THE DISCOVERY OF AN ACTIVE GALACTIC NUCLEUS IN THE LATE-TYPE GALAXY NGC 3621: 
SPITZER SPECTROSCOPIC OBSERVATIONS

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1, INTRODUCTION

The discovery that at the heart of virtually every early-type galaxy in the local universe there lies a supermassive nuclear black hole (SBH) has led to the general consensus that black holes play a pivotal role in the formation and evolution of galaxies. The well-known correlation between the black hole mass, $M_{\text{BH}}$, and the host galaxy’s stellar velocity dispersion, $\sigma$ (Gebhardt et al. 2000; Ferrarese & Merritt 2000), implies that black hole growth and the buildup of galaxy bulges go hand in hand, perhaps as feedback from the active galactic nucleus (AGN) regulates the surrounding star formation in the host galaxy (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000). The connection between black hole growth and galaxy bulges is further intimated by the fact that virtually all currently known actively accreting black holes (i.e., AGNs) in the local universe are found in galaxies with prominent bulges (e.g., Heckman 1980; Ho et al. 1997; Kauffmann et al. 2003). It is unclear how common it is for bulgeless galaxies to contain SBHs and, of those that do, whether they are actively accreting or not. M33, the best-studied nearby bulgeless galaxy, shows no evidence of a SBH, and the upper limit on the mass is significantly below that predicted by the $M_{\text{BH}}$-$\sigma$ relation established in early-type galaxies (Gebhardt et al. 2001; Merritt & Ferrarese 2001). Among the population of known AGNs, there are possibly a handful of extremely late-type galaxies that may show subtle signs of AGN activity in their optical narrow-line nuclear spectra (Ho et al. 1997). The best-studied definitive case of an AGN in a purely bulgeless galaxy is the galaxy NGC 4395, which shows an unmistakable Seyfert 1 spectrum. The inferred black hole mass in this dwarf galaxy is $3.6 \times 10^6 M_\odot$ (Petrosian et al. 2005), which is much less massive than black holes found in galaxies with massive bulges and is comparable to the inferred black hole mass in the other well-known dwarf galaxy with an AGN, POX 52 (Barth et al. 2004). Greene et al. (2004) recently searched the First Data Release of the Sloan Digital Sky Survey for galaxies with similar intermediate-mass black holes and found only 19 broad-line AGNs, suggesting that they are uncommon. Subsequent stellar velocity dispersion measurements revealed that these objects follow the extrapolation of the $M_{\text{BH}}$-$\sigma$ relation (Barth et al. 2005). It is unclear whether the hosts are late-type galaxies or not since the Sloan images are of insufficient spatial resolution to confirm their morphological type.

Are AGNs uncommon in bulgeless galaxies? Is a bulge necessary for a black hole to form and grow? These questions cannot be definitively answered with the current suite of observations, which are largely carried out at optical wavelengths. Such studies can be severely limited in the study of bulgeless galaxies, where a putative AGN is likely to be both energetically weak and deeply embedded in the center of a dusty late-type spiral. In such systems, the traditional optical emission lines used to identify AGNs can be dominated by emission from star formation regions, in addition to being significantly attenuated by dust in the host galaxy. Indeed, searching for AGNs under these circumstances poses unique challenges. Although X-ray observations can be a powerful tool for finding optically obscured AGNs in the non–Compton-thick regime, the X-ray luminosities of weak AGNs will be low and comparable to, and therefore indistinguishable from, X-ray binaries in the host galaxy. Similarly, the radio emission can be dominated by and indistinguishable from compact nuclear starbursts (e.g., Condon et al. 1991). Spitzer mid-IR spectroscopy is the ideal tool to search for AGNs in such galaxies. As has been shown in previous works, AGNs show prominent high-excitation fine-structure line emission, but starburst and normal galaxies are characterized by a lower excitation spectra characteristic of H II regions ionized by young stars (e.g., Genzel et al. 1998; Sturm et al. 2002; Satyapal et al. 2004). In particular, the [Ne v] 14 $\mu$m (ionization potential 96 eV) line is not produced in H II regions surrounding young stars, the dominant energy source in starburst galaxies, since even hot massive stars emit very few photons with energy sufficient for the pro-

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duction of this ion. The detection of this line in a galaxy is therefore definitive proof of an AGN.

In this Letter, we report the discovery of an AGN in the galaxy NGC 3621. NGC 3621 is a relatively isolated nearby (6.2 Mpc; Rawson et al. 1997) SaD III–IV (Third Reference Catalogue of Bright Galaxies [RC3]; de Vaucouleurs et al. 1991) galaxy with no previous published evidence of nuclear activity. The observations presented here add to the growing evidence that a black hole can form and grow in a galaxy with little or no bulge.

2. OBSERVATIONS AND DATA REDUCTION

NGC 3621 was observed by the Infrared Spectrograph (Houck et al. 2004) on board Spitzer using the short-wavelength high-resolution (SH; 4.7′′ × 11.3′′, 9.9–19.6 μm) and the long-wavelength high-resolution (LH; 11.1′′ × 22.3′′, 18.7–37.2 μm) modules as part of the Spitzer Infrared Nearby Galaxies Survey (SINGS) Legacy Proposal (program ID 159; Kennicutt et al. 2003) on 2004 June 28. These modules have a spectral resolution of R ∼ 600. The observations were executed in spectral mapping mode, in which the spacecraft moves in a raster pattern of discrete steps in order to construct a rectangular map of the targeted region. The SH and LH maps included three pointings parallel to and five pointings perpendicular to the major axis of the slit, with half-slit length and half-slit width steps, respectively. The integration time per pointing was approximately 60 s, with each position being covered twice for the SH observations. The total duration for the high-resolution observations of NGC 3621 was 2915 s.

We used BCD-level data products downloaded from the Spitzer archive in conjunction with CUBISM version 1.0.24 (Kennicutt et al. 2003; Smith et al. 2004) to construct the high-resolution spectral cubes for NGC 3621. The BCD-level products were preprocessed by the Spitzer pipeline, version 13.2, prior to download. The overall flux calibration uncertainty is 25%–30%. A detailed description of the postprocessing steps included in CUBISM is given in Smith et al. (2004).

The final full cube map size for SH corresponds to ~24.7′′ × 13.5′′, while the final full cube map size for LH corresponds to ~44.6′′ × 30.8′′. At the distance of NGC 3621, this corresponds to a physical size of 742 pc × 405 pc and 1341 pc × 923 pc, respectively. Given the small spatial extent of both the SH and LH maps, we were unable to perform in situ background subtraction, since the full extent of each map is confined within the galaxy.

The post-BCD software SMART, version 5.5.7 (Higdon et al. 2004), was then used to obtain line fluxes from the extracted one-dimensional spectra. When line ratios were calculated, the line flux was obtained from spectra extracted from the same-sized aperture in both modules corresponding to the same physical region on the galaxy. This aperture can range from a minimum of ~9′′ × 9′′, below which artifacts introduced by an undersampled point-spread function (PSF) can distort the spectrum, to a maximum of 22.6′′ × 14.8′′—i.e., roughly the full extent of the SH map. The FITS output images from CUBISM were smoothed within ds9 using a Gaussian kernel of 2 pixel width. Finally, the line map plots were created using the IRAF routine rotate in conjunction with ds9.

3. RESULTS AND DISCUSSION

In Figure 1, we show spectra extracted from the full aperture of the SH and LH maps near 14, 24, and 26 μm. As can be seen, there are clear detections of the [Ne v] 14 μm (4 σ), [Ne v] 24 μm

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4 See http://ssc.spitzer.caltech.edu/archanal/contributed/cubism/index.html.

5 See the Spitzer Observers Manual at http://ssc.spitzer.caltech.edu/documents/som/.
(6 \sigma), and [O iv] 25.9 \mu m (10 \sigma) lines, providing strong evidence for the presence of an AGN. Continuum-subtracted spectral images reveal that the emission is centrally concentrated and peaks at the position of the nucleus determined from the 2MASS coordinates, as can be seen in Figure 2. Since the ratio of high- to low-excitation lines depends on the nature of the ionizing source, the [Ne v] 14 \mu m/[Ne ii] 12.8 \mu m and [O iv] 25.9 \mu m/[Ne ii] 12.8 \mu m line flux ratios have been used to characterize the nature of the dominant ionizing source in galaxies (e.g., Genzel et al. 1998; Sturm et al. 2002; Satyapal et al. 2004; Dale et al. 2006). The [Ne v]/[Ne ii] ratio for the 13 AGNs with both [Ne v] and [Ne ii] detections by the Infrared Space Observatory (ISO) ranges from 0.06 to 2.11, with a median value of 0.47 (Sturm et al. 2002). The [Ne v]/[Ne ii] ratio corresponding to the maximum aperture (22.6' \times 14.8') for this galaxy is 0.06, similar to the lowest value observed in a similar aperture (27' \times 14') by ISO. The [Ne v]/[Ne ii] ratio does not increase substantially as the aperture size is reduced; the line ratio corresponding to the minimum aperture (9' \times 9') is 0.064. The [O iv]/[Ne ii] ratio for the 17 AGNs with both lines detected by ISO ranges from 0.15 to 8.33, with a median value of 1.73 (Sturm et al. 2002). The [O iv]/[Ne ii] line flux ratio corresponding to the maximum aperture in NGC 3621 is 0.23, again within the range, but at the low end of the observed values in the nearby powerful AGN observed by ISO. The [O iv]/[Ne ii] line flux ratio corresponding to the minimum aperture (9' \times 9') is 0.3, only marginally larger than the ratio obtained from the larger aperture. For comparison, the few starburst galaxies that show detectable [O iv] emission have [O iv]/[Ne ii] line flux ratios that range from 0.006 to 0.647 (median = 0.019; Verma et al. 2003) but no [Ne v] emission. We note that the fact that the [Ne v]/[Ne ii] and [O iv]/[Ne ii] line flux ratios are very low suggests that the Spitzer spectrum is dominated by regions of star formation and that significant contamination from star formation exists even at the smallest Spitzer apertures (9' \times 9' \approx 270 pc \times 270 pc). We note that there is currently no published optical spectrum of NGC 3621. However, an optical spectrum has been obtained by the SINGS team that does show a very low power Seyfert, but it becomes inconspicuous for an aperture size of \approx 1 kpc due to contamination from star formation in the host galaxy (J. Moustakas et al. 2007, in preparation). In the general case, for such low-luminosity AGNs, the standard optical or UV emission lines can be ambiguous indicators of AGN activity because they can all be produced in starburst models (e.g., Terlevich et al. 1995), a problem that is exacerbated in weak AGNs. However, the detection of the two [Ne v] lines by Spitzer provides firm evidence of an AGN in this galaxy and demonstrates that Spitzer can find AGNs in galaxies even when the AGN is energetically minor compared to star formation, regardless of the aperture size from which the spectrum is obtained.

3.1. Estimating the Bolometric Luminosity of the AGN and Limits on the Black Hole Mass

Since there are currently no published optical spectroscopic observations of NGC 3621, it is not possible to estimate the bolometric luminosity of the AGN using traditional optical calibration factors (e.g., Kaspi et al. 2000). However, we can get an order-of-magnitude estimate of the bolometric luminosity of the AGN using the [Ne v] line luminosity since this line is not contaminated by emission from the host galaxy and can therefore be assumed to be associated exclusively with the AGN. Using the [Ne v] 14 \mu m fluxes from a large sample of AGNs recently observed by Spitzer (Dudik et al. 2007; Gorjian et al. 2007), we can determine the relationship between the line luminosity and the nuclear bolometric luminosity of the AGN. Selecting only those galaxies with published bolometric luminosities obtained through direct integration of a well-sampled nuclear spectral energy distribution (SED), we plot, in Figure 2, L_{[Ne v]} versus L_{bol}, demonstrating that there is a clear correlation. The bolometric luminosities for this sample ranged from \approx 2 \times 10^{43} to 4 \times 10^{46} erg s^{-1}, and the black hole masses ranged from \approx 7 \times 10^{6} to 7 \times 10^{9} M_{\odot}. The best-fit linear relation yields

$$\log L_{bol} = 0.938 \log L_{[Ne v]} + 6.317.$$  

Assuming this relationship extends to lower values of L_{[Ne v]}, the total [Ne v] 14 \mu m luminosity from the entire map of NGC 3621 of \approx 5 \times 10^{45} ergs s^{-1} corresponds to a nuclear bolometric luminosity of \approx 5 \times 10^{44} ergs s^{-1}. If we assume that the AGN is radiating at the Eddington limit, this yields a lower limit to the mass of the black hole of \approx 4 \times 10^{5} M_{\odot}. Does this lower mass limit allow us to make any statement on the location of NGC 3621 on the \(M_{\text{bul}}-\sigma\) plane? There are no previously published high spectral resolution optical observations from which the stellar velocity dispersion in this galaxy can be determined. In the absence of an explicit bulge-disk decomposition from the surface photometry, we can get an order-of-magnitude estimate of the bulge luminosity using the morphological type of the galaxy and its total luminosity. We adopt the empirical relation given in Simien & de Vaucouleurs (1986) to estimate the contribution of the disk to the total luminosity of a disk galaxy: If \(3 \leq T \leq 7\), then \(\Delta m_{\text{bul}} = 0.324(T + 5) - 0.054(T + 5)^2 + 0.0047(T + 5)^3\), where T is the numerical Hubble type index, as given in the RC3. The bulge absolute magnitudes is then given by \(M_{\text{bul}} = M_{\text{bul}}^0 + \Delta m_{\text{bul}}\) using the apparent magnitude from the RC3 catalog of \(B_T = 9.20\) and a Hubble index of 7 yields \(M_{\text{bul}} = -15.52\) mag. Using the updated calibration of the Magorrian relationship from Ferrarese & Ford (2005), the expected black hole mass is \(M_{\text{BH}} = 3.1 \times 10^6 M_{\odot}\), approximately 3 orders of magnitude higher than the lower mass limit derived from the Eddington limit. Since the scatter in the \(M_{\text{bul}}-\sigma\) relation is significantly higher than in the \(M_{\text{bul}}-\sigma\) relation (e.g., Ferrarese & Merritt 2000), we can attempt to get an estimate of \(\sigma\) using the maximum rotational ve...
The maximum rotational velocity has been shown to follow a tight correlation with the stellar velocity dispersion in spiral galaxies in which extended rotation curves are available (Ferrarese 2002; Baes et al. 2003; Courteau et al. 2007). As part of the SINGS data deliveries, Hα rotation curves are available for NGC 3621 (Daigle et al. 2006). The maximum rotational velocity obtained from this rotation curve is 180 km s\(^{-1}\), which, assuming an inclination angle of 65° (Daigle et al. 2006), corresponds to an inclination-corrected velocity of \(\sim 200\) km s\(^{-1}\). However, the Hα data cover only the inner \(\sim 6\) kpc of the galaxy, which unfortunately does not extend to the flat part of the rotation curve. Noting that this is an underestimate of \(v_\text{r}\), the value of \(\sigma\) obtained using the \(v_\text{r}-\sigma\) relation from Courteau et al. (2007), shown in spiral galaxies to depend on the bulge-to-total light ratio, is \(\sim 102\) km s\(^{-1}\). The corresponding black hole mass is \(\sim 10^6 M_\odot\), again significantly larger than the lower mass limit derived from the Eddington limit. We note that all of these methods for estimating the black hole mass are indirect and subject to large uncertainties. Some spiral galaxies of Hubble type Sd can contain nuclear star clusters and no bulge, some have bulges and no nuclear star clusters, and some possess both (Boker et al. 2003). A detailed high spatial resolution surface brightness profile analysis is required to determine the bulge and nuclear star cluster content in NGC 3621.

4. IMPLICATIONS

The discovery of an AGN in NGC 3621 adds to the growing evidence that a black hole can form and grow in a galaxy with no or minimal bulge component. Our estimate for the bolo-
tical luminosity of the AGN is approximately 2 orders of magnitude greater than that of NGC 4395 (Peterson et al. 2005),

\[ M \sim 10^6 M_\odot \]

Are AGNs in bulgeless galaxies more common than once thought? Since the optical emission lines in weak AGNs may be dominated by star formation in the host galaxy, it is possible that AGNs are missed in optical spectroscopic surveys and that they are perhaps more common than current optical surveys suggest. Moreover, it is well known that the infrared excess observed in galaxies increases along the Hubble sequence, implying that late-type galaxies are dusty (e.g., Sauvage & Thuan 1994). In order to truly determine how common SBHs and AGN activity are in bulgeless galaxies and whether or not the dark matter mass instead of the bulge mass determines the presence and activity level of a SBH, an infrared spectroscopic study is crucial. Future studies with Spitzer will allow us to gain further insight into these fundamental questions and expand our understanding of the formation and growth of SBHs in low bulge environments.

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