Determining the Local Black Hole Mass Function from the Pitch Angles of Nearby Spiral Galaxies.

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Introduction: It is now widely acknowledged that supermassive black holes (SMBHs) are a nearly ubiquitous feature of the bulges of spiral galaxies. Previous work by the Arkansas Galaxy Evolution Survey (AGES) team [1] has demonstrated a correlation, called the M-P relation, between the mass of a spiral galaxy's central SMBH and the pitch angle of the host galaxy's spiral arms. By measuring pitch angles for a volume- and brightness-limited sample, we have produced a census of pitch angles for spiral galaxies in the local universe. Applying the M-P relation to this census yields a local black hole mass function. We present two results: the distribution of pitch angles and the black hole mass function for spiral galaxies in the local universe.

Sample: Our sample consists of a volume-limited selection of 140 spiral galaxies from the statistically complete Carnegie-Irvine Galaxy Survey Ho et al. [2] of southern galaxies with apparent B-band magnitudes greater than 12.9. The galaxies in our selection satisfy $z < 0.0068$ and absolute magnitude $M_B < -19.528$. These parameters were chosen to maximize the size of the sample. Setting the Hubble constant to $H_0 = 71$ (km/s)/Mpc, the redshift constraint delimits a 99400 Mpc^3 volume centered at the Earth. The images used in the analysis were obtained from the NASA/IPAC Extragalactic Database, which can be found at http://ned.ipac.caltech.edu. A small number of images from the Carnegie-Irvine Galaxy Survey were also used.

Measuring Pitch Angles: Pitch angle quantifies how tightly wound the arms of a spiral galaxy are. More tightly wound arms equate to a smaller pitch angle amplitude. In the extreme cases, a pitch angle of 0° represents a circle, while a pitch angle of 90° represents radial arms. The sign of the pitch angle encodes the chirality of the spiral.

The AGES team has developed a method of measuring pitch angle that uses a two-dimensional fast Fourier transform to decompose an image of a spiral galaxy into a weighted sum of logarithmic spirals. This method is described in detail in a forthcoming paper [3], therefore only a sketch is provided here. The method entails two main steps: deprojecting the galaxy image in IRAF to make it appear face-on, and running the 2DFFT routine on the deprojected image. The fast Fourier transform requires the user to select an annulus containing the spiral arms. Since the result of the 2DFFT is highly sensitive to the choice of inner radius, we perform the routine iteratively over all possible inner radii. Performing the process iteratively reduces the error introduced by having the user select the appropriate annulus by eye.

As explained in Davis et al. (in preparation) [3], we have found this procedure to be robust: the resulting pitch angle is independent of the waveband of the image, and it is negligibly affected by small errors in the deprojection process. Furthermore, reliable measurements can be obtained from galaxies at an inclination angle of up to 60°, and in some cases at even higher inclinations. Errors on the measurements of pitch angle are typically $\sim$3°.

Calculating the Mass Function: Following the literature (e.g., [4]), we calculate the black hole mass function $\delta N/\delta(\log_{10} M)$ from

$$\frac{\delta N}{\delta(\log_{10} M)} = \frac{\delta N}{\delta P}\frac{\delta P}{\delta(\log_{10} M)}, \tag{1}$$

where N is the total number of galaxies, M is the black hole mass, and P is the pitch angle. By this notation, $(\delta N/\delta P)dP$ gives the total number of galaxies with pitch angles between P and $P + dP$, and therefore $\delta N/\delta P$ is the distribution of galaxies as a function of pitch angle. Our census of pitch angles provides this component of the mass function.

For the other component, we use the M-P relation as given in [1]:

$$\log_{10} M_{BH} = (8.44 \pm 0.10) - (0.076 \pm 0.005)P. \tag{2}$$

From differentiation of this relation, we obtain $\delta P/\delta(\log_{10} M)$. The chain rule then yields the black hole mass function.

Results: We present two major results. The first is the distribution of pitch angles for the sample (Fig. 1). Since we drew our sample from a statistically complete survey, the plot in Figure 1 is representative of the distribution of pitch angles among spiral galaxies in the local universe. The only caveat is that the galaxies with the lowest absolute brightness have been neglected because of the restriction on our sample that the absolute magnitude satisfy $M_B < -19.528$. In the future, we intend to probe whether the inclusion of these dimmer galaxies significantly affects the distribution of pitch angles.

The second result is the black hole mass function (Fig. 2). Our mass function for local spiral galaxies

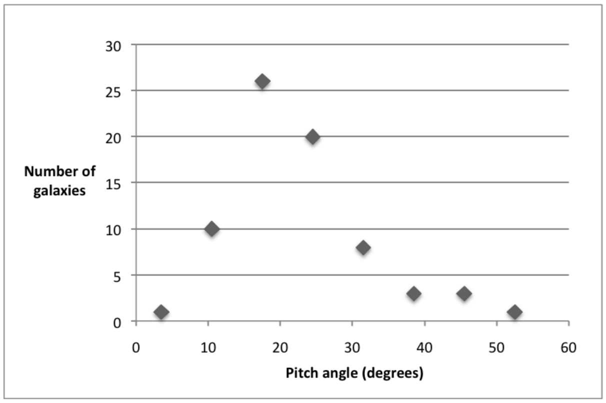

Figure 1: The distribution of galaxies in the sample as a function of pitch angle. Each data point represents the number of galaxies that were measured to have a pitch angle falling within the respective 7° bin. This plot was constructed from the 72 pitch angle measurements that were deemed highly reliable. The remaining measurements for the sample were excluded due to excessively high galaxy inclination angle, low image quality, or distorted morphology.

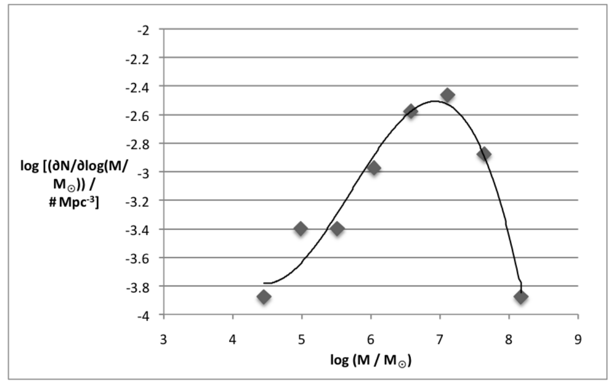

Figure 2: The black hole mass function for local spiral galaxies, fitted with the third-degree polynomial curve of best fit. Appropriately assigning error to this plot and to Fig. 1 is currently under discussion.

resembles the function found for all galaxy types by Greene & Ho (2007) [5] using AGN luminosities. However, our function is more sharply peaked than that found by Greene & Ho. We propose that this discrepancy is due in part to the greater number of elliptical versus spiral galaxies at the highest range of masses. In addition, the lower-mass end of our function is steeper because of the restriction that we placed on the absolute brightness in selecting the sample of galaxies.

Conclusion: Quantitatively analyzing the pitch angles of spiral galaxies is a novel approach to the study of galactic evolution. Although pitch angle is just one among a host of correlates with central black hole mass (along with, e.g., host galaxy mass or luminosity, stellar velocity dispersion of the bulge), the work of the Arkansas Galaxy Evolution Survey (AGES) team is demonstrating the robustness of this approach. The greatest value of using pitch angles to probe galactic structure is the ease with which these measurements can be obtained. With the growing availability of high-quality optical and near-infrared images, the process of measuring pitch angles is becoming increasingly accurate for an expanding population of galaxies.

By taking a census of pitch angles for a statistically complete sample, we have determined the black hole mass function for local spiral galaxies. This result has opened up a number of avenues that invite exploration. The AGES team intends to build on the the findings presented here in order to investigate how the black hole mass function has evolved since $z \sim 1$. In addition to redshift, the degree of galaxy clustering may be related to the distribution of pitch angles. Accordingly, we intend to compare pitch angle functions for samples of field versus cluster galaxies. By examining the effects of clustering on pitch angles, we will test the potential relation between dark matter halo concentrations and spiral morphology.

A limitation of using pitch angles to determine black hole masses is that measurements can only be obtained for disk galaxies. We therefore promote a combination of pitch angle (for disk galaxies) and Sersic index of the bulge (for elliptical galaxies) as a means of determining a complete black hole mass function solely from the use of imaging data. We plan to pursue such a program in the future.

Funding for this project was provided by the National Science Foundation, Award Number 0851150.

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