AGN Spectroscopy
Nature's Most Powerful "Monsters"

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Teaching Notes

A Note From The Authors

This is the sixth release of the AGN spectroscopy project. Most of the changes reflect the experiences of the RBSE teachers who have implemented this project in their classrooms. But of course there are most likely still some errors, omissions and other pitfalls. As this release reflects the insights of RBSE teachers, it is *essential* for future versions of this project that you share with me (and other members of the RBSE group) any problems you have. If you are having a particular problem, odds are that someone else is having it too. So please don't be shy. Of course as you develop experience with these projects, please share any tips and insights with us! I trust that, with your help, subsequent versions of this exercise will be improved.

This is a research program; and as such the "answers" are not known. I must warn you that most students will think this project is tough. Some students will become frustrated trying to determine redshifts for many of the objects, especially the BL Lacs. Determining redshifts of BL Lacs should probably be attempted only by advanced, eager students who aren't easily deterred.

Prerequisites

To get the most out of this activity, students should have a basic understanding of the following concepts:

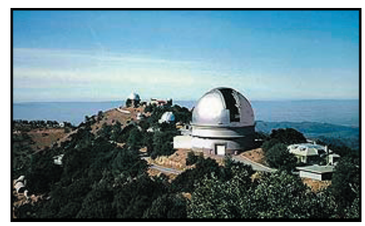
- Spectroscopy in astronomy
- Redshift and Hubble's Law
- Flux, distance and luminosity relation (the "inverse-square" law)
- Galaxies, active galaxies and quasars

Note: You are strongly advised to do the RBSE stellar spectroscopy project first to aquaint yourself with astronomical spectra.

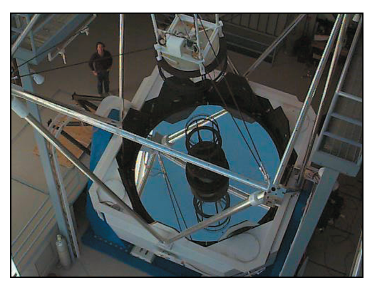
Description of the data

Most of the spectra used in this activity were obtained with the 2.1-meter telescope at Kitt Peak National Observatory, located about 40 miles west of Tucson, Arizona. Additional spectra were also obtained with the 3-meter telescope at Lick Observatory and the 3.5-meter telescope at Apache Point Observatory. These spectra cover the entire optical spectrum (what we can see with our eyes) as well as parts of the ultraviolet and infrared. We have kept the experience to be as authentic as possible!

The 2.1-meter telescope at Kitt Peak National Observatory in Arizona.



The 3-meter telescope at Lick Observatory in California.



The 3.5-meter telescope at Apache Point Observatory in New Mexico.

Object names

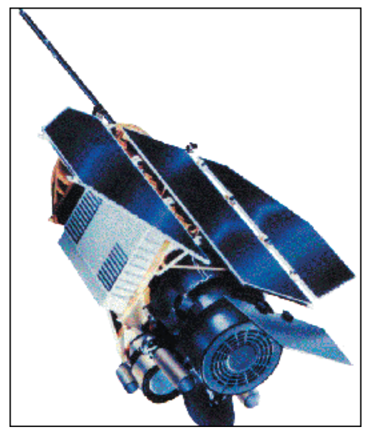
The objects you will be studying have names which must seem very unusual, but they serve a purpose. The prefix (usually a 1 to 3 letter or number code) indicates the catalog to which the object belongs. The suffix, usually a seven or eight number combination (which astronomers jokingly refer to as the object's "telephone number"), roughly gives the location of the object in the sky. For example, the name of the quasar in the first tutorial is "BQ 0740+2537". The "BQ" prefix indicates that it is an object in the FIRST Bright Quasar Survey (see below). It is has a right ascention of approximately 07 hours, 40 minutes and a declination of +25 degrees and 37 arcminutes (in the filename "bq0740p2537" the "p" is for "plus"). These names, while somewhat confusing, help astronomers keep track of the millions of astronomical objects known.

The center of the Very Large Array (VLA). The VLA is a radio telescope in New Mexico operated by the National Radio Astronomy Observatory.

The research projects

Data are available for four research projects:

The goal of the first project is to identify objects in the FIRST Bright Quasar Survey. They were discovered by the FIRST survey, an acronym for "Faint Images of the Radio Sky at Twenty-centimeters". It is a radio survey of a portion of the sky with the Very Large Array (VLA) radio telescope in New Mexico. Assembled by Dr. Sally Laurent-Muehleisen at the Lawrence Livermore National Laboratory, this catalog contains objects which emit radio waves. Over 2000 spectra are available to study. *(Note: Currently these spectra are only in text format and must be imported into Graphical Analysis 3.0 or higher.)*



Röntgen Satellite" (ROSAT) was an X-ray observatory developed through a cooperative program between Germany, the United States, and the United Kingdom." The satellite was designed and operated by Germany, and was launched by the United States on June 1, 1990. It was turned off on February 12,

The second project consists of a spectroscopic study of FIRST radio sources that have a flat radio spectrum. These objects were selectively chosen because they are predominantly "flat-spectrum radio quasars" (FSRQs) and BL Lac objects (which are collectively known as "blazars"). However, other objects are also present in this survey, including elliptical galaxies, starburst galaxies, and perhaps other types of AGN. Spectra of 151 objects from the FIRST survey are available and are labeled with the prefix "FFS". *(Note: Currently these spectra are only in Graphical Analysis 2 format. They cannot be opened with GA 3.)*

The goal of the third project is to search for quasars in the Green Bank 6cm (GB6) catalog of radio sources. This project was initiated by Dr. Jane Dennet-Thorpe at the Rijksuniversiteit Gröningen and by Dr. Rector. Currently spectra of 17 objects are available for analysis. These objects should be analyzed in the same way as the FIRST sources, although we expect most of the objects to be quasars. They are labeled with the prefix "GB" or "GB6". *(Note: Currently these spectra are only in Graphical Analysis 2 format. They cannot be opened with GA 3.)*

The fourth project is to study BL Lac objects from the ROSAT-Green Bank catalog (RGB). Discovered by Dr. Sally Laurent-Muehleisen, these are BL Lacs which are in both the ROSAT and Green Bank 6cm sky surveys. The goal is to determine redshifts for these objects. It is a very difficult project and should not be attempted without first gaining experience with the FFS and GB6 data. *(Note: Currently these spectra are only in Graphical Analysis 2 format. They cannot be opened with GA 3.)*

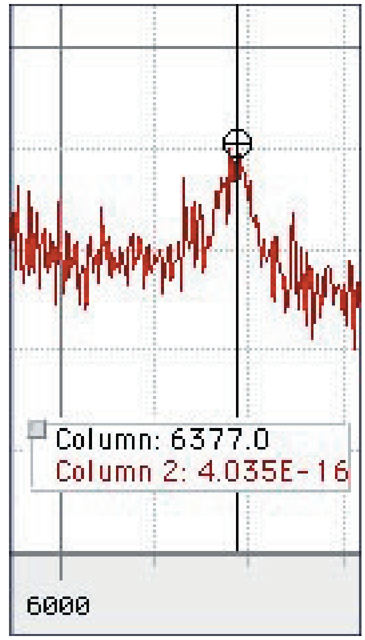
In addition to the research data, example spectra have been included so that students can follow the examples provided. Spectra for different classes of objects are also included for comparison; e.g., a composite quasar spectrum is also included courtesy of Dr. Paul Francis, Australian National University.

About the software

This research project is designed for Graphical Analysis by Vernier Software. Graphical Analysis (GA) was chosen because it is an inexpensive software package which has the necessary analysis tools. As of this writing, v3.2 is the latest version of GA. However, we are in the process of converting most of the spectra into this format. Many of the spectra are still in GA v2.0 and cannot be opened by v3.0 and higher. Also note that these spectra were saved in GA 3.1 format, and cannot be opened by GA 3.0. Go figure. If you have GA 3.0 you should upgrade by going to the website below.

An "🖳" icon appears when analysis of the data with the computer is necessary. Here we use the Macintosh version of Graphical Analysis to illustrate the examples, but the Windows version is identical. To order Graphical Analysis, Vernier Software can be reached at the following address:

Vernier Software, Inc.
8565 S.W. Beaverton-Hillsdale Hwy.
Portland, Oregon 97225-2429
Phone: (503) 297-5317, Fax: (503) 297-1760
email: dvernier@vernier.com
WWW: http://www.vernier.com/



Use the examine tool (using **Analyze/Examine** or ⌘-E) to determine the wavelength of any emission lines present (the X value). The information box, which is normally in the upper left corner of the plot is shown at the bottom. In this example the wavelength of the emission line is 6377 Angstroms (Å). The flux per unit wavelength is 4.035 x 10^{-16} erg cm^{-2} s^{-1} $Å^{-1}$.

Using Graphical Analysis

Summary of Commands

Graphical Analysis 3 has many useful tools that are useful for this project. Below is a brief summary of some of the commands and how they are used in this project. It is not a complete summary of all of the commands available (and useful) in GA 3.

File/Open... (⌘-O)

Opens the spectrum. Each spectrum covers roughly 4000 to 9000Å. Note that this command can only be used to open spectra in GA 3.1 format. GA 3 cannot open spectra in GA 2 format.

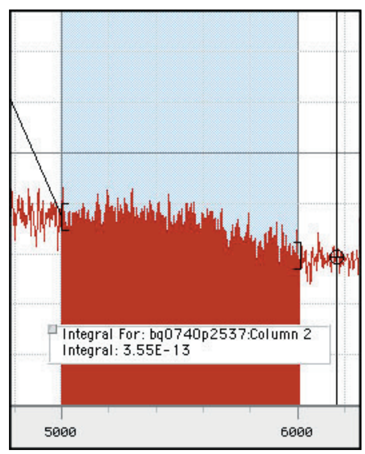
File/Import From Text File...

Use this command to import spectra that are in text format, e.g., the FIRST Bright Quasar Survey spectra.

File/Close is used to close the spectrum.

Analyze/Examine (⌘-E)

Activates the examine tool (the magnifying glass) which gives the wavelength (the X value) and the flux per unit wavelength (the Y value) of the datapoint closest to the cursor. It is used to determine the wavelength of emission and absorption lines in the spectrum (see illustration in the sidebar).



The integrate tool (**Analyze/Integral**) is used to sum the flux over the selected range of the spectrum. The total flux is listed in the upper left corner (shown above). In this example the total flux is 3.55 x 10^{-13} erg cm^{-2} s^{-1} from 4995Å to 6012Å.

Analyze/Integral

Sums the area under the spectrum to give the total flux density over the spectral region selected by the cursor. This is used to measure the amount of total flux density in the selected region, a step in determining luminosity.

Analyze/Statistics

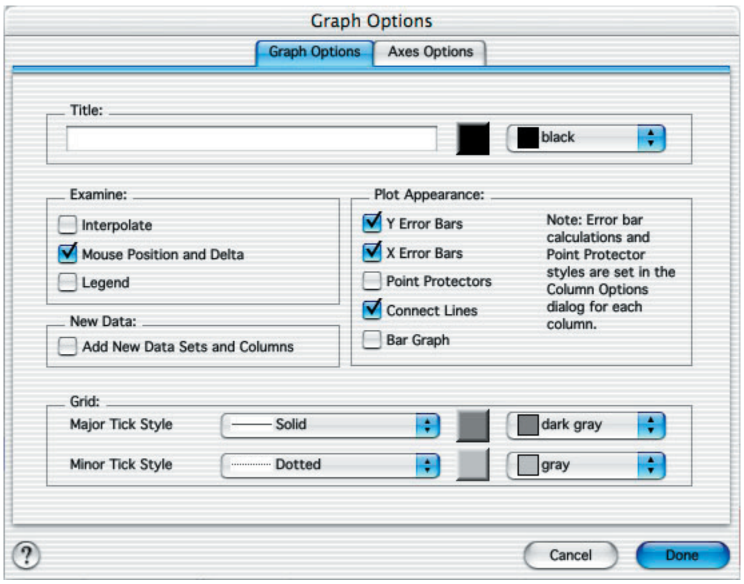
Gives statistical information for the spectral region selected by the cursor, including maximum and minimum datapoint values as well as the average, mean, median and the point count. This tool is useful for determining the CaII break strength.

Analyze/Curve Fit...

This tool is useful for fitting functions to the data. It can be used to fit a "power law" spectrum to the data of quasars and BL Lac objects.

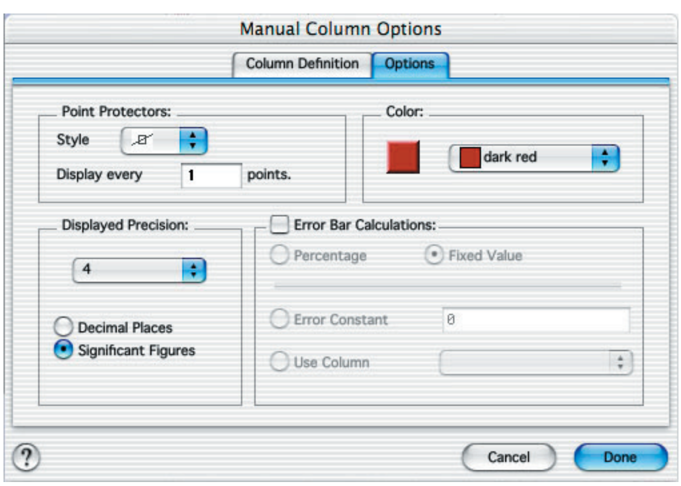
Options/Graph Options...

The graph options window is used to turn off the point protectors after a spectrum is loaded (as shown below). The axes options window is also useful for rescaling the X- and Y-axes by inputting ranges manually or automatically by using the data values. Note that you must first select the graph (i.e., click on it) for this option to be available in the menu.



Data/Column Options

The column options is used to adjust the displayed precision of the data. Sometimes upon loading the data values in column 2 (the flux density column) are shown as zeros because the displayed precision is not correctly set. Set the displayed precision to 4 significant figures as shown below before using the examine tool.



AGN Spectroscopy

Nature's Most Powerful "Monsters"

Quasars, Blazars and BL Lacs: Extreme Astronomy at the Beginning of Time

A personal perspective by Jeffrey F. Lockwood

The dome of the 2.1-meter telescope at Kitt Peak National Observatory.

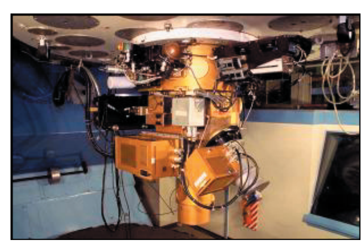
Where do we come from? How did we get here? When did the Universe begin? In astronomy, these basic questions remain tantalizing in their mystery, and shrouded in cosmic doubt. Some of the astronomers who choose to investigate these mysteries select nature's most spectacular creations to study; objects so powerful in their outpouring of energy that the most amazing fact about them is that they exist at all. These objects called quasars (originally an acronym for quasi-stellar radio sources), are billions of light years away and represent a visual time capsule of what the Universe was like when it was young. In fact, tonight at the National Science Foundations' 2.1-meter telescope on Kitt Peak, Dr. Travis Rector, astronomer and explorer of the far reaches of the cosmos, will be studying objects that resemble what our galaxy the Milky Way may have looked like billions of years ago.

The KPNO 2.1-meter Telescope

The 2.1-meter telescope inside the dome. The white dome spot can be seen to the upper left.

I met Travis at the Visitor's Center at Kitt Peak at 3 O'clock one Saturday afternoon. It was his third night of a four night observation run and he looked a little weary having had only 5 hours of sleep before rising three hours ago. At 4 o'clock, we went over to the telescope to begin the long process of preparing the telescope and its camera to take data. As Travis begins explaining the workings of the "Goldcam," the spectrograph which will take the spectra of his target objects during his observing run, three visitors stare at us through the glass partition. Travis decides to invite them in and proceeds to give them an explanation of his research project, shows them the control room, and the primary mirror. They, needless to say, were immensely pleased. More satisfied taxpayers.

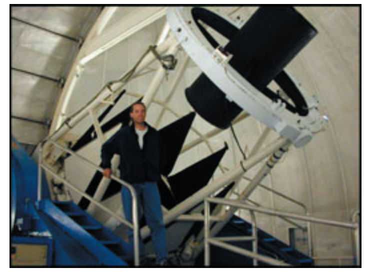
The Goldcam, a workhorse optical spectrograph, has evolved over the years to its present condition. Attached at the Cassegrain focus of the telescope, there are a dozen different metal boxes and cylinders protruding from the main axis of the instrument. A couple of the boxes are TV cameras; two of the cylinders are lamps used to calibrate the instrument and the data display. Some of the attachments are relics of previous incarnations of the spectrograph that are not removed so as not to compromise the balance of the telescope. It takes two technicians three hours to mount Goldcam on the end of the telescope.



The GoldCam spectrograph, attached to the bottom of the 2.1-meter telescope.

The heart of the spectrograph is the diffraction grating at the very bottom of the Goldcam. It is a reflection grating with medium resolution that allows a broad range of optical wavelengths to be studied (3500 to 8000 Å), covering the entire visible spectrum as well as parts of the near infrared and near UV. When studying AGN (active galactic nuclei), astronomers like to have coverage over as much of the spectrum as possible to detect the emission lines common in such objects, which may be at any wavelength.

The light from the AGN being studied is reflected several times before it gives up its secrets to the astronomer. Bouncing off the 2.1 meter primary mirror then off of the convex secondary and through the back of the telescope, the light hits a silvered plate at the focal plane of the telescope that has a 160 μm slit cut in it. A small video camera uses reflected light from the plate to see the slit, allowing the telescope operator to center objects on it during the night. After passing through the slit, the light travels down the axis of the camera and is reflected from the grating at the bottom back up to a flat mirror, which passes the spectrum to the CCD camera. The CCD chip is rectangular (3,096 X 512 pixels) to display the spectral lines over a wide range of frequency space. The whole camera is cooled by liquid nitrogen to reduce "noise" and thereby improve its sensitivity. To keep it cold during the entire night, the camera is enclosed in a device called a dewar, which acts much like a thermos bottle. Then the spectrum is sent to the computer where it is displayed on a monitor. A software package translates the image to a graphical representation that looks a lot like a seismic record of the San Francisco earthquake.

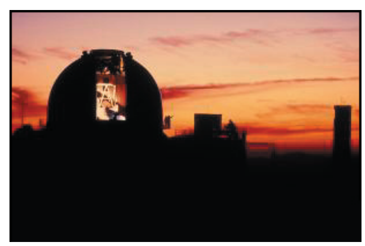


Dr. Travis Rector standing next to the 2.1-meter telescope on Kitt Peak.

At 4:20 PM, Travis starts to calibrate the CCD array. To equalize the response of each pixel in the array, pictures of a flat white spot affixed to the dome are taken and divided into the signal of each pixel. This procedure is accomplished by taking fifty 5-second exposures and averaging them. Then, as a double check and to fine tune the response of the blue end of the spectrum, a quartz lamp that is mounted on the Goldcam is turned on and illuminates the chip. Usually, fifty exposures of 8 seconds are taken with the quartz lamp to finish the flat fielding process. Travis then inserts a cassette-size Exabyte tape to store his data for the night. With a capacity of 4 GB, he can place all of his data for a four day observing run on it with ease. At 5:30 PM, we decide it's time for dinner.

Waiting for nightfall

After eating, we walked back up to the telescope and asked Doug Williams, our telescope operator for the night, to open the door to the catwalk so we can watch the sunset. This is a ritual for many astronomers, including Travis. Its provenance goes back to his first observing run with his doctoral advisor, John Stocke at the University of Colorado. Travis was impressed that his advisor would take time out to appreciate the beauty and tranquility of the setting sun and the approach of darkness despite the mounting pressures in preparing for the hectic night of observing.



The 2.1-meter telescope at sunset.

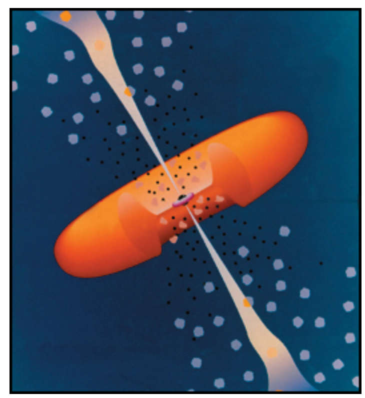
Back in the control room, I reflected on how far removed Travis is in appearance and demeanor from what John Q. Public has in their brains as the "typical astronomer." Tall and slender, Travis is a serious marathon runner. Built like a strong and sinewy greyhound, he is the second astronomer with these personal attributes that I have worked with. The other was Todd Henry, formerly of Steward Observatory, who is now working at Space Telescope. Travis is wearing a green T-shirt, blue jeans, hiking boots and is totally void of facial hair, the former hallmark of many science types in other eras. He has enormously long hair. It is held cascading down to the middle of his back by a purple "scrunchy." Totally at ease in the control room, there doesn't seem to be a nervy bone in his body. Travis grew up in Boulder, Colorado and began his lifetime love of the sky when he was 7 years old. He and his mom started watching the Perseid meteor shower every August, a tradition that lasted into his high school years. They and other family members would lie down head-to-head on a blanket, each facing in a different direction. Whenever someone saw a meteor, they'd yell out their direction in hopes that everyone else could look over and see it.

It never worked,but they had so much fun trying, so they did it anyway. While Travis was in high school, his Mom took him to the University of Wisconsin to visit the astronomy professors; and his interest in a career in astronomy began to take hold. After completing his undergraduate physics degree at Trinity University in San Antonio, Texas, Travis returned home to earn his doctorate at the University of Colorado at Boulder.

At 7:00 PM, Doug centers a 7.5 magnitude SAO star and calculates the "seeing" (the smallest object, diameter measured in seconds of arc, that the telescope can resolve at that moment) with a new computer program. He says, "Pretty good, 1.2 arcseconds." Evidently, even though the skies were pretty free of clouds, the seeing was poor last night, forcing him to only take data on the brightest objects in his observing list. At 7:15 PM, Travis begins a half-hour process of focusing the camera. He takes seven 10-second exposures of a standard star's spectra and displays all of them on the monitor to find the clearest and most distinct image. He repeats the process and settles on a focus of 2650 (mm per focus unit) and Doug adjusts the secondary mirror accordingly.

Doug selects another standard star, a white dwarf this time so a final test exposure can be taken. As the telescope slews slowly towards its position in the sky, stars on the monitor whip by like meteors. Once the star is centered on the slit four two minute exposures are taken. The computer then calculates a sensitivity function that will calibrate the chips response across the continuum to match the star's spectrum, particularly in the blue portion. As the Goldcam was taking the images, I watch in amazement as the star drifts right off the screen. I pointed this out to Doug, who exclaimed, "Oh dear." Travis adds, "I've never seen that happen before." It's something of a mystery and we all hope it doesn't happen again.

Doug has been a telescope operator for one year. Prior to coming to Kitt Peak, he spent 15 years as a fisherman in Alaska. For five months each year, he would work on a salmon or herring boat and earn enough money to support himself the rest of the year. Then, each winter he would take courses at the University of Washington. Once Doug graduated with a degree in physics, he decided to find a second job to supplement his fishing income so he applied for and was hired for the operator's job last year.



An illustration of what an AGN is believed to look like. At the very center is a massive Black Hole which is pulling in stars, gas and dust (the surrounding torus). Nearby gas clouds (the black and white dots) are heated and produce emission lines. Some AGN eject jets of gas which shoot away at nearly the speed of light.

At 7:55 PM, Travis turns on the HeNeAr lamp that is a light source filled with Helium, Neon, and Argon gas. The lamp is attached to the spectrograph and illuminates the CCD s that it can be used to calibrate the wavelength scale of the camera. At 8:00 PM, we are finally ready to begin the actual data-taking phase. Travis gives Doug a BL Lac object from his "cache," a list of 40 or 50 research targets he has supplied to the operator. He figures we will have time to take data on three or four BL Lacs from his list. He needs to take four 30 minute exposures of each object. All four are later averaged for the most accurate spectrum possible. Travis is working with Dr. Sally Laurent-Mueheleisen from Lawrence Livermore Lab and his former advisor, Dr. John Stocke from the University of Colorado on this project. He will be taking much of the data over the course of the spring and summer. The purpose of the study is to survey the entire range of BL Lac objects, from high to low energy.

Mother Nature's "Monsters"

BL Lacs are related to quasars. Specifically, just to confuse things, they are also related to objects called "flat-spectrum radio quasars" (FSRQs). Collectively, they are known as "blazars," a word that comes from the combination of the terms BL Lac and quasar. It appears that blazars are oriented such that their "jets," enormous outpourings of electrons and protons from the black hole, are coming straight at us. The jets, travelling at nearly the speed of light, are ejected along the axis of rotation of the black hole. The particles in the jets are affected by time dilation which "stacks up" their incoming wavefronts to the point where it appears that the energy coming from the BL Lac is as much as a thousand times greater than it really is. The process is called "Doppler boosting." Because the jet is so bright, it tends to overwhelm any emission from the rest of the galaxy, washing out any emission or absorption lines that might be there. For this reason, BL Lac spectra are not easy to interpret. The main thrust of Travis' research is the study of unification models for the different varieties of blazars. The major questions is: How are all these different types of objects related? Is it: 1) Orientation: Do they look different because we see each object from a different direction? 2) Environment: Are they in clusters of galaxies or are they alone? 3) Evolution: How do they change over time? And 4) Intrinsic physical properties: Are they just different? About the size of our solar system, all blazars seem to have a huge black hole powering them, with a mass equal to over 10 million suns. The gas near the black hole yields the emission lines seen in their spectra.

At 8:30 PM, the first 30-minute exposure is done. The data is displayed on the computer screen. The spectrum doesn't look like much as it is a black and white display of the BL Lac's continuous spectrum, with a few bumps and lines here and there. Later, Travis will use the computer to transform the raw data into a graphical form that is much easier to interpret. After the second exposure is done, Travis remarks that observing is a continual process of "hurry up and wait." It's grind it out time, the non-romantic, repetitive push-a-button-and-watch-the-clock-for-30-minutes time. Travis loves to observe, but after three long nights in a row, it gets quite mentally exhausting. Fortunately, the telescope's control room is equipped with a stereo system to help us stay awake during the middle of the night.

At 10 PM we're finished with the first object. Before going to a second one, Travis uses the HeNeAr lamp to recalibrate the camera. Doug checks the temperature to see if the focus of the telescope might have changed during the observation. After programming the computer to take the next two exposures, it's time to get to the dining hall for "midnight lunch."

The Nightly Grind

When we return at 11:42 PM, we have to change the focus a little due to the falling air temperature. On to a third BL Lac object. By this point the romance of observing is definitely starting to wear off. Inside the control room you can't see outside, so you might as well be sitting in your basement. Around 2 AM, Travis decides we should go outside to "check the weather," but he admits that we're really going outside just to enjoy the starry night. Once outside, it becomes obvious why they chose to build telescopes on Kitt Peak. At an altitude of 7000 feet, it offers a spectacular view of the night skies, rivaled by only a few other locations in the world. "Coming out here reminds me of why I do this. It helps give me the energy to stay awake the rest of the night," says Travis. Time on these telescopes is valuable, and not a second of dark skies is wasted, observing from dusk to dawn. We go back inside and whittle away the hours by listening to music and eating cookies from the cafeteria, every so often moving the telescope to the next object and starting a new exposure. Finally, around 5 AM, the approach of dawn tells us its time to close up the telescope and go to bed.

We leave Doug to refill the camera's dewar with liquid nitrogen so that it will be ready for the next night of observing. On the way back to the dormatory, we meet up with astronomers returning from the other telescopes on the mountain. Like modern-day vampires, astronomers try to go to bed before sunrise, in a vain attempt to avoid "observer's hangover."

All in all it was a good night of observing. A tiny piece of the puzzle, data on the nature of four BL Lacs, has been set in place. Blazars are literally time capsules, providing astronomers with information on the Universe just after the first stages of creation. Called "macho astronomy" by some, since the energetic blazars are the Arnold Schwartznegger's of galaxies, their study involves sifting information carried by photons travelling through space for billions of years. Understanding and constructing models of quasars unruly behavior will give us a glimmer of how our own galaxy developed over time, leading inexorably to the miracle of beginning to comprehend our own existence in the cosmos.

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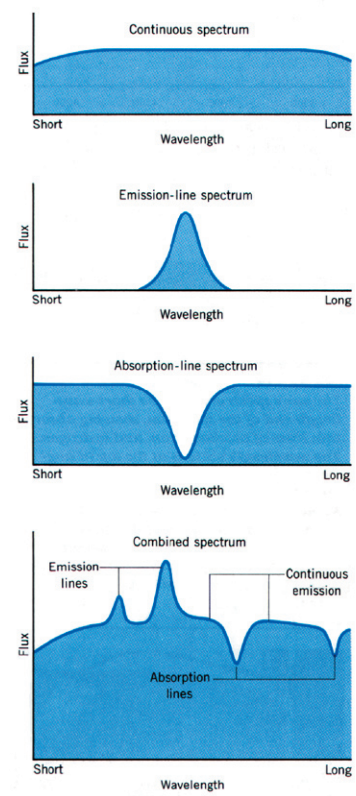
Introduction

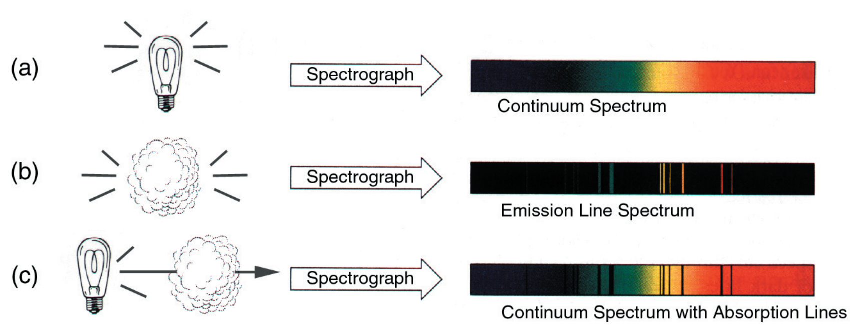
The power of spectroscopy

Spectroscopy is the study of "what kinds" of light we see from an object. It is a measure of the quantity of each color of light (or more specifically, the amount of each wavelength of light). It is a powerful tool in astronomy. In fact, most of what we know in astronomy is due to spectroscopy: it can reveal the temperature, velocity and composition of an object as well as be used to infer mass, distance and many other pieces of information. Spectroscopy is done at all wavelengths of the electromagnetic spectrum, from radio waves to gamma rays; but here we will focus on optical light.

The three types of spectra are shown in the diagram below: continuous, emission line and absorption line. A continuous spectrum includes all wavelengths of light; i.e., it shows all the colors of the rainbow (case "a" in the diagram below). It is produced by a dense object that is hot, either a dense gas (such as a star) or a liquid or solid (e.g., a tungsten filament in a light bulb). In contrast, an emission line spectrum consists of light at only a few wavelengths, i.e., at only a few discrete colors (case "b"). An emission line spectrum can only be produced by a hot, tenuous (low-density) gas. Importantly, the wavelengths of the emission lines depend on the type of gas; e.g., Hydrogen gas produces different emission lines than Helium. Absorption lines can be best thought of as the opposite of emission lines. While an emission line adds light of a particular wavelength, an absorption line subtracts light of a particular wavelength. Again opposite of emission lines, absorption lines are produced by a cool gas. Naturally there must be some light to subtract, so absorption lines can only be seen when superimposed onto a continuum spectrum. Thus, for absorption lines to be seen, cool gas must lie between the viewer and a hot source (case "c"). The cool gas absorbs light from the hot source before it gets to the viewer. Here "hot" and "cool" are relative terms- the gas must simply be cooler than the continuum source. Also note that a gas absorbs the same wavelengths of light that it emits.



Astronomers like to plot spectra differently than you often see in a textbook. Spectra are plotted as flux (the amount of light) as a function of wavelength. In the diagram above the three types of spectra are shown. In the bottom frame they are shown together, as they might appear in an object's spectrum.



Emission and absorption lines are named after the element responsible for the line (remember that different types of gas produce different lines) and the gas' ionization state. Atoms in a hot gas can lose electrons, either by absorbing photons (particles of light) or by collisions with other particles. Losing one or more electrons changes the wavelengths of the emission and absorption lines produced by the gas, thus it is important to know its ionization state. A roman numeral suffix indicates the ionization state, where higher numbers indicate higher ionization states; e.g., “Na I” is neutral (non-ionized) Sodium, “Ca II” is singly-ionized Calcium, etc. In general hotter gases are more highly ionized. Some common lines have special names for historical reasons. Because Hydrogen gas is by far the most common, many of its lines were given special names; e.g., “Ly α” is a very strong ultraviolet line which is produced by neutral hydrogen (H I); it is part of the Lyman series of lines. “Hα”, “Hβ”, “Hγ”, etc. are strong optical lines, also produced by neutral Hydrogen (part of the Balmer series). You will notice that the names of some spectral lines are put in brackets or partial backets (e.g., [N II] and C III]). These line are called “forbidden lines” and “semi-forbidden lines” because they cannot be seen in gas on Earth. These lines can only occur in very low-density gas clouds such as those found in space.

Nomenclature:

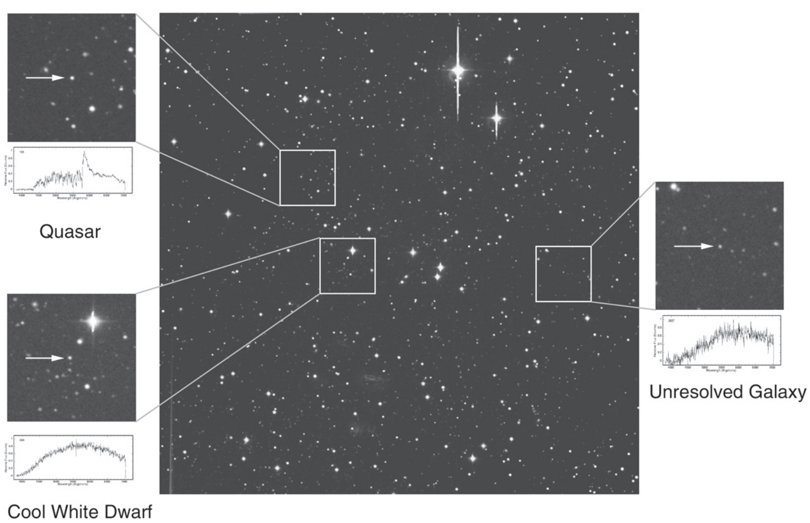
“Na I” is pronounced “sodium one”, “[N II]” is pronounced “nitrogen two” and “Ha” is pronounced “H alpha” or “hydrogen alpha”, etc.

Nomenclature:

The positions of spectral lines are measured in units of Angstroms, or “Å” for short (1 Å = 10^{-10} meters = 0.1 nanometers).

Spectroscopy as an Identification Tool

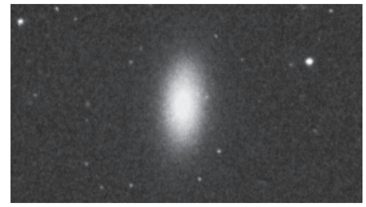
When looking up at the night sky with thousands of stars overhead it is easy to wonder: How do astronomers know what they are?



In the image above there are hundreds of points of light. Most are stars within our galaxy, but not all. In fact, some of these points are distant galaxies which are so far away that they only look like points of light. How do astronomers tell the difference? Often the answer is spectroscopy. As you will find, the spectra of stars, galaxies and active galaxies are very different. In these projects, you will focus primarily on galaxies, both normal and active. The following sections describe the different types of objects you will encounter and what their spectra look like. You can use this information to set up a classification scheme for determining the identity of each object.

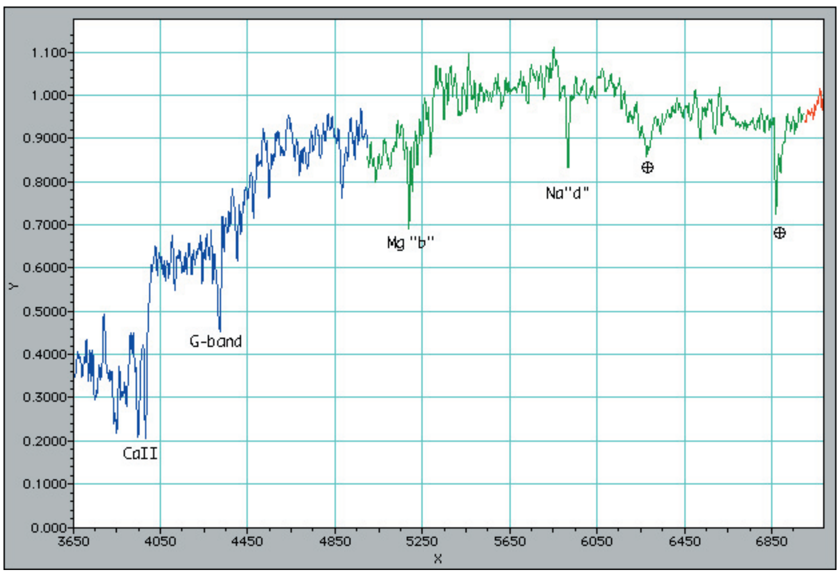
The Milky Way and other Galaxies

Our galaxy, known as “The Milky Way”, is a typical spiral galaxy which is approximately 100,000 light years in diameter. It consists of about 100 billion stars, each with masses ranging from 0.1 to as much as 100 times the mass of our Sun. It is estimated that the entire Universe contains *at least* 400 billion galaxies, with a wide range of sizes, masses and shapes. Most galaxies are considered "normal" because they simply look like a large group of stars, with dust and gas.



The elliptical galaxy NGC 3245.

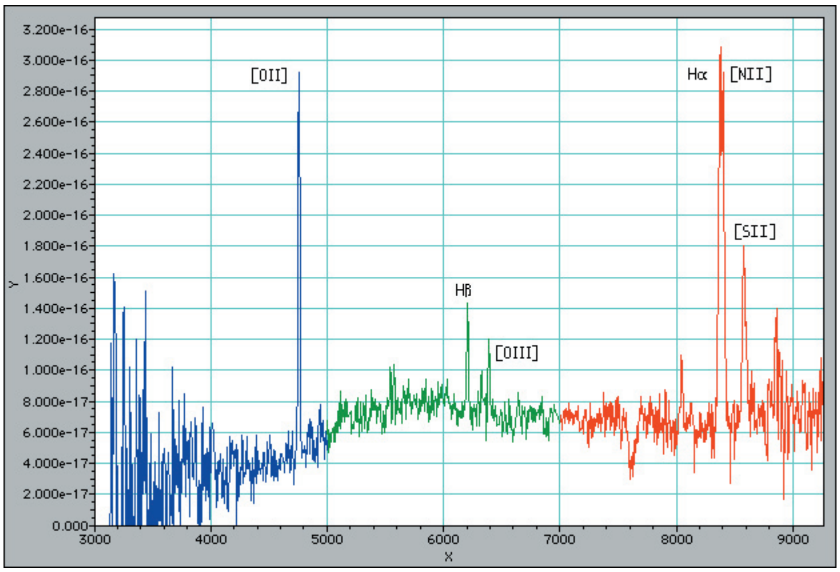
The spectrum of NGC 3245, a nearby elliptical galaxy, is shown below. Note that the spectrum does not show any emission lines, but has several absorption lines. The spectrum of an elliptical galaxy is dominated by cool, giant stars because they are luminous and common in galaxies. The cool outer atmospheres of these stars produce the very strong absorption lines you see in the galaxy's spectrum. The most notable absorption line is the Ca II absorption line doublet at ~4000Å. Note that the continuum flux drops dramatically at wavelengths shorter than the Ca II lines; in elliptical galaxies the flux drops to roughly half its value. This is known as the "Calcium break." Elliptical galaxies are common but they are very weak radio sources; thus we expect to find them in the FIRST survey, but only those that are nearby (i.e., at low redshift) because more distant ones are too faint to detect.



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. At wavelengths longer than ~6000Å there are several "bands" of numerous, closely spaced absorption lines. Because they are caused by our atmosphere, these lines appear in the same locations in every spectrum (although the shapes and strengths of these lines can change slightly). Because we are always looking through the Earth's atmosphere, the telluric lines appear in the spectra of all objects, not just elliptical galaxies.

"Starburst" Galaxies

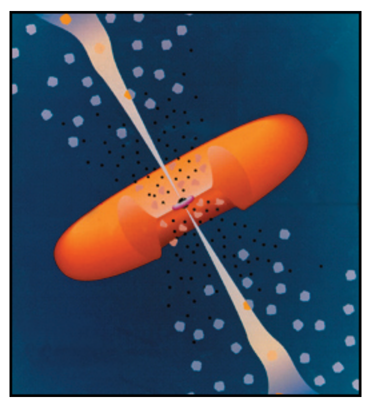
Most galaxies go through a continual cycle of star birth and death. However, some galaxies are currently forming stars at a furious rate, going through a stellar "baby boom." These galaxies are known as starburst galaxies. Often rapid star formation is induced in a galaxy by gravitational interaction or collision with another galaxy. Newly-formed massive stars in the starburst galaxy heat up gas in the interstellar medium and create strong, narrow emission lines which are seen in addition to the galaxy's spectrum. Because of the massive stars, the spectra of starburst galaxies also have more blue light than normal galaxies; therefore the continuum flux does not decrease as much blueward of the Ca II absorption lines (the break strength is <40%). Like “radio galaxies” (described below), starburst galaxies usually have several narrow emission lines. For both of these reasons it is often difficult to differentiate between starburst galaxies and radio galaxies. One difference is that the Hβ and [O III] emission lines in starburst galaxies are usually about the same strength. The same is true for the Hα and [N II] emission lines; however since these two lines are so close to each other they are usually “blended” together, as is the case in the example below. The [O II] and [S II] emission lines are also common is starbursts, but not always present. Starburst galaxies are rare and are weak sources of radio waves, thus we expect



to find very few of them in the FIRST survey.

Active galaxies, quasars and other “monsters”

The Milky Way and NGC 3245 are examples of typical, “normal” galaxies. But some galaxies look very different. They emit enormous amounts of energy, much of it is in the form of radio waves and X-rays, which are not coming from the stars. For this reason they are called “active galaxies.” It is still not yet entirely clear what is producing this energy, but the most widely accepted model is that it is a massive Black Hole (about 100 million times the mass of the Sun) that sits at the center of the galaxy. The Black Hole and its surrounding material are known as an Active Galactic Nucleus, or an AGN for short. The galaxy in which the AGN resides is known as the “host galaxy.”



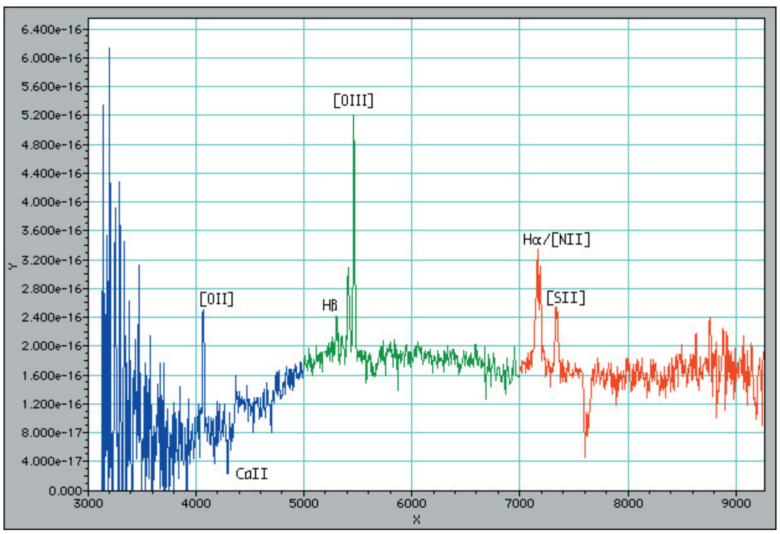
An illustration of what an AGN is believed to look like. At the very center is a massive Black Hole which is pulling in stars, gas and dust (the surrounding torus). Nearby gas clouds (the black and white dots) are heated and produce emission lines. Some AGN eject jets of gas which shoot away at nearly the speed of light.

A Black Hole is a celestial body whose gravity is so strong that nothing can escape from it, not even light itself. The Black Hole attracts nearby matter, which falls inward and forms a disk around the Black Hole. As the matter falls towards the Black Hole, it accelerates and heats up due to compression (much like gas does when it is compressed). While the Black Hole itself cannot be seen, this matter radiates huge amounts of energy as it falls in. The accretion disk becomes so hot (~1,000,000° K) that it emits X-rays. Remarkably, all of this energy comes from a region about the size of our Solar System. Nearby, tenuous clouds of gas are also heated, often enough to produce strong emission lines. To keep producing so much energy the Black Hole must continually pull in nearby dense material. Astronomers refer to this as “feeding the monster.” In some AGN not all of the material is pulled into the Black Hole. Some of it is ejected in jets of ionized gas at nearly the speed of light. These jets are very luminous radio sources, which extend out far beyond the galaxy itself (e.g., see the illustration of the radio galaxy “Centaurus A”).

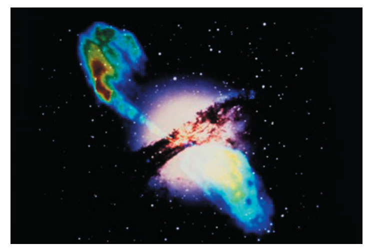
There is a wide range of different types of active galaxies and AGN, which astronomers jokingly refer to as the “AGN zoo.” Because they are luminous radio sources, we expect to find many AGN in the FIRST survey. Below is a description of some of the different classes of AGN we expect to find and how to differentiate them by their spectra.

Radio Galaxies

The term radio galaxy was coined to describe objects that look like normal galaxies in optical images, but were found to emit enormous amounts of radio waves. Their optical spectra reveal the presence of strong, narrow lines and a CaII break strength that is <40%. For these reasons radio galaxies are easily confused with starburst galaxies. The primary difference is the strength of the emission lines: in radio galaxies the forbidden lines [O II], [O III] and [N II] are



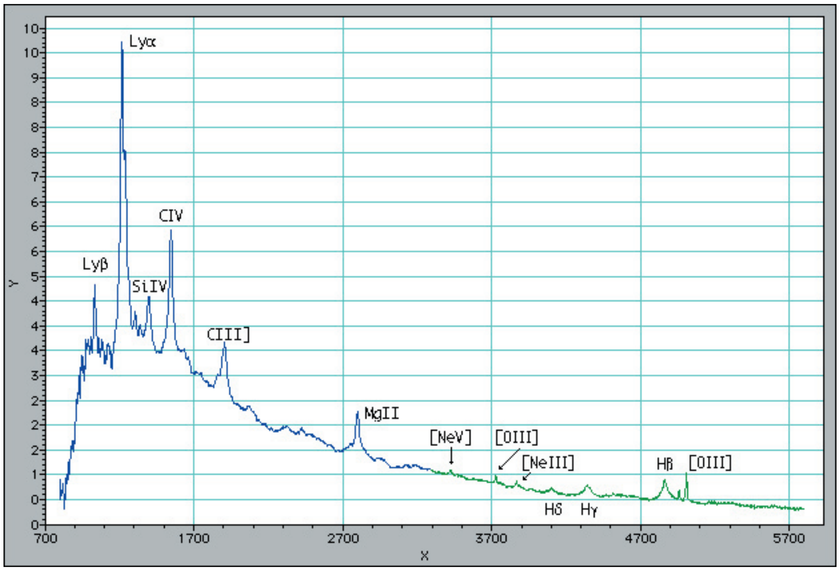
typically much stronger than Hα and Hβ (as in the example below, where [O III] is much stronger than Hβ). Unlike quasars, radio galaxies tend not to have broad emission lines.



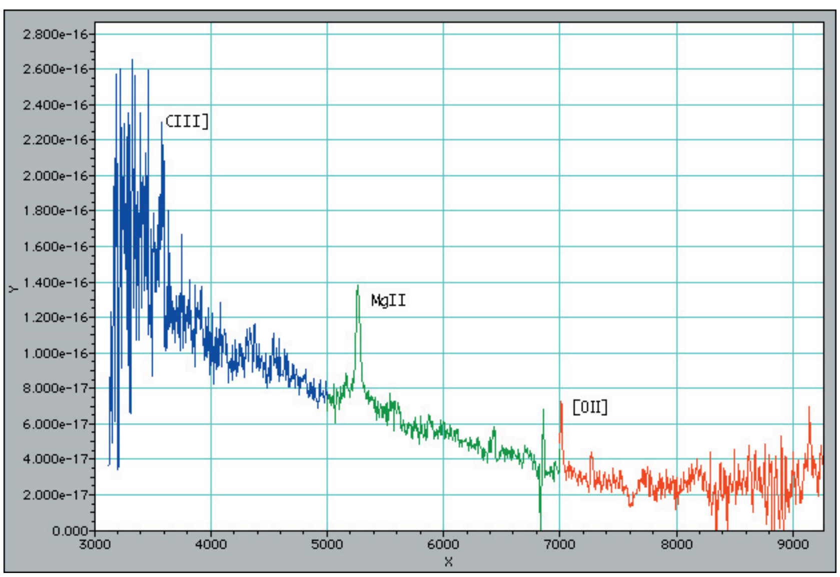
The top picture shows the radio galaxy “Centaurus A” as it looks in an optical image, but a radio telescope reveals a dramatically different view. The bottom image shows the radio image superimposed onto the optical image. Twin radio jets stretch over 100,000 light years from the center of the galaxy. Images courtesy David Malin, Anglo-Australian Observatory and Jack O. Burns, New Mexico State University.

Quasars

Quasars are the most distant and most luminous type of AGN known; and their spectra don’t look like normal galaxies at all. Instead of having an optical spectrum which looks like a galaxy (e.g., with many absorption lines and a CaII break), quasars have a very smooth continuum spectrum with strong emission lines. The continuum you see is not due to starlight but synchrotron radiation from the AGN. Synchrotron radiation is produced by electrons in the AGN’s jet which are moving near the speed of light. The quasar’s emission lines are produced by clouds of gas within the galaxy which are heated by the AGN. Quasars are so luminous they usually outshine their host galaxy, often by as much as 1000 times or more. Imagine: something about the size of our Solar System can outshine over 100 billion stars by a factor of 1000!

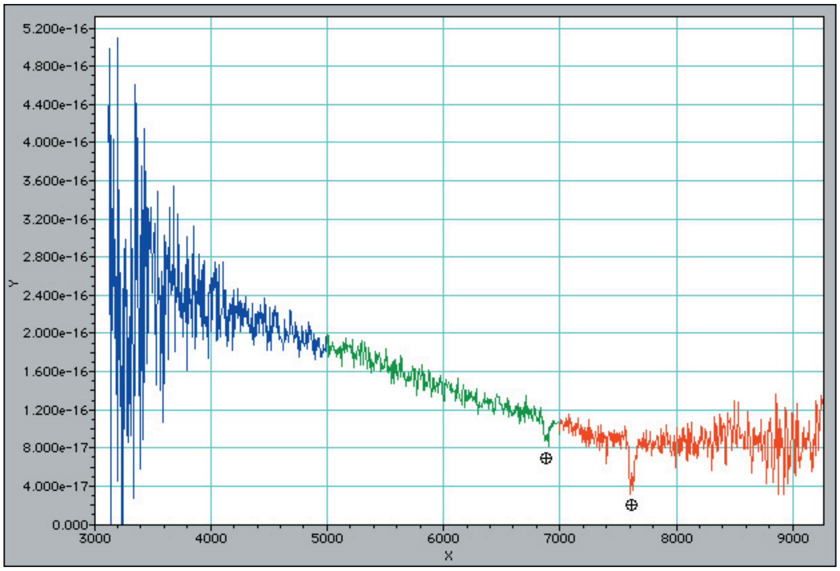


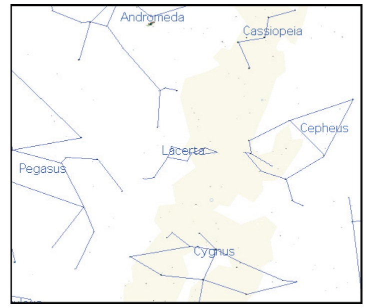
The spectrum above is a composite of over 100 quasar spectra averaged together. The spectrum is shown at zero redshift; i.e., what the quasar would look like if it were not moving away from us. The spectrum below shows a typical quasar spectrum. The emission lines Mg II and [O II] are clearly visible. While the blue portion of the spectrum is very noisy, CIII] appears to be detected too. The jagged line just to the left of [O II] is a flaw in the spectrum; it is not real.



BL Lac Objects

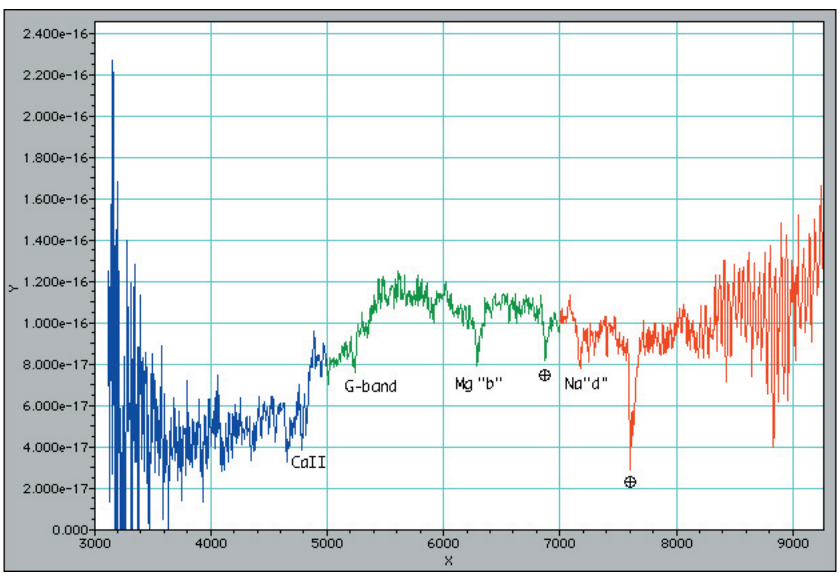
Most AGN have strong emission lines, but a special class of AGN are notorious for having only very weak emission lines, if any at all. They are known as "BL Lacertae objects," or BL Lacs for short. Because they lack strong emission lines, it is often difficult to determine redshifts for these objects. BL Lacs are most easily differentiated from radio galaxies and quasars by their emission lines: quasars and radio galaxies have strong lines, BL Lacs do not. Like radio galaxies, BL Lacs often show a Ca II break in their spectrum whereas quasars rarely do.





BL Lacertae objects are a rare and unusual class of AGN which are named after their prototype, BL Lacerta, an AGN located in the constellation of Lacerta, the Lizard. Lacerta lies between Cassiopeia, the Princess and Cygnus, the Swan.

The above spectrum is clearly a BL Lac because it has no emission or absorption lines, nor does it have a CaII break. The only spectral lines seen are the telluric absorption bands from the Earth's atmosphere (marked with a ⊕). The BL Lac spectrum below is more common. It looks much like a galaxy except that its CaII break is not as strong. Like starburst and radio galaxies, BL Lacs have a CaII break that is <40%. Often the galactic absorption lines and CaII break are used to determine the redshift of a BL Lac.



Redshift and Hubble's law

Not only are spectra used to determine an object's identity, but also its velocity and distance. Spectroscopy is used to determine an object's velocity towards or away from us via the Doppler effect. 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 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). This shift is readily noticable in the emission or absorption lines in an object's spectrum. The amount of shift is given by the following equation:

$$\lambda_{obs} = (1+z)\lambda_{rest}$$

In this equation, "λ_{obs}" is the observed wavelength of an emission or absorption line (i.e., what you measure from the spectrum), "λ_{rest}" is the "rest" wavelength of a line (i.e., what you would measure if the object were not moving) and "z" is called the redshift of the object (here we will only discuss redshifts, in which case the value of $z > 0$). It is important to note that a redshifted spectrum is not only shifted but also stretched. The separation between any two lines therefore increases with redshift. However, the ratio of the wavelengths of the two lines does not change; that is, if you take the ratio of the above equation for two lines at the same redshift (e.g., lines "A" and "B"), the (1+z) redshift term cancels out, giving:

$$\frac{\lambda^a_{obs}}{\lambda^b_{obs}} = \frac{\lambda^a_{rest}}{\lambda^b_{rest}}$$

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:

$$v = H_0 d$$

Where "v" is the object's velocity away from us, "d" is its distance from us and "H_0" is the "Hubble constant". As you can see H_0 gives the relation between velocity and distance. The value of H_0 is not yet precisely known but it is close to 75 km s^{-1} Mpc^{-1} (said, "kilometers per second per megaparsec"). One of the key missions of the Hubble Space Telescope is to accurately determine the value of H_0.

Note that Hubble's Law applies to only moderately distant galaxies. It does not apply to stars and other objects within the Milky Way, nor to very nearby galaxies because gravity counteracts the effects of the expansion of the Universe. In fact, the gravitational pull between the Milky Way and the Andromeda Galaxy (M31) is actually causing M31 to move towards us! Importantly, Hubble's Law is not accurate for distant galaxies either. For the very distant objects we are studying in this project we must use a more complex equation than Hubble's Law which takes into account that the Universe has changed over time. The objects we are studying are as many as billions of light years away, meaning that it has taken billions of years for their light to reach us. During that time the Universe has changed, and we must account for that. How that is done will be described in the next section.

Nomenclature:

Astronomers use the Greek letter "λ" (pronounced "lambda") as a symbol for wavelength.

Nomenclature:

Rest wavelength refers to the wavelength of light the object would emit if it were not moving relative to the observer (i.e., "at rest").

Nomenclature:

A megaparsec (Mpc) is one million parsecs; and a parsec is 3.26 light years. A light year is how far light will travel in one year, which is 9.5 x 10^{12} kilometers.

Procedure

Discovering emission lines

The first goal for each object is to look for emission lines in the spectrum. If found, these will be used to determine the redshift and distance to the object. It will also help us look for other important spectral features, such as absorption lines and the "Calcium break." Finally, this information can be used to identify the type of object. *The best way to learn how to determine redshifts is to first follow the example provided*. Once you feel comfortable determining redshifts you may start the research projects.

To search for emission lines in the spectrum do the following:

Use the examine tool:

• Use **File/Open...** (**⌘-O**) or **File/Import From Text File...** to load the spectrum to be studied.

• Note that the spectra have bumps and wiggles. Most of these are due to "noise." These objects are very faint (about 1 million times fainter that what you can see with your naked eye). We must therefore use large telescopes with very sensitive electronic cameras. Nontheless, there are still inaccuracies in measuring the shape of an object's spectrum. Because spectrographs are not as sensitive to blue light, the spectra are noisier at wavelengths less than ~4500Å and longer than ~7500Å.

• Activate the examine tool (**Analyze/Examine** or **⌘-E**). The information box gives the wavelength (the X value) and flux density per unit wavelength (the Y value) of the datapoint above or below the cursor. Move the cursor to a possible emission line and record its wavelength (the X value). Measure the center, which is not necessarily the peak of the emission line. Noise in the spectrum can distort the shape of the emission line, such that the peak is not necessarily the most accurate measure of a line's wavelength.

• Measure the wavelengths of as many emission lines as you can find and write them down. Especially in the case of the BL Lac objects, some or all of the emission lines may be weak and it may not be clear whether or not some of them are real. Mark those lines which you are uncertain to be real as "tentative."

Determining the redshift

Now you will try to determine the redshift of the object.

- Pick the two strongest lines you measured. Take the ratio of their measured wavelengths by dividing the longer wavelength by the shorter (so that the ratio is greater than one). For example, the rest wavelength of C IV is 1549Å and the rest wavelength of Hβ is 4861Å, the ratio of these two lines is equal to 4861/1549 which is 3.14. Since the ratio of any two lines does not change with redshift we can use the ratio to identify the lines.

- Try to match this ratio to the emission-line ratios given in the table of line ratios below. The table only includes ratios for the strong lines, so other ratios are possible. You may wish to create a large table of emission line ratios that includes the weak lines as well. If you find a ratio which closely matches, you can identify the lines; e.g., if your ratio is 1.49 you may have found C III] and Mg II, the ratio which most closely matches. If no ratio is close, it is possible that one of the lines you chose is not real. If possible, choose one or two new lines and try again.

Emission Line Ratios

	Ly α	C IV	C III]	Mg II	Hβ	[O III]	Hα
Ly α							
C IV	1.28						
C III]	1.57	1.23					
Mg II	2.31	1.81	1.47				
Hβ	4.01	3.14	2.55	1.74			
[O III]	4.13	3.23	2.62	1.79	1.03		
Hα	5.41	4.24	3.44	2.35	1.35	1.31	

- Once you find a close ratio, tentatively identify the lines and determine tentative redshifts for both lines by using the redshift equation:

$$1 + z = \frac{\lambda_{obs}}{\lambda_{rest}}$$

  Average the redshifts for both lines and adopt this as the tentative redshift for the object.

- Try to confirm this redshift by looking for other emission lines at their expected positions. If you do find additional emission lines, this is a good confirmation that your tentative redshift is correct. However, if you do not find any other emission lines at their expected position it does not necessarily rule it out. Not all emission lines appear in all objects.

- Alternatively, try to match other possible emission lines in the spectrum with those listed. Note that these lists are not 100% complete, so it is possible (but unlikely) that you will discover emission lines that are not listed. If you see several emission lines which you believe are real but do not match any lines at your tentative redshift, you should probably try to determine a new tentative redshift.

- Beware of any emission lines which fall within the telluric absorption bands. The telluric bands are very broad absorption lines that are produced by oxygen and water vapor in the Earth's atmosphere. Because they are produced by our atmosphere, the bands will be in the same position in every spectrum (i.e., they are not redshifted).

Measuring the width of emission lines

As you have read earlier, some emission lines are considered to be "broad" while others are "narrow." Astronomers determine the width of an emission lines by measuring what is known as its "full-width half-maximum" (FWHM). This the width of the emission line at the halfway point between the base of the line (i.e., at the level of the continuum) and the peak of the emission line. In some cases the base of the emission line can be difficult to estimate because the continuum is not flat. The sidebar on the right illustrates how to measure the FWHM of

Strong emission lines commonly seen in AGN (Å):

Ly α	1213
C IV	1549
C III]	1909
Mg II	2796,2803*
Hβ	4861
[O III]	4959,5007**
Hα	6563

*Usually these two lines are too close to see separately. They blend into one line at 2798Å.

**Usually blended into one line at 5000Å.

Weak emission lines also common in AGN:

Ly β	1026
Si IV	1400
C II]	2326
[O III]	3133
[Ne V] 3426	
[O II]	3727
[Ne III]3869	
Hδ	4102
Hγ	4340
[O I]	6300
[N II]	6584
[S II]	6717,6731

Galactic absorption lines:
(Strong lines are shown in bold)

Mg II	2796,2803
Ca II	3933,3968
G-band	4304
Mg "b"	5175
Na "D"	5893

Telluric absorption bands:

5860-5990
6270-6370
6850-7400
7570-7700

an emission line. While somewhat arbitrary, lines that have FWHM > 25Å are considered to be broad, while lines with FWHM < 25Å are narrow. Broad lines usually only occur in quasars.

Discovering absorption lines

Often galaxian absorption lines can be found in the spectrum. In the case of quasars, BL Lacs and other AGN, the AGN can be much brighter than the rest of the galaxy, so the galaxy's absorption lines are usually "washed out" and will most likely be weak, if they can be detected at all. Searching for absorption lines in AGN is similar to normal and starburst galaxies, but somewhat more difficult because the absorption lines can be caused by either the AGN host galaxy or by an intervening galaxy. Thus absorption lines can occur at any redshift up to and including the object's emission line redshift (if known). Multiple absorption systems at different redshifts are possible, but resist the urge to identify every bump and wiggle in the spectrum as an absorption line!

- If you have determined a redshift from emission lines, look for absorption lines at this redshift. You may also find absorption lines at a lower redshift due to an intervening galaxy. In particular, look for the strong Mg II and Ca II doublets, which consist of two closely spaced absorption lines. They can be differentiated by their line ratios (1.0025 for Mg II and 1.0089 for Ca II).
- If you find a potential absorption line doublet, try to find other absorption (and emission) lines at the same redshift to help confirm this redshift.
- Like emission lines, be wary of any absorption lines which fall within the telluric bands.

Determining velocity, distance and luminosity

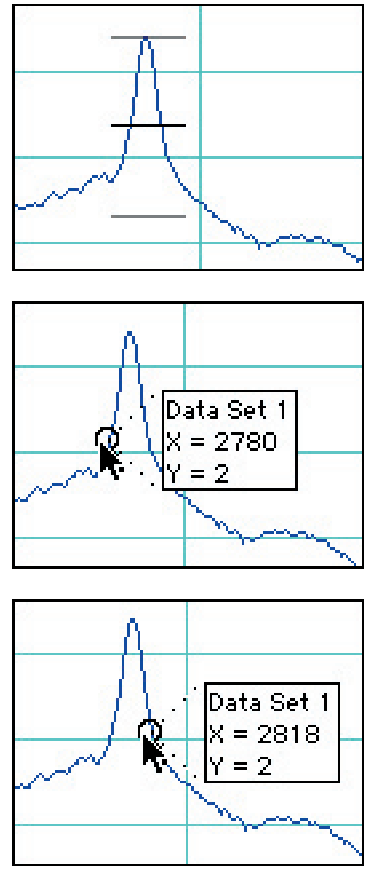
Once an object's redshift has been measured you can use it to determine an object's velocity, distance and luminosity. If an object is relatively nearby, its velocity can be approximated by the equation: v = cz, where "c" is the speed of light ($c = 3.0 \times 10^5$ km s^{-1}). But this equation fails for more distant objects. For example, if an object has a redshift greater than one, this equation incorrectly calculates that the object is moving faster than the speed of light! The correct equation for determining velocities is:

$$v = c\,\frac{(1+z)^2 - 1}{(1+z)^2 + 1}$$

Note that this equation is accurate for all objects, nearby and distant, and you should use this equation to determine the velocity of the objects you study in this project. As discussed earlier, Hubble's Law can be used to determine distance for relatively nearby galaxies only. For the distant objects we are studying, the relationship between velocity and redshift is more complex. Which equation we use depends upon our assumptions about the nature of the Universe, which are not known for certain. However, in a simple model of the Universe (known as the "empty Universe" model), an object's distance is related to its redshift by the equation:

$$d = \frac{cz}{H_0}\,\frac{1+\frac{1}{2}z}{1+z}$$

As mentioned before the value of Hubble's constant (H_0) is known to be approxi-



The top panel shows a typical emission line. The top and bottom horizontal (gray) lines mark the base and the peak of the line. The halfway point is marked with a black line.

Use the examine tool (using **Analyze/Examine** or ⌘-E) to measure the FWHM of the emission line at the halfway point. In the example above, FWHM = 2818Å - 2780Å = 38Å. It is therefore considered to be broad.

mately 75 km s^{-1} Mpc^{-1}. Since it takes light so long to travel to us from these objects we are in effect looking back in time. Because they are so luminous, AGN are some of the most distant objects in the Universe that we can study; and by observing them 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.

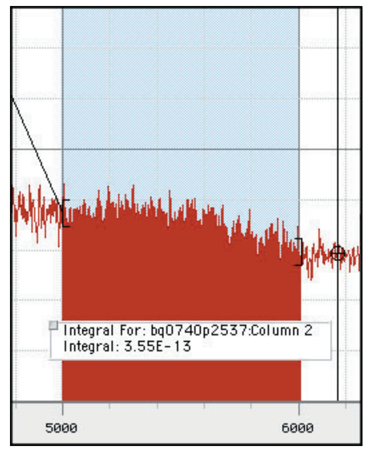
When we observe an object with a telescope we measure its "flux," which is the amount of energy per second that we see from the object. However, what we really want to know is an object's "luminosity," which is the total amount of light it emits per second. Astronomers are interested in determining an object's luminosity because it tells us how much energy it is producing. This in turn is used to understand the true nature of the object. In the case of AGN, we know that they are extremely energetic because they are so luminous. This was one of the first clues that active galaxies must have another source of energy. Stars alone could not produce all the energy seen.

According to the inverse-square law, flux and luminosity are related by the square of the distance to the object. For example, if two objects have the same luminosity but the first object is twice as far away as the second, the flux of the first object will be one-quarter that of the second. The relationship between flux and luminosity for very distant objects is given by:

$$L = 4\pi f d^2 (1+z)^2$$

In this equation "L" is the object's luminosity, "f" is the measured flux and "d" is the distance to the object calculated above. Note that this equation is slightly different than the normal inverse-square law. There is an additional $(1+z)^2$ term which takes into account that the object is moving. Since it is moving away from us, the rate at which the photons (particles of light) arrive slows down, making it seem fainter. Further, when the photons do arrive they are redshifted, and so appear to have less energy. The additional $(1+z)^2$ term corrects for these two effects. Before we can determine an object's luminosity we must first determine its flux. This is a little complicated, so first let us discuss a few important concepts. Flux is measured in units of energy per unit of area per unit of time per unit of wavelength. Astronomers like to use units of erg cm^{-2} s^{-1}Å^{-1}(1 erg = 10^{-7} Joule). The luminosity is the total energy emitted from an object and is measured in units of erg s^{-1}. In general this refers to the total amount of energy produced, called the "bolometric luminosity," which includes the entire electromagnetic spectrum (radio waves through gamma rays). However, here we are only looking at optical light, which is only a tiny fraction of the total electromagnetic spectrum. Thus when calculating a flux and calculating a luminosity you must be sure to specify what portion of the spectrum you are measuring. You are free to choose whatever range you like. Over the years astronomers have divided the optical spectrum in different ways. A common approach is to divide the optical region into the following bands: B-band (4000-5000Å), V-band (5000-6000Å), R-band (6000-7000Å) and I-band (7000-9000Å). As you might have guessed, B-band is the blue portion of the spectrum and R-band is the red. V-band is the green portion ("V" stands for "visible") and I-band is the near-infrared portion of the spectrum.

To measure the flux over a band of the spectrum do the following:

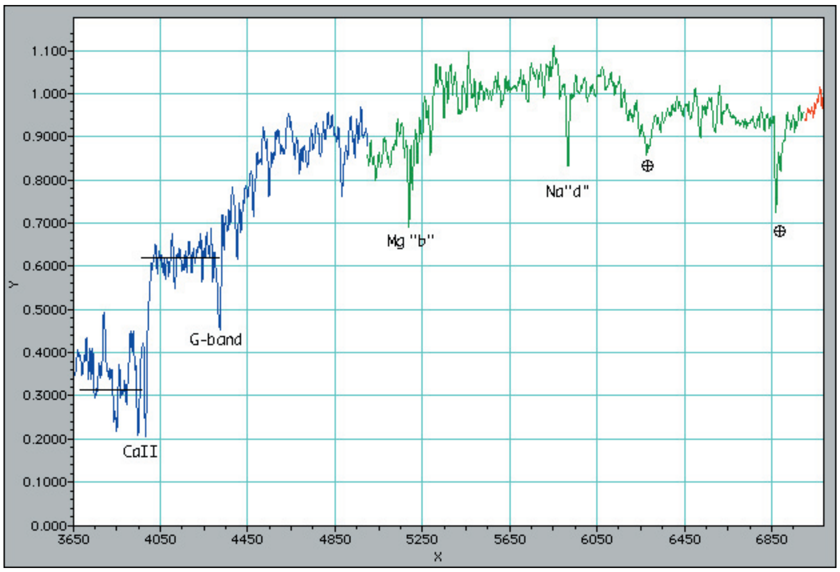


The integrate tool (**Analyze/ Integral**) is used to sum the flux over the selected range of the spectrum. The total flux is listed in the upper left corner (shown above). In this example the total flux is 3.55 x 10^{-13} erg cm^{-2} s^{-1} from 4995Å to 6012Å.

Use the integrate tool:

- Load the spectrum to be studied.
- Use the cursor to select (i.e., draw a rectangle around) the region of the spectrum over which you want to measure the flux. Activate the integrate tool (**Analyze/Integrate** or ⌘-I). At the bottom of the plot it will list the spectral region you have selected (the start and finish values) and the flux over that region for each dataset (see figure to the right). Add the values for each dataset to get the total flux over that region. (See the example for PKS 2029+121).

Now you can determine the object's intrinsic luminosity. Since the flux was calculated in units of erg cm^{-2} s^{-1} be sure to convert the object's distance from megaparsecs into centimeters.



Measuring the Calcium Break

The spectra of some objects have a Calcium break, which is a drop in the continuum flux level blueward of the Ca II absorption line doublet often seen at a rest wavelength of ~4000Å.

The spectrum of the elliptical galaxy NGC 3245 is shown above, with horizontal black lines marking the average continuum flux level on both sides of the CaII break. The *Calcium break strength* is defined by the following equation:

$$\text{Break} = \frac{F_r - F_b}{F_r}$$

Where F_b is the mean continuum flux level blueward of the CaII absorption lines, from 3750Å to 3950Å, and F_r is the mean flux level just redward, from 4050Å to 4250Å in the object's rest frame. In practice you must shift the wavelength ranges you measure to take into account the redshift of the object. In other words, F_b is measured from (1+z)(3750Å) to (1+z)(3950Å) and F_r is measured from (1+z)(4050Å) to (1+z)(4250Å).

To measure F_b and F_r do the following:

Use the integrate tool:

- Load the spectrum to be studied.
- To measure F_b, use the cursor to select the region of the spectrum from (1+z)(3750Å) to (1+z)(3950Å).
- Select **Statistics** from the **Analyze** menu to determine the mean value of the data over the selected region.
- Do the same to determine F_r from (1+z)(4050Å) to (1+z)(4250Å).

Once you have determined F_b and F_r you can determine the calcium break strength.

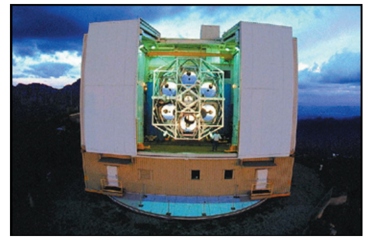
AGN Spectroscopy

Nature's Most Powerful "Monsters"

An Example: The Spectrum of BQ 0740+2537

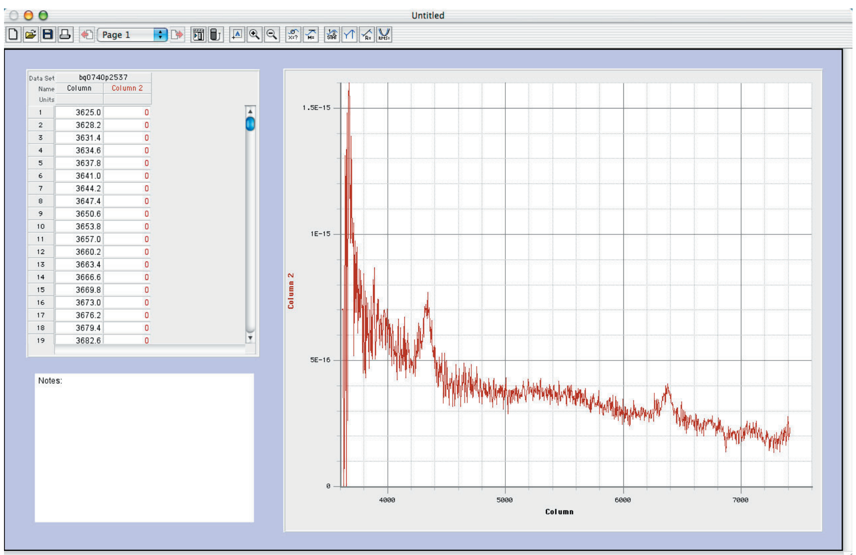
Description of the spectrum

BQ 0740+2537 is a quasar that was discovered by the FIRST Bright Quasar Survey. This spectrum was obtained with the Multiple Mirror Telescope, a 6.5-meter telescope on Mt. Hopkins, Arizona.



The Multiple Mirror Telescope on Mt. Hopkins, Arizona is jointly operated by the Smithsonian Institution and the University of Arizona.

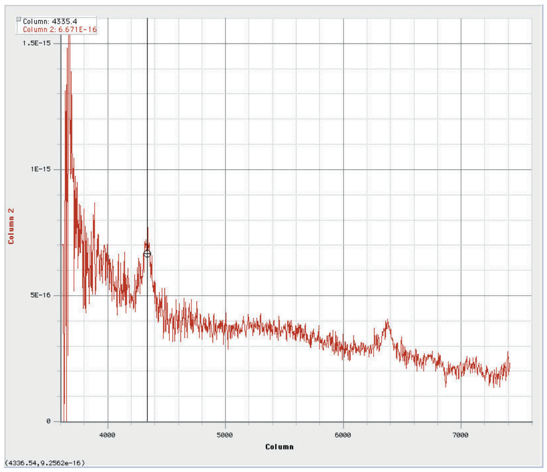
Use **File/Import From Text File...** to load the spectrum "bq0740p2537.txt". Select the graph by clicking on it, and then select **Options/Graph Options...** to turn off the point protectors and **Data/Column Options** to set the displayed precision to 4 for column 2. The graph should look like this:



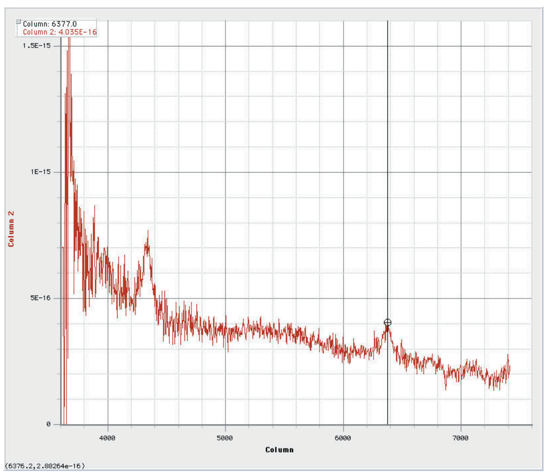
You'll notice that the spectrum is not smooth. It has peaks and valleys. Most of the little bumps and wiggles are due to noise, an intrinsic uncertainty in the measurement of the flux at that wavelength. However, some of these peaks and valleys are emission and absorption lines, respectively. While it is not always easy to tell, the large peaks and valleys are most likely real and not just merely noise.

Measuring the wavelengths of emission lines

In the spectrum of BQ 0740+2537 you will notice that there are two broad humps that are likely real emission lines. To identify the position of the emission lines, activate the examine tool (**Analyze/Examine** or **⌘-E**). A vertical line and a text box in the upper left corner will appear, which shows the wavelength (the X value) and flux per unit wavelength (the Y value) of the datapoint in the same column as the cursor. Use the magnifying glass to measure the center, not the peak of the emission line. Note that noise in the spectrum can distort the shape wavelength. Using the examine tool, the measured wavelengths of the line on the left is roughly 4334.5Å.



Now measure the other broad emission line in the red part of the spectrum. The measured wavelengths of this line is 6377.0Å.



You can now determine their ratio by dividing the longer wavelength by the shorter (so that your ratio is greater than one). For two lines measured above the ratio is 6377.0 / 4334.5 = 1.471. Looking at the table on p. 20, this ratio is close to the ratio of 1.47, which suggests that these are the MgII and C III] emission lines. Since CIII] has an intrinsic rest wavelength that is shorter than MgII, the line on the left must be CIII] and the line on the right must be MgII.

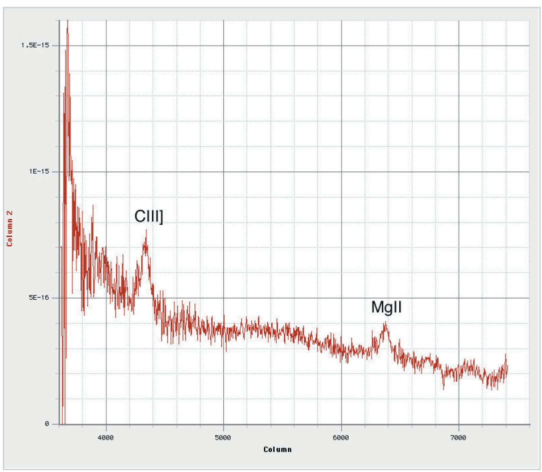
Determining a redshift

We can now determine a tentative redshift for both lines by using the formula:

$$1 + z = \frac{\lambda_{obs}}{\lambda_{rest}}$$

As defined before "z" is the redshift, λ_{obs} is the observed wavelength of a line and λ_{rest} is the "rest" wavelength (i.e., if the object was not moving). For the emission line tentatively identified as MgII, which has a rest wavelength of λ_{rest} = 2798Å, the calculated redshift is z = 1.27912. For C III], which has a rest wavelength of λ_{rest} = 1909Å, the redshift is z = 1.27056. Although not identical these redshifts are close to each other. If these were not close we would suspect that either the line ratio we chose is wrong or that we made in error in calculating the redshift. The average of the two is z = 1.275, which we will adopt as the redshift.

Finding these two relatively strong emission lines (for this object, at least) is solid evidence that this is the correct redshift; however it is not always clear, especially if we don't know if one or both of the lines are real. Thus it helps to confirm a tentative redshift by identifying additional lines in the spectrum. One approach is to look for other strong emission lines at your tentative redshift. For example, in this object, the C IV line is a good line to look for because is a strong emission line often found in AGN spectra whose wavelength is bluer, but relatively close to C III]. If the tentative redshift of z = 1.275 is correct, we would find it at 3523Å [1549Å x (1+1.275) = 3523Å]. Unfortunately this is too far in the blue and off the left side of our plot. Similarly, the Hβ emission line would be too far off of the right side of the plot. Another approach is to look for other possible emission lines in the spectrum and see if their positions match known emission lines. Unfortunately no other possible lines are seen in this example. But since we detect two strong emission lines we conclude that this redshift is well established.



Determining velocity, distance and luminosity

Now we can velocity of BQ 0740+2537 via the equation:

$$v = c\,\frac{(1+z)^2 - 1}{(1+z)^2 + 1}$$

Recall that "c" is the speed of light (3.0 x 10^5 km s^{-1}). From the above equation we calculate that BQ 0740+2537 is moving away from us at 2.03 x 10^5 km s^{-1}. That's 68% the speed of light! The distance can now be determined by the equation:

$$d = \frac{cz}{H_0}\,\frac{1+\frac{1}{2}z}{1+z}$$

Assuming a value of Hubble's constant (H_0) of 75 km s^{-1} Mpc^{-1}, the distance to BQ 0740+2537 is 3,670 Mpc, or about 12 billion light years. Thus we are seeing it now as it was 12 billion years ago.

Now let's calculate the flux for BQ 0740+2537 for the V-band (5000-6000Å). Using the integrate tool (**Analyze/Integrate** or ⌘-I) we measure the flux over this region to be 3.55 x 10^{-13} erg cm^{-2} s^{-1}. The relationship between flux and luminosity for very distant objects is given by:

$$L = 4\pi f d^2 (1 + z)^2$$

Since we calculated the flux in erg cm^{-2} s^{-1} we must convert the distance we calculated earlier into centimeters, which is 1.14 x 10^{28} cm. Doing so we calculate that the V-band luminosity for BQ 0740+2537 is 2.98 x 10^{45} erg s^{-1}. This is about 10^{13} (i.e., 10 trillion) times brighter than our sun!

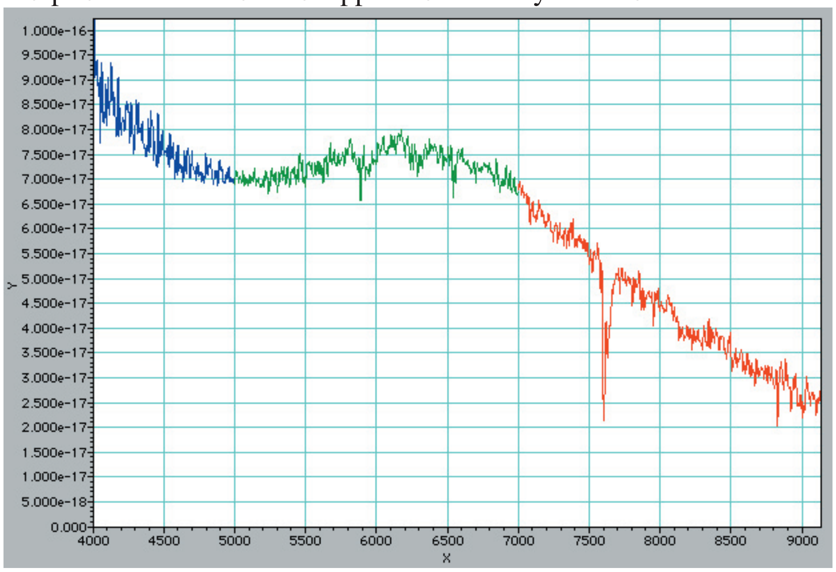
Another Example: The Spectrum of S5 0454+844

Description of the spectrum

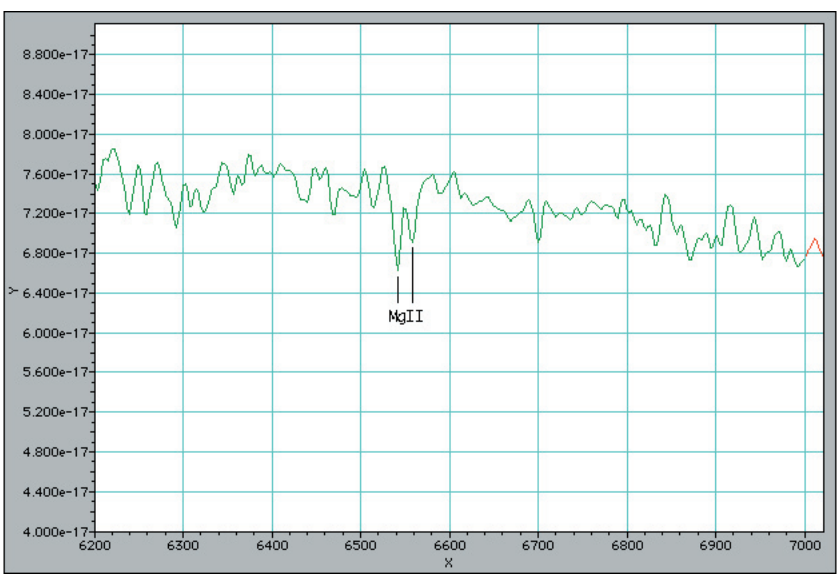
S5 0454+844 is a BL Lac object in the Strong Source #5 catalog of radio sources. This spectrum was obtained with the 2.1-meter telescope on Kitt Peak. *(Note: This spectrum is currently in GA 2 format.)*

Measuring wavelengths of emission and absorption lines

The spectrum of S5 0454+844 (shown below) is smooth except for several sets of absorption lines. It does not appear to have any emission lines.



Nearly all of the absorption lines are telluric lines, which are due to the Earth's atmosphere. However, there is a closely-spaced pair of absorption lines at 6542Å and 6559Å (shown below). The ratio of these two lines is 1.0026, indicating that this is the Mg II doublet. It is determined to be at a redshift of z = 1.340.

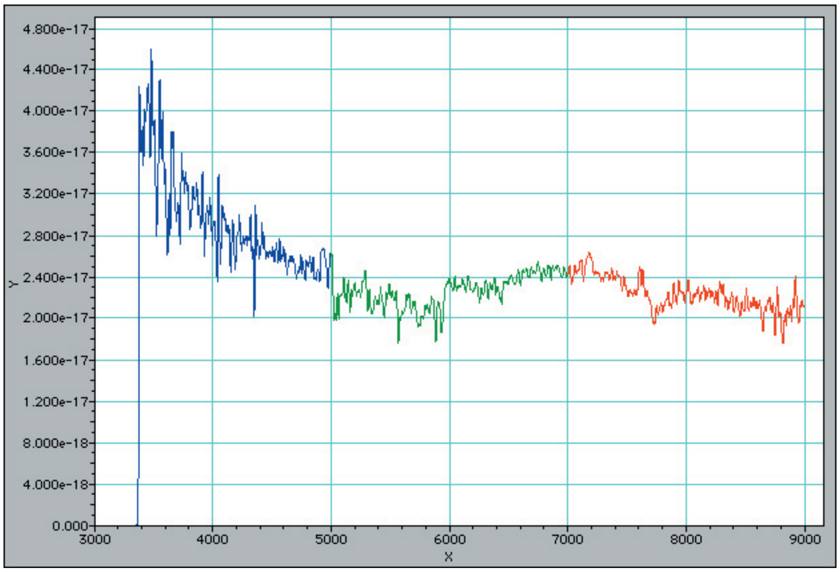


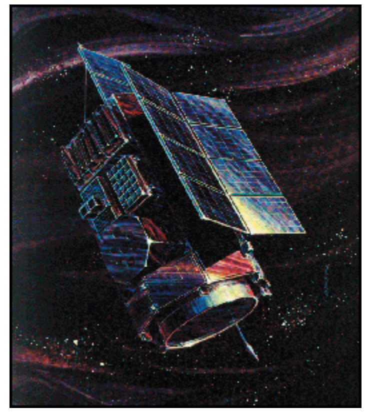
As discussed before Mg II is a very strong galactic absorption line, thus it is not surprising that we do not see any other absorption features (they are probably too weak to detect). Since we did not discover any emission lines in this object we identify it as a BL Lac object. We do not know whether or not the Mg II absorption lines belong to the BL Lac's host galaxy or to an intervening galaxy. Thus the measured redshift of z = 1.340 is only a lower limit to the redshift.

Yet Another Example: The Spectrum of MS 1408+59

Description of the spectrum

The prior two examples are of objects at unusually high redshift. The last example is MS 1408+59, a BL Lac object discoverd by the Einstein X-ray satellite. Its redshift is more typical of BL Lacs. Its spectrum, shown below, was obtained with the Palomar 5-meter telescope. *(Note: This spectrum is currently in GA 2 format.)*





The HEAO-2 X-ray observatory. After launch it was renamed in honor of Albert Einstein. It was the first X-ray imaging telescope to be put into space. It operated from November 1978 to April 1981.

Measuring wavelengths of emission and absorption lines

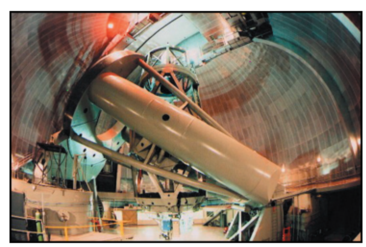
The spectrum of MS 1408+49 does not show any emission lines, however there are several absorption lines. First, we identified an absorption doublet at 5857Å and 5934Å as Ca II at z = 0.496 because its line ratio is 1.0080. We also see the "Ca II break", where the continuum flux drops slightly blueward of the Ca II absorption doublet. Looking for other galactic absorption lines at z = 0.496 we find G-band at 6442Å, Mg "b" at 7733Å and Na "D" at 8818Å (see below).

Measuring the calcium break strength

To determine the calcium break strength we use the equation:

$$\text{Break} = \frac{F_r - F_b}{F_r}$$

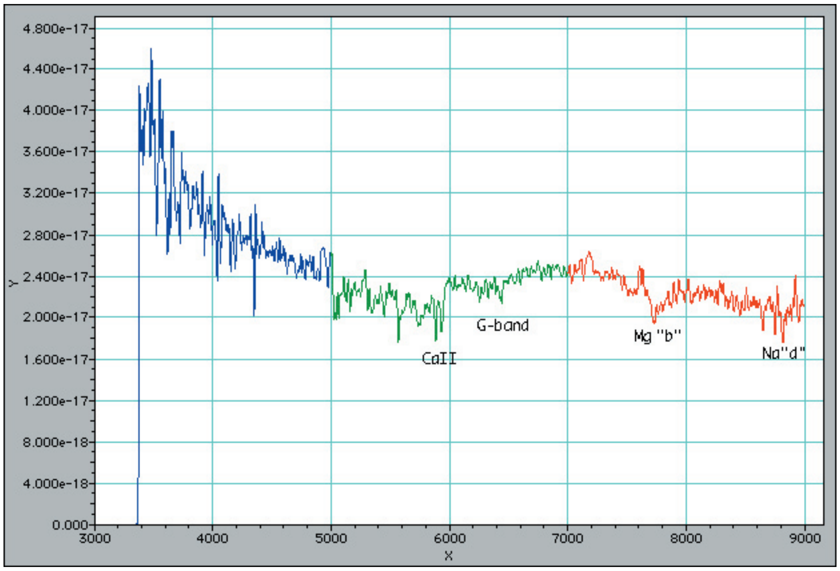
F_b is the continuum flux level blueward of the CaII absorption lines, from 3750Å to 3950Å, and F_r is the flux just redward, from 4050Å to 4250Å in the object's rest frame. In practice you must shift the wavelength ranges you measure to take into account the redshift of the object. In this example the object is at a redshift of z = 0.496, so F_b should be measured from 5610Å to 5909Å and F_r is measured from 6059Å to 6358Å.



The Palomar 5-meter (200-inch) telescope is owned and operated by the California Institute of Technology.

On a PC, use the cursor to select the region of the spectrum from 5610Å to 5909Å. Select **Statistics** from the **Analyze** menu to determine the mean value, which is F_b. Follow the same steps to determine F_r from 6059Å to 6358Å.

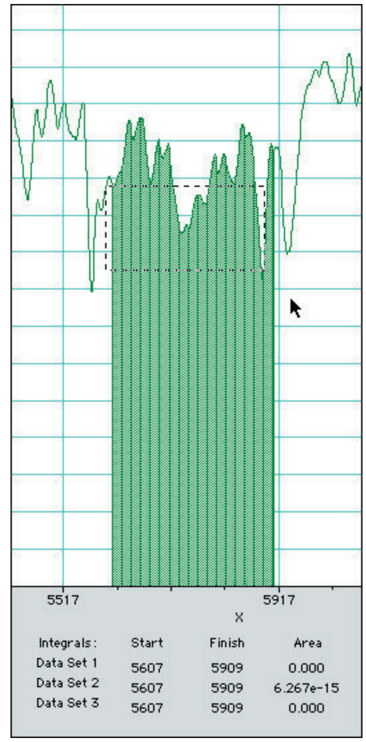
On a Macintosh, the total flux densities over the F_b and F_r regions of the spectrum are determined by integrating over these wavelength ranges and dividing by the size of the wavelength range. The figures in the sidebar illustrate how to

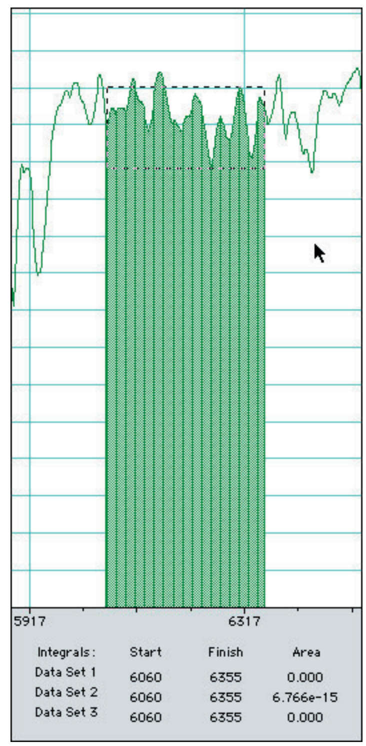


determine the total flux denisity for each region. The next step is to determine the wavelength size of each region. For F_b, it is 5909Å - 5610Å = 299Å. For F_r the size of the wavelength range is 6358Å - 6059Å, which is also 299Å. Notice that both regions are the same size. In fact, the size of both regions equals (1+z)(200Å).

F_b and F_r are the average flux values over these regions, which are determined by dividing the total flux density over a region by the wavelength size of that region. From the values determined above, $F_b = 6.267 \times 10^{-15}$ erg cm^{-2} s^{-1} / 299Å = 2.096×10^{-17} erg cm^{-2} s^{-1} Å^{-1}. Similiarly, $F_r = 2.263 \times 10^{-17}$ erg cm^{-2} s^{-1} Å^{-1}. These values should agree with the mean values on the PC. Looking at the plot above these values look correct.

Putting these values into the equation above we determine the break strength for this object is 0.074, or 7.4%.





The integrate tool (**Analyze/ Examine** or ⌘-I) is used to sum the flux over the selected range of the spectrum. The total flux for F_b (top) is 6.267×10^{-15} erg cm^{-2} s^{-1} from 5607Å to 5909Å. The total flux for F_r (bottom) is 6.766×10^{-15} erg cm^{-2} s^{-1} from 6060Å to 6355Å.

AGN Spectroscopy

Name(s) ______________________ Class ____________________

______________________ Date ____________________

Teacher Leaders in Research Based Science Education

Lab Notebook

Do the following for each object you study:

- Search for emission lines in the spectrum. Identify as many lines as you can.
- Determine a redshift for the object from any emission lines you have discovered.
- Determine the FWHM of the emission lines. Do you consider any of these lines to be broad?
- Search for absorption lines in the spectrum and try to determine their redshift(s). Are they at the same redshift as the emission lines?
- If you found the CaII absorption line doublet, estimate the break strength.
- How fast is it moving away from us? What fraction of the speed of light is this?
- Find the distance to the object (in Mpc).
- At this distance how long would it take light from this object to travel to us?
- Measure the flux in one or more of the B, V, R and I bands.
- Calculate the luminosity for each spectral band you measure.
- Compare its luminosity to the elliptical galaxy NGC 3245.

For all of the objects you study:

- Which class, or classes, of object is the most common in the survey?
- Which objects are the closest, and which are the furthest away?