Lab 8

Properties of Galaxies

8.1 Overview

Exercise eight focuses on galaxy properties and their constituent stellar populations. We introduce the morphological sequence and augment luminosities, sizes, colors, and redshifts with modern morphological indices based on concentration and asymmetry. Students analyze both images and spectra of a sample of nearby galaxies drawn from the Sloan Digital Sky Survey (SDSS), determining intrinsic properties and estimating morphological types based on various factors.

The first activity (see Figure 8.1) is designed to help students to realize how much information is present in a galaxy image. Students sort a mosaic of 25 galaxies of varied types into groups, based on their own first reactions to the images (before having been exposed to definitions of galaxy types or basic structures). They then have a companion sort the same mosaic, and compare and contrast the results afterward. No two people sort the mosaic in the same way. This exercise thus provides a way for students to observe how different viewers focus on different aspects of the images (such as colors, shapes, and levels of sub-structure). The companion for this exercise can be another student, providing an opportunity for peer-to-peer discussion in a cooperative environment, or an adult or older child.

Two more web-applications are provided, similar to the image and spectral analysis tools used in exercise seven. These versions are augmented with morphological type options. As shown in Figure 8.2, students again analyze galaxy images and fit apertures to light profiles to determine structural parameters. Additional measurements are made, of concentration (the fraction of light within the central 30%) and asymmetry (the fraction of light after differencing the normalized image with a copy rotated by 180°) indices. They estimate morphological types as well, having read through a discussion of the observable properties of elliptical galaxies, lenticular galaxies, the spiral sequence, and peculiar and interacting

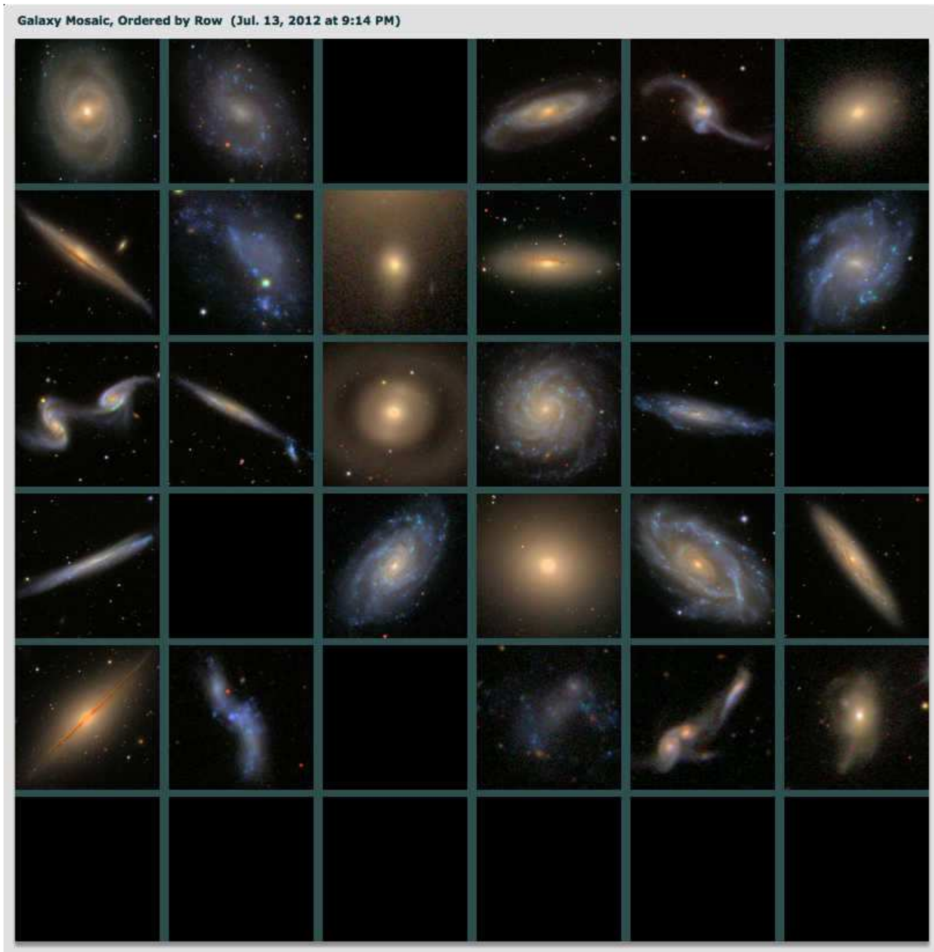
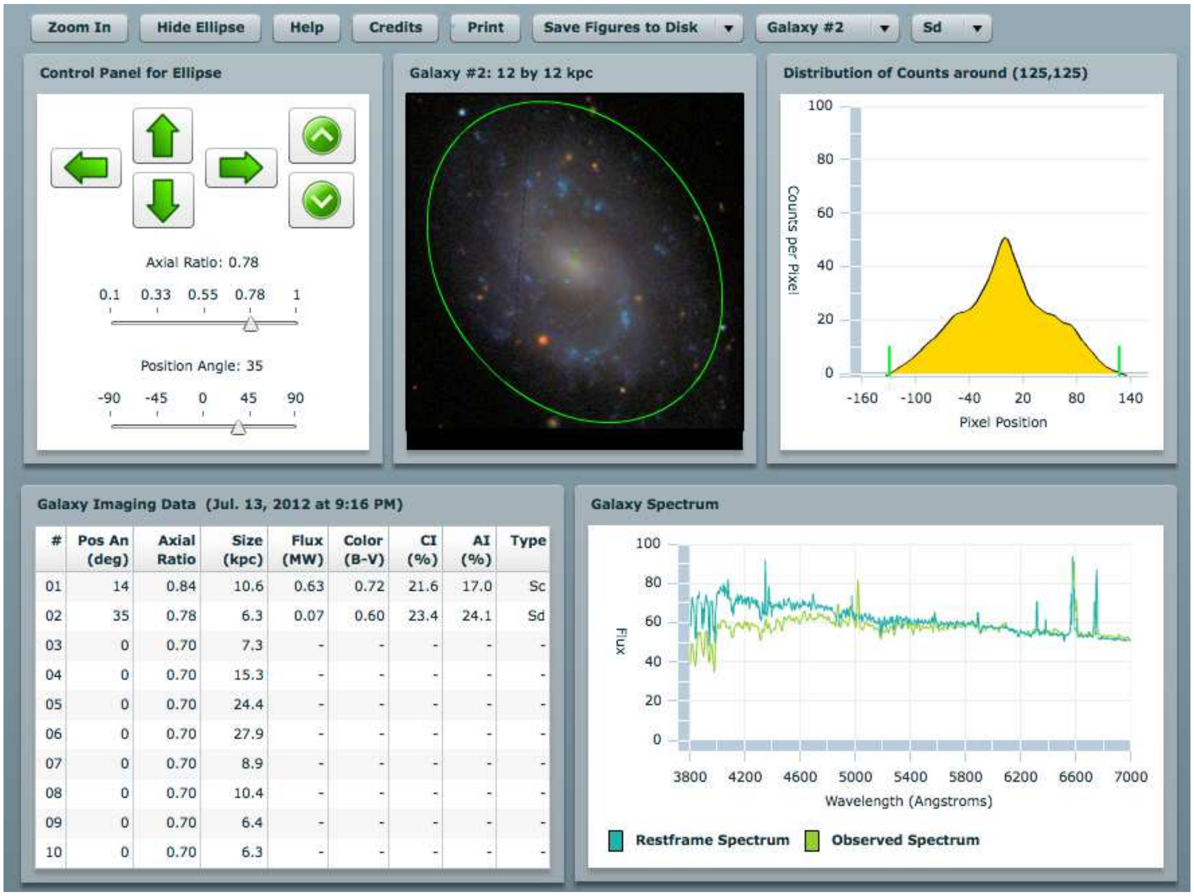


Figure 8.1: A screen capture of our galaxy sorting tool. Students sort the 25 galaxies into 4 to 6 rows, based on what they think are the most important aspects. Everyone sorts the galaxies differently, leading to discussions about various factors being used to place galaxies in different groups.

systems. Basic properties are interpreted in terms of bulge and disk stellar populations and galaxy interaction histories. We also emphasize the difference between observable properties such as bulge-to-disk fraction which vary with the intrinsic properties of the galaxy and those such as disk inclination angle which are purely products of viewing angle, prominent in images but unrelated to galaxy evolutionary history.

Students determine galaxy redshifts from optical spectra (see Figure 8.3). They are also furnished with comparison spectra overlays of various morphological types within the spectral analysis tool, in order to make an independent estimate of type based on the continuum shape and the strength of various absorption and emission features.

As in exercise seven, we want students to experience the process of analyzing images and spectra for themselves. Our web-applications are designed without the need to install software, compile packages, or learn complicated commands in order to examine data and conduct



#	Pos An (deg)	Axial Ratio	Size (kpc)	Flux (MW)	Color (B-V)	CI (%)	AI (%)	Type
01	14	0.84	10.6	0.63	0.72	21.6	17.0	Sc
02	35	0.78	6.3	0.07	0.60	23.4	24.1	Sd
03	0	0.70	7.3	-	-	-	-	-
04	0	0.70	15.3	-	-	-	-	-
05	0	0.70	24.4	-	-	-	-	-
06	0	0.70	27.9	-	-	-	-	-
07	0	0.70	8.9	-	-	-	-	-
08	0	0.70	10.4	-	-	-	-	-
09	0	0.70	6.4	-	-	-	-	-
10	0	0.70	6.3	-	-	-	-	-

Figure 8.2: A screen capture of our galaxy imaging analysis tool. The top row contains three windows related to fitting an aperture to capture the galaxy light: (1) a control panel for varying the aperture center, radius, axial ratio, and position angle, (2) the galaxy image, and (3) a radial plot of the galaxy light, showing the light profile within and beyond the aperture. The aperture is marked as a green ellipse on the image, and as two green bars on the radial light profile. The bottom row contains (1) a table of fit parameters for each of ten galaxies, including concentration, asymmetry, and morphological type, and (2) the observed galaxy spectrum and a rest-frame comparison spectrum of the selected morphological type. Students fit both images and spectra during the exercise. We include a diagram of the spectrum when analyzing the image, and a copy of the image when analyzing the spectrum, to help students to connect the observables within each type of data.

basic analyses. This allows students with no background in data processing to focus on astronomical issues.

At the end of the exercise, students return to the original mosaic of 25 galaxies and re-evaluate the way in which they originally grouped the galaxies into subsets. They are now able to describe variations in color in terms of stellar populations, and to discriminate between disturbed morphologies indicating galaxy interactions and differences in disk appearance due merely to, for example, viewing angle. The result is a more nuanced view of what is

Figure 8.3: A screen capture of our galaxy spectrum analysis tool. Students determine galaxy redshifts by shifting the galaxy spectrum left and right in wavelength so as to match up absorption and emission features, as well as the general shape of the continuum, to a rest-frame spectrum of a galaxy of the selected morphological type. The correlation coefficient is reported numerically and also shown graphically on a symbolic thermometer – the better the match between the two spectra, the higher the level of the green "liquid" in the thermometer.

significant when we study galaxies.

8.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Classify galaxies by morphological type, according to optical images and spectra.
- Understand the relationship between the spectra of individual stars within a galaxy and the resultant galaxy spectrum.
- Describe the basic properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies observed in optical images.
- Describe the basic properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies observed in optical spectra.
- Connect the observed optical properties of elliptical, lenticular, spiral, peculiar, and interacting galaxies to their stellar populations and their gas content.

- Fit an elliptical aperture to a galaxy image to determine its basic structural parameters.

- Describe and identify the continuum, and absorption and emission features, in an optical spectrum of a galaxy.

- Shift a galaxy spectrum in wavelength to determine its redshift, by studying the underlying shape of the continuum and the observed absorption and emission features.

8.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

8.4 Keywords

Aperture – A circle, or ellipse, with an open center. Astronomers often place an aperture around a single star or galaxy, and then add up all the light contained within this region in order to determine how bright the object is.

Asymmetry Index (AI) - The percentage variation in the difference between the flux emitted at one position within a galaxy and at a corresponding position located 180° around the galaxy center-point. This index tends to be quite low for elliptical galaxies because they have smooth, symmetric light profiles, higher for spiral galaxies due to the spiral arm structure in the disks, and higher still for interacting galaxies, which can appear quite distorted.

Color index – A number used to gauge a star's color, or relative intensity, at two wavelengths. Often based on the difference between how bright a star appears in two different filters, e.g. B–V for the blue and visual filters.

Concentration Index (CI) – The ratio of the amount of flux emitted by the inner 30% of a galaxy and by the total galaxy. Because elliptical galaxies are centrally concentrated they have higher CI values than spiral galaxies, which generally have more slowly decaying, exponential light profiles across their disks.

Correlation coefficient – The correlation coefficient R is a measure of the strength of the relationship between two variables x and y. It ranges from -1 to 1, where +1 indicates the strongest possible positive correlation (as x increases, so does y), zero indicates no predictive relationship between quantities, and -1 indicates the strongest possible negative correlation (as x increases, y decreases). Correlation coefficients are well-suited for determining zero-point offsets in periodic relationships (such as syncing sine waves to remove phase offsets).

$\Delta\lambda$ – The shift in wavelength for an absorption or emission feature in a spectrum between its observed (λ_{obs}) and its rest-frame (λ_{rest}) wavelengths.

Flux - The flux from a celestial object is the amount of emitted light that is observed, by eye or through a telescope, at a certain distance.

Galaxy – A galaxy is a gravitationally bound set of stars, gas, and dust, spanning up to hundreds of kiloparsecs in size and containing thousands to billions of stars. Our galaxy is called the Milky Way.

Galaxy Cluster – A galaxy cluster contains hundreds or thousands of galaxies, all bound together by their combined gravitational attraction.

λ_{obs} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object moving at some velocity with respect to the observer.

λ_{rest} - The wavelength of an absorption or emission feature in a spectrum at which it is observed to occur within a celestial object at rest with respect to the observer.

Luminosity – A measure of intrinsic brightness defined by how much energy a star (or other object) radiates into space per second.

Major axis – The major axis of an ellipse is its longest side, the longest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the minor axis.

Milky Way – The Milky Way is the name of our own galaxy, a barred intermediate-type spiral.

Minor axis – The minor axis of an ellipse is its shortest side, the shortest line segment which can be placed within it (passing from one side through the center to the other side). It is perpendicular to the major axis.

Morphology – Shape, or form.

Redshift – The redshift z of a galaxy is defined as $\Delta\lambda/\lambda_{rest}$, the ratio of the shift in wavelength $\Delta\lambda$ observed for a spectra feature of rest-frame wavelength λ_{rest}.

Semi-major axis – The semi-major axis of an ellipse is half the length of the major axis.

Semi-minor axis – The semi-minor axis of an ellipse is half the length of the minor axis.

Spectral class – A classification based on the appearance of a stellar spectrum, analogous to the temperature sequence, with blue O class stars being hottest, yellow G stars like the Sun being intermediate, and red M stars being cooler.

Velocity of recession – The velocity of an object which appears to be moving away from us. For galaxies, recessional velocities can be measured from spectral redshifts.

8.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 24: The Milky Way, Chapter 25: The Expansion of the Universe, and Chapter 26: A Universe of Galaxies, as well as Chapter 16: Absorption and Emission, Chapter 17: Stellar Temperatures, and Chapter 19: Binary Stars.

8.6 References and Notes

1. The image of the Milky Way as seen from the Black Rock Desert in Nevada shown in Figure 8.1 was taken by Steve Jurvetson on July 22, 2007 using a Canon EOS 5D. It is made available under the Creative Commons Attribution 2.0 Generic license, and can be found at http://www.flickr.com/photos/44124348109@N01/898622334.

2. The image of a galaxy similar to the Milky Way shown in Figure 8.1 is a product of the Sloan Digital Sky Survey (SDSS), identified as J083909.27+450747.7 and extracted with the DR7 Finding Chart Tool from http://cas.sdss.org/dr7/en/tools/chart/chart.asp.

3. The drawings in Figure 8.2 and Figure 8.5 are shown courtesy of Nicole Vogt.

4. The images of galaxies NGC3168, NGC4814, and ARP240 shown in the top row of Figure 8.3 (to illustrate the asymmetry index) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

5. The images of elliptical galaxies NGC3168, NGC163, NGC4187, NGC4839, NGC2675, and NGC2937 (shown from left to right, top to bottom in Figure 8.4) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

6. The images of spiral galaxies NGC5375, NGC5448, NGC2654 (Sa), NGC3351, NGC4814, NGC5777 (Sb), NGC5375, NGC5448, NGC2654 (Sc), and NGC3351, NGC4814, NGC5777 (Sd) (shown from left to right, top to bottom in Figure 8.6) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

7. The images of S0 galaxies NGC2911, NGC4124, NGC3593, NGC5750, NGC4293, and NGC4880 (shown from left to right, top to bottom in Figure 8.7) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

8. The images of peculiar or interacting galaxies NGC660, NGC3628, NGC3187, ARP240, UGC8584, and UGC10770 (shown from left to right, top to bottom in Figure 8.8) are products of the SDSS, extracted with the DR7 Finding Chart Tool.

9. The images of M81 shown in Figure 8.9 are a product of the SDSS, extracted with the DR7 Finding Chart Tool (optical image) and a VLA 21 cm map (courtesy Min Su Yun, radio image).

10. The optical spectrum of a galaxy shown in Figure 8.10 is a product of the SDSS, identified as SPSPEC-53713-2292-634, and extracted from http://das.sdss.org/www/ cgi-bin/fiber?PLATE=2292&MJD=53713&RERUN=26&FIBER =634.

8. The optical spectra of elliptical galaxies shown in Figure 8.11 are SDSS spectra taken from the sixth data release (DR6). The rest-frame spectrum was created by combining the spectra of 26 $z < 0.1$ galaxies taken from the journal article "How Special are Brightest Group and Cluster Galaxies?" by von der Linden, Best, Kauffmann & White in *Monthly Notices of the Royal Astronomical Society*, vol. 379, issue 3, pp. 867–893 (2007) and 10 $z > 0.1$ galaxies taken from the SDSS DR6 Galaxy Clusters Catalog at http://heasarc.gsfc.nasa.gov/W3Browse/galaxy-catalog/sdsswhlgc.html.

9. The optical spectra of nearby elliptical and lenticular galaxies shown in Figure 8.12 are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these spectra represent only the inner few percent of the galaxies.

10. The optical spectra of nearby spiral galaxies shown in Figure 8.13 are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these

spectra represent only the inner few percent of the galaxies.

11. The ten optical images of galaxies used in the image web-application for this exercise are products of the SDSS, extracted with the DR7 Finding Chart Tool. These galaxies are all members of the New General Catalog of Nebulae and Clusters of Stars (NGC; Dreyer, 1888), and so are identified by NGC numbers. Basic optical properties of the sample were taken from the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs et al., 1994).

12. The ten optical spectra used in the spectral web-application for this exercise are SDSS spectra taken from the seventh data release (DR7). The SDSS fibers are $3''$ in diameter, so these spectra represent only the inner few percent of the galaxies.