Lab 7

Hubble's Law and the Cosmic Distance Scale

7.1 Overview

Exercise seven is our first extragalactic exercise, highlighting the immense scale of the Universe. It addresses the challenge of determining distances on large scales, working from standard candle techniques to cosmological redshifts. Students study samples of Cepheid variable stars out to 30 Mpc and then move outwards to Type Ia supernovae. They also examine galaxy spectra, using Hubble's Law and observed shifts in the wavelengths of key features to determine distances.

The primary activity involves analyzing a set of 36 brightest cluster galaxies (BCGs) observed by the Sloan Digital Sky Survey (SDSS). In order to clearly connect the outputs of standard candle techniques and redshift-determined distances, we have student utilize both types of techniques on the sample. We begin with the assumption that BCGs have relatively uniform properties, under which their angular size and the square of their observed brightness will both be inversely proportional to distance (for redshifts $z < 0.1$).

Students use the web-application shown in Figure 7.1 to fit apertures to a sample of SDSS BCGs. As with the stellar aperture-fitting tool in the sixth laboratory exercise, this involves balancing the need to extend each aperture outward far enough to contain a maximum amount of light from the galaxy with minimizing the contamination from neighboring galaxies and foreground stars. We want students to realize that there is no "perfect" solution to these types of problems, and that two astrophysicists analyzing the same galaxy image by hand would inevitably place and size their apertures slightly differently, leading to slightly different measurements of such properties as galaxy total brightness and size. This should be regarded as one source contributing to the errors associated with such measurements. We

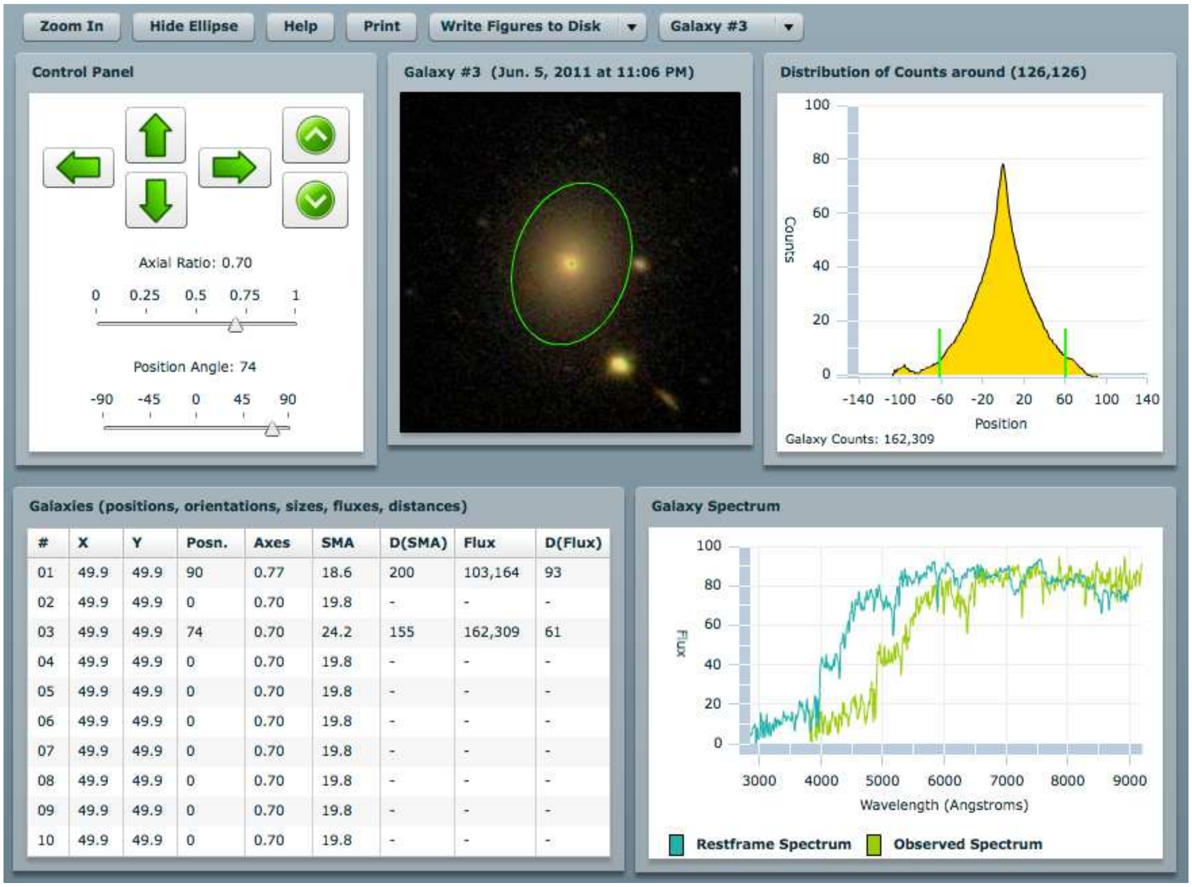

Figure 7.1: A screen capture of our galaxy imaging analysis tool. The top row contains three windows related to fitting an aperture to capture the galaxy light: (1) a control panel for varying the aperture center, radius, axial ratio, and position angle, (2) the galaxy image, and (3) a radial plot of 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 distances derived from the semi-major axis (SMA) and the brightness (flux), and (2) the observed galaxy spectrum and a rest-frame comparison spectrum. Students fit both images (in which the galaxies have smaller and smaller angular sizes with increasing distance) and spectra (in which the galaxy light is shifted to longer and longer wavelengths) 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 changes that occur within each type of data as a function of galaxy distance.

also want them to wrestle with the compromises required in working with real astronomical data, realizing that one has to make informed choices by weighing multiple factors, rather than seeking to “match” a magical answer written down somewhere else by someone else.

Note that the exercise discussion restricts itself to the simple scaling relations that apply between angular size and brightness with distance for nearby galaxies, but the web-applications calculate complete cosmological solutions (for a λCDM universe with $\Omega_0 = 0.30$, $\Omega_\lambda = 0.70$, and $H_0 = 72$ km per second per Mpc).

Figure 7.2: 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 an equivalent galaxy. 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. The galaxy image in the lower right-hand corner has a constant angular size, so that galaxies that are further away from us appear smaller.

A second web-application contains spectra for the same set of BCGs, as shown in Figure 7.2. The distances derived from the spectra are less ambiguous than those found from the imaging properties of the galaxies, being defined by the maximum of the correlation coefficient between the observed galaxy spectra and a rest-frame equivalent. Students also line up individual features within the two spectra by eye, such as the sodium feature at 5990Å and the Ca H and K lines.

Having made three estimates of galaxy distance for ten galaxies, students now use a specialized plotting tool to plot these estimates against distances determined for the clusters that contain these galaxies. The cluster values are of course derived from combining the redshifts of the cluster members. We emphasize the idea that combining measurements for up to 100 galaxies provides a large sample with better statistics through averaging – a point we have been making since exercise one. We want students to understand how simple scaling arguments motivate all standard candle estimates. They should also realize that the differences in the intrinsic properties of these galaxies are far greater than those within samples of, for example, Type Ia supernovae, making this a weak technique for these types of objects. We have them derive distances three different ways, emphasizing the connections between the imaging and spectral data, to better connect the concept of redshift to distance. The theoretical connection between a shift in wavelength and a change in galaxy distance is more complicated and so more difficult to grasp than the simple idea that objects which are further away appear smaller and fainter.

To emphasize the dependency of size- or brightness-derived distances on the spread in galaxy properties throughout a sample, we next have students examine histograms of the intrinsic properties of the sample of BCGs. They also verify that on average BCGs that are intrinsically larger are also intrinsically brighter.

In the final section of exercise seven we introduce the concept of a telescope as a time machine, emphasizing that the images of the most distant galaxies show them not as they are today, but as they appeared in the early epochs of the Universe. We then guide them through the exercise of using the value of H_0 to estimate the age of the Universe.

7.2 Learning Objectives

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

- Appreciate that the Universe is expanding.
- Understand how we combine various methods of distance estimation to determine distances to astronomical objects in the solar system, within the Milky Way galaxy, and to other galaxies in the nearby and distant Universe.
- Connect Hubble's Law, the form of Hubble diagrams, and the value of the Hubble constant H_0 to measured velocities and distances to galaxies.
- Connect the value for the Hubble constant to the rate of expansion of the Universe and to the age of the Universe.
- Apply the idea of a standard candle to determine distances to objects, based on apparent brightness or apparent size.
- Fit an elliptical aperture to a galaxy image to determine its basic structural parameters.
- 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.

7.3 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.

7.4 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.

Arcminute – An arcminute is a unit of angular size, equal to 1/60 of a degree (recall that there are 90 degrees in a right angle). There are 60 arcseconds in an arcminute (see below).

Arcsecond – An arcsecond is a unit of angular size, equal to 1/60 of an arcminute or 1/3600 of a degree (recall that there are 90 degrees in a right angle). Astronomers often measure the angular separation between neighboring objects on the sky in units of arcseconds.

BCG – The brightest cluster galaxy (BCG) is the brightest galaxy within a cluster of galaxies. It typically resides in the core of the cluster. BCGs are known for having moderately uniform properties (such as linear size and luminosity).

Cosmology – Cosmology is the study of the structure and the evolution of the entire Universe.

Degree – A unit used to measure angles. There are 90 degrees in a right angle, and 360 degrees in a full circle.

Distance Scale – The distance scale, or the cosmic distance ladder, is the combination of various techniques used to determine distances to cosmological objects such as stars and galaxies.

$\Delta\lambda$ – 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.

Hubble constant – The Hubble constant, H_0, is the slope of the relationship between recessional velocity v and distance d observed for nearby galaxies (those within 400 megaparsecs of the Milky Way galaxy). The current accepted value for H_0 is 72 km sec^{-1} per megaparsec.

Hubble diagram – A Hubble diagram is a plot of recessional velocity v versus distance d for nearby galaxies.

Hubble's Law – Hubble's Law is the relationship $v = H_0\, d$, observed between recessional velocity v and distance d for nearby galaxies.

Inverse square law for light – The observed intensity of light emitted by an object varies inversely with the square of the distance from an observer ($f \propto 1/d^2$). A star or galaxy placed twice as far away from us would thus appear one-fourth as bright.

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.

Light curve – A light curve is a plot of the observed brightness of a star (plotted on the vertical y-axis) as a function of time (plotted on the horizontal x-axis).

Light year – A unit of distance (not time), equal to the distance which light travels in a year. One light year is equal to 0.307 parsecs.

Linear size – The linear size of an object is its length, in units of length such as centimeters (small) or miles (large).

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.

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.

Parsec – A unit of distance defined as the distance at which an object exhibits a parallax shift of one arcsecond. As the Earth rotates around the Sun and shifts by a length of one astronomical unit, a star which lies one parsec away from Earth will appear to shift by one arcsecond across the sky. One parsec is equal to 3.26 light years or 206,265 astronomical units.

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}.

RMS (root mean square) deviation – The rms deviation is the square-root of the average square of the offsets in y between a set of N data points and a fit function. For a linear fit, where $y = mx + b$,

$$\text{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[y_i - (mx_i + b)\right]^2}.$$

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.

Standard candle – A class of objects assumed to be of uniform brightness. Any variation in observed brightness for a set of standard candles can be attributed to the distance to each object.

Variable star – A star which varies periodically in luminosity over time.

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.

7.5 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 19: Binary Stars.

7.6 References and Notes

1. Edwin Hubble's original data forming a Hubble diagram were taken from the journal article "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae," by Hubble in *Proceedings of the National Academy of Sciences of the United States of America*, vol. 15. issue 3, pp. 168–173 (1929).

2. The optical spectrum of a galaxy shown in Figure 7.2 is a product of the Sloan Digital Sky Survey, 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.

3. The optical spectra of brightest cluster galaxies (BCGs) shown in Figure 7.3 are Sloan Digital Sky Survey 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 Sloan Digital Sky Survey DR6 Galaxy Clusters Catalog at http://heasarc.gsfc.nasa.gov/W3Browse/galaxy-catalog/sdsswhlgc.html.

These spectra, and images of the same galaxies, are used in the two web applications for this laboratory exercise which allow students to fit elliptical apertures to galaxy images and to fit redshifts to galaxy spectra.

4. The M100 Cepheid variable star images in Figures 7.4 come from the Space Telescope Science Institute HubbleSite news center, at http://hubblesite.org/newscenter/archive/releases/1994/49/image/b/, courtesy of Wendy L. Freedman and NASA.

5. The M100 Cepheid variable star light curves in Figures 7.5 and 7.7 are taken from the journal article "Distance to Virgo Cluster Galaxy M100 from HST observations of Cepheids" by Wendy L. Freedman et al. in *Nature*, vol. 371, pp. 757–762 (1994).

6. The data for the Hubble diagram for Cepheid variable stars in Figure 7.6 are taken from the journal article "Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant" by Wendy L. Freedman et al. in *The Astrophysical Journal*, vol. 553, pp. 47–72 (2001), and (for M100) "Distance to Virgo Cluster Galaxy M100 from HST observations of Cepheids" by Wendy L. Freedman et al. in *Nature*, vol. 371, pp. 757–762 (1994).

7. The data for the Hubble diagram for Type Ia supernovae in Figure 7.8 are taken from the journal article "Type Ia Supernova Discoveries at $z > 1$ from the Hubble Space Telescope: Evidence for Past Deceleration and Constraints on Dark Energy Evolution" by Adam Riess et al. in *The Astrophysical Journal*, vol. 607, pp. 665–687 (2004).

8. Figures 7.9 through 7.11 are based on observational data taken from the seventh data release (DR7) of the Sloan Digital Sky Survey.