Quantitative Method for Bar/Non-bar Classification of Galaxies

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Galaxy classification is a necessary means of organizing galaxies in order to better understand the physics that underlies the structural features of galaxies and galaxy evolution. However, many classification schemes are largely qualitative, and depend upon the subjective views of the classifier. My project concentrated on making galaxy classification a more quantitative practice, so that the morphology and evolution of galaxies can be studied in detail using numerical data. Due to the difficulty of the problem, Dr. Steve Odewahn and I focused only on obtaining classification parameters that determine whether a galaxy is barred or non-barred. Through the use of Fourier analyses performed on several galaxies using a computer program called LMORPHO, we were able to find a set of parameters that show a clear distinction between barred and non-barred galaxies.

Much of my initial work was preliminary to the actual search for parameters. I had to familiarize myself with LMORPHO, and in particular I had to become adept at using a specific program package called IGALPHOT. LMORPHO is a software program created by Dr. Odewahn that contains a variety of tools for analyzing astronomical data. For instance, the IGALPHOT program provides a means of reconstructing galaxy images using Fourier series.

After learning the necessary functions in LMORPHO, we began work on processing galaxy images for analysis. Several BVR images of 5 galaxies were obtained using the 30-inch telescope at McDonald Observatory, and were initially planned to be part of the galaxy sample used for categorization, but were discarded because of poor image quality due unfavorable photometric observing time. As a result, 44 Ohio State University (OSU) bright galaxy images were used in the analysis. The 44 OSU images were part of a larger sample of OSU galaxy images taken from various telescopes around the world; we selected the images based on how clearly the galaxy featured a bar or not. For this project, we tried to include only distinct SB or SA galaxies, while avoiding transitional or interacting galaxies. Each of the 44 images were classified visually as either barred or non-barred by myself and Dr. Odewahn, and then processed for the Fourier image reconstruction. The preparation phase included star removal and fitting an ellipse profile around each galaxy. Bright stars near or in the galaxies were patched from the original images in order to assure a more accurate recreation of the galaxies" morphological qualities. The ellipse profile determined the center and orientation of each elliptical annulus that was to be used during the Fourier analysis, as explained below.

After processing each galaxy image, we used IGALPHOT to create Fourier models of each galaxy. The Fourier analysis was performed on the star-patched image. IGALPHOT created a model for each galaxy image by measuring the flux at each point of an elliptical annulus having a center and orientation defined by the original ellipse profile, and then finding a Fourier series that modeled the azimuthal flux profile, and repeating the process for a user-determined number of annuli that progressively enlarged in area and extended out to the original ellipse profile. The Fourier data allowed for investigation of azimuthal and amplitude profiles of individual or multiple annuli. The amplitude profiles consisted of the largest values of a particular Fourier term coefficient for each annulus plotted as a function of annulus number. The azimuthal profiles displayed the flux measured at each point of a particular annulus ring as a function of phase angle. We generally used 30 annuli for each galaxy, and the Fourier series for each annulus contained 16 terms. In fact, in order to acquire an acceptable model for strong bars and other bright galactic spatial features, higher-order Fourier terms were required to reconstruct the large peaks in flux.

Upon completion of the Fourier model, we used IGALPHOT to display the model and star-patched images together. Several of the galaxy model images were poor, and required that the star-patched image be refined to obtain a better Fourier model. For example, several models would show distinct ringing, in which an area of strong flux in the image would be smeared around one of the elliptical annuli. Ringing can actually mimic a morphological component of a galaxy in the Fourier data, causing a possible misclassification. To fix such problems, the source of the ringing had to be identified and then either patched out or altered. Two such sources included bright stars and bad pixels that were not properly removed during the image reduction. Once found, both were easily patched from the image. Ringing was also caused by the ellipse profile being off-centered with respect to the brightest part of the galactic nucleus; this type of problem was solved simply by adjusting the ellipse center. Another refinement was to make the ellipse profiles for some of the galaxies bigger, so that all of a galaxy's light in the image was included in the Fourier analysis, which can have consequences when experimenting with and determining parameters for classification.

After each image was reconstructed though Fourier series, we began looking for parameters that could provide a good bar/non-bar separation based on the numerical data. Our initial attempts involved different combinations of the amplitude profiles for various Fourier terms of each galaxy. For example, one parameter space that gave a decent separation was the combination of the median values of the 2-theta amplitudes for all annuli and just the inner half of annuli. However, none of the parameter spaces based solely on amplitude profiles showed a clear distinction between barred and non-barred galaxies. The best results came from the use of azimuthal profile data. An excellent, distinct grouping of barred and non-barred galaxies occurred for the parameter set consisting of the ratio of the two highest peaks and the mean measure of the two largest peaks, with both parameters averaged over all azimuthal profiles using 16 Fourier terms. In this case, the barred and non-barred galaxies had distinct groupings with very little overlap. For the average ratio of the two highest peaks in the azimuthal profiles, non-barred galaxies generally had values significantly different from one because the two highest peaks did not have similar values. A non-barred galaxy could have a bright area of flux caused by a star or other attribute, resulting in a large peak somewhere in an annulus' azimuthal profile, but there were generally no regions on the annulus that could cause a second, similar large peak. But for bars, the two highest peaks often were very close in value, and therefore had an average ratio near one.

During the process of analyzing the Fourier data and experimenting with different sets of parameters, we learned that there are a couple of factors that are important to take into account. One factor is the centering of the original ellipse profile, which if not centered on the bright part of a galaxy's nucleus can cause ringing, and thus incorrectly indicate higher flux values for areas around the galaxy. Even an ellipse off-centered by a few arcseconds resulted in ringing for galaxies that had a strong central bulge. Another important factor was the number of annuli we specified for the Fourier reconstruction. With more annuli, strong spatial features such as bright bars were modeled much more accurately; that is, the increased resolution improved the model. For example, the model image of NGC5921 using 30 annuli resulted in a false ring around the center of the galaxy's bulge; using 60 annuli removed the ring and gave an excellent model image. However, more annuli did not always help for most images, because a certain threshold would be reached, at which point higher resolutions did not affect, or even decreased the quality of the model image. For most galaxies, 30 annuli produced the best models.

There were also several aspects of the project that I learned were important to consider before running the Fourier analysis. For instance, images in which the galaxy makes up a large percentage of the image are not ideal for use, because they will require large ellipse profiles and therefore will have less resolution for a given number of annuli as compared to galaxies that take up smaller portions of the images. Also, a galaxy's relative orientation and environment are important factors. We did not want to use images in which galaxies were interacting, because the morphological properties were often distorted and poor representations of bar or non-barred galaxies. In addition, if a galaxy was largely edge-on in the image, then it was not used.

While our project focused mainly on finding parameters for determining if galaxies are barred or non-barred, there are many possibilities for future work. Extending upon the success of the parameter space for bars, we can use different azimuthal profiles for studying spirals. For instance, the azimuthal profiles of bars and spirals could be compared to see if there is a noticeable, continuous phase shift in the two strongest flux peaks for spirals but not for bars. For certain intervals of annuli, bars are not expected to have any significant phase angle shifts for the highest peaks in the azimuthal profiles, but for spirals the peaks should shift continuously. Also, spirals could be investigated in detail to improve classification of specific spiral arm types, as well as quantitatively describe how strong they are for various galaxies. Some of the strong spatial features, including bars and bright spiral arms, need higher-order Fourier terms to be modeled accurately. The strength of these higher-order terms could be compared to look for a correlations between galaxies having strong features and those that don't. While searching for classification criterion, it is important to recognize that parameter spaces for classifying galaxies with various characteristics may depend largely upon what interval of annuli are used in the parameters; that is, whether sets of parameters focus only on the inner, outer, or other combinations of annuli.

Classifying galaxies through a quantitative means is an important step in understanding the physical nature of galaxy morphology. The results of my project indicate the ability to classify galaxies as either barred or non-barred using a parameter set that is based on the measurement of the two largest peaks in the azimuthal flux profiles. Different galactic characteristics may require more creative or specific parameter spaces to achieve good classifications, but there are already several interesting ideas to consider for further investigation.