The Sloan Digital Sky Survey

Objective

Characterize stars, galaxies and QSOs using photographs and spectra.

Introduction

The Sloan Digital Sky Survey (SDSS) is one of the most ambitious projects of its kind ever undertaken. When completed, it will cover half of the northern sky, with positions and magnitudes for each object, together with spectra for over a million stars, galaxies and quasi-stellar objects (QSOs, also called quasars). As of this writing, there have been three major data releases, available on the internet. You will be using data products from the first release that have been processed into convenient form.

The main instrument used by the SDSS is a 2.5 m telescope. It has an unusually wide field of three degrees. Light from the telescope is split into five wavelength regions and then directed to large charge-coupled devices (CCDs). Thus, a large number of objects are imaged simultaneously in five bands. Five magnitudes for each object are measured, which are listed below. Wavelengths are in Ångstrom (Å) units, rather than the nanometer (nm), (1 nm = 10 Å). The limiting magnitudes represent the faintest objects that are imaged using a standard exposure time.

m	band	center wave length (Å)	limiting magnitude
m_u	ultra violet	3551	22.0
m_g	green	4686	22.2
m_r	red	6165	22.2
m_i	infrared	7481	21.3
m_z	infrared	8931	20.5

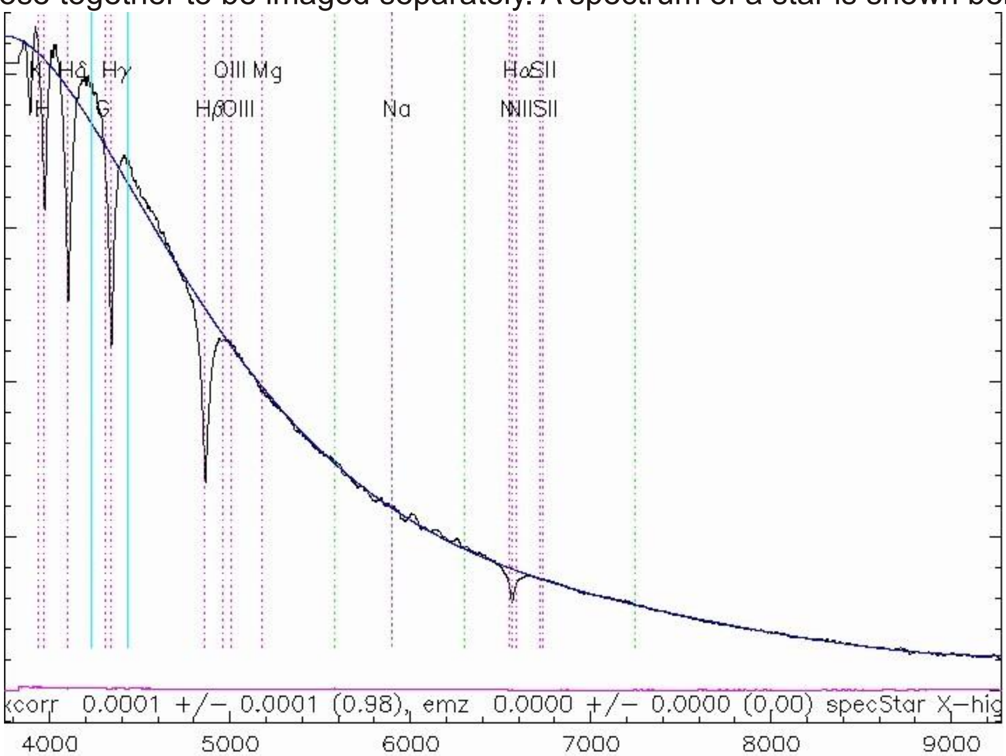
The setup for spectroscopy uses an aluminum plate with 640 precisely drilled holes, each hole corresponding to a selected position in the sky. Each three-degree field of view requires its own plate. Each hole is fitted with a glass fiber that conducts light from an object to the spectrometer. Thus, 640 spectra are obtained simultaneously. Typically, 32 fibers are aimed at blank sky for calibration purposes.

What We See

What we see is not quite the same thing as what we would see if we traveled to an astronomical object in a space ship. Starting from the objects themselves, information initially in the form of light waves winds up on our computer screens. That information is modified and degraded in many steps along the way. Understanding of each step is essential for the difficult process of going backwards from what we see to what is really out there. Here, I will start with the objects and wind up with the data products from the SDSS that you will be using.

Stars

While the SDSS emphasis is on galaxies and QSO's, a lot of images and spectra are of individual stars. Bright stars are avoided, so these stars will be either dwarfs or very far away, though still within our galaxy. The star's spectrum reveals a star's composition, temperature and speed along our line of sight. These speeds will be comparatively small, since a star with a very high velocity would probably have left the galaxy long ago. We can expect that a large fraction of these stars is actually double or even multiple, and will be too close together to be imaged separately. A spectrum of a star is shown below.

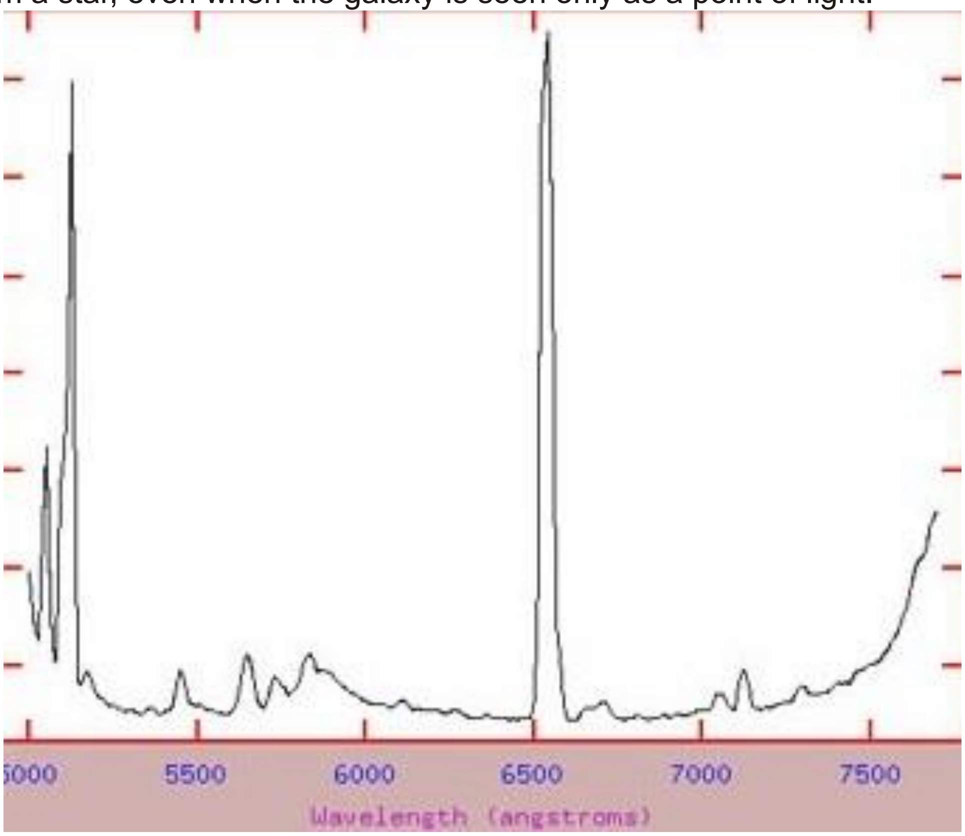


Galaxies

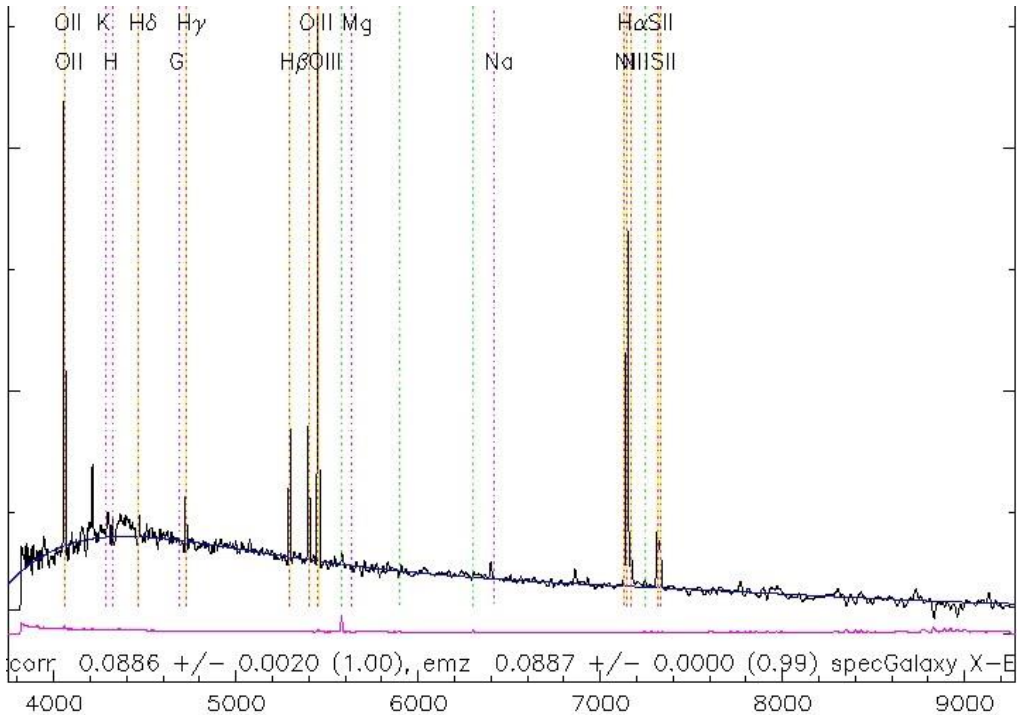
Galaxies are large collections of stars, much like our own galaxy, the Milky Way. While the Hubble Deep Field images taught us that the early galaxies were not much like our own, the more limited "look-back time" available here does not include objects from the early universe. A faint galaxy is too far away to image the individual stars and nebulae, so we see a diffuse glow, much like we see the Milky Way with the naked eye.

Galactic spectra are a hodgepodge of contributions from all the individual stars and nebulae. Compositions are found to be the same as in our own neighborhood, an old result. We can obtain a Doppler shift and measure the speed that the galaxy is moving away from us.

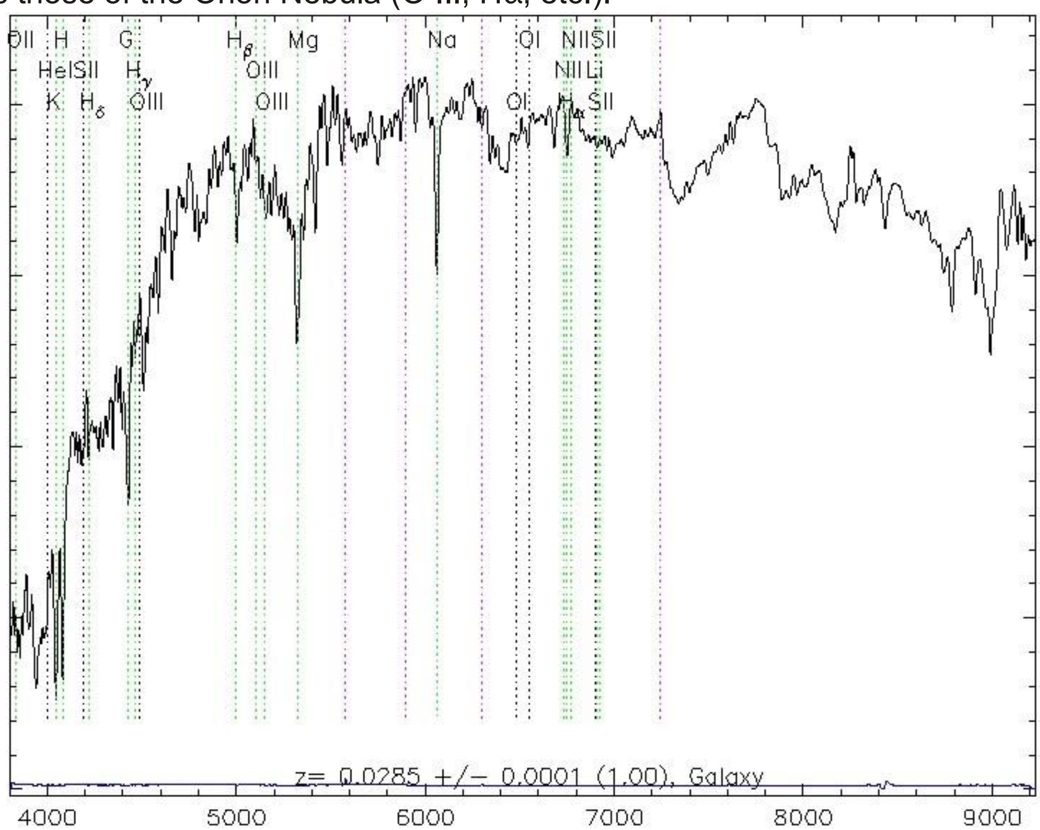
Stars show spectrum lines in absorption; gaseous nebulae show spectrum lines in emission. If a galaxy contains a lot of gas, hydrogen spectrum lines are bright; otherwise, hydrogen lines are dark. A spectrum line that is only seen in nebulae, such as the “forbidden” green spectrum lines prominent in the Orion nebula, are not canceled by absorption lines in stars, and we see them in emission even when hydrogen lines are seen in absorption. These emission features in the spectrum enable us to distinguish a galaxy from a star, even when the galaxy is seen only as a point of light.



Spectrum of the Orion nebula (M42). The strong emission lines at 4959 Å and 5007 Å are the “forbidden” lines of oxygen ionized twice (O^{++}, or OIII). The emission line at 6563 Å is Hα. The wavelength scale is off a bit.

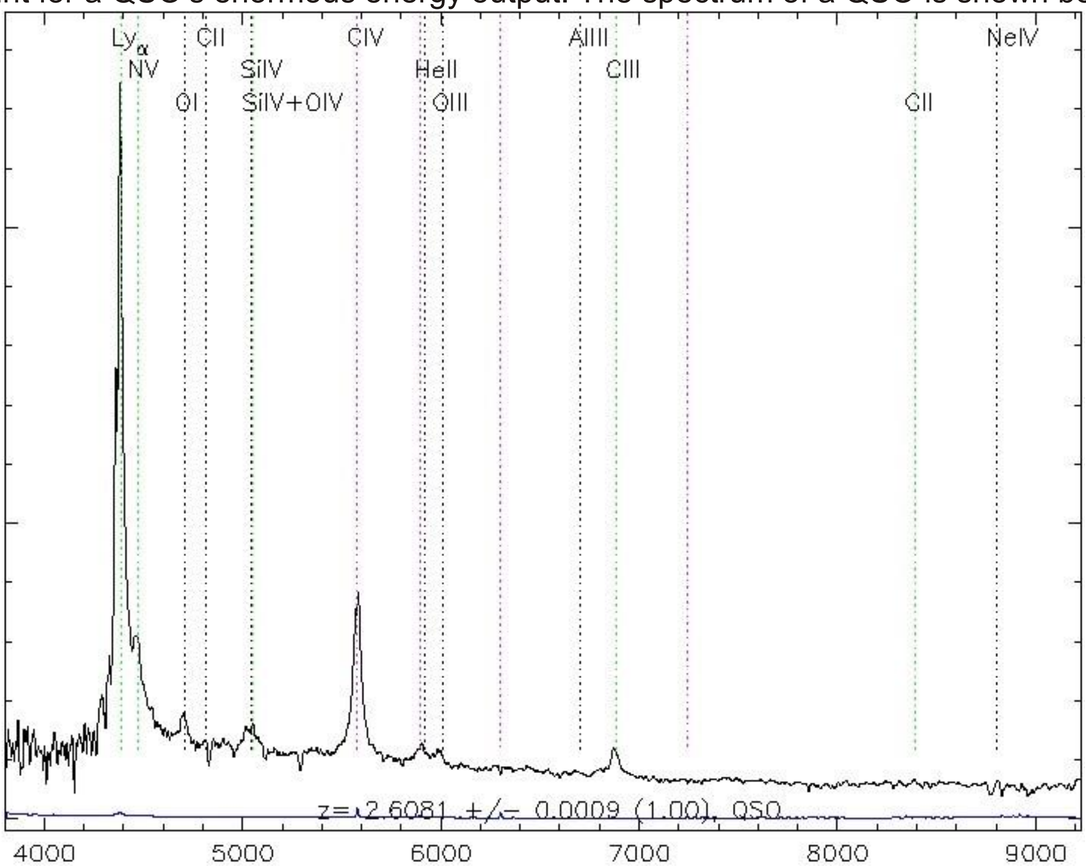


This is a spectrum of a galaxy that has a lot of gas. We see the same strong emission lines as those of the Orion Nebula (O III, Hα, etc.).



This is a spectrum of a galaxy that has only a little gas. Stars dominate, and the hydrogen lines now appear in absorption. The O III lines appear in emission, but are weak.
QSO's

Quasi-stellar objects are the very bright nuclei of galaxies that are extremely far away. Their appearance is star-like, hence the name. The galaxies themselves are only seen in images that are extremely deep, as faint as m~28. The Doppler shifts are very large, and are due to the expansion of the universe. We are looking back to an early era of the universe's history. The currently prevalent theory of QSO's calls for a large infall of matter into a central galactic black hole. Such a drastic theory is required in order to account for a QSO's enormous energy output. The spectrum of a QSO is shown below.



The strong emission line at 4384 Å labeled Lyα (Ly stands for Lyman) is the hydrogen line corresponding to the transition n=2 to n=1, normally found at a wavelength of 1216 Å, in the extreme ultraviolet. The hydrogen Balmer series (e.g. Hα normally at 6563 Å) has been shifted out of range. The other emission lines are characteristic of very hot gas, consistent with the infall theory.

This completes the list of objects studied by the SDSS. Next comes a description of how information from these sources is degraded.

Intergalactic Gas

Gas clouds between us and a distant QSO have smaller Doppler shifts than the QSO. Lyman α absorption lines due to such clouds are seen at shorter wave lengths than the Lyα emission line of the QSO. When there are a lot of them, they are referred to as the Lyman α “forest”. Each absorption line corresponds to a gas cloud. See spectrum, p5.

Foreground Stars

An obvious source of interference with an image of a galaxy is the presence of stars in our own galaxy that are in front of the galaxy. This problem has been largely avoided in the SDSS project by avoiding the Milky Way, at least in the early SDSS work.

Interstellar Gas and Dust

Interstellar gas and dust have the effects of reddening and dimming an object. Dense clouds of gas and dust, such as the Orion Nebula, are avoided in the SDSS, but they cannot be avoided altogether. There is no consensus on exactly how to compensate for this, and the data releases from the SDSS do not include such compensation.

Earth’s Upper Atmosphere

There are emission lines due to atoms and small molecules being struck by particles from the Sun. This is much like what happens inside a fluorescent lamp. There is also a continuous spectrum component. To compensate for this, a spectrum is taken of a nearby blank portion of sky simultaneously with other spectra. The spectrum of the blank sky is then subtracted out. The sky background is shown in the SDSS spectra on pages 2, 4 and 5. At times of strong solar activity, the sky glow is strong and not easily compensated for. When solar activity is so strong as to produce an Aurora Borealis visible from Arizona, as happened in January 2005, the astronomers get a night off.

Earth’s Lower Atmosphere

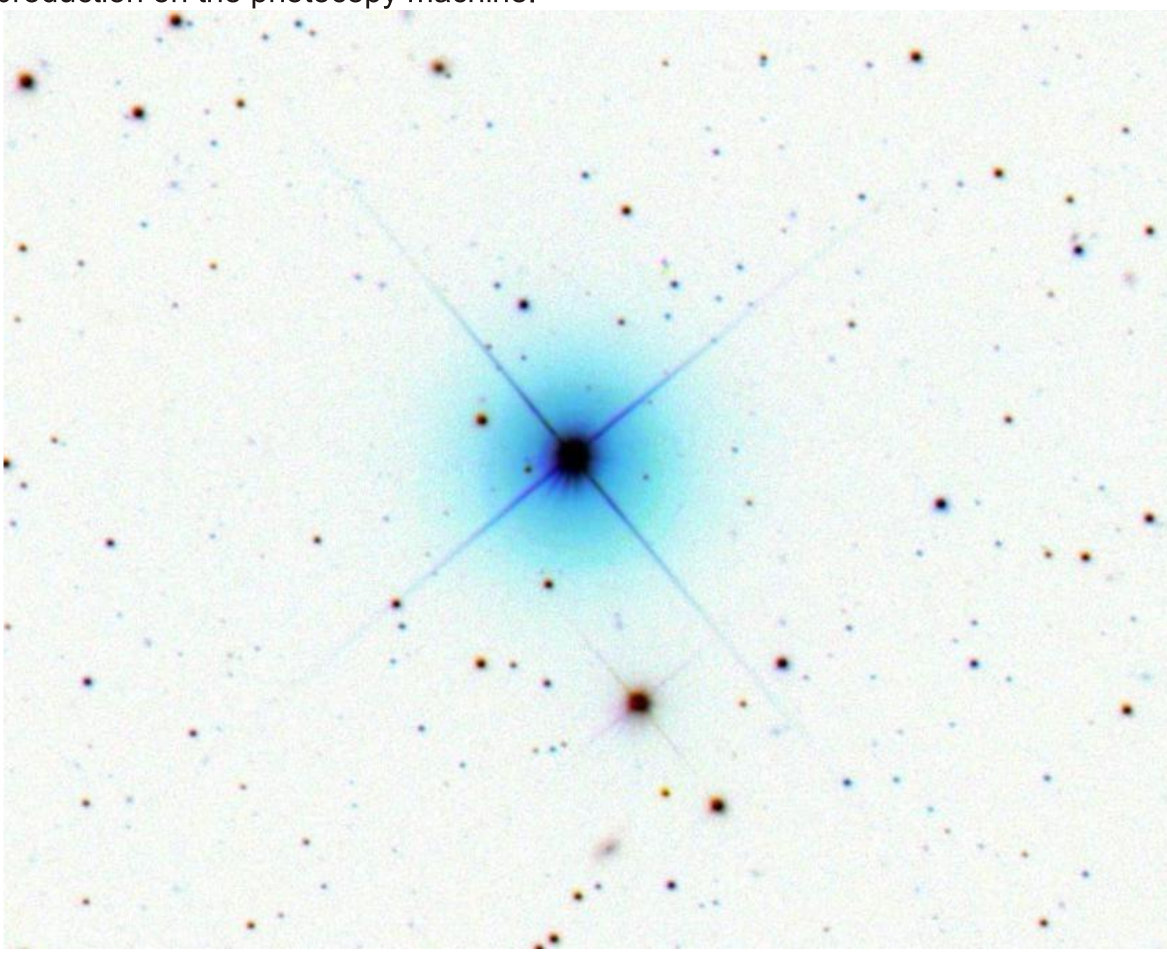
Turbulence in the atmosphere reduces our ability to see fine detail in both images and spectra. The air strongly absorbs light at wavelengths far removed from the visible range. Light from the Moon or from a nearby city ruins our ability to see deep sky objects. These effects are minimized by wavelength range selection, site selection, avoiding parts of the sky close to the horizon and waiting for moonless nights.

The Telescope Itself

A telescope designed for survey work must have very good pointing accuracy, and be shielded from the wind. It must also be stable with respect to temperature changes. Apparently, the Pyrex mirror, much cheaper than the modern low expansion materials, is adequate. The resolution of the telescope is limited by the atmosphere, not by the theoretical resolution of the 2.5 m diameter mirror.

CCD Detectors

CCD detectors are more stable, uniform and efficient than photographic film. A flaw shared with film (and your TV) is that a bright object appears bigger than a dim object. This is evident in the picture shown below, shown in a negative version for clear reproduction on the photocopy machine.



Here are star images that are different sizes. The brightest ones appear larger than the galaxy (near the bottom, just right of center). The galaxy is easily distinguished by its appearance: It is not round, and it is not bright. Note that other galaxy images could be much harder to distinguish from stars. Incidentally, the bright stars have crosses on them because of diffraction from the secondary mirror support.

Computer Processing

The pictures presented by SDSS as "Finder Charts", such as the one above, are in color, which makes them very useful. However, they are not of high quality, and are not suitable for measurements of any sort. Ultra-violet is used as a substitute for blue, so the colors are not quite right. Color registration errors, dotted lines and colored streaks are sometimes visible, and it is to be hoped that this sort of thing will be avoided in the future.

The Data Set

The data you will be working with is a selection from the spectra of 640 objects on a single plate (#634). This plate was chosen because it has a lot of stars on it, and because it is in a location in the sky where there is not very much in the way of gas and dust. There is about the usual number of sky spectra, and about the usual number of mistakes. There is even one that is entirely blank.

The pictures are to a scale of 0.39612 arc-seconds per pixel. This rather odd size corresponds to the scale of the original CCD, so nothing has been lost or distorted. The picture occupies an area of 850 pixels wide by 680 pixels high, which is most of a 1024x768 pixel screen. and corresponds to an area in the sky of a little over 5x4 arc-minutes.

The spectra are reproduced at a scale of about 7 Å per pixel. The error in estimation in wavelength is about half a pixel or a little over 3 Å. These spectra were worked on exclusively by a computer. The computer assigned spectrum features, including the Doppler shift, and did a good job. The computer then went on to assess what kind of an object it was, and did not do so well. Lists of the objects and their type from people associated with SDSS often have a different assignment from the computer, and also from each other. From this we learn that the identification process is not straight forward. The questionable assignments mainly arise when the image is faint and the spectrum is noisy.

Theory

Three aspects of spectroscopy are discussed here.

Flux

The SDSS spectra are carefully calibrated so that the flow of energy from an astronomical object to one square cm on the Earth in each band of color 1 Å wide is presented. This depends on the astronomical object, its distance, and a possible lack of transparency of space, but not on the Earth's atmosphere, and not on the instrumentation.

Blackbody radiation

A star is describable as a not-quite-blackbody. You will be finding the theoretical blackbody curve that best fits the spectrum of a star, using sliding controls for the temperature and the flux. What you will have found is called an effective temperature. Such a fit is shown in the spectrum of a star on page 2. Note that the fit is very good at long wave lengths where, in this case, absorption lines are weak, but not so good at short wave lengths where the absorption peaks are quite strong.

If the maximum flux of the blackbody component of the radiation from the star is within range, you will also use Wien's to find the temperature of the star.

Here, we will use Wien's law in the form

$$T = \frac{2.90 \times 10^7}{\lambda_{max}}$$

Example: The spectrum on page 2 has a blackbody peak at 3900 Å. Then

$$T = \frac{2.90 \times 10^7}{3900} \approx 7400\ K$$

Here, it must be noted that the concept of effective temperature can be misused. The best fit to a blackbody curve does not have to be very good at all, and can be found for any light source that isn't monochromatic. You will be treating a star as a blackbody, but not a galaxy, nor a QSO. The galaxy is a mix of stars and other objects at different temperatures, while a large part of the light from a QSO is non-thermal in origin.

Doppler Effect

The Doppler effect is described with the formula

$$\frac{\text{apparent wavelength}}{\text{true wavelength}} = 1 + \frac{\text{recession velocity}}{\text{wave speed}}$$

Here, I will use the speed of light for wave speed, λ_{obs} for apparent wave length, and λ for true wavelength. Then, after putting the 1 on the left side, I have

$$\frac{\lambda_{obs}}{\lambda} - 1 = \frac{v}{c}$$

The point of my doing this is that the quantity on the left side of the above equation is called z, and appears on the SDSS spectra.

Example: using the spectrum on the bottom of page 4, the observed wave length for the hydrogen α line is 6750 Å. The true wavelength is 6563 Å. Then

$$z = \frac{\lambda_{obs}}{\lambda} - 1 = \frac{6750\ \AA}{6563\ \AA} - 1 = 0.0285$$

The classical recession velocity is obtained by multiplying z by the speed of light.

$$0.0285 \times 3.00 \times 10^5\ \frac{km}{s} = 8550\ \frac{km}{s}$$

We get into a lot of trouble when we try this on the QSO spectrum (p 5). For the Lyα line, λ_{obs} = 4384 Å and λ = 1216 Å. When we try the formula on the previous page, we obtain

$$z = \frac{\lambda_{obs}}{\lambda} - 1 = \frac{4384\ \text{Å}}{1216\ \text{Å}} - 1 = 2.6081$$

So far, so good. The classical form for the Doppler shift leads to a recession velocity far above the speed of light, which is wrong. We need Einstein's special relativity here. To calculate the velocity from z, the formula we need is

$$v = \frac{c\ z\ (2+z)}{2+z\ (2+z)}$$

Substitution for c and z give the correct recession velocity

$$v = \frac{c\ z\ (2+z)}{2+z\ (2+z)} = \frac{3.00 \times 10^5 \frac{km}{s} \times 2.6081 \times (2+2.6081)}{2+2.6081 \times (2+2.6081)} = 2.57000\ \times 10^5\ \frac{km}{s}$$

which is about 86% of the speed of light.

I now have two expressions for the recession velocity. Which is right? My answer is that we have to ask "Which is adequate?" instead. We use the classical Doppler formula for low recession velocities, and use the relativistic formula for high recession velocities, say, over z = 0.1. The same sort of question comes up in mechanics. Do we use Newton's Laws, or do we need the Einstein version? For low velocities, we use Newton's laws, which are perfectly adequate.

Procedure

The program name is SDSS. Double-click on the SDSS icon to start the program.

1) Click on the Slide Show menu entry. This opens a series of nine pictures for you to look at. Captions for all the pictures are shown in a panel on the right. On slide number three, count the galaxies and write the answer on the data sheet (question 1).

2) A list of objects to be studied will have been given to you by your instructor. Click on the Select Object menu entry. This opens a window with a scrollable list of objects. Click on the desired object.

Here is a possible list of objects: #'s 89, 92, 147, 150, 193

3) On the left side of the screen is a photograph of the sky, with a scale of 0.39612 arc-seconds per pixel. The total size is about 5x4 arc-minutes. The circle is 30 arc-seconds in diameter. On the right side of the screen is an object description, buttons for changing the view and a 10x blowup, a little less than 7 arc-seconds wide. Record a detailed description of the object on the data sheet.

4) Change the view to the spectrum. The left side of the screen now shows the spectrum of the object. The spectrum is in black, a sky background is in blue and a default blackbody curve is in red. Vertical green lines indicate positions expected for spectrum lines of the astronomical object. Vertical red lines indicate positions expected for atmospheric spectrum lines. The right side of the screen shows the object description, buttons for changing the view, slider controls for adjusting the temperature and flux for the blackbody curve, a box that shows the chosen blackbody temperature and a box for showing the current cursor position, calibrated in Å units.

a) For each of the spectrum lines listed on the data sheet that you can see, write the observed wave length in the space provided. Also note whether you see the line in absorption or emission.

Notes:

Some of these spectrum lines will always be out of range.

Always measure a line position using the black line (where the line is) and not the green vertical line (where the peak should be)

If the assignment of a spectrum line is doubtful, use a question mark.

The O III lines that are to be measured (if present) are just to the right of the Hβ line.

b) Calculate z for each observed spectrum line.

c) Calculate an average z

d) Calculate the recession velocity. Use the classical formula if $z < 0.1$ and the relativistic formula if $z > 0.1$

5) Make an identification of the object type. Justify your answer.

6) This step is to be done only in the case of a star.

a) Using the temperature and flux controls, adjust the blackbody curve to get the best fit to the spectrum. Record the temperature on the data sheet.

b) Find the maximum of the blackbody component of the spectrum. This will typically not be exactly the same position as the curve in step 6a. Record the peak wave length on the data sheet.

Note: In some cases, the maximum of the blackbody curve will be off the scale, and you will not be able to do steps 6b or 6c. In this event, please write “can’t be done” on the data sheet.

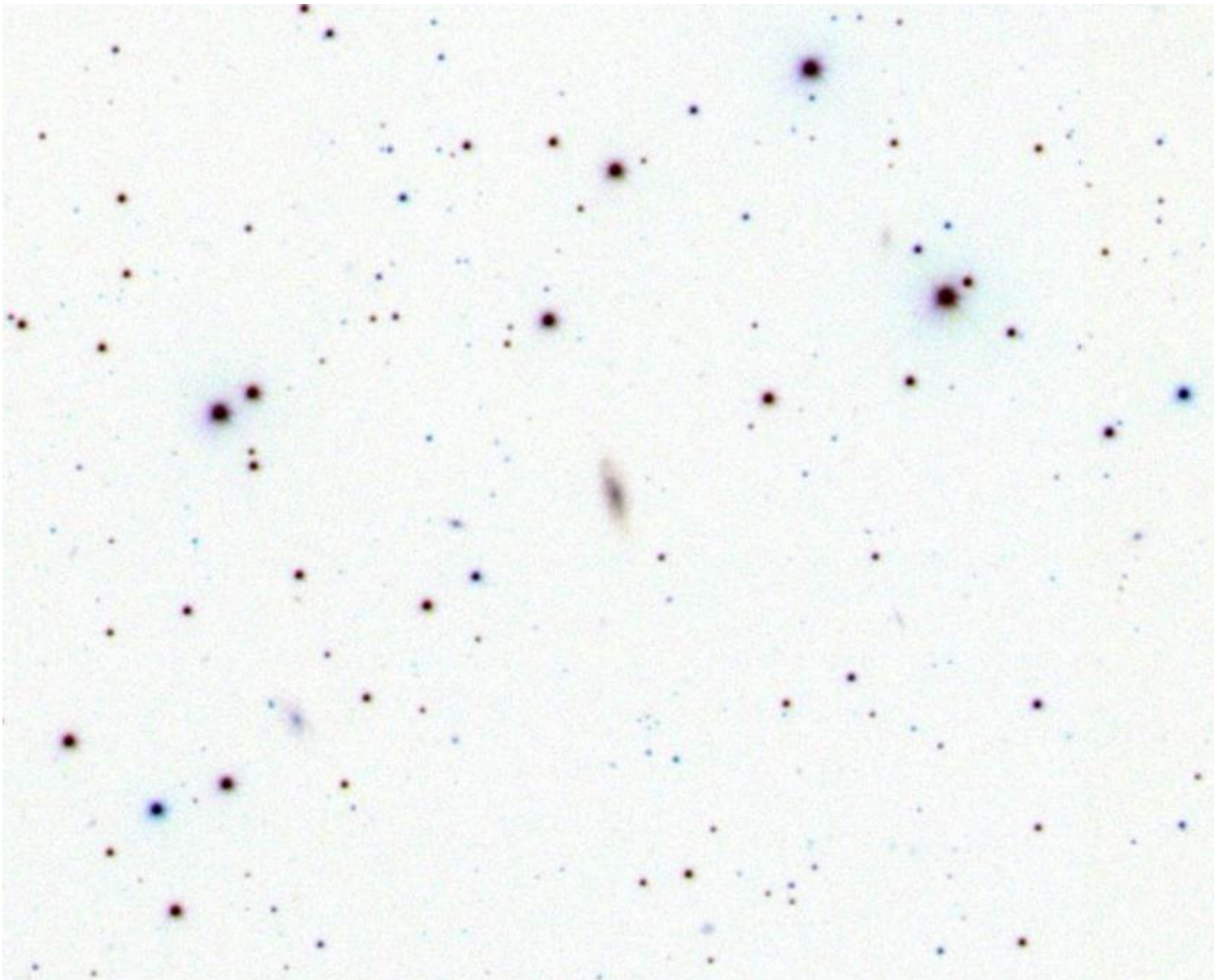
c) Using Wien’s law, calculate the temperature. Enter the result on the data sheet.

7) Repeat steps 2-6 for each object assigned to you. Extra data sheets will be provided.

8) Answer the questions on the first data sheet.

9) Use the Quit menu entry to halt the program.

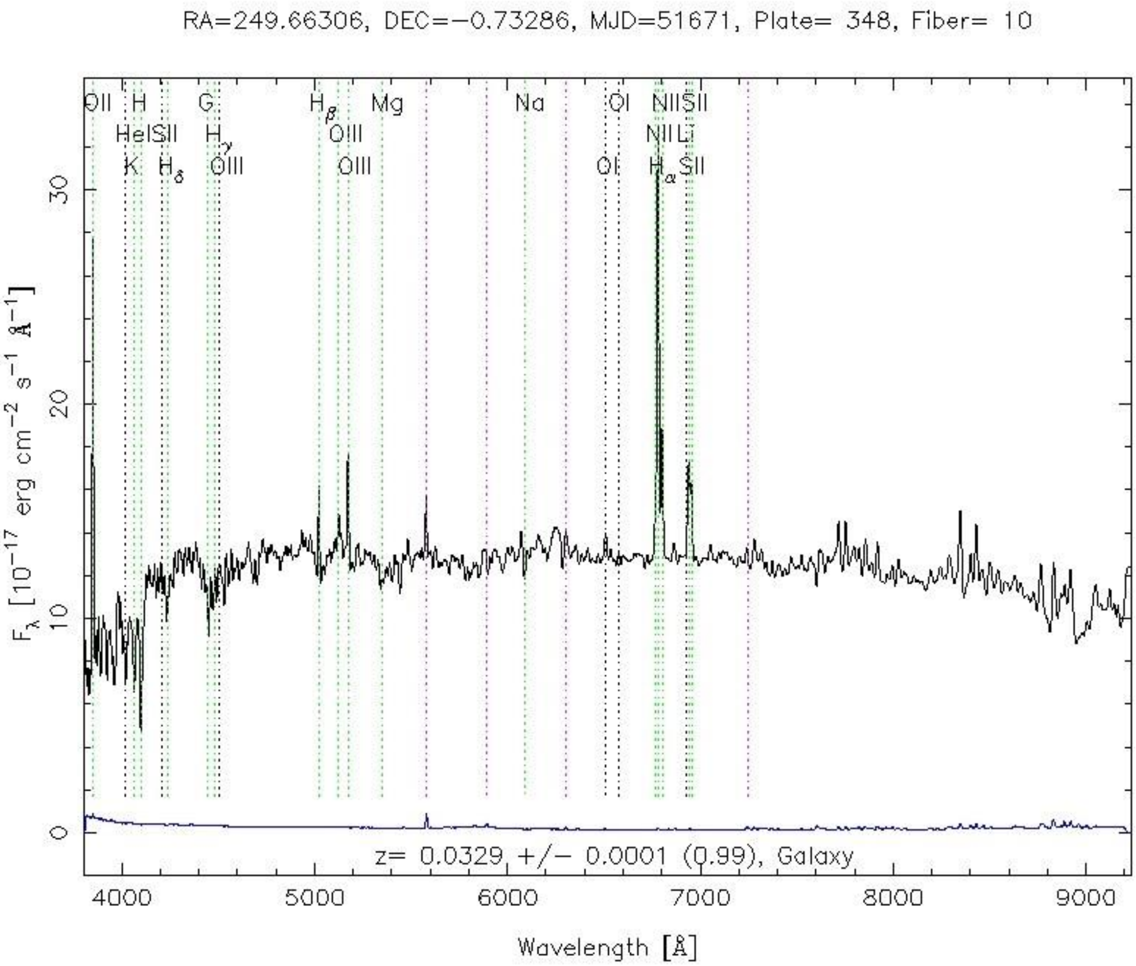
10) Hand in all the data sheets.



Example

Here is a completely worked example of what you are to do. The astronomical object is not part of your data set (Plate 338 Fiber 10). The picture is shown as a negative.

The object is in the center of the picture. It is obviously a galaxy, and the image is about 20 arc-seconds long. On the original, the color was reddish gray. It was fairly faint.



The spectrum for this object is shown above.

The H_α and H_β lines are seen clearly in emission. The H_δ line is seen in absorption. I don't see the $H\gamma$ line very clearly, so I will leave it alone. The Na (sodium) line seems to be in absorption, but it has an emission line just to the left of it, which may also be Na. I will leave this one alone as well.

SDSS Data Sheet Example

Name(s) Example Date ____________

Plate Number 438. Object Number 10

Appearance

Shape, size (e.g. small, round,1", 10") (the 10x window is 6.7" wide) 20" long, not round

Brightness (e.g. Bright, Dim) dim

Color reddish-gray

Doppler Shift Calculation

Line	λ	λ obs	absorption/emission	z
Ly $_{\alpha}$	1216	off the chart	____________	____________
H $_{\delta}$	4102	4229	absorption	0.0310
H $_{\gamma}$	4340	?	?	____________
H $_{\beta}$	4861	5020	emission	0.0327
O III	4959	5127	emission	0.0339
O III	5007	5173	emission	0.0332
Na (average)	5892	?	?	____________
H $_{\alpha}$	6563	6779	emission	0.0329
average z				0.0327

Recession Velocity Calculation (If z > 0.1 do the classical calculation) 9820__________

What type of object is this? Justify your answer.

Galaxy. Appearance. It looks like a galaxy (not round, extended, fairly faint). Spectrum does not look like a blackbody curve, O III emission lines, other emission lines present. High z

Note: Do the following if (and only if) you have identified your object as a star:

Temperature estimated from the blackbody curve fit: <u>not done</u>

Note: On some objects the Peak flux wave length is off the scale, so the following calculation cannot be performed.

Peak flux wavelength (λ_{max}) <u>can't be done</u>

<u>can't be done</u>

Wien's law temperature calculation: $T = \frac{2.90\ \lambda 10^{7}}{\lambda_{max}} =$

SDSS Data Sheet

Name(s)____ Date _______________

Plate Number 634. Object Number _______________

Appearance

Shape, size (e.g. small, round,1", 10") (the 10x window is 6.7" wide) _______________

Brightness (e.g. Bright, Dim) _______________

Color _______________

Doppler Shift Calculation

Line	λ	λobs	absorption/emission	$z = \frac{\lambda_{obs}}{\lambda} - 1$
Ly α	1216	________	_______________	_______________
H δ	4102	________	_______________	_______________
H γ	4340	________	_______________	_______________
H β	4861	________	_______________	_______________
O III	4959	________	_______________	_______________
O III	5007	________	_______________	_______________
Na (average)	5892	________	_______________	_______________
H α	6563	________	_______________	_______________

average z _______________

Recession Velocity Calculation (If z > 0.1 do the classical calculation) _______________
What type of object is this? Justify your answer.

SDSS Data Sheet (Continued)

Note: Do the following if (and only if) you have identified your object as a star:

Temperature estimated from the blackbody curve fit: ________________

Note: On some objects the peak flux wave length is off the scale, so the following calculation cannot be per formed.

Peak flux wavelength (λ_{max}) ________________

Wien's law temperature calculation: $T = \dfrac{2.90 \times 10^7}{\lambda_{max}} =$ ________________

Questions

1) How many galaxies did you spot in the picture of NGC 6070 (Slide Show #3)?

2) How did you go about deciding whether the objects you studied were stars, galaxies or QSO's? (answers will de pend on the list of assigned objects)

3) Calculate the recession velocity for an object with z = 0.1 using both the classical and relativistic methods. Compare your answers.

4) The SDSS, with its emphasis on galaxies and QSO's, has not (initially) selected regions of the sky for study that are in the Milky Way, even those that are dust free. Why do you think this might be so? (Hint: look again at NGC 6070 in the Slide Show picture #3)