EVIDENCE FOR A STRONG END-ON BAR IN THE RINGED $\sigma$-DROP GALAXY NGC 6503

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ABSTRACT

We use WIYN High-resolution Infrared Camera $H$-band (1.6 $\mu$m) imaging, archival Spitzer, Hubble Space Telescope, and Galaxy Evolution Explorer data simulations, and data from the literature to argue for the presence of a strong end-on bar in nearby spiral galaxy NGC 6503. The evidence consists of both photometric and kinematic signatures as well as resonant structures present in the galaxy which are most often associated with bars. These include a central peak followed by a plateau in the surface brightness profile, an extreme decrement in the central stellar velocity dispersion (a $\sigma$-drop), and the presence of an inner ring as well as a circumnuclear disk with spiral structure. In this framework, the previously identified nuclear star-forming ring is instead a young inner ring spanned in diameter by the strong end-on bar.

Key words: galaxies: individual (NGC 6503) – galaxies: structure – infrared: galaxies

1. INTRODUCTION

Near-infrared (NIR) observations reveal stellar bars in a majority of disk galaxies (Eskridge et al. 2000; Marinova & Jogee 2007). Observations at these wavelengths probe older stellar populations (the primary components of bars), and, unlike optical observations, are relatively unaffected by young stars and dust. Bars play an important role in redirecting gas from the outskirts of galaxies toward small radii by gravitationally torquing the gas, causing it to lose angular momentum and flow radially into the center of the galaxy (Heller & Shlosman 1994). However, these flows may be stopped by the inner Lindblad resonance (ILR), and the gas redistributed into a disk or ring which may form stars (Shlosman et al. 1990; Buta & Combes 1996). To fuel an active galactic nucleus (AGN) or nuclear starburst, it is then necessary for another mechanism to perturb this gas, causing it to further flow into the inner $\sim$10 pc. Possible mechanisms include gravitational perturbation from a companion galaxy and instabilities in the disk, including small nuclear bars (Shlosman et al. 1989).

Some 20% ± 5% of local spirals have nuclear star-forming rings (Knapen 2005), and most are thought to be associated with non-axisymmetric structures like bars (Comerón et al. 2010; Shlosman et al. 1990; Athanassoula 1994). There are, however, a few examples of disk galaxies with nuclear star-forming rings and no obvious bar structure (Mazzuca et al. 2008). These cases are often explained by the perturbations from other non-axisymmetric structures such as spiral density waves, oval distortions, or minor mergers (Knapen et al. 2004; Sil’chenko & Moiseev 2006). Spiral density waves can drive gas into the center of galaxies, but this mechanism is not thought to be efficient considering the lack of stability of the wave in the absence of a bar (Buta & Combes 1996). Oval galaxies are thought to evolve similarly to barred galaxies because, although the elongation is weaker than a bar, a larger fraction of the disk mass are affected by the non-axisymmetry (Kormendy & Kennicutt 2004). Athanassoula et al. (1997) showed that the impact of a small satellite can produce a ring that is indistinguishable from a resonance ring.

Mazzuca et al. (2008) surveyed 22 nearby spirals with nuclear star-forming rings in $H$, $B$, and $I$ bands and did not find bars in five of these systems. From this sample of galaxies with star-forming rings but no detected bars, we have chosen NGC 6503 for NIR imaging, with the new WIYN$^3$ High-resolution Infrared Camera (WHIRC) on the WIYN 3.5 m on Kitt Peak in order to further search for a bar associated with the star-forming ring. The highly inclined disk in NGC 6503 makes this source an interesting target for NIR observations. Table 1 lists some general properties of this galaxy and its star-forming ring.

NGC 6503 is a spiral galaxy at a distance of 5.3 Mpc, near the edge of the Local Void (Karachentsev et al. 2003). It appears to be extremely isolated with only one possible faint dwarf companion, whose radial velocity is unknown (Karachentseva & Karachentsev 1998; Karachentsev et al. 2003) and no $H_\alpha$ detections nearby (Greisen et al. 2009). This galaxy provides a unique laboratory to study a nearby system which is likely unperturbed by neighbors. There is evidence for modest gas inflow onto a central black hole, as Lira et al. (2007) classified the bright nucleus as a LINER and Ho et al. (1997) used an uncertain designation of transition object or Seyfert 2. It is a low-luminosity spiral galaxy with a star formation rate of 0.2 $M_\odot$ yr$^{-1}$ (Kennicutt 1998), and an inclination of 74$^\circ$ (Bottema & Gerritsen 1997).

NGC 6503 hosts the most extreme known case of a decrement in the stellar velocity dispersion in the center of a galaxy, also known as a $\sigma$-drop (Bottema 1989, 1993; Bottema & Gerritsen 1997; Bureau & Athanassoula 2005; Comerón et al. 2008). Within the central $\sim$10$''$ the velocity dispersion drops approximately in half, from $\sim$50 km s$^{-1}$ to $\sim$25 km s$^{-1}$ (Bottema 1989). The $\sigma$-drop phenomenon is seen in 30%–50% of disk galaxies (Comerón et al. 2008), and is often attributed to a bar or a circumnuclear disk. In the case of a bar, stellar orbits in the center

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of a bar circularize, decreasing the velocity dispersion (Bureau & Athanassoula 2005). In the case of a circumnuclear disk, the decrease in velocity dispersion is caused by dynamically cold gas clouds which form a population of stars whose velocity dispersion, like that of the clouds they formed in, is small (Emsellem et al. 2001; Wozniak et al. 2003). This young stellar population dominates the luminosity from the central region of the galaxy and may overpower the light from a physically coincident older population which would not show a σ-drop. These two hypotheses are not mutually exclusive; indeed, as discussed earlier, bars are often invoked as a mechanism to transfer gas into the centers of galaxies. Wozniak & Champavert (2006) found that the timescale to form a σ-drop in a circumnuclear disk can be as short as ~500 Myr, and the signature will last as long as the gas content of the circumnuclear disk remains high enough that stars continue to form. Therefore, it remains a curiosity that NGC 6503 displays two signatures which are commonly associated with bars, yet no bar has been detected in this galaxy to date. Here, we use new NIR data, multi-wavelength archival data, and kinematics from the literature to revisit this system and search for evidence of a bar which might simultaneously explain its star-forming ring and strong σ-drop.

2. OBSERVATIONS

We observed NGC 6503 with the WHIRC camera on WIYN during a single night in 2008 September. The WHIRC instrument is a 2048 × 2048 HgCdTe infrared array with a field of view of 3' × 3' which is capable of sub-arcsecond resolution for broadband and narrowband imaging between 0.8 and 2.5 μm (Meixner et al. 2008). The pixel scale is 0.098 pix⁻¹. The detector is mounted on the WIYN tip-tilt module which enables spatial resolution as good as 0.3 FWHM through active image correction, although this capability was turned off during our observations. We imaged the galaxy in the H band (1.6 μm) which provided the best compromise between sensitivity to the old stellar component and minimization of the sky background. In order to facilitate sky subtraction, we obtained a series of images both on and off the source with integration times ranging from 50 s to 200 s. The data were reduced in IDL following a procedure recommended by the WHIRC science team (D. Joyce 2008, private communication). All image frames were bias-corrected and flat-fielded. A linearity correction was applied using the coefficients listed in the WHIRC manual (http://www.noao.edu/kpno/manuals/whIRC/WHIRC.htm). A master background frame was produced by median combining the off-source images and then subtracted from each image of the galaxy. Finally, the object images were stacked to produce the H-band image shown in Figure 1. The stacked image of NGC 6503 has a final FWHM seeing of 0.9 and a combined exposure time of 1500 s.

In addition to the WHIRC NIR data, we retrieved co-added near-ultraviolet (NUV) observations of this galaxy from the Galaxy Evolution Explorer (GALEX) archive (PI: Hoopes, Proposal ID 97) which have a combined exposure time of ~4300 s. Far-ultraviolet (FUV) survey observations were available with a combined exposure time of 1600 s. We also retrieved archival Hubble Space Telescope (HST) observations in the F814W and F658N filters with exposure time of 700 s and 1700 s, respectively (PI: Ford, Proposal ID 9293), and public Spitzer Space Telescope IRAC images at 3.6 μm and 4.5 μm (PI: Leitherer, Proposal ID 3674). Greisen et al. (2009) provided us with their total intensity H1 image from the Very Large Array. This C-configuration radio data have a resolution of 14.4 × 13.5 with 500 minutes on source.

3. THE STRONG END-ON BAR

Bureau & Athanassoula (2005) performed self-consistent three-dimensional N-body simulations of disks with bars of varying strength and orientation in order to identify the signatures of bars in highly inclined galaxies. These simulations contain only a luminous disk and dark matter halo; no bulge component is included. Bar diagnostics arise from simulated long-slit spectra along the major axis of the disk and include position–velocity (PV) diagrams, surface brightness profiles, velocity profiles, velocity dispersion profiles, and the Gauss–Hermite terms h₂ and h₄. Here, we compare observations of NGC 6503 to these theoretically predicted features using our WHIRC data as well as the following data from the literature. When comparing surface brightness profiles, we use B- and R-band data published in Bottema (1989) and the 3.6 μm and 4.5 μm data from the Spitzer archive. Rotation curves for NGC 6503 have been published using H₁ data in Bottema (1989) and Hα data in de Vaaucoleurs & Caulet (1982). The stellar velocity dispersion profile was first presented in Bottema (1989).
The ellipse fits reveal interesting structure in the ellipticity and P.A. profiles at small radii, shown in Figure 2. The ellipticity rises from the center of the galaxy monotonically while the P.A. remains relatively constant. Both the ellipticity and P.A. change abruptly at a radius of 3′.5. These are the standard signatures of a bar as outlined above. However, to unambiguously be considered a bar, the ellipticity needs to reach a global maximum within this structure; we see that the central structure in NGC 6503 only reaches a maximum ellipticity of $\epsilon = 0.35$, as compared with the outer disk which displays $\epsilon = 0.7$. In addition, the P.A. of the central structure ($119.8^\circ$) is closely aligned to that of the disk ($122^\circ$). These characteristics match the criteria for an inner disk laid out by Erwin & Sparke (2002), and we therefore interpret this structure as a circumnuclear disk according to the ellipse fitting.

The circumnuclear disk also appears to have a scale similar to that of the sharp central peak in the surface brightness profile, which is also derived from ellipse fitting and shown in Figure 4. Moving out in radius past the circumnuclear disk, the P.A. profile continues to rise till it reaches a maximum value at a radius of $\sim 11''$. This gradual change in position angle is a result of the prominent NIR spiral arms that are visible in the H-band image (Figure 1).

Our H-band surface brightness profile is plotted in Figure 4 and compared with four other wavelength bands: B- and R-band data published in Bottema (1989) and the 3.6 $\mu$m and 4.5 $\mu$m data from the Spitzer archive. The profiles in all five bands are Freeman Type II (Freeman 1970); namely, NGC 6503 is well fit by an exponential profile at large radii ($r > 40''$), the surface brightness profile almost completely levels out at intermediate radii ($10'' < r < 40''$), and then it increases sharply at small radii ($< 10''$). Anderson et al. (2004) found surface brightness profiles of this type in barred galaxies at four times the rate that they are seen in non-barred systems. Bottema (1989) claims that the B-band surface brightness profile shows a more dramatic plateau than the R-band profile, and that the plateau is characterized by redder colors than the rest of the galaxy. They therefore attribute the surface brightness plateau to dust extinction which is concentrated in an annulus at intermediate radii. However, in Figure 4, we see that the plateau is still clearly visible in the IR bands, which should be significantly less affected by dust. The bottom panel of Figure 4 shows the residuals after an exponential fit has been subtracted from the surface brightness profiles; the plateau regions lie below the $y = 0$ line at radii $r < 40''$. We see that these residuals have equivalent amplitudes in the $B$, $H$, $[3.6]$, and $[4.5]$ bands (the Bottema 1989 R-band data are likely affected by additional contamination from H$\alpha$ emission which is quite strong in the inner $40''$ of NGC 6503), therefore implying that the plateau remains strong in the IR and excluding dust extinction as its cause.

An alternative explanation for this surface brightness plateau is a bar. In the simulations of Bureau & Athanassoula (2005), galaxies with a wide range of bar strengths, orientations, and inclinations display surface brightness profiles with quasi-exponential central peaks and a plateau at moderate radii. We note that the plateau extends out to a semi-major axis of $40''$, which is strikingly similar to the semi-major axis of the star-forming ring at $37''5$ (Mazzuca et al. 2008). These spatial coincidences are consistent with the simulations of bars by Bureau & Athanassoula (2005), which predict that the lengths...
Figure 4. Top panel: surface brightness profiles in arbitrary units of mag arcsec$^{-2}$ measured at five different bands: $B$ and $R$ from Bottema (1989), WHIRC $H$, and Spitzer IRAC bands at 3.6 $\mu$m and 4.5 $\mu$m. At each band, an exponential profile is fit to semi-major axes between 45$''$ and 120$''$; these fits are shown as black dotted lines. Bottom panel: the residuals in the surface brightness profiles after subtraction of the exponential fits. Each band is plotted and color coded as in the top panel.

(A color version of this figure is available in the online journal.)
inner ring at the bar ends in NGC 6503 because of recent star formation which has temporarily depleted or expelled it from those regions.

We look for gradients in the age of the star formation around the ring which would identify where gas has most recently entered the ring and formed stars. For nuclear rings, these are called the “contact points” and they typically occur in the ring at points perpendicular to the bar major axis (Mazzuca et al. 2008). There is some evidence for this in Infrared Space Observatory (ISO) data at 12 μm, which shows a ring of hot dust coincident with the star-forming ring and whose brightest emission is seen along the major axis of the galaxy at points nearly perpendicular to the bar major axis (Bendo et al. 2002). Additionally, the HST narrow-band Hα image shows similar structure with the brightest H II regions seen along the major axis of NGC 6503.

We attempt to quantify any existing age gradient using UV colors. The H I data are used to correct the UV data for extinction using the conversion of hydrogen column density to optical extinction from Predel & Schmitt (1995) and the relationship between optical reddening and UV reddening from Rey et al. (2005). Figure 7 shows the FUV−NUV color in regions around the ring. Close examination of dust lanes in the HST image indicates that the regions marked 1–8 in the left panel of Figure 7 are located on the near side of the galaxy. These regions appear to have...
bluer UV colors than those on the far side of the galaxy. We interpret these differences in FUV–NUV color as being caused by additional extinction which is hard to account for entirely in such an inclined system. Due to the location and size of the bar proposed here, the star-forming ring is much more likely to be an inner ring than a nuclear ring (inner rings are spanned in diameter by the length of the bar whereas nuclear rings are contained within the bar). Thus, the physical mechanism that is thought to produce contact points in nuclear rings is not likely to be present for this structure, and if the youngest stars are indeed located perpendicular to the bar major axis this characteristic should be attributed to the dynamics of inner rings.

The star-forming ring is a young structure and not strongly visible in our WHIRC NIR data which traces older stellar populations. The UV colors (FUV–NUV < 1) of regions in the ring indicate that its age is less than ~0.5 Gyr (see Figure 3 in Jeong et al. 2007).

5. SUMMARY

The star-forming ring in the nearby low-luminosity spiral galaxy NGC 6503 is likely an inner ring and not a nuclear ring. We present evidence that the ring is caused by a strong end-on bar which is embedded inside it. Although the surface brightness profile does not argue exclusively for a strong end-on bar, in the simulations of Bureau & Athanassoula (2005) a strong end-on bar is the only configuration capable of producing a central σ-drop. While it is likely possible to mimic the surface brightness plateau and the central velocity dispersion minimum with axisymmetric structures, we consider the combination and spatial coincidence of these characteristics with resonant features (specifically the inner star-forming ring and circumnuclear disk with spiral structure) to be compelling evidence of a strong end-on bar in this galaxy.

These results can be tested further with high-quality long-slit stellar spectroscopy. Construction of the rotation curve and velocity dispersion profile with better resolution data, as well as the Gauss–Hermite terms, would allow for further comparison with the predictions given in Bureau & Athanassoula (2005). Specifically, a strong end-on bar should show a “double-hump” signature in its rotation curve such that the rotational velocities rise steeply but then experience a local minimum before rising again to flatten out at large radii. There may be some evidence for the local minimum in the rotation curves presented in de Vaucouleurs & Cautel (1982) and Bottema (1989), but the data are not adequate to tell conclusively. Additionally, the velocity dispersion profile for a strong end-on bar should show not only a broad central maximum with a σ-drop, but also a sharp drop at larger radii and a secondary local maximum.

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