Photometric Z
Discovery of Distant Galaxies

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Teaching Notes

A Note from the Authors

The goal of this research project is to discover and to study distant galaxies. Galaxies are "island universes," each one containing as many as a trillion stars. Using a technique known as "photometric redshift," we will measure the distance to these galaxies. We will also estimate for how long stars have been forming inside each galaxy, as well as calculate its luminosity.

Please note that it is assumed that the instructor and students are familiar with the prerequisites listed below. This document is an incomplete source of information on these topics, so further study is encouraged. This is a real research program; and as such the "answers" are not known. The purpose is for students to use the same tools and techniques as professional astronomers to complete authentic research projects.

Prerequisites

To participate in this project, you will need a basic understanding of the following concepts:

- Photometry and color
- Spectroscopy
- Redshift and Hubble's law
- Galaxies
- Star formation

Description of the Data

The data used in this project were taken with the Mayall 4-meter telescope and Mosaic I camera at Kitt Peak National Observatory, which is located about 40 miles west of Tucson, Arizona. The data were obtained for the NOAO Deep Wide Field Survey (NDWFS).

The data will be downloaded via the NDWFS cutout server in FITS format. The data files are named for the celestial coordinates (right ascention and declination) of the center of the image and the filter. An example is shown to the right.

About the Software

This project is designed for *ImageJ*, a JAVA implementation of the popular program *NIH Image*. *ImageJ* runs on many platforms, including Macintosh OS 9 and OS X as well as on Microsoft Windows and LINUX on the PC. *ImageJ* is

The Mayall 4-meter Telescope at Kitt Peak National Observatory

Nomenclature:

NOAO is the National Optical Astronomy Observatory. It is the national center for ground-based nighttime astronomy in the United States and is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation. NOAO is responsible for the operation of Kitt Peak Natinal Observatory.

Decoding file names

FITS files downloaded from the NDWFS cutout server have the following format:

Dec

NDWFS_J1438070p345540_Bw

RA   filter
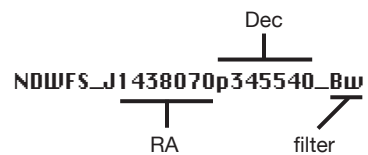
free and can be found online at *http://rsb.info.nih.gov/ij/*

In this documentation an "⊞" icon appears when analysis of the data with *ImageJ* or another computer application is necessary.

Installation of the Polaris Plug-In

A "plug-in" called **Polaris** has been written for *ImageJ*. It is designed for analysis of astronomical imaging data in FITS format. The plug-in is distributed as a zip file with a name such as "Polaris_20080515.zip" When unzipped, a folder will appear titled "Polaris." Place this folder inside the "plugins" folder within the ImageJ application directory. Note: Do *not* place it inside the "macros" folder. Also note: The current version of the plug-in works best with ImageJ version 1.40 or higher.

After starting *ImageJ*, check to make sure that the plug-in is properly installed by looking under the Plugins menu. A submenu titled "Polaris" should be present, as shown below:
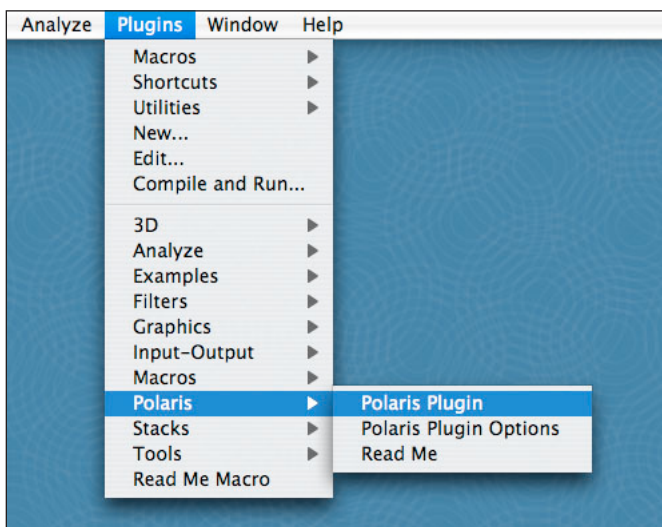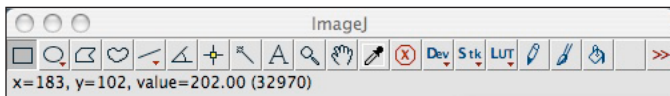
ImageJ

The ImageJ Toolbar

When *ImageJ* is started a toolbar will appear that looks like the one shown below. The rectangle tool is shown as selected. At the bottom of the toolbar the current location of the cursor, and pixel value underneath the cursor, are shown.

The name of a tool is shown when the cursor is floated over the tool's button. There are several tools in the toolbar that are useful for this project:

Selection tools   The first four tools can be used select portions of the image. Each tool functions differently. These tools can also be used to draw on the image. This is useful for marking objects that are to be studied. The perimeter of the selected region can be drawn onto the image by typing ctrl+d (hold down the ctrl key and hit the "d" key).

Text tool   The text tool can be used to write comments on the image. This is useful for labeling objects. Once the text is entered it is drawn onto the image by typing ctrl+d.

Magnifying glass tool   This tool can be used to zoom in to portions of the image. On the PC, to zoom in on a region of the image, left-click on the center of that region. To unzoom right-click on the image. On the Macintosh, to zoom in click on the region. To unzoom, hold down the control key while clicking on the image. To completely zoom out, double-click on the 🔍 icon in the toolbar window.

Scrolling tool   This tool is useful for panning around an image after zooming in with the magnifying glass. Click and drag within the image to move around.

Summary of Menu Commands

Below is a summary of some of the useful menu commands in *ImageJ*:

File/Open...
This command will open a single FITS image file. Use this command to open a file for astrometric and photometric measurements.

File/Save As...
This command can be used to save an image in another format. *Do NOT overwrite the existing FITS files*. This command is useful for saving an image that has been drawn upon with the text and selection tools. Note: Only FITS data files can be used for astrometry or photometry measurements.

Edit/Options/Memory & Threads...
This command can be used to adjust the maximum amount of memory that *ImageJ* will use. It can be increased if a very large image is to be loaded. This should not be necessary for this project.

Image/Show Info
Displays the header of the FITS data file. Contains useful information such as the date of observation, exposure time, etc.

Image/Adjust/Brightness & Contrast
Opens the control panel that is used to adjust the display of the data. Adjust the minimum and maximum sliders to get a good display range.

Image/Lookup Tables
Different color "look-up tables" (LUTs) can be used to display the data. Choose whatever color scheme you like best.

Image/Lookup Tables/Invert LUT
Inverts the image color table. If used on the normal grayscale LUT, the stars will appear black and the background white. Many find it easier to see faint objects with the LUT inverted. The Polaris plug-in options can be set to do this automatically.

Plugins/Polaris/Polaris Plugin
Use this command to start the Polaris plug-in. This will attach a data window to the right side of the image. The plug-in will work on either a single image or a stack of images.

Plugins/Polaris/Read Me
This command gives the update notes for the most recent version of the plug-in. It also lists update notes from the previous versions.
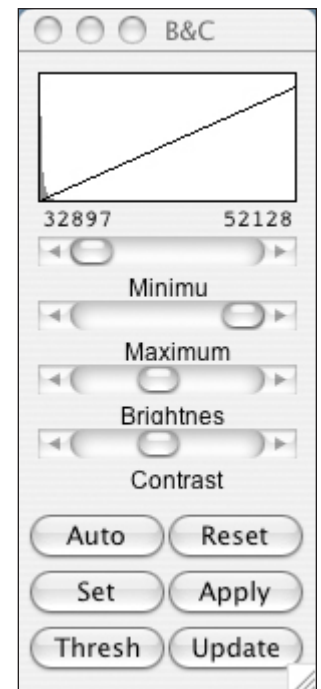
The brightness and contrast (B&C) window

Plugins/Polaris/Polaris Plugin Options

Use this command to change the nova plug-in options:

The "Invert image on load" option will automatically invert the LUT of the image or stack when the plug-in is started.

The "Seek brightest pixel" option will attempt to center the photometry aperture within a 5x5 square centered on the cursor location. This is useful when attempting to center the aperture on a star, but it should not be used on galaxies. Thus, this option should remain turned off for this project.

The "Write to log file" option allows the output of the plug-in to be written to a file. By default the file is written in the ImageJ application directory. If the user does not have write permission to this directory, ImageJ will ask for another location to save the logfile.

The aperture radii for photometry measurements can also be adjusted here. If the "Astrometric output only" option is selected, pressing the space bar will not generate photometric measurements of the selected object.

The MPC-Format Options are not used in this project.

Summary of Polaris Plug-in Keystrokes

Once the Polaris plug-in is started, the following keystrokes are used for the aperture photometry:

b   Can be used to calibrate the photometer by measuring the brightness of stars of known magnitude (known as "standard stars"). Place the cursor over a standard star and hit the "b" key. An *enter magnitude* box will appear, into which you enter the known magnitude of the standard stars. *Note:* Data from the NDWFS survey are already photometrically calibrated. Thus it is not necessary to calibrate the photometer.

space bar   Measures the brightness of the object inside the aperture.
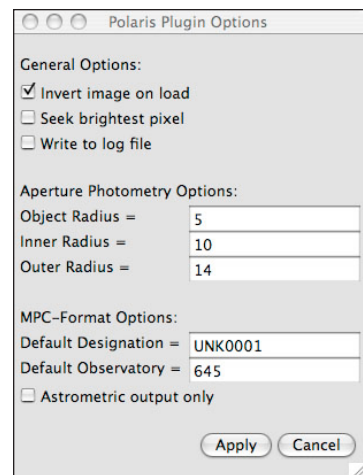
The Polaris plug-in options window

Note!
If the user does not have write permission to the *ImageJ* application folder, the Polaris options cannot be saved. Any changes to the options will remain in effect only until the application is closed.

Photometric Z
Background for Research Project

Introduction

The Universe originated about 13.7 billion years ago in what is known as the "Big Bang." Not long afterwards galaxies started to form, including our own galaxy, the "Milky Way." Our Sun is but one of about 200 billion stars inside the Milky Way. Learning how galaxies form, and how the stars inside them form, live and die, are major goals of astronomical research.

The Project

In this project, we will search for and study some of the most distant galaxies ever observed. This will be done by first searching for faint galaxies in data from the NOAO Deep Wide Field Survey (NDWFS). This survey was completed with the Mayall 4-meter and 2.1-meter telescopes at Kitt Peak National Observatory. We will measure the apparent brightness of each discovered galaxy through three filters, using a technique called aperture photometry. For each galaxy we will use this photometry to determine its photometric colors. The distance to the galaxy will then be estimated using a technique known as photometric redshift. We will also be able to estimate for how long star formation occured in the galaxy. And using the inverse-square law, we can also calculate the galaxy's luminosity. To do this project you must first understand several concepts, including star formation, photometry and redshift. These, and other important concepts, are discussed below.

The Masses and Lifetimes of Stars

The formation of a star takes place inside an enormous molecular cloud of dust and gas within a galaxy. These clouds contain the raw materials needed to make thousands of stars. Once formed, a star spends approximately 90% of its life fusing hydrogen (H) into helium (He) in its core. During this time, it is known as a *main-sequence* star. These nuclear reactions are the source of the star's energy.

Stars form in a range of masses, from as large as 100 times the Sun's mass to as small as only 8% the mass of the Sun. The mass of a star is very important in determining what it does. Since the force of gravity is proportional to mass, gravity squeezes massive stars more tightly. This causes the interior of a high-mass star to become hotter, causing the rate of nuclear reactions to increase dramatically. High-mass stars are therefore much more luminous. For example, a star 10 times the Sun's mass can be 10,000 times more luminous than the Sun. As a result, it will also burn its hydrogen fuel more quickly, and will live for only 1/1,000th as long as the Sun. Massive stars may have more hydrogen gas than smaller stars, but they use it much faster and therefore live for a shorter time. Similarly, low-mass stars use their fuel very slowly and can live for a very long time. Depending on its mass, a star will live from one million to 100 *billion* (10^6 to 10^{11}) years. Because high-mass stars produce so much energy they are hotter, giving them a bluish-white color. Stars like the sun are yellowish; and cooler stars are reddish in color.

Kitt Peak National Observatory

Nomenclature:
Molecular clouds are giant clouds of gas inside a galaxy. They are large and dense enough to contain gas in molecular form. They consist primarily of molecular hydrogen (H_2). These clouds can be 100 to 1 million times the mass of the Sun. They are important because it is in these clouds that stars form.

Fun Fact:
The coolest stars are red in color, while the hottest stars are bluish-white. This is counter-intuitive, since we associate the color blue with cold (e.g., ice cubes). But blue light is of a higher energy than red. And, as an object gets hotter, it emits more high-energy light and becomes bluer. In fact, knowing the color of a star is all you need to know to determine its temperature.

Star Formation Inside Galaxies

Imagine a cluster of stars that has just recently formed inside a molecular cloud within a galaxy. In clusters, redder, low-mass stars are always much more common. However, the bluer, high-mass stars that also formed are so luminous they easily outshine the rest of the stars. Thus, most of the light from the cluster will, at first, be bluish. But the high-mass stars don't live for very long. Once they die, only the low-mass stars will remain. Then, most of the light coming from the cluster will be reddish.

Galaxies come in a wide range of shapes and sizes. They can have as few as a hundred-million stars, to as many as over a trillion. Elliptical galaxies, as the name implies, are galaxies that tend to look spherical or oblate (football) shaped. Ellipticals tend to have very little gas inside them; and therefore little star formation is occuring. The high-mass stars inside these galaxies have long since died. All that remains are the cooler, low-mass stars. For this reason, ellipticals are yellowish-red in color. Spiral galaxies look very different from ellipticals. They show a twisted, spiral shape structure that can look very similar to a hurricane. In contrast to the ellipticals, spiral galaxies are usually rich in gas. Inside these clouds of gas star formation is still occuring. The massive and luminous stars in the star-forming regions inside spiral galaxies make them bluer than ellipticals.

The spiral galaxy M33

Spectroscopy of Galaxies

Spectroscopy is a powerful tool used in astronomy. It is the study of what kinds of light, and in what amounts, are coming from an object. A spectrum is simply a plot of the intensity of light from an object as a function of wavelength. An example spectrum of NGC 3245, a nearby elliptical galaxy, is shown below. The horizontal axis is the wavelength of light. The energy of light is inversely propotional to its wavelength, so in the spectrum below higher-energy (bluish) light is on the left end. And lower-energy (reddish) light is on the right end. The vertical axis is the intensity of light at a particular wavelength.

The elliptical galaxy NGC 3245
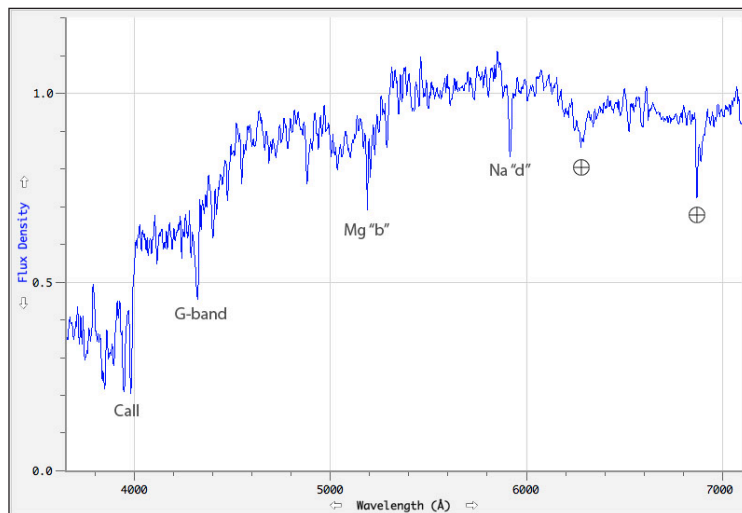
Notice that there is less blue light than red light. This is because the spectrum of an elliptical galaxy is dominated by old and cool red giant stars that are luminous and common in eliptical galaxies. You'll also notice several "dips" in the spectrum. These are absorption lines, which are caused by the cool outer atmospheres of red giant stars. The absorption lines are labeled with the elements responsible for producing them. Note that two of the absorption lines in the spectrum above are marked with a "⊕" symbol. These are called telluric lines, which are caused by oxygen and water vapor in the Earth's atmosphere.

Spectroscopy is used to learn many things about an object. It is particularly useful for determining its velocity away from us with an effect known as redshift.

Redshift and Hubble's Law

The Doppler effect in sound is familiar to most of us: the pitch of a train whistle is higher when the train is approaching us and lower when it is moving away. The Doppler effect on light is similar. As an object emitting light moves towards you, the wavelengths of light become shorter (i.e., they become bluer; the light is said to be blueshifted). Conversely, if the object is moving away from you, the wavelengths of emitted light become longer (i.e., the light is redshifted).

In the early 20th century the astronomer Vesto Slipher noted that absorption lines in the spectra of many galaxies had longer wavelengths (i.e., they were "redder") than those observed in stationary objects. Assuming that the redshift was caused by the Doppler effect, Slipher concluded that these galaxies were moving away from us. Interestingly, he noted that virtually all galaxies (with the exception of a few nearby ones) are moving away from us. Soon thereafter the astronomer Edwin Hubble discovered that more distant galaxies are moving away from us faster than nearby galaxies; and that there was a direct correlation between a galaxy's distance and its velocity away from us. This is known as "Hubble's Law"; and it is a powerful tool for determining a galaxy's distance. Hubble's Law is expressed by the equation:

$$v_{rec} = H_0 D_{now}$$

Where v_{rec} is the object's velocity away from us (known as the "recession" velocity) due to the expansion of the Universe, D_{now} is its distance from us right now (as compared to the distance of the object when the light we now see was first emitted). And H_0 is the Hubble constant. As you can see H_0 gives the relation between an object's recession velocity and its distance. The value of H_0 is estimated to be around 71 km s^{-1} Mpc^{-1} (said, "kilometers per second per megaparsec").

Note that Hubble's Law applies only to distant galaxies. It does not apply to stars and other objects within the Milky Way, nor to very nearby galaxies because for these objects gravity is strong enough to counteract the effects of the expansion of the Universe. This is because an object's velocity will be dominated by its "peculiar velocity" through space, which is the result of the gravitational pull of other, nearby galaxies. In fact, the gravitational pull between the Milky Way and the Andromeda Galaxy (M31) is so strong that M31 is moving towards us! How to determine an object's velocity, distance and luminosity once you know its redshift are described in the next section.

Many Distances, Many Cosmologies

Because space is expanding, and it takes time for light to travel to us, the distance to an object is not trivial to determine. Distance in General Relativity is a complex issue that is not simply defined. While the distance D_{now} can in principle be measured, in practice it cannot. Astronomers therefore also use three other measures of distance. These have the advantage that they can be measured directly from astronomical measurements. One is the "angular size distance" D_a, which is the distance at which the object agrees with the simple relation:

$$\theta = \frac{d}{D_a}$$

Note:
The **Hubble constant** changes over time. It is, however, constant in all locations *in space* at any particular moment in time. H_0 is the value of the Hubble constant *right now*.

Nomenclature:
A **light year** is how far light will travel in one year, which is 9.46 x 10^{12} kilometers. A **gigalight year** (Gly) is a billion light years.

A **megaparsec** (Mpc) is one million parsecs; and a **parsec** is 3.26 light years.

Nomenclature:
Peculiar velocity refers to an object's velocity *through* space, as a result of gravitational attraction.

Recession velocity refers to an object's velocity due to the expansion of space itself (as a result of the Big Bang).

Where θ ("theta") is the angular size of the object (as it appears in the sky), and d is the physical diameter of the object. Note that θ is measured in units of radians.

Similarly, the "luminosity distance" D_l is defined as:

$$f = \frac{L}{4\pi D_l^2}$$

Where f is the observed flux density of the object; and L is the object's luminosity. This is simply the "inverse square law." Finally, the "light travel time" distance D_{ltt} is defined as:

$$D_{ltt} = c\,(t_o - t_{em})$$

Where t_0 is the current time (i.e., the time at which the light from an object is seen) and t_{em} is the time at which the light was emitted. And c is the speed of light. This distance usually cannot be measured directly because we usually don't know t_{em}.

Why the need for four distances? In a normal "Euclidean" geometry, and if the speed of light were infinite, all four distances would be the same. However, the Universe is more complex in that it is expanding and has a curved geometry as described by General Relativity. Furthermore, it takes time for light to get from one point to another. Using these four distances allows us to make sense of the things we can measure, in particular redshift, flux density, and angular size. All of these distances are related to each other. So once you know one distance you can derive the others. Unfortunately, the relations are dependent on the assumed cosmological model and therefore can't be listed here. However, as an example, the relationship between D_a and D_l is always:

$$D_l = D_a\,(1 + z)^2$$

Using Hubble's Law, calculating the distance to an object requires that you know its recession velocity. This can be determined from the object's redshift. However, the relationship between redshift and velocity (and therefore distance) also depends on what cosmological model you use. In a simple model of the Universe, known as the "Empty Universe" model, the relationship between velocity and redshift is relatively straightforward:

$$1 + z = e^{v/c}$$

Combining this with Hubble's Law, the distance to an object is therefore:

$$D_{now} = \frac{c}{H_0}\,\ln\,(1 + z)$$

While easier to calculate, the Empty Universe model is not accurate for objects at high redshift. It is also not very realistic- clearly there is plenty of matter in the Universe! The cosmological model that best fits the observed fluctuations in the cosmic microwave background (CMB) is the ΛCDM (pronounced "lambda CDM") model. Unfortunately, calculating velocities and distances in this model are rather complicated- too much so for a hand-held calculator. Fortunately, a web-based cosmology calculator, written by astronomer Ned Wright at UCLA, is available online at:

http://www.astro.ucla.edu/~wright/CosmoCalc.html

An example on how to use this calculator is given in the tutorial.

Faster than the Speed of Light?

Astute readers will notice that, according to Hubble's Law, objects will be moving faster than the speed of light if $H_0D_{now} > c$. In the Empty Universe model this occurs when $z > 1.718$; and in the ΛCDM model it occurs roughly when $z > 1.4$. Does this mean that objects with redshifts above this value are currently moving faster than the speed of light? The answer is yes! This may seem to be a violation of special relativity, but it isn't. This is because there are two fundamentally different kinds of velocities: peculiar velocity and recession velocity. Peculiar velocity is an object's velocity *through* space; and recession velocity is an object's velocity due to the *expansion* of space. An analogy is that of a pawn on a rubber chess board. The pawn moving from square to square is a peculiar velocity, because it is changing its position in space on the chess board. Now imagine that you have two pawns- one on each end of your rubber chess board. If you grab the edges of the chess board and stretch it, the pawns will move away from each other even though they are still sitting on the same squares as before. This is a recessional velocity. Notice how it is a different kind of motion than a peculiar velocity. In fact, even though they are moving apart, each pawn will think it is not moving because it is still sitting on the same square!

General Relativity prohibits peculiar velocities greater than the speed of light (which is analogous to the rule that pawns, in general, can move only one square at a time). But it doesn't place limits on recessional velocities. Space itself is free to expand at any rate it likes. For this reason we see distant galaxies and AGN moving away from us at speeds greater than the speed of light. And it isn't a violation of special relativity because it is a recession (cosmological) velocity, not a peculiar velocity. Special relativity can only be used when there is an global inertial frame of reference, which is not the case here.

This also explains why we can see objects that are further away than the age of the Universe times the speed of light (i.e., objects further away than about 13.7 Gly). Remember that Hubble's Law gives you the distance and recessional velocity of an object *now*. But the photons of light we are currently seeing were emitted by the object a long time ago, when the Universe was smaller and the object was closer.

Time Machine

Because it takes time for light to travel through space, we are seeing a galaxy not as it is now but as it looked when the light we observe left the galaxy. For distant galaxies this can be as long as billions of years. We are therefore looking back in time. By observing these galaxies we are in effect investigating the Universe as it was long ago, when it was young and a very different place than it is now. But to know how long ago we need to know how far away the galaxy is. To estimate a galaxy's distance from us, we will use a technique known as photometric redshift. This relies on another technique, known as photometry.

Aperture Photometry

The apparent brightness of an object is measured using a technique called photometry. By the inverse-square law, an object's apparent brightness is proportional to its luminosity, which is the total amount of energy that it emits per unit of time, and inversely proportional to the distance to the object *squared*.

$$f \propto \frac{L}{r^2}$$

The inverse square law states that the flux density (f) from a star is directly propotional to the luminosity (L) of the star and inversely proportional to the distance (r) to the star *squared*.

You will measure the apparent brightness of each galaxy using a technique known as aperture photometry. The term aperture refers to an opening that allows light to pass through; and photometry refers to the measurement of light.

When doing aperture photometry, you must choose an aperture size that is large enough to include all of the galaxy. But it must not be so large that it allows light from other objects to enter the aperture as well. What passes through the aperture will include the light from the galaxy, plus additional background light from the Earth's atmosphere. To correctly determine the apparent brightness of the galaxy, the amount of background light must be measured and subtracted from the aperture measurement. The background level is calculated by measuring the brightness of pixels in a ring (known as an "annulus") that surrounds the aperture. The radii of the aperture and the annulus can be changed by the user.

While it may sound complex, aperture photometry isn't difficult because most of the steps are done by the computer. Better still, the data from the NDWFS survey are photometrically calibrated, so all you need to do is use the photometry tool on the Polaris plug-in. You will measure the apparent brightness of each galaxy on what astronomers call the *magnitude scale*.

The Magnitude Scale

Always trying to be difficult, astronomers use an unusual scale to measure the apparent brightness of an object. The magnitude scale is a logarithmic scale in which each integral step corresponds to a change of approximately 2.5 times in brightness. In addition, the scale is inverted, so that brighter objects have smaller magnitudes than dimmer ones. For example, an object with magnitude *m=1* is about 2.5 times *fainter* than an object with magnitude *m=0*.

The origin of the magnitude scale dates back to Hipparchus in the 2nd century BC. He cataloged about 1000 stars that were visible to the naked eye. He classified the twenty brightest stars as 1st class (magnitude *m=1*), the next brightest as 2nd class, and so on down to 6th class (*m=6*), the faintest stars he could see. The human eye isn't very good at determining brightness, so the magnitude scale was at first only approximate. Once astronomers were able to make accurate photometric measurements, the magnitude scale was quantified. The British astronomer N. Pogson determined that 6th magnitude stars (as Hipparchus had classified them) were roughly 100 times fainter than 1st magnitude stars. Thus, 5 steps in magnitude was specified to equal a factor of 100 in brightness. Each step in magnitude is therefore the 5th root of 100, or 2.512 times fainter than the last step.

The bright star Vega, in the constellation of Lyra, "the harp," is defined to be an *m=0* star. The brightnesses of all other objects are measured relative to it. Sirius, the brightest star in the sky (except for the Sun of course) has a magnitude of *m=-1.4*. The Sun's magnitude is *m=-26.8*, or about 10 billion times brighter than Sirius. This is of course because the Sun is so much closer than Sirius. The galaxies you will study have magnitudes ranging from roughly *m=21* to *m=26*, or approximately one million to 100 million times fainter than what you can see with your naked eye. Their faintness is because they are billions of light years away from us. This is also why we need to use such large telescopes to see them!

Photometric Color

The color of an object depends on the relative amounts of the different wavelengths of light it emits. For example, an object will appear bluish in color if it emits more shorter-wavelength (bluer) light than longer-wavelength (redder) light. Astronomers measure an object's color by calculating its magnitude through different filters. An object's "color" is then calculated by taking the difference between the magnitudes in two filters. Note that the color is calculated by sub-


Aperture radii

Object radius (10 pixels)

Inner radius (15 pixels)

Outer radius (25 pixels)
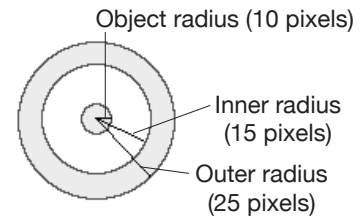
tracting the magnitude of the longer-wavelength filter from the magnitude of the shorter-wavelength filter. Also note that more than one color can be calculated. For example, imagine a galaxy that has a B_w-band (the "blue wide" filter) magnitude of $B_w=23$, an R-band (the "red" filter) magnitude of $R=21$, and an I-band (the "infrared" filter) magnitude of $I=20$. The B_w - R color is +2 and the R - I color is +1. Note that, in both cases, the more positive the color the redder the object. And a negative number indicates it is a bluer object. This is because, on the magnitude scale, fainter objects have a higher magnitude.

Photometric Redshift

Knowing a galaxy's redshift is very important because, using Hubble's Law, we can determine its distance. Using the technique of spectroscopy, it is possible to accurately measure an object's redshift. But it is often not possible to obtain a spectrum if an object is very faint. Instead we can use a technique called *photometric redshift* to estimate an object's distance. This technique takes advantage of the fact that a galaxy's photometric colors depend on its redshift. Its colors also depend on the galaxy's history of star formation, as shown in the plot below:
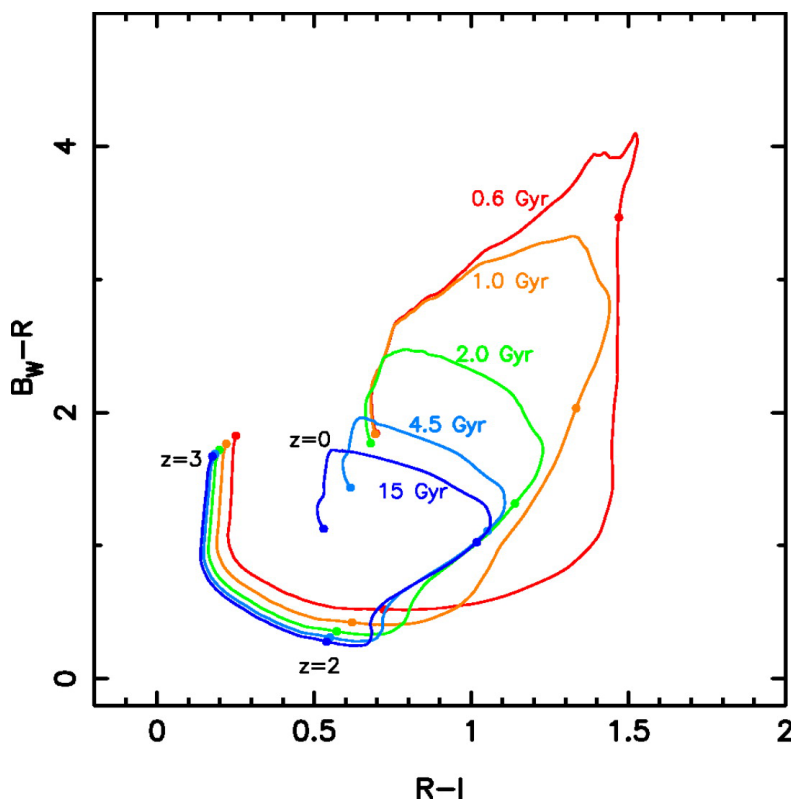
The plot above is called a color-color diagram. This particular one was developed for use with the NDWFS survey and is from Brown *et al*. (2003). In this case, the *Bw-R* color is plotted on the vertical axis; and the *R-I* color is shown on the horizontal axis. The plot shows the colors for five hypothetical galaxies, each with a different star-formation history. Each line corresponds to a different galaxy model and is known as an "evolutionary track." A galaxy's position on its evolutionary track depends on its redshift, with dots showing the z=0, 1, 2 and 3 locations. These five models differ only according to how long star formation was active in each galaxy. Each track is labeled with this length of time, known as the tau (τ)value, measured starting from the formation of the galaxy itself shortly after the Big Bang. This is known as the τ (tau) value. For example, in the case of the topmost (red) line, star formation occurred only during the first 600 million years (τ =0.6 Gyr) after the Big Bang. In the case of the bottom-most

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Nomenclature:

The wavelengths of optical light are typically measured in units of Angstroms, or "Å" for short (1 Å = 10^{-10} meters = 0.1 nanometers).

Nomenclature:

Astronomers use many different kinds of filters. Each filter is designed to let only a specific range of wavelengths pass through to the telescope's camera. For this research project we will use data taken through three filters:

The **B_w** filter (the "blue wide" filter) allows blue-violet light from roughly 3400Å to 4500Å to pass through.

The **R** filter (the "red" filter) allows red light from roughly 6000Å to 7000Å to pass through.

And the **I** filter (the "infrared" filter) allows infrared light from roughly 7000Å to 9000Å to pass through.

Also Note:

The magnitude of an object through a particular filter is given by the filter's name; e.g., B_w = 21 indicates the object is a 21st magnitude object through the B_w filter.

Nomenclature:

Each line on the color-color plot is known as an **evolutionary track** because it describes how a galaxy's colors change as it ages. (Astronomers refer to a star or galaxy's aging process as "evolution." It has nothing to do with the evolution of life.)

(violet) line, star formation will occur for $\tau =15$ Gyr; which means that, since the Universe is only 13.7 Gyr old, in this galaxy star formation is still going on.

Why are the lines different? To understand this plot you must keep in mind that galaxies started to form very shortly after the Big Bang. Also keep in mind that, because of the time it takes for light to travel from there to here, we are seeing very distant objects as they appeared when they were very young. For example, objects at redshifts near $z=0$ are seen essentially as they are now. Since the Universe is about 13.7 Gyr old, we are seeing them as they appear at this age. For comparison, the light travel time for a distant galaxy at $z=3$ is about 11.5 Gyr. That means we are seeing it not as it really looks now but as it looked 11.5 Gyr ago, when it was only about 2.2 Gyr old.

Thus, it may be easier to interpret the plot if you start at $z=3$ (long ago) and move to $z=0$ (the present). Why are the colors of the five different galaxies very similar from $z=3$ to $z=2$? That is because during this time only about 1 Gyr has elapsed, and so star formation is still occuring in all of the galaxies (except for the 0.6 Gyr galaxy). They should all therefore have very similar stars in them. But from $z=2$ to $z=1$ the colors of the galaxy start to change dramatically.

Remember that star formation produces stars with a range of masses. And that the high-mass stars are rare, but blue and very luminous. As long a star formation is occurring in a galaxy, it will keep itself "stocked" with these luminous, high-mass stars, making the galaxy colors bluer. But once star formation stops, the high-mass stars start to die and aren't replenished. The galaxy will then, over time, become more and more red. Looking at the plot, you'll notice that the redder galaxies are ones for which star formation has stopped. Whereas in the bluer galaxies star formation continues.

The importance of this plot is that it allows you to estimate the redshift *and* the star-formation history for any galaxy you observe in the NDWFS survey. By measuring the galaxy's apparent brightness (magnitude) in each filter, you can calculate its photometric colors and determine its location on the color-color diagram. Based upon its location you can estimate what redshift, and what star-formation history, would the galaxy need to have to be at that location on the plot. An example of how to do this is given in the tutorial.

How Well Does it Work?

Photometric redshifts aren't as accurate as spectroscopic redshifts. With spectroscopy, it is possible to measure an object's redshift to an accuracy of ±0.001 or better. However, as mentioned before, many objects are too faint (or telescope time is unavailable) to get a spectrum. The photometric redshift technique is less accurate; but it can be used to get a redshift with an accuracy of about ±0.01. In the case of this project it is realistic to estimate redshifts to about an accuracy of ±0.1. While not as precise, it is still sufficient to discover very distant (high redshift) galaxies that are worth further study.

How well you can estimate an object's redshift also depends on its redshift. Looking at the color-color plot, you'll notice that there are locations where the lines for the different kinds of galaxies intersect or are very close to each other. If a galaxy is located in one of these locations on the plot, it is harder (or impossible) to estimate its redshift or star-formation history. Because of the many locations where the lines overlap, it is essentially impossible to estimate the redshift of a galaxy with $z < 0.3$. That's not a concern, however, because we are mostly interested in galaxies at higher redshift than this. Also note that for galaxies at

Nomenclature:

A **gigayear** (Gyr) is a billion years.

Nomenclature:

The length of time for which star-formation occurs in a galaxy is given by the Greek letter τ ("tau"). The different evolutionary tracks on the color-color diagram are known as "tau models."

Note!

When we refer to an object's location on the color-color diagram, we are *not* referring to its location in space. The color-color diagram has only to do with an object's photometric colors, not where it is in space.

redshifts $z > 2$ it is very hard to estimate a galaxy's star-formation history (i.e., its τ value) because the lines are so close to each other. For these objects, we at least know that they are at very high redshift, which makes them very interesting. Because they are so far away, these very high-redshift galaxies are very faint. We therefore do not expect to find many of them.

Stars, Quasars and Other Imposters

Within the survey area of the NDWFS a wide range of kinds of objects can be found, not just distant galaxies. But these objects should have colors that are different than galaxies; e.g., quasars are typically much bluer than galaxies. To avoid "contamination," you should exclude objects whose colors do not lie within the boundaries of the given color-color diagram (i.e., those objects that do not lie within the region of $0 < B_w - R < +4$ and $0 < R - I < +2$).

Celestial Coordinates

Finally, it is important to record the location in the sky of each galaxy found. This is done by recording its celestial coordinates. Astronomers measure the positions of objects in the sky by imagining that astronomical objects lie upon a *celestial sphere*, an imaginary hollow sphere within which the Earth resides at the center. The positions of objects on the celestial sphere are described by two *celestial coordinates, right ascension* and *declination*.

Right ascension (α) is analogous to longitude on Earth; it describes an object's position in the East-West direction. Because the celestial sphere appears to complete one rotation every 24 hours (due to the Earth's rotation), right ascension is measured in units of time. Right ascension is reported in units of hours, minutes and seconds. Like real units of time, there are 60 minutes in an hour and 60 seconds in a minute of right ascension. Declination (δ) is equivalent to latitude; it describes an object's position in the North-South direction. Declination is measured in degrees (°), arcminutes ('), and arcseconds ("), wherein there are 60 arcminutes in a degree and 60 arcseconds in an arcminute. A declination of 0 degrees marks the *celestial equator*, which divides the sky into the northern and southern hemispheres. The celestial equator is the projection of the Earth's equator onto the celestial sphere. A declination of +90 degrees marks the north celestial pole (just as +90 latitude is the North Pole on Earth) and -90 degrees marks the south celestial pole. A celestial coordinate marks a unique location, and is used by astronomers to mark the locations of objects in the night sky. For example, the celestial coordinates for the center of M31, the Andromeda Galaxy, is: α = 00h42m45.9s, δ = +41°16'18". For simplicity they are written with colons, e.g., α = 00:42:45.9, δ = +41:16:18.

The Polaris plug-in will be used to measure the celestial coordinates. The information necessary for the plug-in to measure the coordinates is given in the FITS file header and is used automatically.

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Photometric Z
Data Analysis Instructions

Searching for Galaxies

The primary goal of this project is to seach the NDWFS survey data for distant galaxies. To do this, the first step is to download data from the NDWFS image cutout server:

🖳 Download data from the NDWFS cutout server:

- Open a web browser and go to the URL:

  `http://archive.noao.edu/ndwfs/cutout-form.html`

- The cutout server offers three ways to download data files. The "Single Image Cutout Download" allows for a field in a single filter to be downloaded. The "Multi-Image Cutout Download" allows for more than one field to be downloaded, and in more than one filter. If you wish to view images of the field before downloading them, use the "Multi-Image Cutout Viewer" at the bottom of the web page.

- For either the first or third options, the celestial coordinates (Right Ascention and Declination) for the center of the field must be entered. The RA and Dec must be formatted as shown in the default settings: Colons must be entered between the hours, minutes and seconds in RA, and between the degrees, arcminutes and arcseconds for Dec. Note that coordinates must be within the NDWFS Boötes field area. Leave the coordinate system to the default value of J2000 coordinates unless your coordinates are in B1950 values.

- For the multi-image cutout viewer and download options, a menu allows you to specify which filters to download. In general we won't use the K-band images, so you will usually set the filters menu to "B_W,R,I".

- You must also specify the size of the image you wish to download, either in units of pixels or arcseconds. The default is to download a 200x200-pixel image.

- The single image option will download a single FITS file for the chosen filter. For multi-image cutouts, a file titled *ndwfs_images.tar* will be downloaded. This is a "tar file" (short for "tape archive" file) that contains the FITS datafiles.

- A tar file must be unpacked. To unpack a tar archive on a Macintosh, simply double-click on the tar file. A folder will be created. Inside the filter will be three files with names like *NDWFS_J1428070p344540_Bw.fits*.

The "NDWFS" prefix is to indicate from which survey the data came. After the underscore is the letter "J" or "B". The "J" indicates that the coordinate system is J2000; and "B" indicates the B1950 coordinate system. The set of numbers after the "J" or "B" are the RA and DEC of the center of the image. The "p" before the declination stands for "plus", indicating that the declination is positive("m" is for minus). The letter(s) at the end of the filename (but before the fits suffix) indicate the filter for that dataset.

NDWFS Boötes Field:

The NDWFS Boötes field covers an area of roughly 2.9° x 3.5°. The center of the field is RA = 14:32:05.71 and Dec=+34:16:47.5. Note that a section of the southeast corner is missing.

3.5°

2.9°
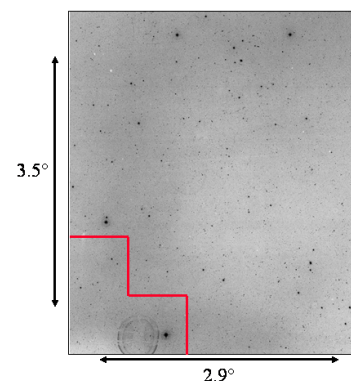
Note:

Only data from the NDWFS survey may be used for this project. The color-color plot used in this project shows the evolutionary tracks for galaxies as they appear in the three filters (B_W, R and I) used specifically for this survey.

The multi-image cutout viewer is particularly useful when searching for distant galaxies because you can compare the relative brightness of a galaxy in the different filters. Look for galaxies that are relatively faint in B_W, but brighter in R and I. Of particular interest are galaxies that are seen in R and I, but not in B_W. These are known as "B-band dropouts" and are at very high redshift.

Once you've found galaxies that look interesting, download the data and unpack it. *ImageJ* will be used to analyze the data. But first make sure the Polaris plug-in options are set correctly:

- ▣ Launch *ImageJ*
- ▣ Set the Polaris plug-in options:
  - Choose **Plugins/Polaris/Polaris Plugin Options** to open the plug-in options window.
  - Make sure the "invert image on load" option is selected. Doing so makes the sky background white, and stars and galaxies black. This will make it easier to see faint galaxies.
  - Make sure the "seek brightest pixel" option is *not* selected. This option will search for the brightest pixel within a 5x5 square centered on the cursor location and then center the aperture on this pixel. It is a useful option when observing stars, where you wish for the aperture to be centered on the star. But it is not useful for galaxies, which can have distorted shapes such that the brightest pixel is not necessarily at its center.
  - For the aperture photometry, set the object radius, the inner radius, and the outer radius. The object radius sets the radius of the aperture. It must be made large enough to contain the entire galaxy observed, so you may need to increase its size depending on the object. In general the sky annulus should contain at least 3 times as many pixels as the aperture. If the annulus is too small, the Polaris plug-in will warn you.

We will now open and analyze the datasets in *ImageJ*.

- ▣ Open the first dataset:
  - Choose **File/Open... (⌘-O)** and select the *FITS* file.
  - Use the **Image/Zoom/In (⌘-+)** command twice to zoom in to 300%.
  - Use **Plugins/Polaris/Polaris Plugin** to start the plug-in. The plug-in window will attach to the right edge of the stack.
  - Since we've set the plug-in preferences to do so, the image LUT should be automatically inverted. This will cause the stars and galaxies to appear dark against a white background. If this doesn't occur, choose **Image/Lookup Tables/Invert LUT** to invert the LUT.
  - Choose **Image/Adjust/Brightness & Contrast** to adjust the brightness and contrast to better see the stars and galaxies. At first the image will be mostly white. Move the sliders until the fainter stars in the image are visible. To start, try clicking on the "auto" button a few times. The tutorial gives an example of how the display should look.

Search the image for fuzzy objects that do not look like stars. Stars will look like sharp, almost perfectly circular points of light. Galaxies will look fuzzy and diffuse, and will not look like points of light. Once you have found some galaxies of interest, use the aperture photometer to measure their apparent brightness:
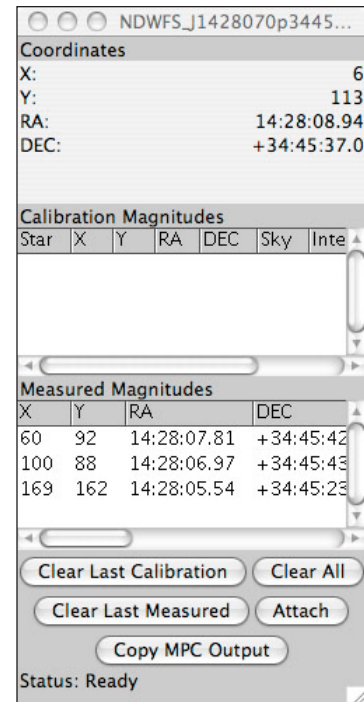
The Polaris plug-in window

The X,Y and celestial coordinates of the current cursor location are shown in the top part of the window. The recorded magnitudes of standard stars are listed in the middle (which are not used in this project). And the measured magnitudes are listed at the bottom.

Add example images of stars vs. galaxies.

🖳 Measure the magnitudes for the galaxies of interest:

- Place the cursor over a galaxy. Press the **Space Bar** to measure its magnitude. Three blue circles should mark the galaxy. The inner-most circle is the aperture. The two outer circles show the location of the annulus used to measure the sky background.

- All of the galaxy should be inside the aperture (the innermost circle). If it is not, delete the measurement by clicking on the "Clear Last Measured" button. The three blue circles around the galaxy should disappear. Resize the aperture in the Polaris plug-in options so that the aperture is large enough to enclose the entire galaxy, and try the measurement again. Note that you will need to resize the inner and outer radii of the sky annulus so that it contains three times as many pixels as the aperture.

- Measure the other galaxies of interest. A row of text should now be in the measured magnitudes table for each galaxy.

The measured magnitudes table contains all of the important information for each measured galaxy. To see all of the information use the horizontal scroll bar under the table. The table includes the X,Y coordinates in the image and the RA and DEC celestial coordinates of the measured galaxy. The aperture radius (*r1*) and the sky annulus radii (*r2* and *r3*), as set in the plug-in options, are also given. The next three columns include information used to calculate the magnitude. The 'sky' value is the average pixel value inside the sky annulus. This value is subtracted from each pixel inside the aperture. The 'intensity' value is the sum of all the pixels within the aperture, after the sky is subtracted. The 'MAGZERO' value is the magnitude of an object that has an intensity value of 1. This value is obtained from the header of the FITS file; it is different for each FITS file. The magnitude of the object is automatically calculated from these values; it is given in the last (rightmost) column.

To calculate photometric colors of a galaxy, its apparent brightness must be measured in all three of the filters (B_w, R and I):

🖳 Measure the magnitudes of the galaxies in the other filters:

- To open the next dataset, follow the same steps as for the first dataset. Zoom to 300% and start the Polaris plug-in.

- Place the cursor over the first galaxy at the same X,Y coordinates as you used for the first dataset. Note that the X,Y coordinates must be the same, or the photometry will be less accurate. Press the **Space Bar** to measure its magnitude. Three blue circles should mark the galaxy.

- Also measure the other galaxies. A single row of text should now be in the measured magnitudes table for each galaxy.

- Repeat the above steps for the last dataset.

The next step is to calculate the photometric colors for each galaxy. This is as simple as taking the difference of the magnitudes, i.e., calculating B_w - R and R - I. Each galaxy is then plotted on the color-color diagram. Now you can use the tracks on the color-color plot to determine additional information about each galaxy. In particular, a galaxy's star-formation history (i.e., its "tau" value τ) can be estimated by determining its evolutionary track. If the galaxy does not reside on or near any of the evolutionary tracks on the color-color diagram, you can interpolate; e.g., if it lies equidistant from the 1.0 and 2.0 tracks, then estimate τ=1.5 Gyr. A galaxy's redshift can be estimated by measuring how far along it is along the evolutionary track. The z=0,1,2 and 3 values are marked with dots. Detailed examples of how to do this are given in the tutorial.
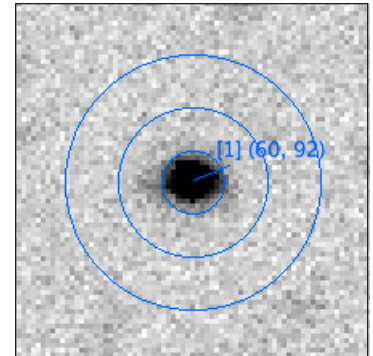
Determining the Distances

Once you have a redshift, use Ned Wright's cosmology calculator:

http://www.astro.ucla.edu/~wright/CosmoCalc.html

When using the calculator, enter the redshift (z) for your object into the appropriate box. Also use the default values $H_0 = 71$, $\Omega_m = 0.27$, and $\Omega_{vac} = 0.73$, and then click on the "general" button. The calculator will give you several important pieces of information. In particular, the total age of the Universe (i.e., how much time has elapsed since the Big Bang), the light travel time (i.e., how long it has taken for the light from the galaxy to get to us), the comoving radial distance (the distance to the galaxy now), and the luminosity distance.

Determining the Luminosities

To determine the object's luminosity, we first need to calculate the flux density of light coming from this object. The magnitude scale is defined as:

$$m - m_0 = -2.5 \; log_{10} \left(\frac{f}{f_0} \right)$$

Where m is the magnitude of an object through a particular filter. And f_0 is the "zero point" flux density (i.e., it is the flux density of an object with a magnitude $m=0$ for that filter.) Since, by definition, $m_0=0$, this can be rewritten as:

$$f = f_0 \left[10^{-0.4m} \right] (1 + z)$$

Notice the *(1+z)* term added to the end. This is known as the "K correction." When an object's spectrum is redshifted, it is stretched so that less of its light passes through the filter. The K correction accounts for this. Use this flux density in the inverse-square law to calculate the luminosity:

$$L = 4\pi D_l^2 f$$

Note that you need to use the luminosity distance D_l from the cosmology calculator. The flux is calculated in units of erg cm^{-2} s^{-1} so D_l must be converted into centimeters. The cosmology calculator provides the conversion factor. Also note the flux density and luminosity must be calculated separately for each filter.

Comparison to Other Galaxies

Comparing the luminosity of one galaxy to another is complicated because luminosity must be measured over a set range of wavelengths. For consistency, we'd like to measure the same wavelength range for every galaxy, but the redshift effect causes an object's spectrum to be shifted and stretched. That is to say, light that would be seen through the B_w filter if the galaxy were not redshifted will be shifted, at least in part, out of this filter and into other, redder filters. Ideally, we'd like to know the "bolometric" luminosity of a galaxy, which is the total amount of energy per second emitted by a galaxy over all wavelengths, from radio waves to gamma rays. But in general this isn't practical. Fortunately, most of the light from "normal" galaxies is optical light. Thus, we can roughly compare galaxies by using their R-band luminosities.[1]

The luminosity of the Sun in the R-band is approximately 2×10^{33} erg s^{-1}. You can therefore calculate how many Suns a galaxy would need to contain to account for its luminosity. For reference, this can also be compared to an L* galaxy.

Nomenclature:

The *zero point* (f_0) for a filter is the flux density of a magnitude zero object. The zero points for each filter are:

B_w: $f_0 = 6.6 \times 10^{-6}$ erg cm^{-2} s^{-1}
R: $f_0 = 3.0 \times 10^{-6}$ erg cm^{-2} s^{-1}
I: $f_0 = 2.1 \times 10^{-6}$ erg cm^{-2} s^{-1}

Nomenclature:

An *L* ("L star")* galaxy has a mass of about 1.4×10^{10} suns. This is about the size of our Milky Way.

---

1. This is not a very accurate method for a variety of reasons, but it is a reasonable approximation considering the rough accuracy of the photometric redshift technique.

An Example: Searching for Distant Galaxies

In this example we will choose a field from the NDWFS survey at random and look for distant galaxies.

> ▣ Download data from the NDWFS cutout server:
>
> - Open a web browser and go to the URL:
>
>   `http://archive.noao.edu/ndwfs/cutout-form.html`
>
> - The cutout server offers three ways to download data files. Scroll down to the "Multi Image Cutout Viewer" at the bottom.
>
> - For RA, enter "14:28:07" and for DEC, enter"+34:45:40". Note that these numbers are only slightly different than the default values. (In fact, only the DEC is slightly changed.)
>
> - Change the filters menu to "B_W,R,I". We won't use the K-band image. Leave the default values of J2000 coordinates and a 200-pixel image size at these values.
>
> - Click on the "View Cutouts" button.

You should now see three images (one from each filter) as shown below:
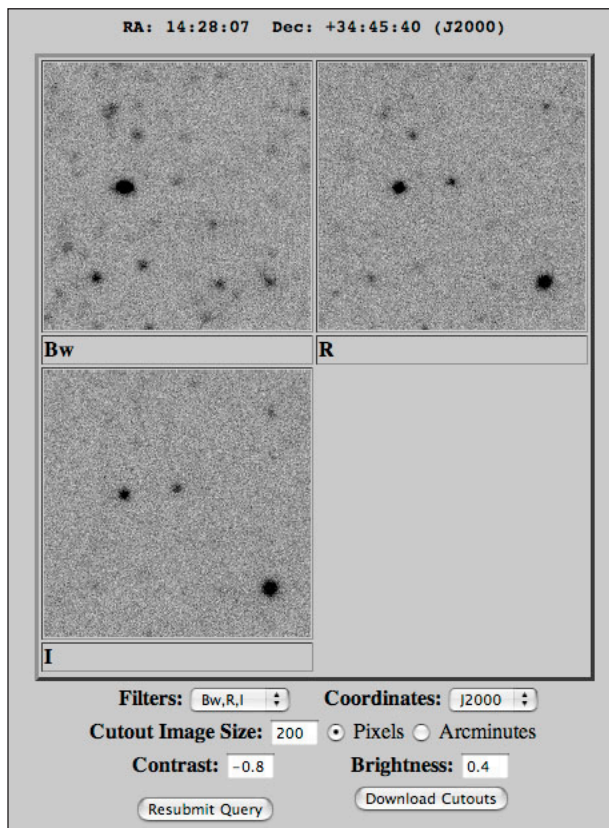
Looking at the B_W-band image we see quite a few objects. However, fewer of

these are noticeable in the R-band image. And only three of these objects are prominent in the I-band image. These three objects are of particular interest, because we expect high-redshift galaxies to be very red. They will appear to be relatively faint in the B_W image, but brighter in the R and I images. We will therefore download the datafiles for the three filters and study these three objects.

▣ Now download the datafiles:

- Click on the "Download Cutouts" button. The file *ndwfs_images.tar* will be downloaded. This is a "tar file" (short for "tape archive" file) that contains the three FITS datafiles.

- Now unpack the archive. To unpack a tar archive on a Macintosh, simply double-click on the tar file. A folder will be created. Inside the filter will be three files with names like *NDWFS_J1428070p344540_Bw.fits*.

We will analyze these datasets, but first we must start *ImageJ* and set the Polaris plug-in options. Then we will open the datasets in *ImageJ*.

▣ Launch *ImageJ*

▣ Set the Polaris plug-in options:

- Choose **Plugins/Polaris/Polaris Plugin Options** to open the plug-in options window. Set the values as shown on the right.

▣ Open the B_W dataset:

- **File/Open... (⌘-O)** the *NDWFS_J1428070p344540_Bw.fits* file.

- Use the **Image/Zoom/In (⌘-+)** command to zoom in to 300%.

- Use **Plugins/Polaris/Polaris Plugin** to start the plug-in. The plug-in window will attach to the right edge of the stack.

- If the image doesn't automatically invert, choose **Image/Lookup Tables/Invert LUT** to invert the LUT.

- Use **Image/Adjust/Brightness & Contrast** to adjust the brightness and contrast so the window looks roughly as shown below:
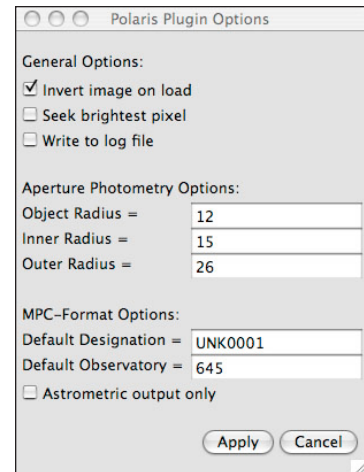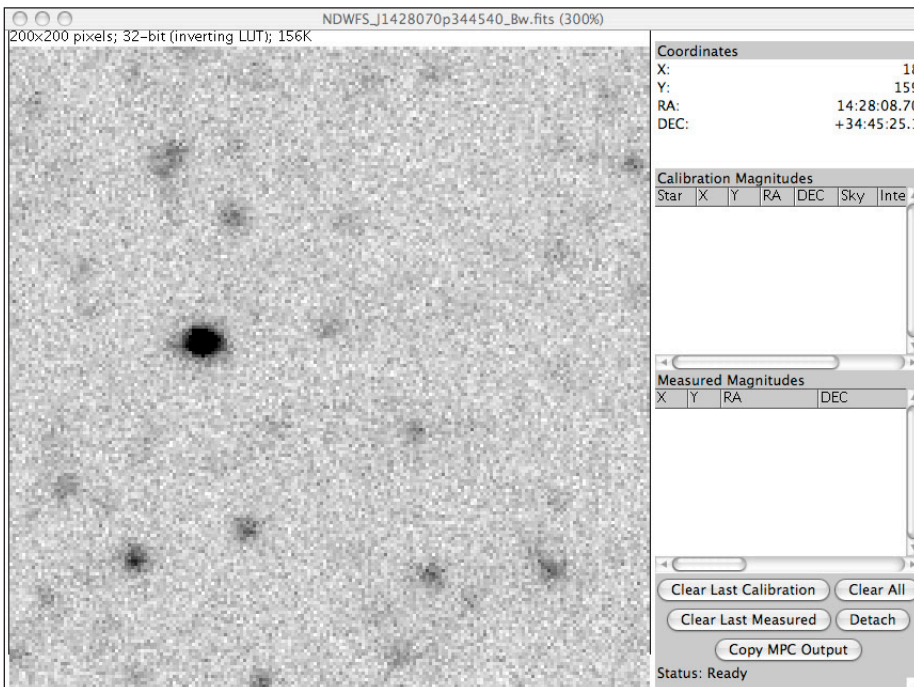
The Polaris plug-in options window

We will now use the aperture photometer to measure the magnitudes of the three galaxies of interest:

- ▣ Measure the magnitudes for the three galaxies:
  - Place the cursor over the galaxy at X=60, Y=92. Press the **Space Bar** to measure its magnitude. Three blue circles should mark the galaxy.
  - Also measure the galaxies at X=100, Y=88 and X=169, Y=162.
  - Three rows of text should now be in the measured magnitudes table.

The window should now appear as shown below:
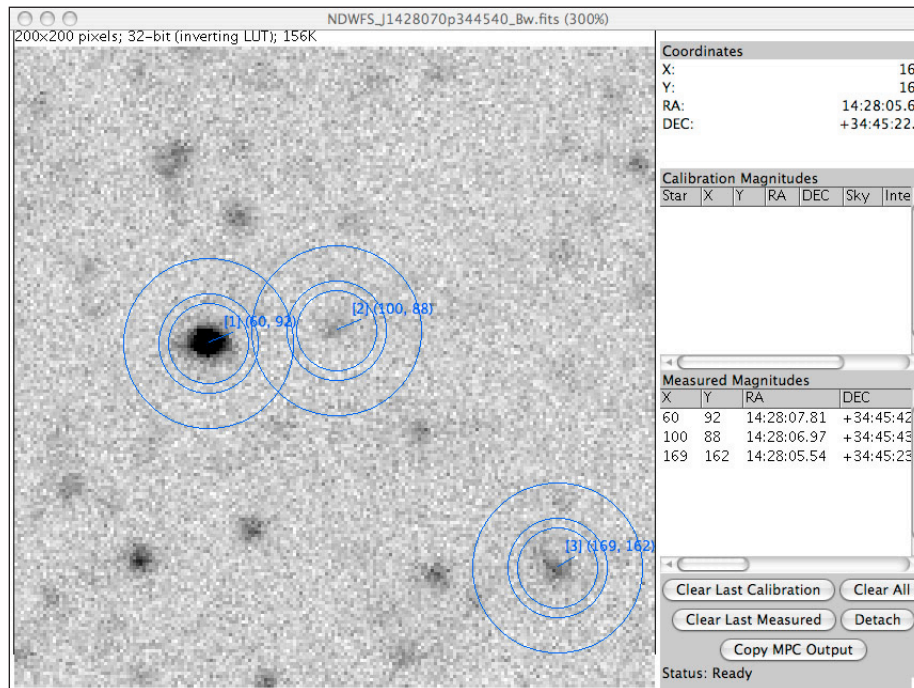
The measured magnitudes table contains all of the important information for each galaxy. It includes the X,Y coordinates in the image and the RA and DEC celestial coordinates. The magnitude of the object is given in the last (rightmost) column. In this case the B_W magnitudes for the three galaxies are 22.704, 25.475 and 24.262 respectively. Note that these values will be slightly different if the aperture for each galaxy is not located at the X,Y coordinate given above. The next step is to measure the three galaxies in the R-band and I-band filters:

- ▣ Measure the magnitudes for the three galaxies in the R and I filters:
  - Follow the same steps as for the B_W dataset to open the R dataset. It is the *NDWFS_J1428070p344540_R.fits* file. Zoom to 300% and start the Polaris plug-in.
  - Place the cursor over the galaxy at X=60, Y=92. Press the **Space Bar** to measure its magnitude. Three blue circles should mark the galaxy.
  - Also measure the galaxies at X=100, Y=88 and X=169, Y=162.
  - Three rows of text should now be in the measured magnitudes table. The R-band magnitudes of the three galaxies should be 21.745, 22.874 and 21.239 respectively.
  - Repeat the above steps for the I-band dataset. The I-band magnitudes of the three galaxies should be 21.204, 22.015 and 20.180 respectively.

Note:

Each measured galaxy will be labeled with three blue concentric circles: the aperture radius, and the inner and outer radii of the sky annulus. Each galaxy will also be labeled with a set of numbers. The first number, shown in brackets, is the object number in the measured magnitudes table. The second set of numbers, shown in parenthesis, is the X,Y location of the center of the aperture.

The next step is to calculate the photometric colors for each galaxy. For galaxy #1 (at X=60, Y=92) the colors are:

$$B_w - R = 22.704 - 21.745 = +0.959$$

$$R - I = 21.745 - 21.204 = +0.541$$

For galaxy #2 (at X=100, Y=88) we calculate $B_w - R = +2.601$ and $R - I = +0.859$. And for galaxy #3 (at X=169, Y=162) we find $B_w - R = +3.023$ and $R - I = +1.059$. The location of each galaxy on the color-color plot is shown:
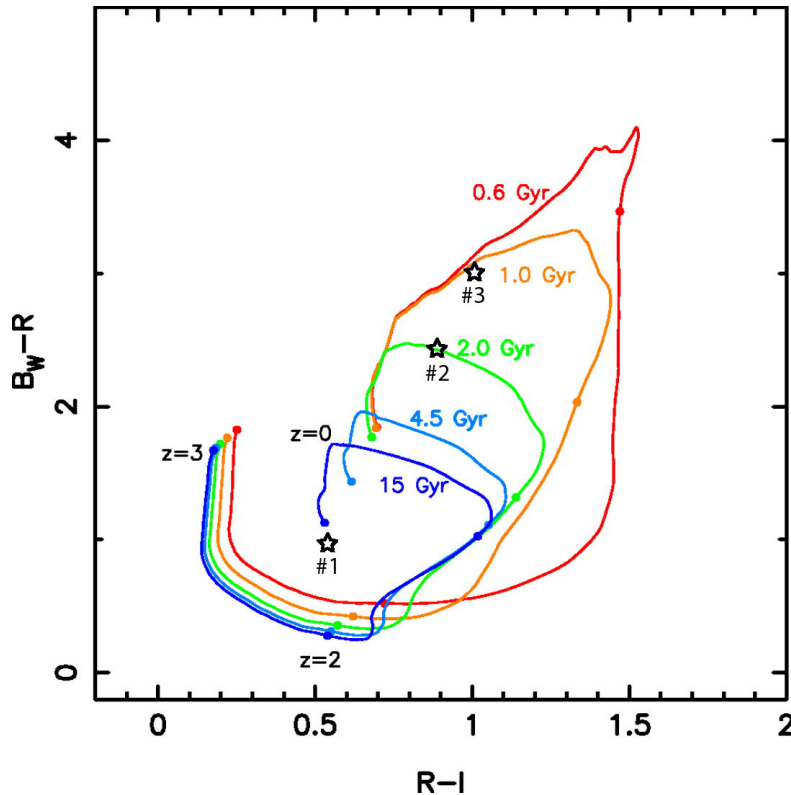
From their locations on the color-color plot we can now estimate the redshift and star-formation history (τ) for each galaxy.

The photometric colors for galaxy #1 are consistent with a nearby galaxy in which star-formation is still occuring (τ=15 Gyr). While we know the redshift is not exactly zero, the galaxy is still relatively nearby ($z < 0.2$). We are therefore not interested in it and we won't study it further.

The colors for galaxy #2 are consistent with an older (τ=2 Gyr) galaxy. Based upon its location on the evolutionary track for a τ=2 Gyr galaxy, we estimate it to be at a redshift of approximately $z=0.35$.

At the location of galaxy #3 on the color-color plot the evolutionary tracks for the τ=1 Gyr and τ=0.6 Gyr galaxy models overlap. We therefore cannot differ-entiate between the two models, but we at least know that star formation stopped long ago in this galaxy; and only old, redder stars remain. We also estimate the redshift to be approximately $z=0.4$.

While galaxy #1, turned out to not be as interesting, we are interested in learning more about galaxies #2 and #3. We will now calculate the distance, recession velocity, flux density and luminosity for galaxy #2.

Determining the Distances

We will now use Ned Wright's cosmology calculator to determine the distances to galaxies #2. For galaxy #2, use the values z = 0.35, H_0 = 71, Ω_m = 0.27, and Ω_{vac} = 0.73, and then click on the "general" button. The following results should appear:

For H_o = 71, Omega$_M$ = 0.270, Omega$_{vac}$ = 0.730, z = 0.350

- It is now 13.666 Gyr since the Big Bang.
- The age at redshift z was 9.828 Gyr.
- The light travel time was 3.837 Gyr.
- The comoving radial distance, which goes into Hubble's law, is 1366.5 Mpc or 4.457 Gly.
- The comoving volume within redshift z is 10.689 Gpc^3.
- The angular size distance D_A is 1012.2 Mpc or 3.3015 Gly.
- This gives a scale of 4.907 kpc/".
- The luminosity distance D_L is 1844.8 Mpc or 6.017 Gly.

1 Gly = 1,000,000,000 light years or 9.461*10^{26} cm.
1 Gyr = 1,000,000,000 years.
1 Mpc = 1,000,000 parsecs = 3.08568*10^{24} cm, or 3,261,566 light years.

There are several important pieces of information given. In particular, note that the light travel time is 3.837 Gyr. That means we are seeing this galaxy as it appeared almost 4 billion years ago! Several distances are also given. We will now use the luminosity distance to determine the object's luminosity.

Determining the Luminosities

We will use the inverse-square law to determine the object's luminosity through the three filters. To do this, we first need to calculate the flux density of light coming from this object. This can be determined from the apparent magnitude (including the K correction):

$$f = f_0 \left[10^{-0.4m}\right] (1 + z)$$

Where m is the magnitude of an object through a particular filter. And f_0 is the "zero point" flux density. For the B_w filter, f_0 = 6.6 x 10^{-6} erg cm^{-2} sec^{-1}. For galaxy #2, recall that B_w = 25.475. Using the above equation, we calculate that, for galaxy #2 in the B_w filter, f_{Bw} = 5.8 x 10^{-16} erg cm^{-2} sec^{-1}. We can now use the inverse-square law to calculate this object's luminosity:

$$L = 4\pi D_l^2 f$$

Remember that you need to use the luminosity distance D_l. Since we calculated the flux in erg cm^{-2} s^{-1} we must convert D_l into centimeters. The conversion factor is conveniently provided by the cosmology calculator:

$$1 \text{ Gly} = 9.461 \text{ x } 10^{26} \text{ cm}$$

We calculate that D_l = 5.7 x 10^{27} cm for galaxy #2. Using this value with the inverse-square law equation above we calculate that the B_w-band luminosity for galaxy #2 is L_{Bw} = 2.3 x 10^{41} erg s^{-1}. Now let's calculate the flux density and luminosity in R-band. For the R filter, f_0 = 2.9 x 10^{-6} erg cm^{-2} sec^{-1}. And for galaxy #2, R = 22.874. The flux density in R-band is therefore f_R = 2.8 x 10^{-15} erg cm^{-2} sec^{-1}. And the luminosity L_R = 1.2 x 10^{42} erg s^{-1}. Finally, we calculate that the I-band flux density is f_I = 4.4 x 10^{-15} erg cm^{-2} sec^{-1}. And the luminosity L_I = 1.8 x 10^{42} erg s^{-1}.

This galaxy is five times more luminous in R than B_w. And it is 7.7 times more luminous in I than B_w. The galaxy is much brighter at red wavelengths for two

reasons: Star formation ceased in this galaxy long ago, so all that remains are older, redder stars. And because it is redshifted, the light from this galaxy is pushed even further into the red.

Comparison to Other Galaxies

Since star formation stopped in galaxy #2 long ago, it is most likely an elliptical galaxy. The question now is, what size?

The R-band luminosity of galaxy #2 is $L_R = 1.2 \times 10^{42}$ *erg s^{-1}*. And the luminosity of the Sun in this band is approximately 2×10^{33} erg s^{-1}. Thus this galaxy contains approximately 600 million solar masses of stars. This may sound like a lot, but recall that an L^* galaxy is about 2×10^{10} Suns. Thus, galaxy #2 is only about 4% the size of our Milky Way. Again, these numbers are very approximate. They do not account for the effects of redshift, nor do they include the effects of gas (which does not emit optical light), dust (which absorbs optical light) or dark matter (which does not emit or absorb any light).

Celestial Coordinates

Finally, we wish to note the location of this galaxy so that other astronomers will know which object we have studied, and will know how to find it for future research. Accurding to the plug-in, the RA is 14:28:06.97 and the Dec is +34:45:43.2. These values are given in the measured magnitudes table.