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Nuclear Clusters and Massive Black Holes in Spiral Galaxies

M. A. HUGHES[1], D. J. AXON[2], A. ALONSO-HERRERO[3], and C. SCARLATA[4]
(1) Department of Physical Sciences, University of Hertfordshire, Hatfield, AL10 9AB, UK.
(2) Dept. of Physics, RIT, 84 Lomb Memorial Dr., Rochester, NY 14623-5603
(3) Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721
(4) Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

Abstract

We have used Hubble Space Telescope (HST)*, Space Telescope Imaging Spectrograph (STIS) R-band images and longslit spectra (including the H α, [NII] complex) and archive Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) images of the central regions of 23 nearby spiral galaxies to study both the morphology of central gas and dust structures and the nature of any compact luminous sources present at the centers of these galaxies. Using near-IR NICMOS H (1.6 μm) and STIS ∼R-band (7230 Å) images we produced color maps to determine the morphology of gas and dust in the central regions. We find a great variety in the different morphologies, from smooth distributions to well defined mini-spirals and dust lanes. We also produce surface brightness profiles (SBPs) from the NICMOS-H band images and compare them to previous SBPs derived from STIS images. The purpose of these profiles is to search for the presence of central stellar clusters. We find that although, compact luminous sources are present in some galaxy centers, they are difficult to isolate from the underlying bright galaxy emission and so we are unable to constrain their size. It is possible that they are either stellar clusters or weak active galactic nuclei. Here we summarize our results which will appear in a future paper.

1.1 Central Black Hole Masses from Gas Kinematics

The field of massive black hole astrophysics has expanded greatly in recent years due the increase in resolution now available through the Hubble Space Telescope and adaptive-optic assisted ground based observations. To establish the mass distribution of MBHs in nearby spiral galaxies we have undertaken a *HST*/STIS program (GO:8228, PI:Axon) to determine MBH masses for a sample of 54 emission line spiral galaxies within a recessional velocity of 2000 km s^{-1}. The restriction to only including nearby galaxies allows us to resolve scales of about 10 pc at a typical distance of 20 Mpc. The galaxies are late-type, ranging from Sb to Sd. The HST observations are now complete and modelling of the velocity fields is currently underway. Here we report on our progress in using these data for the additional objective of understanding the nature of the central stellar population.

The data include both spectra and images. The STIS images were originally taken to acquire the nucleus of each galaxy so that spectroscopic apertures could be accurately placed. These 'acquisition images' were taken using the F28X50LP longpass filter. They are optical

* Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

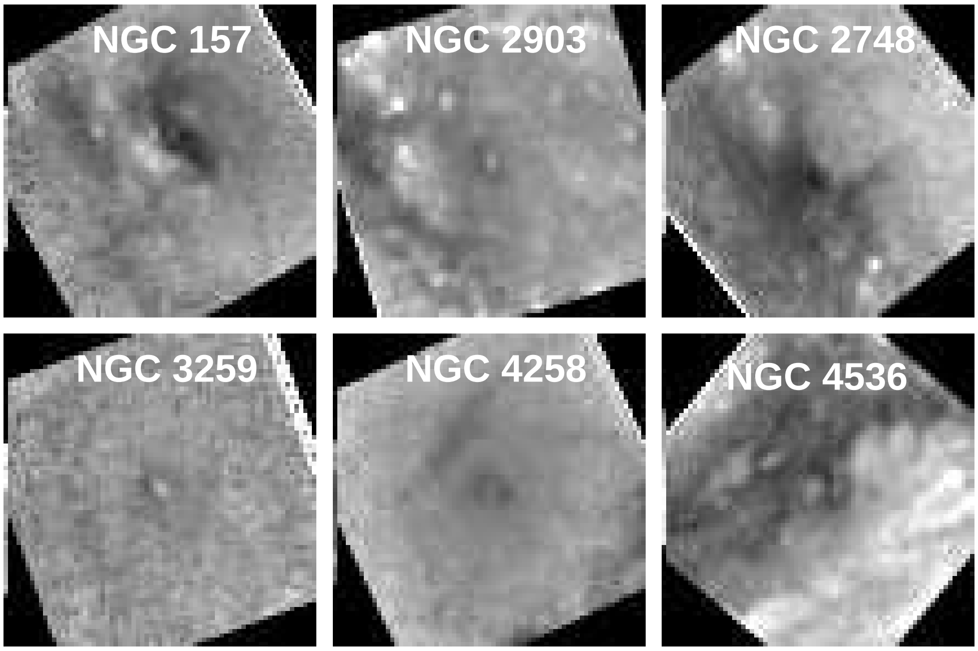

Fig. 1.1. Examples of some of the R-H color maps showing a wide range of different morphologies

(central wavelength 7230 Å), and are roughly equivalent to R-band. The field of view is 5x5 arcseconds.

The STIS spectra were used to map the velocity field of nuclear gas disks, and hence determine any central mass concentration. Spectra of the galaxy centers were taken and covered 5 emission lines [NII] (6549.9Å), H α (6564.6 Å), [NII] (6585.3 Å) and [SII] (6718.3 Å & 6732.7 Å). Our strategy and results for NGC 4041 are described more fully in Marconi et al. (2003).

1.2 The Morphology of Galaxy Centers

Ground based telescopes and HST have been used to investigate the central regions of many galaxies (e.g. Martini & Pogge (1999), Perez et al. (2000) & Laine et al. (2001)). We used the STIS acquisition images and archive NICMOS images to produce color maps and surface brightness profiles to investigate the morphology within the central 5 arcseconds of the nucleus. A few examples are shown in figure 1.1. Even though the galaxies are all late type spirals they show a surprisingly wide range of morphologies in their central regions. Some show distinct organised structures such as mini spirals, while others appear almost featureless.

1.2.1 Surface Brightness Profiles

Many galaxies have been found to have distinct cores, photometrically and morphologically distinct from the surrounding bulge (e.g. Carollo et al. 2002).

To invesitigate this for our sample of galaxies we used the STIS and archival NICMOS

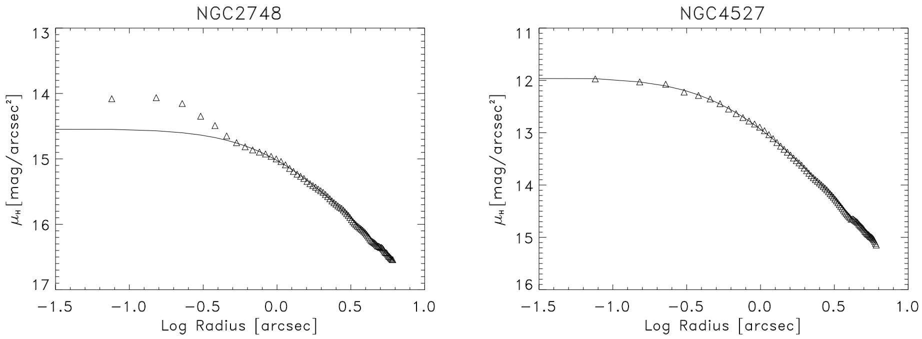

Fig. 1.2. Examples of NUKER law fits to surface brightness profiles generated from archival NICMOS images. (Some of which overlap with the sample of Seigar et al. (2002)) The left panel shows an example where an excess above that of the bulge indicates the presence of a central source.

images to produce surface brightness profiles. We used the NUKER law fit (Lauer et al. (1995)) as a description of the bulge,

$$I(r) = 2^{(\beta-\gamma)/\alpha} I_b \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha} \tag{1.1}$$

where, β indicates the steepness of the outer profile, γ measures the steepness of the inner profile, α indicates the sharpness of the transition between these two profiles, while r_b is the point of this transition at which the SBP has a brightness of I_b. The surface brightness profiles from several of the STIS and NICMOS images show excess light in the central regions (see figure 1.2). These indicate a bright compact nuclear source, however generally we are not able to confidently resolve the extent of these sources.

1.3 How old is the Central Stellar Population?

Since some of the spiral galaxies exhibit a compact nuclear source it is prudent to determine their nature. Unfortunately, many of the sources are difficult to isolate from the bright underlying galaxy and so from the STIS images alone it is not possible to say whether the light is from stars or an AGN. Central sources have been detected in many other galaxy centers and are generally assumed to be stellar clusters. However, most have not been observed spectroscopically (a notable exception is NGC 4449 (Böker et al. 2001)).

The key point for the black holes program is that we need to determine how much of the central mass in the spiral galaxies is *not* due to a black hole. If we detect the presence a nuclear cluster composed primarily of old stars then this would indicate a high mass to light ratio. These stars could then acount for a significant proportion, perhaps even 100% of the central mass concentration that we determine from the gas kinematical modelling. The correlations between black hole mass and host galaxy properties indicate that we might expect a black hole to have a mass comparable with a stellar population ($\leq 10^7$ M_{sun}). Hence it is vital to distinguish between the different scenarios.

To constrain the mass of a stellar population we must first determine its age. We found that using only H and R color information alone was not enough to constrain the ages of the

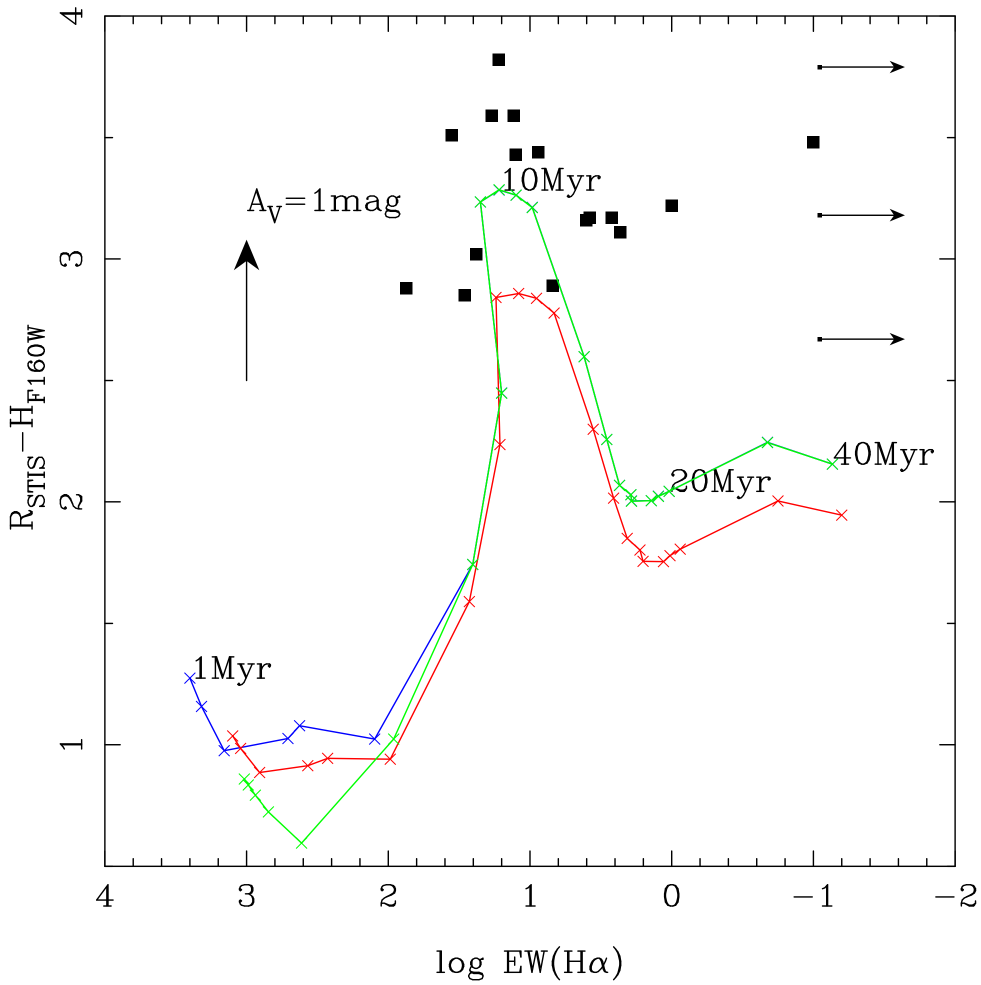

Fig. 1.3. R-H colors against the equivalent width of H α within an aperture size of 100 pc centered on the nucleus (Hughes et al, in prep). The different colors represent different Inital Mass Functions. The EWs constrain the ages to a few 10 Myrs. However the assumption is that all the ionizing photons are from a nuclear cluster.

population. However since we already had STIS spectra for many of the galaxies we were able to use the equivalent width of H α as a futher constraint. Since we were not confident in determining the sizes of the nuclear clusters we fit a 100 pc aperture to the central regions of the spectra and images. In figure 1.3 we show the R-H color indices and the equivalent widths (EWs) of H α and compare them to stellar evolutionary models of Leitherer et al. (1999). If the ionization is due to the nuclear stellar population then the EW indicates young stars of only a few 10 Myr. However we cannot exclude the possibility that an AGN is doing the ionizing, though most of our spectra do not show broad lines so any AGN should be weak. Since the nuclei of many of these galaxies are dusty, high resolution IR spectroscopy is required to resolve the issue of the age, and hence mass, of the stellar populations.

1.4 Summary

In a series of future papers we will present all the sucessful STIS images and spectra from our massive black holes program. From our first attempt at determining a central black hole mass (Marconi et al. 2003) it became clear that accounting for all the luminous mass at the center of the galaxy is crucial before a reliable black hole mass can be extracted. Two lines of evidence highlight the importance of accounting for the luminous matter. 1. Many spiral galaxies exhibit central sources, many of which may be nuclear stellar clusters and 2. The recent correlations between various host galaxy properties and black hole mass indicate that spiral galaxies probably have black holes with masses $\leq 10^7$ M_{sun}. These suggest that central mass concentrations in spiral galaxies could easily be accounted for by stars alone. Hence determining, as accurately as possible, the mass in stars is crucial before we can say whether or not a central black hole is present.

References

Böker, T., van der Marel, R. P., Mazzuca, L., Rix, H., Rudnick, G., Ho, L. C., & Shields, J. C. 2001, AJ, 121, 1473
Carollo, C. M., Stiavelli, M., Seigar, M., de Zeeuw, P. T., & Dejonghe, H. 2002, AJ, 123, 159
Laine, S., Knapen, J. H., Pérez-Ramírez, D., Englmaier, P., & Matthias, M. 2001, MNRAS, 324, 891
Lauer, T. R., et al. 1995, AJ, 110, 2622
Leitherer, C., et al. 1999, ApJS, 123, 3
Marconi, A., et al. 2003, ApJ, 586, 868
Martini, P., & Pogge, R. W. 1999, AJ, 118, 2646
Pérez, E., Márquez, I., Marrero, I., Durret, F., González Delgado, R. M., Masegosa, J., Maza, J., & Moles, M. 2000, A&A, 353, 893
Seigar, M., Carollo, C. M., Stiavelli, M., de Zeeuw, P. T., & Dejonghe, H. 2002, AJ, 123, 184