The Lop-sided Spiral Galaxy NGC 247: Clues to a Possible Interaction with NGC 253

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Abstract

Observations that span a broad range of wavelengths are used to examine asymmetries in the disk of the nearby late-type spiral galaxy NGC 247. The northern spiral arm is over-luminous at all wavelengths when compared with other parts of the galaxy at similar galactocentric radii, while the density of very luminous red stars in the void that is immediately south of this arm matches that in other parts of the disk at the same galactocentric radius. Two bubbles with spatial extents of many kiloparsecs are identified in the disk, and many of the young stars in the southern disk of NGC 247 are located in the walls of these structures. Dynamical age estimates of these bubbles coincide with the last large-scale star formation event in the nucleus, suggesting that there was large-scale star formation throughout the disk of NGC 247 a few hundred megayears in the past. Morphological similarities are seen with the classical lop-sided galaxy NGC 4027, and it is concluded that NGC 247 is a significantly lop-sided spiral galaxy. The void in the northern disk is then the area between the main body of the disk and the northern arm viewed in projection. The implications of a lop-sided morphology for NGC 247 in the context of interactions with its nearby starburst galaxy companion NGC 253 are discussed.

Unified Astronomy Thesaurus concepts: Disk galaxies (391); Late-type galaxies (907); Spiral galaxies (1560); Interacting galaxies (802)

1. Introduction

Nearby galaxies are unique laboratories for examining the processes that shape galaxy evolution. NGC 247 is a nearby SAB(s)d (De Vaucouleurs et al. 1991) galaxy. While it is one of many seemingly non-descript late-type disk galaxies located within a few megaparsecs of our Galaxy, there are hints that NGC 247 has had an eventful past, and so might be of special interest. For example, there are hints that NGC 247 has interacted with another galaxy. The H I disk of NGC 247 is compact (Carignan & Puche 1990), and this characteristic is seen among galaxies in crowded environments (e.g., Chung et al. 2009). The stellar disk of NGC 247 also extends well beyond the H I disk (Davidge 2006), and spatially extended stellar disks may be the result of angular momentum transfer via interactions with other galaxies (e.g., Hammer et al. 2007). While galaxy–galaxy interactions are not in themselves rare events, NGC 247 is a companion of the much more extensively studied late-type spiral galaxy NGC 253 (Karachentsev et al. 2003), which is one of the nearest large starburst galaxies. The relationship between NGC 247 and NGC 253 might then provide clues into the cause of the starburst in the latter galaxy.

In addition to the evidence of a possible interaction, the recent specific star formation rate (sSFR) of NGC 247 suggests that it has been quiescent when compared with other spiral galaxies of similar mass. Based on the properties of bright main-sequence stars, Davidge (2006) found that the most recent episode of star formation ended ~6 Myr in the past, and that the recent SFR is ~0.1 M⊙ year−1. This SFR places NGC 247 almost an order of magnitude below the main sequence of galaxies on the sSFR versus stellar mass plane presented by Popesso et al. (2019).

The central regions of galaxies are the deepest part of the gravitational potential well and so, in the absence of feedback, are areas where star formation might continue after activity in the disk has been quenched. Galaxy nuclei should then harbor supplemental information about the past history of the host. Davidge & Courteau (2002) find that the J–K color of the NGC 247 nucleus is not remarkable. While the J–K color is redder than that of the circumnuclear surroundings and the nucleus of NGC 2403, it is similar to that of the center of M33. Kacharov et al. (2018) conclude from an analysis of blue and visible wavelength spectra that the nucleus of NGC 247 is predominantly old, with the bulk of stellar mass forming >1 Gyr ago. Still, the nucleus has not been quiescent during the past 1 Gyr, as there is evidence for an uptick in the nuclear SFR 0.1–0.5 Gyr in the past. Curiously, Kacharov et al. (2018) also find that the stars that formed at that time have super-solar metallicities.

The suggestion that stars with super-solar metallicities are present in the nucleus of NGC 247 is intriguing, as the integrated K brightness of NGC 247 (MK ∼−20.5 assuming a distance modulus of 27.9, see below, with Ktot = 7.4, Jarrett et al. 2003) is similar to that of M33. Young stars in NGC 247 should then have an M33-like (i.e., subsolar; Rosolowsky & Simon 2008) metallicity if NGC 247 falls along the metallicity versus stellar mass relation defined by other galaxies (e.g., Saviane et al. 2008). Barring a peculiar chemical enrichment scenario for the center of NGC 247, a super-solar metallicity for stars in this part of the galaxy might require a special origin for the gas from which they formed.

The morphological properties of a galaxy also yield insights into its past. The nucleus of NGC 247 is offset from the geometric center as defined by isophotes near the edge of the disk. NGC 247 also has a conspicuous asymmetry in the form of an area of low stellar density (hereafter referred to as the...
“void”) in the northern part of the disk (e.g., Carignan 1985). Finally, the rotation curve of NGC 247 is asymmetric along the major axis (Carignan & Puche 1990).

The nature of the void and other asymmetries in the disk are of obvious importance for understanding the evolution of the galaxy. Wagner-Kaiser et al. (2014) examine the stellar content in the void and find an absence of bright blue stars, suggesting a lull in recent star formation during at least the past 1 Gyr. They find that the void contains luminous red stars, signalling that a substrate of older stars is present. Referencing H I maps presented by Ott et al. (2012) and Warren et al. (2012), Wagner-Kaiser et al. (2014) note that the void also has a lower H I density than its surroundings, although there are areas with similar H I densities at other locations in the disk. Wagner-Kaiser et al. (2014) discuss mechanisms that might produce the void, and propose that it is a region of low gas content that is the result of the recent passage of a \( \sim 10^8 M_{\odot} \) dark subhalo that contains gas.

In the present study, the structure of the NGC 247 disk is examined using archival images that cover ultraviolet wavelengths. These images trace light from stars that formed during a broad range of epochs, including when NGC 247 may have experienced events that shaped its evolution. Efforts to study the morphology of NGC 247 are complicated by its oblique orientation on the sky. Therefore, the images are deprojected to provide a panoramic view of the galaxy, thereby facilitating the exploration of asymmetries in the disk.

During the past two decades, a number of studies have examined the distance of NGC 247, producing very similar results. Observations of Cepheids over a broad range of wavelengths yield a distance modulus between 27.6 and 28.0 (Garcia-Varela et al. 2008; Gieren et al. 2009; Madore et al. 2009), with the majority of measurements favoring a distance modulus of 27.8 (Gieren et al. 2009). For comparison, stars near the giant branch tip yield a distance modulus of \( \sim 27.9 \) (Davidge 2006; Karachentsev et al. 2006). The distance based on the giant branch tip is adopted for the present work, placing NGC 247 at a distance of 3.8 Mpc.

The paper is structured as follows. Details of the observations that serve as the basis for this study are presented in Section 2. Deprojected images of NGC 247 are used to examine the large-scale photometric characteristics of asymmetric structures in Section 3. The distribution of partially resolved objects in the SPITZER IRAC [3.6] and [4.5] images are discussed in Section 4, where the projected density of objects in the northern void is compared with that in other parts of the galaxy at similar galactocentric radii. Comparisons are made with a classic lop-sided spiral galaxy in Section 5, and it is concluded that NGC 247 is an overt lop-sided spiral galaxy. A discussion and summary of the results follows in Section 6.

### 2. Archival Images

Processed archival images recorded with the GALEX (Martin et al. 2005), WISE (Wright et al. 2010), and SPITZER (Werner et al. 2004) satellites are used in the present study. The SPITZER and WISE images were downloaded from the IRSA website.\(^3\) The GALEX observations were downloaded from the Nasa Extragalactic Database (NED).\(^4\)

\(^3\) https://irsa.ipac.caltech.edu/Missions/

\(^4\) https://ned.ipac.caltech.edu/classic/

The GALEX images are from the Atlas of Nearby Galaxies (Gil de Paz et al. 2007). The FUV images are most sensitive to massive stars that formed within the past few megayears, while the NUV images are more sensitive to lower mass stars that formed a few hundred megayears ago. When considered together, the FUV and NUV images thus probe light from stars that formed from the present day to the epoch that Kacharov et al. (2018) identify with recent star formation in the nucleus of NGC 247.

The WISE images are from the All-sky survey (Wright et al. 2010). The light that dominates the W1 and W2 images originates predominantly in luminous red stars that formed during early or intermediate epochs; hence, the W1 and W2 images trace stellar mass. In contrast, much of the light sampled in the W3 and W4 images may originate from thermal emission, and in late-type spiral galaxies such as NGC 247 much of the emission at these wavelengths comes from dust that is heated by massive main-sequence stars (e.g., Cluver et al. 2014) and/or post-asymptotic giant branch (AGB) stars. While much the same can be said for W4 observations, the W3 images detect fainter structures than those in W4 and have better angular resolution. Given that the depth and image quality of the W1 and W3 images are superior to those in W2 and W4, it was decided to consider only the W1 and W3 images for this study.

The SPITZER IRAC (Fazio et al. 2004) recorded [3.6] and [4.5] images of NGC 247 as part of the SPIRITS Survey (Kasiwal et al. 2017). The galaxy was observed a number of times, and the images cover a range of epochs and on-sky orientations. However, only two pointings include the void and the northern spiral arm that are important targets for the present study. These have astronomical observation request (AOR) identifications 50548736 and 50548992, and only images from these AORs are considered here.

### 3. Integrated Light in the UV and IR

NGC 247 is inclined to the line of-sight, and images were generated to simulate the face-on appearance of the galaxy. This was done by assuming that the disk is infinitely thin and restricted to a single plane. An inclination of 74° was adopted, as deduced from H I observations by Carignan & Puche (1990).

With the assumptions described above, a deprojected image can be constructed by stretching the disk along the minor axis by an amount defined by the inclination. Circular isophotes will result if the disk is symmetric and the inclination is correct. This procedure is passive in nature, as signal is neither added to nor subtracted from the original image. Rather, the manner in which information in the images is presented is altered by compressing the frequency distribution along one axis in a linear (i.e., reversible) way. The structures discussed here are present in the original images, although they tend to be less obvious in those images due to the orientation of NGC 247 on the sky. Deconvolution filters can be applied to assess distortions introduced by deprojection, and this is discussed in the Appendix.

There are inherent limitations to deprojecting a three-dimensional structure using two-dimensional information. The deprojection procedure used here does not account for three-dimensional features such as warps that might result from, say, tidal interactions. Warps will smear the deprojected image, with asymmetries in the overall structure being one possible result. Still, there are indications that warping is not a...
factor in NGC 247. Carignan & Puche (1990) do not find evidence of warping in HI observations of the outer disk of NGC 247, although they do find that the rotation curve is highly asymmetric along the major (roughly north–south) axis. Hlavacek-Larrondo et al. (2011) also do not find evidence of warping in Fabry–Perot Hα observations of NGC 247.

The finite thickness of disks is another factor that could introduce smearing, and the extent of this smearing becomes progressively more important as one moves to larger inclination angles. However, stars with different ages have different characteristic distance dispersions from the disk plane, and so the degree of smearing depends on the age of the population being studied. Images that sample younger stars, such as those recorded through the FUV or NUV filters, should be less susceptible to disk thickness effects than, say, the W1 image. A comparison of images that sample populations with very different ages then have the potential to monitor smearing induced by disk thickness; structures that appear in deprojected images that span wide wavelength ranges will likely not be artifacts of disk thickness. An obvious complication is that the spectral energy distributions of stellar populations will also introduce differences between images that span a broad wavelength range.

Observed and deprojected images of NGC 247 are shown in Figures 1 (FUV and NUV images) and 2 (W1 and W3 images). The eighth-magnitude foreground star 2MASS00470164-2052106 is seen against the southern disk of NGC 247 and is a prominent feature in the W1 and W3 images. Light from this star was subtracted from the images prior to deprojection. Low-level noise artifacts remain, and the area that contains these is indicated with a blue box in Figure 2.

3.1. Diffuse UV Light

Much of the light in the GALEX FUV and NUV images originates from young, massive stars, and these define prominent structures in the deprojected UV images. There is a concentration of bright sources near the northern and eastern edge of the spiral arm that defines the northern edge of the disk (hereafter the “northern arm”). There is also a serpentine-like structure that winds its way south of the nucleus that is also prominent in the distribution of young stars shown in Figure 8 of Rodriguez et al. (2019). Deprojection reveals that this structure appears to be the walls of circular bubbles, which are discussed at greater length in the next section.

The northern void has a surface brightness in the UV images that is markedly lower than its surroundings and is close to background values. Still, the presence of diffuse light in the northern void in the deprojected NUV image suggests that it may contain stars that formed a few hundred Myr in the past. Main-sequence turn-off (MSTO) stars of this age fall below the faint limit of the images discussed by Wagner-Kaiser et al. (2014). The northern void is also not unique, as there is a notch-like area at the edge of the southern disk that is deficient in hot stars.

A map of FUV–NUV colors generated from the deprojected GALEX images is shown in the middle column of Figure 3. The northern arm has blue FUV–NUV colors that extend over much of its angular extent, highlighting it as an area of very recent star formation. The northern void has an FUV–NUV color that is not unique in the NGC 247 disk, although UV colors are sensitive to variations in extinction.

A radially symmetric light profile was constructed by combining azimuthally the light in each of the deprojected

Figure 1. GALEX FUV and NUV images of NGC 247, rotated so that the major axis is vertical. North is indicated in the upper left panel. As with all images shown throughout this paper, the intensity map has been inverted to produce a negative image. The left column shows the observed images, while the middle column shows the images deprojected with an assumed inclination of 74°. The right column shows the deprojected images after the subtraction of an azimuthally symmetric model of diffuse light. The northern void is seen in both filters. The northern spiral arm is the dominant structure after the removal of the smooth disk component, highlighting the lop-sided nature of the galaxy. In addition to the northern void, there is also a region with little or no FUV and NUV signal at the southern edge of the disk. Prominent ring-shaped structures are also seen in the deprojected images.
GALEX images. The nucleus was taken to be the true center of the galaxy, and the median signal at each radius was found. The median, rather than the mean, was taken at each radius to suppress the discrete structures that dominate the UV images. The disk profile constructed solely from the southern half of the disk, where there are fewer asymmetries than in the northern half of the disk, is similar to that obtained from the entire disk. While a model of diffuse disk light could be extracted from a conventional isophotal analysis, the intent of the current work is to examine asymmetric structures in the disk, justifying the use of the azimuthal smoothing technique employed here.

The results of subtracting the diffuse disk component from the deprojected FUV and NUV images are shown in the right column of Figure 1. The asymmetric distribution of recent star formation sites in NGC 247 is highlighted with the removal of diffuse light. The northern arm is the dominant UV structure in the disk-subtracted images, emphasizing the lop-sided nature of NGC 247 at these wavelengths.

3.1.1. Rings in the Disk

Prominent large-scale bubbles are seen in the deprojected UV images, and two of these are examined in Figure 4. The circular shape of these bubbles is suggestive of expansion into a uniform interstellar medium (ISM). One of the rings is near the base of the northern arm and is adjacent to the void. This ring has a diameter of \( \sim 100'' \), or \( \sim 2 \) kpc, placing it within the size range found in dwarf galaxies (e.g., Pakhrel et al. 2020). The other ring is in the southern part of the disk and has a diameter of \( \sim 180'' \), or \( \sim 3.3 \) kpc, making it larger than bubbles found in dwarf galaxies.

The light in the rings originates from diffuse nebular emission and light from discrete sources, with the latter including bright stars, H\( \text{II} \) regions, and compact star clusters. Individual sources are seen inside the bubbles, although none are near the geometric centers of the rings. Both rings intersect with concentrations of bright blue stars in Figure 8 of Rodriguez et al. (2019), as well as with H\( \alpha \) emission sources in Ferguson et al. (1995). Neither ring stands out in the W1 or W3 images. This is not unexpected, since even though discrete hot sources will power hot dust emission that could be detected in the W3 image, on their own, discrete sources may not define an obvious ring structure. Neither ring stands out in the HI maps discussed by Braun (1995).

The southern ring is part of an extensive distribution of young stars. Figure 8 of Rodriguez et al. (2019) shows the distribution of bright stars in the southern half of NGC 247, and the majority of these define a serpentine-like structure. The lower part of this structure forms one arc of the southern bubble shown in Figure 4. The bright stars to the north of this form a counter-arc in the deprojected image, and there is a less well-defined bubble immediately above the southern bubble in the left panel of Figure 4. The diameter of this other bubble is similar to that of its southern neighbor, suggesting a similar age.

Dynamical age estimates for the rings can be found if the expansion velocity is assumed. A caveat is that a single expansion velocity likely does not apply throughout the lifetime of a bubble, since the bubble shock front will encounter inhomogeneities in the ISM as it expands. Still, Puche et al. (1992) examine superbubbles in the dwarf galaxy Holmberg II, and their HI observations reveal structures that
span a range of sizes and ages. The dispersion in expansion velocities is only a few kilometers per second, suggesting that variations in expansion velocity with age may not be substantial in that galaxy. The largest bubbles in their sample have expansion velocities of \( \sim 7 \text{ km s}^{-1} \). Applying this velocity to the southern bubble in NGC 247 yields an age of 230 Myr, while, for the northern bubble, an age of 150 Myr is found. These age estimates fall within the range of ages estimated for the latest episode of star-forming activity in the nucleus of NGC 247 by Kacharov et al. (2018). The bubbles in Figure 4 may then have formed as part of a large-scale episode of star formation that also included the galaxy nucleus. In fact, one model for bubble formation proposes that they are the result of outflows from concentrated areas of star formation, with star formation induced in the bubble as a shock front moves outward (e.g., McCray & Kafatos 1987). This mechanism satisfies the energy balance requirements needed to produce bubbles in dwarf galaxies (Warren et al. 2011).

There are bubbles, including those in the NGC 247 disk and many of those studied by Warren et al. (2011), that lack an obvious central OB association or H\textsc{ii} region. This could simply be because the central source has aged and faded with time. The age estimates for the NGC 247 bubbles, as well as many of those studied by Puche et al. (1992), are consistent with such an explanation. Still, it has also been suggested that bubbles may result from the infall of high-velocity clouds (HVCs; e.g., Park et al. 2016). An intriguing feature of interactions with HVCs in the case of NGC 247 is that they may deliver material to the galaxy that does not reflect its chemical enrichment history. An infall of material stripped from another galaxy, notionally NGC 253 in the case of NGC 247, might then provide a means of delivering metal-enriched material into the regions near the NGC 247 nucleus, thereby explaining the presence of the metal-rich population found by Kacharov et al. (2018).

### 3.2. Diffuse IR Light

The inner disk of NGC 247 in the deprojected W1 image has a comparatively smooth light distribution that is centered on the galaxy nucleus and extends over \( \sim 11' \). The central few arcminutes of the W1 image have a boxy morphology that includes a central bar. The northern spiral arm is also a prominent feature in W1, reinforcing the visual impression of NGC 247 as a lop-sided spiral galaxy.

The surface brightness of the void in the deprojected W1 image is higher than in the background, and is not greatly different from that in other parts of the disk at similar galactocentric radii. This similarity in red stellar density is demonstrated further in Section 4 using star counts. The void near the southern edge of the disk that was identified in the FUV and NUV images is not evident in the W1 image, indicating that this feature is populated by red stars, like its northern counterpart.

While there is expected to be some similarity between the UV and W3 images, the diffuse component in the W3 image in Figure 2 is more centrally concentrated than in the UV, as expected if the light originates from stars that span a broader age range than in the UV. If there was large-scale star formation in the NGC 247 disk a few hundred megayears in the past (Section 3.1.1), then some of the sources in the W3 image may be dust-enshrouded AGB stars. Much of the light in the W3 image is in the southern part of the disk.

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**Figure 3.** UV and IR colors in the deprojected disk of NGC 247. Lighter shading indicates redder colors. The deprojected NUV image from Figure 1 is shown to aid in the identification of structures, and the void is marked with a green box in each panel. The northern void has a UV color that is not remarkable when compared with other areas in the disk. The void has a blue color in the W1–W3 map, and the white area in the void is likely due to low signal in the W3 image. The northern arm has blue UV colors and red W1–W3 colors, and this is consistent with it being an area that contains very hot stars that are heating nearby dust.

**Figure 4.** Two large-scale bubbles in the disk of NGC 247. The deprojected disk-subtracted NUV image of NGC 247 is shown to the left, while the areas centered on the northern (top) and southern (bottom) bubbles are shown to the right. Sources are seen inside both bubbles, although none are near the geometric centers. Note that there is also a less well-defined bubble immediately above the southern bubble in the disk-subtracted NUV image.
W1–W3 colors in NGC 247 are shown in the right panel of Figure 3. There are sources with red W1–W3 colors in the northern spiral arm, and this is consistent with thermal emission from hot dust that is heated by young stellar groupings. The northern void also contains pockets of localized blue W1–W3 color, although the W3 signal is weak there, making integrated light measurements uncertain in that filter. In fact, the white area in the void in the W1–W3 color map corresponds to an area of low W3 signal. Still, the overall W1–W3 color of the void is not exceptional, as there are other areas in the disk that have a similar color.

The result of subtracting a radially smoothed light profile from the W1 image is shown in the right column of Figure 2. The residuals near the galaxy center are due to the removal of a symmetric light profile from a region that contains a bar. There are also negative residuals in the northern void in the disk-subtracted W1 image in Figure 2. While seemingly at odds with the void W1 surface brightness noted earlier in this section, as well as with star counts (Section 4), we suspect that the low surface brightness in the disk-subtracted W1 image may be an artifact of the radial smoothing procedure in the presence of asymmetries. In fact, a similar result is seen in the space between a tidal arm and the main disk body of a classic lop-sided galaxy that is similar in appearance to NGC 247 (Section 5). The prominent nature and large angular extent of the northern spiral arm is consistent with NGC 247 being a lop-sided spiral galaxy.

The residuals in the disk-subtracted W3 image highlight the star-forming regions and luminous AGB stars in the NGC 247 disk. While the northern spiral arm is prominent after the removal of diffuse light, it is the sources in the southern part of the disk that are the most luminous in the W3 image. The northern void in the disk-subtracted W3 image also has a lower than average surface brightness for that radius, in agreement with what is seen in the UV.

### 3.2.1. The Smoothed Infrared Light Profile

Carignan (1985) examined the light profile of NGC 247 at blue and red wavelengths. The profiles at both wavelengths show a central cusp that extends over 2–3 kpc in radius, and a disk component that can be traced out to at least 20 kpc. Carignan (1985) also notes that NGC 247 has a comparatively low central surface brightness. The blue and red profiles of NGC 247 have very different behavior at large radii; while the red profile defines a single exponential that extends over much of the galaxy, the blue profile flattens at large radii, suggesting a gradient in luminosity-weighted age in the outer disk. Davidge (2006) resolved bright blue stars at large radii in NGC 247, with MSTO ages between \(\sim 16\) Myr and \(\sim 40\) Myr, confirming that a young component is present at large radii.

The azimuthally smoothed light profile constructed from the W1 image is shown in Figure 5, where a distance of 3.8 Mpc has been assumed. The W1 profile can not be characterized by a single exponential law, and there is no evidence of truncation. The W1 profile is similar in shape to the Carignan (1985) blue profile, in the sense that both profiles flatten at large radii. The blue and W1 light profiles are suggestive of a Type III (i.e., anti-truncated; Erwin et al. 2005) morphology, although we caution that the red profile from Carignan (1985) follows a single exponential profile. Type III profiles have been attributed to external drivers, such as interactions (e.g., Younger et al. 2007; Roediger et al. 2012). However, secular factors, such as the initial angular momentum of a system can also produce a Type III profile (Herpich et al. 2015).

### 4. The Angular Distribution of IR Sources

The brightnesses of luminous red objects in the NGC 247 disk can be measured from the SPITZER images discussed in Section 2, although the poor intrinsic resolution of the observations (\(\sim 800\) parsecs\(^2\) per resolution element at the distance of NGC 247) means that what appear to be individual sources are in reality blends. The certainty of blending notwithstanding, the light in individual resolution elements that do not contain large star clusters might be dominated by a single intrinsically bright star, and this expectation is consistent with the peak brightnesses in the NGC 247 CMD (see below). In any event, the identification of unblended sources is not critical for the comparative analysis that is conducted here.

The brightnesses of objects in the SPITZER images were measured with the point-spread function (PSF)-fitting program ALLSTAR (Stetson 1994), with the PSFs, source catalogs, and initial photometric measurements that are used by ALLSTAR generated with routines in DAOPHOT (Stetson 1987). The resulting ([3.6], [3.6]–[4.5]) CMDs of stars in four radial intervals are compared in the top portion of Figure 6. The northern void is located in the 480″–660″ interval.

With the exception of a smattering of sources that may be dust-enshrouded stars or background galaxies, the majority of points in the CMDs define a vertical sequence. This vertical trajectory is due to the low temperature sensitivity of objects at MIR wavelengths that have effective temperatures that are characteristic of stellar photospheres (i.e., \(\log(T_{\text{eff}}) \gtrsim 3\)). The faint limit in the CMDs shown in Figure 6 moves to progressively fainter magnitudes as the radius grows, reflecting the effect of stellar density on the faint limit.

Foreground stars and background galaxies occur in significant numbers at the magnitudes examined in Figure 6. To estimate the angular densities of these contaminants, number counts were made in one corner of the SPITZER images where there is little or no contribution from bright sources belonging to NGC 247. The resulting number counts are compared with those in the four radial NGC 247 intervals in the lower panel of Figure 6.

The angular densities of objects in all four intervals exceed that in the control field when \([3.6] \sim 17\), indicating that \([3.6] = 17\) is the approximate peak of the CMD sequence throughout much of NGC 247, again with the caveat that many NGC 247 sources are expected to be blends. Blending should be most noticeable in the innermost annulus, and there is an excess number of sources with respect to foreground/background objects near \([3.6] \sim 16\) in that annulus. These objects are intrinsically brighter than individual stars (see below), and are probably compact star clusters and/or stochastic density fluctuations. There is not an obvious transition signature in the CMDs in Figure 6 near \([3.6] = 16–17\) due to the modest temperature sensitivity of the [3.6]–[4.5] color, although there may be an onset in the number of objects to the right of the vertical sequence at [3.6] magnitudes between 16 and 17.

Blum et al. (2006) examine the IR properties of stars in the LMC, and their results provide benchmarks for interpreting the NGC 247 CMDs. Assuming a distance modulus of 18.5 for the LMC, red supergiants (RSGs) in the LMC have a peak absolute magnitude of \(M_{\text{[3.6]}} = -10.5\), while AGB stars have...
M_{[3.6]} = -9.5. In NGC 247, these correspond to [3.6] = 17.5 for RSGs and [3.6] = 18.5 for AGB stars.

The spatial distribution of stars in the deprojected disk is examined in Figure 7. The comparisons made in the lower panel of Figure 6 indicate that the majority of sources in the left panel are likely foreground/background objects, and this is consistent with the uniform distribution of sources in that panel that are more than a few tens of arc seconds from the nucleus. The modest number of sources in the left panel that are clustered near the nucleus of NGC 247 are likely unresolved star clusters and/or statistical fluctuations. The more concentrated nature of sources in the right panel are consistent with many of the objects in the [3.6] = 17—18 interval belonging to NGC 247.

The location of the northern void is indicated in both panels of Figure 7, as are the locations of three reference fields at the same galactocentric radius as the void. If the stellar content of the NGC 247 disk is well mixed, the incidence of blending should be the same in areas that have the same stellar density. Comparisons of photometric properties between areas that have similar surface brightnesses thus provide a means of assessing whether or not there are differences in the properties of the brightest stars even in the presence of blending. The distribution of stars in the right panel of Figure 7 indicates that the number of IR bright stars in the northern void is not remarkable when compared with other parts of the disk at similar galactocentric radii. This is consistent with the deprojected W1 image that was examined in the previous section, where the surface brightness of the void was found to be consistent with its location in NGC 247.

The ([3.6], [3.6]−[4.5]) CMDs of sources in the northern void and the disk reference areas indicated in Figure 7 are compared in the top panel of Figure 8. There are a modest number of objects with [3.6]−[4.5] > 1 in all four CMDs with [3.6] > 18, and these are resolution elements where the light might be dominated by C stars. The number densities of these very red objects are similar in all four fields.

The LFs of stars in the void and the disk reference areas are compared in the lower panel of Figure 8, along with number counts from the control field. Comparisons with the control field are consistent with the main body of sources in the NGC 247 SPITZER images having [3.6] > 17, in agreement with that found in Figure 6 using larger areal coverage. In addition, while Wagner-Kaiser et al. (2014) find that there has not been recent star formation in the void during the past 1 Gyr, the similarities between the LFs in Figure 8 suggests that the number density of stars in the northern void that formed during later epochs agrees with that in other parts of the disk at the same radius.

5. Comparisons with the Lop-sided Spiral Galaxy NGC 4027

That NGC 247 is a lop-sided spiral galaxy has important implications for understanding the nature of the northern void. A lop-sided morphology opens the prospect that the northern void is the gap between the main body of the disk and the
densely populated (when compared with other parts of the galaxy at the same galactocentric radius) northern spiral arm when seen in projection. Comparisons with the photometric properties of well-established late-type lop-sided spirals are then of obvious interest.

NGC 4027 (Arp 22) is a lop-sided late-type barred spiral galaxy that is viewed almost face on. NGC 4027 has the second-highest $A_1$ Fourier coefficient in the Zaritsky & Rix (1997) K-band sample of lop-sided spiral galaxies, placing it in their “significantly lop-sided” category. NGC 4027 is in the same group of galaxies as the interacting pair NGC 4038 and NGC 4039 (the “Antennae”), and Phookun et al. (1992) detect a ring of gas around NGC 4027 that they attribute to an interaction with a companion.

NGC 4027 is a good reference object for the current study as it is viewed almost face on, has an unmistakeable lop-sided character, is relatively nearby by cosmic standards, and has a body of high-quality observations. We emphasize that the comparisons made here do not assume that NGC 247 and NGC 4027 have similar global properties (e.g., total mass, mass-to-light ratio, environment, etc.) and/or SFHs. Rather, we simply compare their appearances at wavelengths that sample the dominant contributors to stellar mass.

W1 and [3.6] images of NGC 4027 were downloaded from the IRSA website. The [3.6] images are the AOR 49579264 observations from SPITZER program 10046 (PI: D. B. Sanders). While sampling a similar range of wavelengths, the W1 and [3.6] images have different image qualities and photometric depths. Systematic effects that arise from the differences between these quantities simulate the impact of distance on the observations, which in turn affects intrinsic resolution within a galaxy and the brightnesses of sources that

Figure 6. ([3.6], [3.6]–[4.5]) CMDs of stars in four radial intervals in NGC 247 are shown in the top row. The angular distances shown in each panel are measured from the galaxy nucleus in the deprojected images. Stars in the northern void are in the 480°–660° interval. The LFs of objects in these intervals, as well as that of a control field selected to monitor objects that are not members of NGC 247, are compared in the bottom panel, where $N_{0.5}$ is the number of objects per square deprojected arcminute per 0.5 magnitude interval in [3.6]. The source counts for the innermost region are consistently higher than in the other three regions at the bright end, and these are likely unresolved star clusters and density fluctuations in the central regions of the galaxy. The density of sources in all four fields exceed those in the control field near [3.6] = 17, suggesting that many of the objects with [3.6] > 17 belong to NGC 247.
can be detected within a galaxy. NGC 4027 images in the FUV, NUV, and W3 filters are not considered since the present comparison is restricted to the global morphological properties of NGC 247 and NGC 4027 as defined by the stars that contribute most to their stellar masses.

As with the NGC 247 images, the W1 and [3.6] images of NGC 4027 were rotated to align the major axis with vertical. A smooth disk component was then constructed by azimuthally averaging the light profile about the nucleus, and the result was subtracted from the downloaded images. The initial rotated and disk-subtracted images of NGC 4027 are shown in the left and central columns of Figure 9.

The disk-subtracted W1 and [3.6] images of NGC 4027 are broadly similar, suggesting that distance effects should not be an issue when making comparisons with NGC 247. Of greater importance for the present work is that there are clear similarities between the deprojected and disk-subtracted images of NGC 4027 and their NGC 247 counterparts in the top row of Figure 2. As with NGC 247, there is a prominent spiral arm along the major axis of NGC 4027 that stands out after disk subtraction. There is also residual structure near the center of the disk-subtracted image of NGC 4027 that is similar to that near the center of NGC 247. The area between the upper spiral arm and the main body of NGC 4027, which corresponds to the northern void in NGC 247, has negative residuals in the disk-subtracted image, as is seen in the corresponding NGC 247 image.

The NGC 4027 images were also compressed to simulate its appearance if viewed with the same line-of-sight inclination as NGC 247 and the results are shown in the right column of Figure 9. There is good overall agreement between these NGC 4027 images and their NGC 247 counterpart in Figure 2. The space between the upper spiral arm and the main body of the NGC 4027 disk is similar in appearance to the void in NGC 247.

The NGC 4027 light profile that was obtained by azimuthally smoothing the W1 image is shown in Figure 5. While there is a clear offset in surface brightness, there are clear similarities with the shape of the NGC 247 light profile. The NGC 4027 light profile cannot be characterized by a single exponential and extends out to large radii without signs of truncation.

6. Discussion and Summary

Archival UV and IR images have been used to examine the structure of the late-type spiral galaxy NGC 247. This galaxy is of particular interest as (1) it is a companion of the starburst galaxy NGC 253 and (2) it has been suggested that there was an interaction with a dark halo within the past 1 Gyr that scoured gas from its disk. The light in the images examined in this paper originates from stars that span a range of stellar ages from the youngest (FUV, NUV, and W3 images) to the oldest (W1 images) stars. The images have been deprojected to examine the face-on appearance of the galaxy. Disk light that is uniformly distributed in the azimuthal direction has also been removed to enhance asymmetries.

The main conclusions are as follows:

(1) The surface brightness of the northern spiral arm of NGC 247 exceeds that in other parts of the disk at the same galactocentric radii. This applies over a wide range of wavelengths, suggesting that the northern spiral arm contains a comparatively high number density of stars that span a range of ages. This does not mean that the northern spiral arm is an old structure, but simply that it contains stars that formed over a range of ages. The age of this structure notwithstanding, it gives the disk of NGC 247 a highly lop-sided appearance when viewed face on.

(2) While the incidence of blending is high in the SPITZER images, it is still possible to conduct a differential comparison between areas that have similar stellar densities. The density of luminous red sources in the northern void of NGC 247 measured from the SPITZER [3.6] and [4.5] images agrees with that in other parts of the galaxy at similar galactocentric radii. This agreement applies not only to the total number of detected sources, but also to LFs. This agreement is consistent with the void being the gap between the northern spiral arm and the main body of the disk in a lop-sided system (see below). Blending issues aside, a detailed assessment of the SFH based on these data is complicated by stellar variability among luminous evolved stars, which blurs age sensitivity at these wavelengths (Davidge 2014).

(3) Prominent bubbles are seen in the UV images. One is near the base of the northern spiral arm, while a second is in the southern disk. Light from these bubbles likely
originates from young stars and nebular emission, and their presence hints at widespread star formation within the past 1 Gyr. Indeed, dynamical ages have been estimated for these bubbles by adopting expansion velocities measured for similar structures in the disk of Holmberg II by Puche et al. (1992), and the results coincide with a recent episode of elevated levels of star formation in the nucleus of NGC 247. We speculate that the luminous sources in the central few kiloparsecs of NGC 247 that are seen in the W3 image are luminous dust-enshrouded AGB stars that also formed at this time.

While large-scale bubbles are usually attributed to energy injected into the ISM by star-forming activity, Mirabel & Morras (1990) find that the accretion of HVCs by the Galaxy can inject significant amounts of energy into the ISM that can be comparable to what is needed to form supershells (e.g., Park et al. 2016). If this is the case, then the area of highly active star formation in the NGC 247 may have been localized near the areas affected by HVCs within the past 1 Gyr.

(4) Images of NGC 247 that are processed to simulate a face-on orientation show similarities with the classic lop-sided spiral galaxy NGC 4027 (Arp 22). Not only do NGC 247 and NGC 4027 have similar asymmetric structure, but they also have azimuthally smoothed light profiles with similar shapes. The gap between the dominant spiral arm and the main body of the disk in both galaxies is deficient in light in W1 after light from a smooth disk component is removed. Given the evidence that NGC 247 is a lop-sided spiral galaxy, then the northern void is actually the gap between the high surface brightness northern spiral arm and the main body of the disk.

NGC 4027 is an example of a “significantly” lop-sided spiral galaxy using the structural criterion discussed by Zaritsky & Rix (1997), and the comparisons made here indicate that this characterization also holds for NGC 247.

**Figure 8.** ([3.6], [3.6]–[4.5]) CMDs of stars in the northern void (left panel), and the reference areas indicated in Figure 7. The LFs of all four regions are compared with the LF of the foreground/background control field in the lower part of the figure, where $N_{0.5}$ is the number of stars per 0.5 magnitude interval in the [3.6] filter per square arcminutes. The LFs of the four fields are similar when [3.6] > 17, and this is also where the star counts are consistently higher than in the control field. The number density of luminous red sources in the void agrees well with that in the disk reference fields.
247. We emphasize that similarity in appearance does not imply that NGC 247 and NGC 4027 have had similar SFHs or have been subject to similar evolutionary processes. Lop-sided structures can result from a number of factors (see discussion below), and NGC 247 and NGC 4027 are in very different environments.

Rudnick et al. (2000) find comparatively high SFRs in lop-sided systems. While the apparent low present-day SFR in NGC 247 appears to run counter to this, the quenching timescale for star bursts in low-mass galaxies is 0.5 − 1.3 Gyr (e.g., McQuinn et al. 2010). It is then possible that elevated levels of star formation in NGC 247 within the past few hundred megayears may have been recently quenched.

Lop-sided spiral galaxies are not rare (e.g., Bournaud et al. 2005; Reichard et al. 2008), suggesting that the formation of the asymmetries that define these galaxies is somehow tied to events that are common in disk galaxy evolution (Zaritsky et al. 2013). A number of mechanisms have been forwarded to explain the origins of lop-sided disks (e.g., Reichard et al. 2009; Zaritsky et al. 2013 and references therein), and these can be categorized as external (e.g., tidal interactions, mergers, and the cosmological accretion of gas) and internal (e.g., secular evolution and asymmetries in the halo) in nature. Zaritsky et al. (2013) suggest that weak lop-sided structure is tied to internal origins, such as halo asymmetries. If this is correct, then the large-scale nature of the asymmetric disk of NGC 247 makes it likely that its lop-sided nature is external in origin. Therefore, two external mechanisms (tidal interactions and gas accretion) are discussed here to assess their viability as possible causes of the lop-sided nature of NGC 247.

Zaritsky & Rix (1997) discuss evidence of a tidal origin for asymmetric arms. Tidal arms likely arise from an interaction during the past 1 Gyr (i.e., within a few disk rotation times), and tend to have elevated SFRs (e.g., Holincheck et al. 2016) when compared with the main body of the host galaxy. The latter is consistent with the FUV and IR observations of the northern spiral arm in NGC 247 that indicate it is an area of concentrated star-forming activity. The transfer of angular momentum due to an interaction could also form an extended disk (e.g., Hammer et al. 2007), with a Type III light profile (e.g., Younger et al. 2007 but see also Herpich et al. 2015), as might be the case for NGC 247 (Section 3).

If the northern arm in NGC 247 is tidal in origin, then where is the perturbing galaxy? Arguably the most obvious candidate is the well-studied starburst galaxy NGC 253. NGC 247 and NGC 253 are close together physically (Karachentchev et al. 2003), and have angular momentum vectors that are consistent with a common origin (Whiting 1999), and/or a history of angular momentum exchange. An interaction between NGC 247 and NGC 253 may have triggered the elevated levels of star formation that are seen at this day in the latter galaxy. In fact, the timing of the uptick in the nuclear and circumnuclear SFR of NGC 247 a few hundred Myr in the past found by Kacharov et al. (2018), and the ages estimated for bubbles in NGC 247 in Section 3 more-or-less coincide with the timing of

![Figure 9. W1 and [3.6] images of NGC 4027, rotated so that the major axis of the galaxy is aligned with vertical. The initial rotated images are shown in the right column, while the middle column shows the results of subtracting an azimuthally smoothed disk component. Differences due to image quality and exposure time are such that the W1 image simulates NGC 4027 as it would appear if viewed by SPITZER in [3.6] at a distance that is 4–5× greater than its actual value. The right panel shows NGC 4027 as it would appear if viewed with the same line-of-sight inclination as NGC 247. The apparent “void” in the NGC 4027 disk when the galaxy is tilted to the line of sight is the region between the main body of the disk and the perturbed spiral arm.](image-url)
the onset of the NGC 253 starburst (e.g., Davidge 2010). As the nearest galaxy of comparable size to NGC 247, NGC 253 may also have been a donor of chemically enriched material for star formation, thereby accounting for the higher-than-expected metallicity of recently formed stars found by Kacharov et al. (2018).

There are problems with a recent tidal interaction between NGC 247 and NGC 253. Perhaps the most significant of these is that a debris field would be a likely outcome of such an event. However, a debris field between NGC 247 and NGC 253 has yet to be detected.

There are alternatives to a close encounter with NGC 253 that could explain a tidal origin for the northern spiral arm in NGC 247. NGC 247 and NGC 253 are accompanied by an entourage of smaller companion galaxies, and most of these appear to be centered around NGC 247 (Karachentsev et al. 2003). However, these galaxies are modest in size, and it is unlikely that they could induce a large-scale tidal feature like the northern arm.

NGC 247 may also have been perturbed during a flyby encounter with another galaxy. The identification of the perturbing galaxy in such an encounter is problematic, given that the interaction happened hundreds of megayears in the past. While the Sculptor group has considerable depth along the line of sight, most of its galaxies are within 1 Mpc of NGC 247 (Karachentsev et al. 2003). Given that NGC 247 and NGC 253 are physically close, then a flyby might even have triggered elevated SFRs in both galaxies.

Bournard et al. (2005) point out that tidal interactions cannot explain all of the properties of lop-sided spirals, and suggests that asymmetries may also be induced by the accretion of cosmological gas. Dupuy et al. (2019) discuss the accretion of HVCs onto barred spirals and conclude that they can produce low amplitude lop-sided structure. This conflicts with the large-scale nature of asymmetries in the NGC 247 disk. Reichard et al. (2009) also note that the events that drive lop-sidedness tend to involve the inflow of low-metallicity gas, and this is contrary to what has been inferred for recently formed stars near the center of NGC 247 by Kacharov et al. (2018).

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**Appendix**

**Deconvolution Experiments**

The deprojection procedure described in Section 3 elongates the PSF in images, smearing light along one axis. To examine the effect of this smearing on diffuse sources in the disk of NGC 247, Wiener filters were applied to the deprojected NUV image to correct for this distortion. One filter (“aggressive Wiener”) was designed to reproduce a Gaussian PSF with a full width at half maximum (FWHM) that matches the PSF in the original (i.e., with no deprojection) image. Such a filter greatly amplifies noise in the frequency spectrum along the elongated axis. A less ambitious filter (“moderate Wiener”) was also generated to produce a Gaussian PSF with a FWHM that is midway between that of the original and elongated PSF.

The deconvolved images are shown in Figure A1. The low-frequency response function of the filters produce streaks that become evident when the filter is convolved with very bright sources. The streaks are along the horizontal axis as that is the orientation of the distortions that the filters are designed to correct. The filter response artifacts extend over large angular scales as the low-frequency component of the signal must be altered substantially to produce a symmetric Gaussian PSF from the elongated PSF. Ringing is also seen in the image produced with the aggressive Wiener filter. All in all, the artifacts of the deconvolution procedure highlight the pitfalls of extracting information from portions of the frequency spectrum that have a low signal-to-noise ratio.

![Figure A1](image-url) Results of the application of the two Wiener filters described in the text to the initial NUV image. The filters collapse the elongated PSFs that are the result of the deprojection process. The horizontal streaks are the low-frequency component of the filter response functions that are highlighted when the filter is convolved with bright sources, and these could be suppressed with additional filtering. That the shapes of structures in the deconvolved images are similar to those in the unfiltered image demonstrates that the deprojection process has not greatly distorted features in NGC 247.
By design, the PSFs of stars in the deconvolved images are round. The noise introduced by the filters aside, the structures seen in the initial image are largely unchanged in the deconvolved images. The deprojection procedure thus has not greatly distorted structures in the NGC 247 disk.

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