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HST/NICMOS Imaging of 250 Normal and Active Spirals: Evidence for Morphological Evolution

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Abstract

We have analyzed NICMOS images of 250 normal, starburst and Seyfert galaxies. We use several objective measures to quantify the presence of morphological peculiarities in these galaxy samples. The starburst galaxies show the most disturbed morphologies, from unsharp masking, and large residual $cos(3\theta)$ terms in their surface brightness distributions. The next most disturbed group is the Seyfert 2 galaxies. LINER galaxies show the most smooth and regular morphologies. We suggest that this sequence can be understood as the time-evolution of a galaxy interaction, that first stimulates star formation, and later feeds the central engine.

1.1 Introduction

As soon as galactic nuclei were recognized to be the unique habitat of non-stellar activity, connections were sought between the active nucleus and the galaxy in which it resides. An accreting black hole became the established theoretical explanation for Seyfert activity, fueled by gas that has lost most of its orbital angular momentum. It also become evident that many, if not most, galaxies harbor black holes in their nuclei. Yet it is not understood why some galaxies contain AGNs, while the majority do not. Although part of the difference might be due to a lack of fuel, there is only weak evidence for larger gas fractions in Seyfert galaxies (e.g., Hunt et al. 1999b). Most work has instead considered the mechanism by which disk gas loses its angular momentum, thereby becoming available to feed the BH. One candidate has been galactic bars, but Seyfert galaxies have not shown an excess of bars (McLeod & Rieke 1995, Ho et al. 1997, Mulchaey et al. 1997; Hunt & Malkan 1999, but see Laine et al. 2002). Another focus has been on interactions, since these are also a mechanism for inward gas transport (Barnes & Hernquist 1991). However, Seyferts are found neither preferentially in interacting systems nor with an excess of companions (de Robertis et al. 1998).

Hence, it appears that large-scale galactic structure in Seyfert host galaxies (with the possible exception of their disks, see Hunt et al. 1999a), has little bearing on the AGN. However the effects (or causes) of the AGN might still be revealed on the smaller spatial scales observable with HST. We therefore analyzed a sample of normal and active galaxies, imaged with HST/NICMOS in the F160W filter. This filter is well suited for morphology studies because it is much less affected by dust extinction than optical bands, and suffers very little gas contamination. Moreover, it traces the bulk of the stellar mass.

1.2 NICMOS Galaxy Samples

We have reduced NICMOS F160W images of 30 Seyfert galaxies from a GO Snapshot Program (Malkan PI) and over 200 F160W snapshot images from the HST Archive (PIs Pogge, Mulchaey, Sparks, Stiaveli, Peletier). We used STSDAS/calnica and Van der Marel's depedestalling routine. The final images are photometrically calibrated to H-band magnitudes.

What our sample lacks in homogeneity, it compensates for in size: we have analyzed more than 250 galaxies in five exclusive activity classes (based on optical spectroscopy from NED): 36 Sy 1s, 69 Sy 2s, 28 LINERs, 20 HII/starbursts, and 96 normal spirals. Our AGN, starburst, and normal subsamples are well matched in their basic properties, including distance, Hubble type, and luminosity. Since we use three cameras with different scales (0.043"/pix, 0.075"/pix, 0.2"/pix), we ensured that the parsec-to-pixel scale was comparable in the five subsamples.

1.3 Methods of Analysis of Circumnuclear Morphology

The images were deconvolved using TinyTim PSFs. The elliptically-averaged brightness profiles were subtracted from the original image to create unsharp masks, revealing residual asymmetric structures not fitted with ellipses. Quantitative procedures identified 5 morphological peculiarities:

- **Bars** (PA constant, while e rises to a maximum, then falls McLeod & Rieke 1995); implies non-axisymmetric radial stellar streaming.
- **Isophotal twists** (ellipse position angle-PA-varies by ≥ 10 deg over a region with monotonically varying ellipticity-e): may imply a projected triaxial bulge.
- **Boxy/disky isophotes** ($cos4\theta$ residuals–A4–non-zero over a substantial range in radius; ≥ 0 for disky, ≤ 0 for boxy: suggests a merger origin.
- **Banana- or heart-shaped isophotes** ($cos3\theta$ or $sin3\theta$ residuals-A3,B3-non-zero over a range of radii); can be caused by dust and/or bending or "firehose" instabilities and young mergers (Hernquist et al. 1993).
- **Non-axisymmetric structure in the unsharp masks** (original/ellipse model $\geq$ or ≤ 0.27 for two offset sets of boxes of 180pc size outside of nuclear PSF); negative residuals are associated with dust, while positive features usually indicate star clusters or HII regions.

Finally, we have fit "nuker" models (5-parameter two-slope power laws) to the elliptically-averaged brightness profiles. Figure 1.1 illustrates these for the representative case of the Sy 1 galaxy NGC 4235.

1.4 Results: Morphology Statistics by Activity Class

We have compared the morphological diagnostics for each activity class using the z statistic, and find significant ($\geq 95\%$) trends for the following

- **Isophotal twists** are more frequent in Sy 2 than in any other class.
- **Bars** are less frequent in Sy1s relative to normal galaxies.
- **Disky isophotes** are less frequent in HII/starbursts than in any other class.

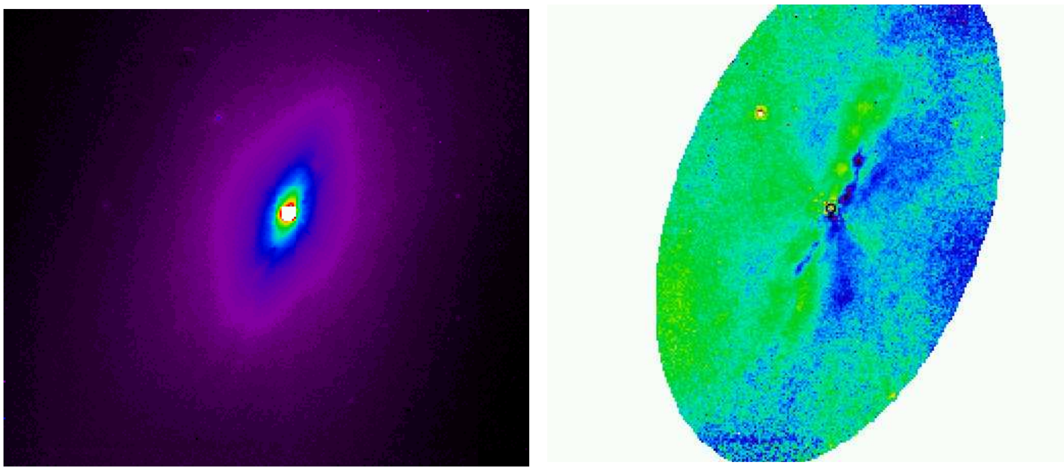

Fig. 1.1. The upper left panel shows the F160W image of the Sy 1 galaxy NGC 4235; the right panel shows the unsharp mask.

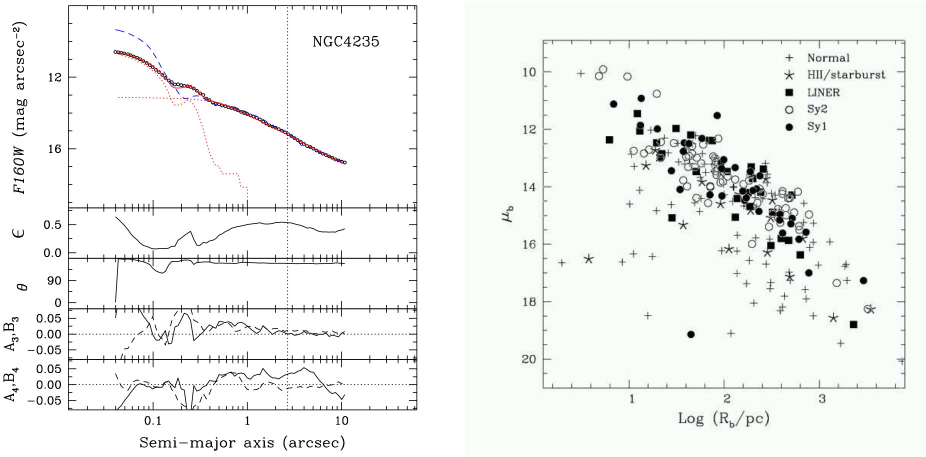

Fig. 1.2. Left: elliptically-averaged surface brightness profile, together with the deconvolved profile, the nuker fit, and the higher-order residuals of the ellipse fitting. The cosine residuals are solid lines, the sine dashed. The vertical line indicates a radius of 500pc. In the lower panel, the deconvolved profile is shown as a dashed line; the nuclear point source becomes brighter. The sum of the nuker+PSF fit is shown as a solid line, with the separate contributions as dotted. The diskiness seen in USM is also evident as the positive A4 residual; note the hint of a dust lane bisecting the nuclear region. Right: Nuker fit break-surface brightness μ_b plotted against break-radius R_b (Kormendy relation).

- 3θ **residuals** (A3) are more frequent in HII/starbursts than in any other class, more frequent in Sy 2s relative to normal galaxies, and less frequent in Sy 1s, relative to HII/starbursts.

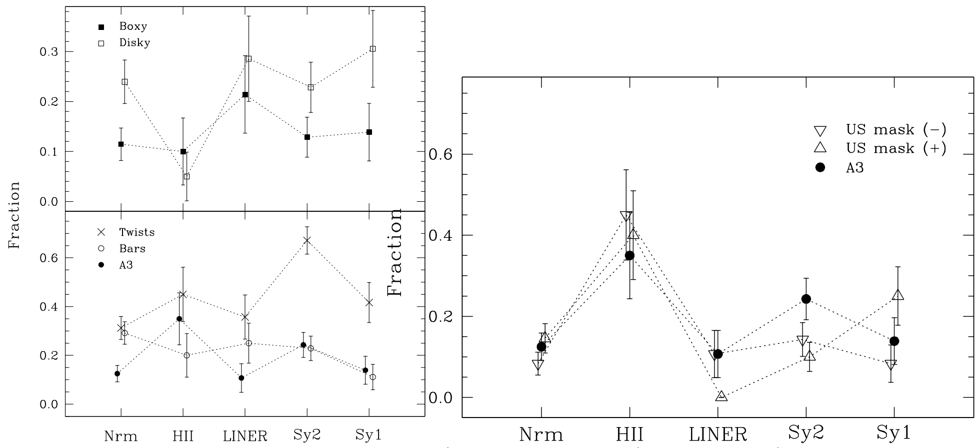

Fig. 1.3. Left: Fractions of boxy/disky isophotes (upper panel) and isophotal twists/bars/$cos3\theta$, $sin3\theta$ (denoted as A3) (lower panel) versus activity class. Right: Fractions of positive unsharp-mask residuals, negative unsharp-mask residuals, and $cos3\theta$, $sin3\theta$ (denoted as A3) versus optical activity class.

- **Unsharp-mask negative residuals** occur more often in HII/starbursts than in any other activity class (Fig. 1.3b).
- **Unsharp-mask positive residuals** occur more often in HII/starbursts than in normal, LINER, and Sy 2s, but are also more frequent in Sy 1s, relative to Sy 2s and LINERs. They are less frequent in LINERs than in any other class.
- **Nuker fits** show that Seyfert galaxies follow the same parameter trends as in normal galaxies. For example, surface brightness and radius are correlated in the same way as in other samples (Fig. 1.2b). However, the upper left corner of break-radius R_b smaller than a few pcs and break-surface brightness $\mu_b \leq 12.5 mag/arcsec^2$ is populated almost exclusively by Seyferts and LINERs!

1.4.1 Discussion

The similarity of the nuker parameters for all the galaxy subsamples suggests that AGNs reside in galaxies globally very similar to their quiescent counterparts, with the possible exception of being slightly brighter and more compact. That Seyfert galaxies have brighter disks than normal galaxies of similar Hubble type was found by Hunt et al. (1999b), although detailed 2D bulge-disk decompositions of a larger sample did not confirm this (Hunt et al. 2000).

The *non-axisymmetric component* in active galaxies, on the other hand, may help explain the mechanisms for fueling the AGN, and their relation to star formation. The active galaxies showing the fewest morphological peculiarities are LINERs: 0/28 show significant positive US mask residuals. They also have the smallest fraction of significant A3 residuals. In contrast, LINERs show the highest fraction of boxy isophotes, although the small sample size precludes statistical significance.

1.5 Conclusions

HII/starbursts appear the most morphologically disturbed. If large A3 is a signature of young mergers as suggested by Kenney et al. (1996), and if large US mask residuals signify dust and irregular emission features associated with recent star-formation, then we infer that HII/starbursts have been in recent mergers which triggered the starburst. *Inner* bars are not implicated for the starburst (unlike the case of *large-scale* bars-Hunt & Malkan 1999). In terms of morphological peculiarities, the Seyferts lie between the HII/starbursts and the LINERs. Sy 2s are the more disturbed, since they show more isophotal twists than any other class, and their A3 fraction is second only to the HII/starbursts. They also show a higher fraction of negative US mask residuals than either LINERs or Sy 1s. If large A3 is associated with dust, then Sy2s would be dustier than Sy1s, in agreement with Malkan et al. (1997). If large A3 signifies young mergers or interactions, then perhaps Sy2s have undergone more recent encounters than Sy1s. The large twist fraction could imply a larger percentage of triaxial bulges, which might be dynamically younger than their spheroid counterparts. The Sy 1s show the highest fraction of disky isophotes. They also show the lowest bar fraction on these scales, a more significant result, and a low $cos3\theta$ fraction. The high fraction of positive US mask residuals appears to be a real effect since most of the US mask structures are not aligned with the diffraction spikes of the central point source (e.g., Fig. 1.1)

Speculations: These patterns of small-scale structural peculiarities may be understood in an evolutionary scenario, in which HII/starburst galaxies are the "youngest", viewed soonest after a merger or accretion event. Sy 2s appear to be more structurally relaxed than HII/starbursts, but are more disturbed than Sy 1s and LINERs. If boxy/disky isophotes are a signatures of advanced equal/unequal mass mergers, then the high frequency of boxy/disky isophotes in LINERs and Sy 1s could mean that they are "older" systems, i.e., viewed long after the merger or accretion event. Finally, LINERs could be "exhausted" Seyferts which are reaching the end of their fuel supply, as they appear to be the most morphologically "settled down", viewed perhaps much after the event which triggered the onset of nuclear activity.

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