PITCH ANGLE SURVEY OF GOODS SPIRAL GALAXIES. Benjamin Boe[1,2], Douglas Shields[2,3], Casey Henderson[2], Dr. Daniel Kennefick[2,3], Dr. Julia Kennefick[2,3], William Ring[4], Marc Seigar[4], Jazmin Medina[2,3]. [1]Department of Physics, University of Puget Sound, [2]Arkansas Center for Space and Planetary Sciences, University of Arkansas, [3]Department of Physics, University of Arkansas, [4]Department of Physics and Astronomy, University of Arkansas at Little Rock

Introduction: This research looks at how the pitch angles of galaxies change over scales of cosmic time. We measure the pitch angle, or tightness of spiral winding, using a new code, Spirality. We then compare the results to a widely used software, 2DFFT (2 Dimensional Fast Fourier Transform). We investigate any correlation between pitch angle and redshift, or distance from Earth.

Previous research indicates that the pitch angle of a galaxy correlates with its central bulge mass and the mass of its central black hole.[1] This means that measuring a galaxy's pitch angle can give an estimate of its central black hole mass.

Pitch Angle: The arms of spiral galaxies can usually be modeled as a logarithmic spiral with a constant pitch angle. Pitch angle refers to the tightness of winding, the higher the pitch angle the looser the winding and vice versa. A pitch angle of 0^0 is a concentric circle on the origin, while a pitch angle of 90^0 are radial lines like the spokes on a bicycle wheel. See Figure 1 for some examples of different pitch angles. Note that a positive pitch angle means that the spiral curves clockwise and a negative pitch angle counter-clockwise. The direction that the galaxy curves is referred to as chirality.

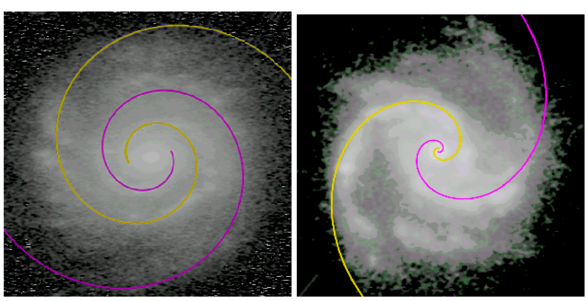

Figure 1. Example logarithmic spirals. Left is 12.25^0, right is -26.76^0

GOODS Survey: Galaxies from the GOODS (Great Observatories Origins Deep Survey) North and South were measured. GOODS is a survey of a very small, dark portion of the Northern and Southern sky containing a total of 320 square arcminutes.[2] The GOODS field was observed by many different NASA and ESA telescopes. The survey captured images of galaxies that are dimmer and farther away than what had previously been measured. For the purposes of this research, we used the images taken by the Hubble Space Telescope. Figure 2 shows a portion of the Hubble GOODS South.

Figure 2. Image of Hubble GOODS South Survey[2]

Spirality: Spirality was used to measure the pitch angle of GOODS galaxies. The code works by generating spiral templates for many different pitch angles and finding a best match for the galaxy. This process is repeated from multiple inner radii to a common outer radius at the edge of the galaxy. Multiple inner radii allow for the code to measure any slight fluctuations in the pitch angle and find a stable region of a peak in pitch. For each inner radius the code generates a graph like those seen in Figure 3. Once a peak is found we make a fine measurement, looking over a smaller range of pitch angles and radii. The code then computes an average pitch over the radii measured and finds the error in that measurement.

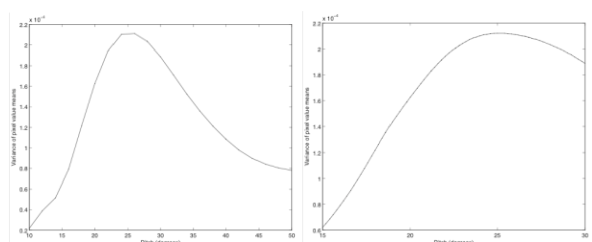

Figure 3. Example Spiraltiy outputs. Left is rough measurement, right is a fine measurement of a 25^0 pitch angle.

Symmetric Components: Sometimes it can be challenging to find a stable pitch. This problem is often due to foreground stars, satellite galaxies, star forming regions, flocculent arms, or low resolution galaxy. In order to solve this problem, we can take symmetric components of the galaxy. An example of a symmetric image generated by Spirality can be seen in Figure 4.

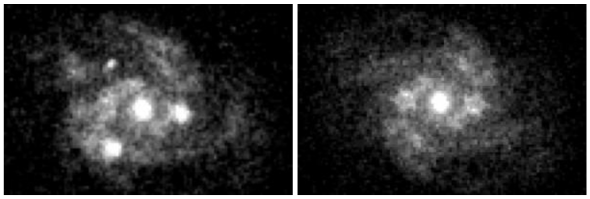

Figure 4. Galaxy GN32.4682.6219 before (left) and after (right) a 180^0 symmetric component was taken.

Results: In order to check the effectiveness of Spirality, we compared pitch angle measurements made in Spirlaity to measurements of the same galaxies in 2DFFT. Figure 5 shows the plot of 2DFFT pitch angle vs Sprialty pitch angle. If the codes agreed on a galaxy then it would be located on the red line of y=x. The farther from the line, the worse the agreement. If the error bars overlap with the y=x line then the codes were consistent. The blue line is the line of best fit, calculated using a Monte Carlo simulation. Many thousands of points were generated, mapping each galaxy to a Gaussian distribution according to its error bars. The error in slope was calculated by determining the spread of Monte Carlo points away from the line of best fit. The average error bar size from 2DFFT was 7.1^0 while the average error bar size from Sprialtiy was 4.8^0.

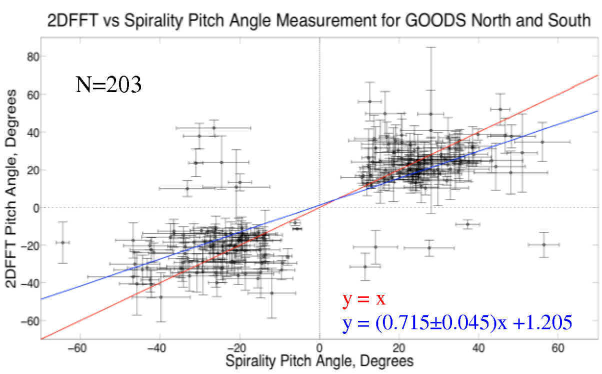

Figure 5. Measured pitch in 2DFFT vs Spirality

To investigate the evolution of galaxies we looked at how the average pitch angle of a galaxy changes over cosmic time. Since more distant galaxies are seen farther back in time, we can use distance as an analogue for time. Figure 6 is a plot of the absolute value of the measured pitch angle in Spirlaity vs redshift. We plotted only those galaxies for which 2DFFT and Spiraltiy agreed on the pitch angle of a galaxy (to within error bars) and for which redshift data was available. The blue line is the line of best fit, calculated using a Monte Carlo simulation like the previous graph.

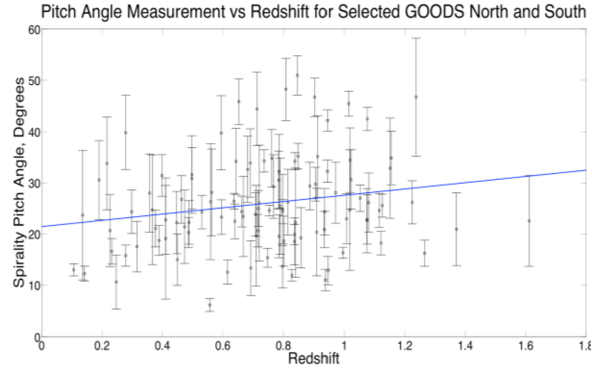

Figure 6. Measured pitch in Spirality vs Redshift

Discussion: Spirality appears to be an effective way of measuring pitch angle. The majority of galaxies agreed to within error bars, and many were very close to agreement. There were some outliers, including 12 (5.9%) that did not agree on chirality.

For the 2DFFT vs Spiraltiy graph, the slope was significantly less than 1. This indicates that on average Spirality measures a slightly higher pitch angle than 2DFFT. This slope is not very far from 1 however, so the codes are usually consistent. It is important to note that since many of these galaxies are on the edge of our ability to measure, it is probable that the outliers are simply too difficult to measure accurately by any method.

The pitch vs redshift graph indicates that pitch angle increases with distance or, equivalently, with lookback time. The increase is a significant 6.15^0 per unit redshift, with an error that makes the slope inconsistent with 0. This result implies that black holes at the center of galaxies used to be smaller than they are today. We are assuming that the relationship between black hole mass and pitch angle has remained constant over time.

It is important to note that this survey is by no means a complete survey of galaxies over this time period and there is selection bias. We are biased to select the brighter galaxies because they are easier to find, there are no doubt many galaxies that we did not measure due to their dimness.

References: NSF Grant #1157002
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