillations comparable to the disk scale height). Any growth via accretion of the extended low surface brightness disk surrounding NGC 2841 would also require satellites with similar angular momentum to the existing stellar material (Zhang et al. 2018). Similarly, simulations of "mini-mergers" in the disk plane yielded radial disk growth without increasing the disk’s scale height (Karademir et al. 2019).

If satellite galaxies are generally accreted isotropically, low surface brightness structures like these in the outskirts of disks should be rare. If instead they are common, this would suggest a preferred direction for accretion of satellites. Our ongoing study of edge-on spiral galaxies through DEGS (C. Gilhuly et al. 2020, in preparation) will help clarify the frequency of these structures. The role that the accretion of satellite galaxies plays in (thin) disk growth merits greater attention.

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