EXPLORATION OF A SMBH MASS-PITCH ANGLE RELATION AT INTERMEDIATE REDSHIFTS.

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Introduction: The nature of and possible evolution in the relationship between galaxies and the supermassive black holes found at their centers is currently a topic of high interest in astronomy and cosmology. Numerous studies have established correlations between black hole mass and various characteristics of the host galaxy, including bulge luminosity, stellar velocity dispersion, and the pitch angle of arms in spiral galaxies [1,2,3]. The black hole mass-pitch angle (M-P) relation may prove to be especially useful in the study of galactic evolution, as it can be used to estimate black hole masses from imaging data only. Previous studies on the M-P relation have utilized local galaxies ($z < 0.04$) to develop its mathematical form; the form of the correlation at higher redshifts, however, is still an open question [1,2]. This project aims to assist in the development of an extended M-P relation, using spectroscopic techniques to estimate black hole masses and image analysis to measure spiral arm pitch angle in disc galaxies with type 1 active galactic nuclei (AGN).

Sample: The use of type 1 AGN is prompted by the presence of both broad and narrow emission lines from which it is possible to estimate black hole masses using spectroscopic techniques. For our sample, we began with a selection of 545 type 1 AGN from the XMM-COSMOS survey [5]. This sample was limited to those with available spectral data for a total of 327 of 545 galaxies; of these 327, 21 have redshifts in the range of interest ($z < 0.64$), and only six of these 21 had detectable spiral structure. Of the objects that met all criteria, one was found to be a dual AGN that recently underwent a merger; thus the structure is thought to be a tidal tail rather than spiral arm. The final sample consists of five objects with $0.196 < z < 0.554$. Spectra were taken from the Sloan Digital Sky Survey and the zCOSMOS survey and accessed from the VizieR Catalogue Service; HST images were used by Lilly et al. (2007) and accessed from the Mikulski Archive for Space Telescopes (MAST).

Methods: Black hole masses of four galaxies were calculated using optical spectroscopic information from two emission lines: the broad-line component of Hβ and the core component of [OIII] λ5007. Each spectrum was extinction corrected using data from the IRSA Galactic Dust Reddening and Extinction calculator. Each spectrum was also fitted with an FeII template; the template was then subtracted from the spectrum to reduce contamination from FeII near the Hβ and [OIII] λ5007 lines. Using the IRAF specfit task, emission lines were fit with Gaussian curves and an underlying power law curve to account for continuum radiation. For Hβ, luminosity and FWHM of the broad-line component were used to estimate black hole mass using an empirical relationship developed by Vestergaard & Peterson [4]. For [OIII] λ5007, the FWHM of the curve divided by 2.35 acts as a proxy for the stellar velocity dispersion σ_* from which black hole mass can be calculated using the relationship found by Salviander & Shields [3,7].

Black hole mass of the remaining object in the sample was calculated using UV spectroscopic information from the CIV broad emission line. This spectrum was also extinction corrected, but no FeII template was subtracted from it due to a lack of a known FeII emission line near the point of interest. Using specfit, the CIV emission line and underlying continuum were fitted with a Gaussian curve and power law, respectively. The luminosity at 1350 Å and FWHM of the curve were used to estimate black hole mass using another relationship developed by Vestergaard & Peterson [4].

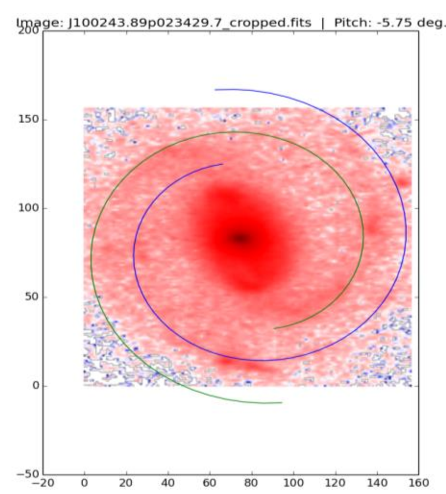

Figure 1: Spiral with m = 2 and P = -5.75° superimposed onto image of J100243.89+023429.7.

Image analysis: Spiral arm pitch angles were determined using a number of image and data analysis programs. Hubble images retrieved from MAST were each formatted for and run through 2DFFT (2-Dimensional Fast Fourier Transform), an analysis program developed within the AGES group [8]. Output from 2DFFT was plotted in SM; these plots were then inspected for a reasonable number of spiral arms (as compared to the image file) and for ranges of inner radii that produced stable pitch angles. A related Python program, also developed within the AGES group, was used to calculate average pitch angle on those ranges of inner radii using output from 2DFFT.

Results & Discussion: The left-hand plot in Figure 2 shows mass estimates for the five objects based on FWHM(Hβ) and L(Hβ) (blue), FWHM(CIV) and L_λ(1350 Å) (green), and FWHM([OIII]) (pink) as a function of pitch angle. The right-hand plot shows only broad-line data from this project combined with broad-line data previously gathered by the AGES group for other type 1 AGN. The dashed line represents the previously-published M-P relation [2]. The solid line is a weighted least squares fit to all plotted data points.

When comparing the fit to the Berrier et al. M-P relation, it is clear that the correlation between black hole mass and pitch angle has changed. However, it must be noted that the objects in each study are not only at different ranges of redshift, but are of differing types as well. Further analysis is required before it can be concluded that the correlation necessarily evolves with lookback time. The results of this project will be incorporated into a larger study on the evolution of the M-P relationship at intermediate-to-high redshifts. They will also contribute to the development of a black hole mass function for spiral galaxies at a wide range of redshifts.

References: [1] Seigar, M. S. et al. 2008. ApJL, 678, 2. [2] Berrier, J. C. et al. 2013. ApJ, 769, 2. [3] Salviander, S. & Shields, G. A. 2013. ApJ, 764, 82. [4] Vestergaard, M. & Peterson, B. 2006. ApJ, 641, 2. [5] Lusso, E. et al. 2010. A&A, 512, A34. [6] Lilly et al., 2007. ApJS, 172, 70. [7] Greene, J. & Ho, L. 2005. ApJ, 627, 2. [8] Davis, B. et al. 2012. ApJS, 199, 2.

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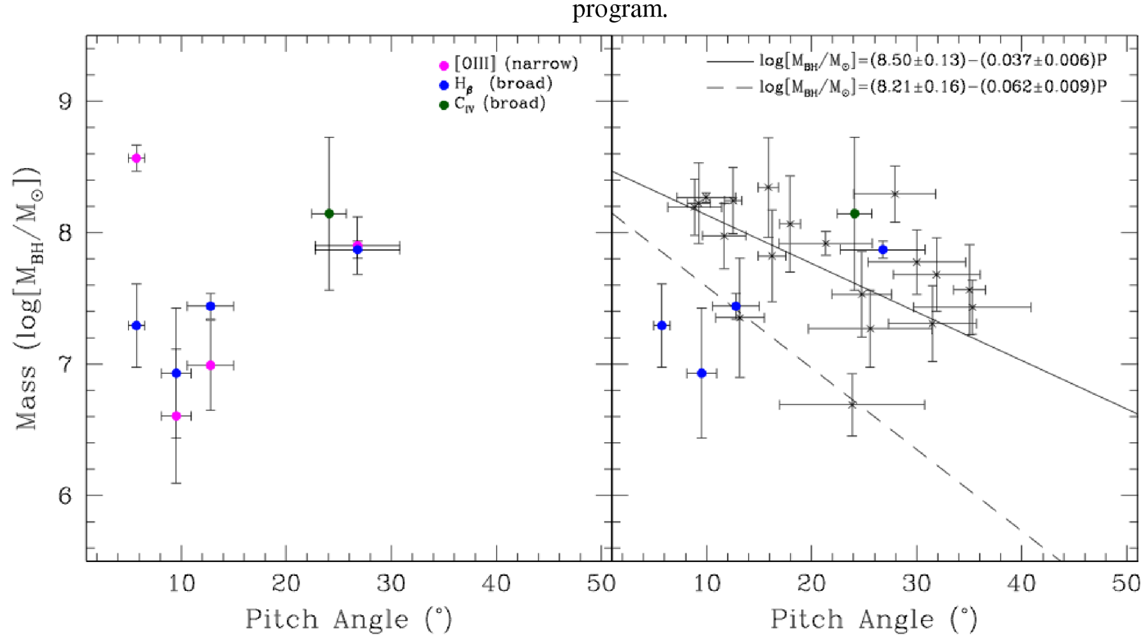

Figure 2: Mass vs. spiral arm pitch angle (left) and best fit for combined type 1 AGN data (right).