Lab #6 – Gravitational Lensing

Version 2: November 24, 2010

1. Overview

This lab exploits gravitational lensing to teach a variety of topics. By the end of this lab you should be able to:

(1) Choose any topic in observational astronomy and then locate, download, and analyze observations from the *Hubble Space Telescope* (HST) data archive that are related to this topic.

(2) Understand the instrumentation and resources available with HST, their capabilities and limitations.

(3) Gain knowledge of IRAF and DS9 as tools for processing and visualizing data in concert with IDL.

(4) Discover for yourself that spacetime is warped by mass, mass governs the motion of light in a vacuum, and that dark matter exists. You will do this by analyzing HST images of the first Einstein double lens SDSSJ0946+1006, not to mention reading a few words from Einstein himself.

(5) Perform a tabletop experiment to help understand the Universe, as well as to be able to describe it to grandma.

(6) Understand the basic concepts of ethical conduct in research, such as plagiarism, fabrication and falsification.

2. Timeline

There will be two lab lectures on Nov. 16 and 23, 2010. The final lab write-up is due no later than noon on December 7. Additionally, I will be available Nov. 22 & 24 and Dec. 6. Since this is a new lab for this course, I would be interested to hear from you either in person or anonymously in your course evaluations whether or not you found it interesting, easy or hard, too short or too long given the time available, etc.

3. Early step – find the HST data.

The goal is for everyone to attempt to find the HST data in the archive, request it for themselves, and ftp it back to your own directory. Since it could take an hour for the HST data to become available, we start with this task, then do a few other things, and then return to the data when it becomes available. If the data take too long to become available, I will give it to you.

Let's suppose that you find the following announcement very intriguing:

http://hubblesite.org/newscenter/archive/releases/exotic/gravitational-lens/2008/04/

Your mission is to find the original data in the data archive. Good luck.

The HST data archive can be searched here:

http://archive.stsci.edu/hst/search.php

Note that you have several options on how to search. Please click "ALL" under imagers. You might have to try a few things to find the data. For example, try the target name, or RA &

Dec, or Proposal ID. Hint: Does the target name have a bunch of numbers that might indicate RA & Dec?

When you find the data, you might see some fields in yellow, these data are not available for download, yet. Please check data that only use the WFPC2 instrument.

Note that your search results should give you valuable information that would go into your lab report, such as date of observation, instrument, and filter. It is also customary to cite the Program ID and the name of the PI (Principal Investigator).

Note that you can learn more about HST and WFPC2 from the pdf documentation supplied on the Lab website.

4. Early step – request the HST data.

You should have selected four data sets using the WFPC2 camera and the F606W filter. You hit the button "Submit marked data…" which takes you to a page "Retrieval Options". You can register for your own Username/Password if you wish. You can also type in "anonymous" as a username, and your email address as the password. Your email address must be correct because the archive will send you two emails that (1) confirm your request, and (2) tell you when the data are ready to be downloaded.

Please select "Stage the data…" and "Compress the files using gzip". Unclick "Calibrated" and near the bottom under "File Extensions Requested" select "DRZ". Note that normal circumstances, you would probably ask for all the "Calibrated" data, but here we want to work quickly with a few files.

Now you are ready to submit the request. In a few minutes you should get an acknowledgement email.

By selecting the *drz* files, you are getting the pipeline calibrated data files. No need to worry about flat flields, geometric distortions, and so on and so forth, unless you really want to do it yourself. Later I will point out that sky subtraction may be necessary. The data pipeline is well-documented if you want to learn more by searching through the HST website (http://www.stsci.edu/hst/).

5. Intermediate Step – Introduction to IRAF & DS9

While you are waiting for the data to appear, you could introduce yourself to IRAF and DS9. If you wish to ignore IRAF and DS9 in terms of completing the lab, that is OK, but I would like you to try them in this lab – you may like them, you will see.

IRAF has a variety of packages for data reduction and analysis. At the very least, you can study the help file of any package, and the information in the help file may give you ideas on how to write your own IDL scripts. Also, when reading the scientific literature, you will often find statements of which IRAF packages were used for analysis, and this can be helpful if you need to understand the details of someone's work. IRAF can also be installed and used without cost on many operating systems.

DS9 is image display software with many interesting and useful features. If you do not use IRAF, you can nevertheless take advantage of DS9. It can also be installed quickly on most operating systems. It's a keeper.

IRAF & DS9 are installed on CERES, and you need to ssh into this machine as ugastro. Since everyone will log in as ugastro, you need to create your own data directory on Ceres with your name.

(1) login to a workstation with your username/password

(2) open a terminal window

(3) ssh –XC ugastro@ceres [and then supply the password for user ugastro]

(4) note that on ceres, everyone has logged in as user "ugastro". You will have to keep your data in your own data directory, e.g., *mkdir yourname*

(5) you have to spawn a xgterm (graphics terminal) by typing: *xgterm &*

[you should resize the new xgterm window to something like 120x65]

(6) use the xgterm window and now you can *cd* into your data directory, and you might try *ls* to see what's in it.

(7) to make IRAF available from within your data directory, type *mkiraf*

(8) type *ls* to confirm that your data directory now has the file *login.cl* and a directory called *uparm.* You are now ready to use IRAF from within this directory, and you do NOT have to repeat step (7) every time you want to use IRAF.

(9) start IRAF by typing *cl*.

(10) in case you need to, you can transfer files between directories on CERES and other machines using *scp*, e.g., this will move all fits files from a directory on your usual workstation into the new directory created on ceres : *scp *.fits ugastro@ceres:/home/ugastro/mydata/*

IRAF has many packages, but not all will be loaded at startup. To find out where a package resides you would look at the help file. For example, if I want to use the package *radprof*, I would look at the first line (the middle top) of the help file and note the path. For example:

cl>help *radprof*

cl>*noao*

cl>*digiphot*

cl>*apphot*

Now you are ready to use *radprof*. If you did NOT navigate to this package from within IRAF, you will not be able to see the parameter file or use the package. To see a parameter file for a given package, try this:

cl>epar *radprof*

cl>:wq [to get out of it, w=write, q=quit; control-D might also work]

USING IRAF PACKAGE PARAMETERS:

Each IRAF package has a variety of optional parameters. For example, to combine three images, you could use the package *imcombine*, and imcombine wants to know if it should calculate and average or a median value. You could tell it what to do either by using the command line or by editing the parameter file for the package imcombine. For the combine line:

cl> *imcomb* image1.fits,image2.fits,image3.fits output1.fits *comb=average*

Note that the command line will accept abbreviations (*imcombine* = *imcomb*), and note that the parameter is "*comb*". I could change my mind and specify "*comb=median*" in the command line. However, suppose I always want to use *comb=median*, yet the default is *average*. Instead of typing my preference every time in the command line, I can edit the parameter file (epar):

cl>*epar imcombine* [then navigate to the parameter and change it]

:wq

cl> *imcomb* image1.fits,image2.fits,image3.fits output2.fits

Because I changed the parameter file, output2.fits is now the median combination of images. If I want the package to return to its default parameters, use the command *unlearn*:

cl>*unlearn imcombine*

Finally, note that in IRAF, typing "*e* <return>" brings back the previous command, and by hitting the up and down arrows you can scroll through your command history.

One more thing, to execute an UNIX command from within iraf, precede the command by an exclamation point, e.g.

cl> *!rm junkfile.fits*

FIXING YOUR IRAF SETUP:

You might encounter problems where only a portion of your image is displayed, or perhaps you cannot get IRAF to display an image on DS9 on your terminal, but it displays on another terminal in the lab, or maybe interactive packages do not work such as *phot* or *radprof*. These three problems can be fixed using the command line in IRAF:

cl> *set stdimage=imt4096* [IRAF can now display images as large as 4096x4096 pixels]

cl> *set node = "myworkstation!"* [look at your lab LCD display and find its name or IP address; this is the name of your workstation. Include the trailing exclamation point in the command.]

cl> *set stdimcur=stdimage* [this will enable interactive plotting such as when using the packages *phot* or *radprof*]

You can type these commands every time you start IRAF, or you could also edit the *login.cl* file BEFORE you start IRAF. For example, quit out of IRAF (*logout*). Then edit the login.cl file in your data directory, for example, using emacs or *vi*.

>*vi login.cl*

Note that many lines in this file are commented out by the # symbol. You have to delete the # to have a line recognized and used. With *vi* you can use arrows or letters to navigate through the file (for example, letter j moves the cursor down), the letter x will delete whatever is at the cursor, the letters *dd* will delete an entire line, the letter *i* will insert a value at the cursor position (hit *escape* to get out of editing), the letter *a* will allow you to insert text after the cursor (hit *escape* to get out of editing). To save changes, *:w*, to save and quit, *:wq*.

OK, it should be obvious that the "*set*" commands above can now be executed automatically by editing certain lines in the *login.cl* file. As an added bonus, near the end of the *login.cl* file, you can "List any packages you want loaded at login time". This allows you to skip the hassle of navigating to certain package directories every time you start IRAF.

START DS9

DS9 does not have to be started from an xgterm. Any xterm will do. Type in "*ds9 &*". Ignore the warning concerning XPA. If you have already started IRAF in a xgterm, you can still start ds9 from within IRAF:

cl> *!ds9 &*

EMERGENCIES:

If things are not working or stopped working, you might try quitting out of IRAF and DS9 and starting from scratch. In IRAF, you might try the following commands that tend to solve some problems:

cl> *flpr* [flush process]

cl> *gflush* [graphics flush]

6. Intermediate Step – Read some Einstein

While you are waiting for your data to appear in the archive, study the Einstein 1936 paper (pdf file on the lab web site). A lot of his most important work is written in German, but here you have a chance to read it straight from the i-pencil of the genius.

Lab 6 assignment: Find an envelope, locate the back of the envelope, sketch Einstein's Figure 1. Einstein's paper has NO figure, but he provides enough information for you to sketch the lens geometry he is talking about. Write your name on the envelope and submit it for inspection.

7. Download your HST data

Perhaps you have by now received an email from archive@stsci.edu that tells you what to do to download your data. All you need is to ftp into the archive and get your data. You should be logged into CERES, and in case you didn't already make your own data directory with your name…

>*mkdir myname*

>*cd myname*

>*ftp stdatu.stsci.edu*

>enter archive username and password, or, *anonymous* and email [note that anonymous ftp has the user name simply as "anonymous" and NOT anything like "anonymous95481"]

>*cd /stagewhatever/the/email/says* [if this does not work, break it up into pieces of navigation, starting with *cd /stage* and then *ls* to see what is in the directory, then continue].

>*bin*

>*prompt*

>*mget *.gz*

>*bye*

>*gunzip *.gz*

8. First look at your HST data – where is the lens?

You should have ds9 running and here I will describe what to do in IRAF (but you can use IDL if you want).

You can display the image in ds9 without using IRAF or IDL. Click the top menu item "Open" and navigate to your file to open it. Then play with all the image adjustment tools to your hearts content. Note that if you place your cursor over an object and click the middle mouse button, the field will center on that position. If you click the right mouse button and drag it across the field, you will change image intensity and grayscale gradient. If you click the left mouse button, you will draw a shape, and the shape can be adjusted by selecting from the options under the top menu item Region->Shape. Also, if you double click a shape, a window will pop up to adjust the parameters of the shape.

Using IRAF, you can type in the command *display*. First check out the help file:

cl> *help display*

Also, check the parameter file for the display variables:

cl>*epar display* [to quit out of it, type *:wq*]

Display your images from the command line:

cl> *disp image1.fits[sci] 1*

cl>*disp image2.fits[sci] 2*

And so on and so forth. Note that these data are *fits* files with several layers or extensions. If you forget to specify which extension you want, the command will fail. IDL will also fail. In this case the extension is designated by *[sci]*. Some fits files DO NOT have multiple extensions. For example, I can use *imcopy* to copy the layer *[sci]* into another file which has only a single layer, and this second file is now simpler to use in terms of syntax at the command line.

cl> *imcopy image1.fits[sci] exposure1.fits*

cl>*disp exposure1.fits 2*

You can load all the images in different frames. Sometimes the dynamic range is not what you want. You could also type in the commands:

cl>*disp imagename1.fits[sci] 1 zr- zs- z1=-0.01 z2=0.2*

cl>*disp imagename2.fits[sci] 1 zr- zs- z1=-1 z2=1 ztrans=log*

You should read the help file on the package *display*, AND you should experiment on your own, but the short explanation is that pixel values less than z1 will be depicted as black and values greater than z2 will be white, and the image grayscale will only be effective for values between z1 and z2.

If you would like to DELETE an image file, you can use the IRAF command.

cl>*imdel image.fits*

Bored already? Go to the DS9 top menu item and test out all the options under "Color".

9. Basic Properties of your HST data.

For your lab report, you need to understand the basic properties of your data. Some of this information was seen on the archive web site. You can also examine the headers. DS9 will display the header for a file under File-> Display Fits Header.

With IRAF, you can type:

cl>*imhead imagename1.fits[sci]*

cl> *imhead imagename1.fits[sci] l+*

Recall from step 8 that you only need to include *[sci]* when dealing with a multi-extension fits file.

What should you find out for your lab report? For starters please determine the angular size of your field, filters, exposures, and, later, we will determine the image quality be finding the FWHM of a star.

Create a data logbook or table. In IRAF you can try the following, or some version of the following:

cl>help hselect

cl>hselect ua1l2901m_drz.fits[sci] $I,TARGNAME,DATE-OBS,TIMEOBS,FILTNAM1,EXPTIME

Note that these values such as TARGNAME are what you find by examining the fits header for these HST data.

You might find the data file names are too long. You could change the file name like you would any file in your directories. Another way in IRAF is to copy the file into another name, which would have the benefit of preserving the original file in case something goes wrong down the road with your processed files. For example:

cl>*imcopy ua1l2901m_drz.fits[sci] exposure01.fits*

Recall (from step 8) that the new file is no longer a multi-extension fits file. If you wanted to preserve multi-extension properties as files are processed, you would use packages such as *gcopy*.

10. Cosmic Ray Rejection

You probably already did this in previous labs (by taking the median value of stack of images). Please go ahead and remove the CR's. This step might be more challenging compared to previous labs.

There are various possibilities in IRAF. Basically you have to find the centroids of a star that is detected in all four frames, find the offsets, and shift to some fiducial image position. To find the centroid of a star, you could try simple packages such as *imcntr*:

cl>*help imcntr*

cl> *imcntr ua1l2901m_drz.fits[sci] 366.5 376.5 cboxsiz=7*

To shift an image, you could try *imshift*, but notice how the choice of interpolation function influences the final result:

cl> *help imshift*

cl> *imshift ua1l2902m_drz.fits[sci] w2s.fits -5.011 -2.433 interp=spline3*

cl> *imshift ua1l2902m_drz.fits[sci] w2s1.fits -5.011 -2.433 interp=constant*

Then display these results. Of course you can use whatever file names you like. You would then combine the images in a fashion that rejects CR's. In IRAF, you could try:

cl> *help imcombine*

cl> *imcomb image1.fits,image2.fits,image3.fits,image4.fits output1.fits comb=median*

In case you are using IDL, you might want to study the help file for *imcombine* to learn about other methods for CR flagging and rejection that you could adopt for IDL.

Your method for CR rejection should also succeed in lowering the background sky noise, which you can measure in blank regions of sky. For example, in IRAF:

cl> *help imstat*

cl> *imstat output1.fits[125:174,135:184]*

HST images can have a sky background, for example, due to Zodiacal light. You would want to subtract the sky background after you measure its value. For example, in IRAF use *imarith*:

cl> *help imarith*

cl> *imarith exp1.fits – 1.02E-3 exp1.fits*

11. Cleaning up the image

CR rejection may not work perfectly. After combining images, CR's may still contaminate your field. At least in the region surrounding the lens, we need to clean up the image.

Study the structure of the lens. ***Are any of the knotty features real?***

To see if they could be due to cosmic rays, you should blink through your four registered exposures. You can use DS9 for this too.

Troublesome cosmic rays in individual exposures or in the final image can be removed by interpolating over these pixel regions as you have done in previous labs. IRAF has a task called *fixpix* which you can use. Note that it modifies the input file and does not create a new output file, so you need to be careful with this step.

Another option is to smooth the image using a median box, of say, 3x3 pixels, which will also degrade your angular resolution. For example, in IRAF use *median*:

cl> median filename1.fits filename2.fits 3 3

12. Angular resolution of the observation?

Now that your final image is starting to look better in terms of CR properties and noise, find a star in the image and measure the FWHM. *Your lab report should state the angular resolution achieved with these data, in this bandpass.*

You might produce the wrong answer if you select something that looks like a point source but it is really a galaxy.

In IRAF you can try the package *pradprof*. Cuts across portions of the image can be made using *implot* and/or *graph*.

13. Study the Universe - Describe your findings using scientific terminology.

Study the central galaxy lens and the rings. Please include in your lab, in this step and throughout your work, a description of what you see. Use succinct, technical vocabulary as much as possible. Some of the correct terminology can be learned by reading the review article by Richard Ellis.

This might be a good time to prepare a figure for your lab report. DS9 can save the displayed image under various formats. In DS9, Region->Shape->Text allows you to mark your image with text. Double-click on the text to change its properties.

Study the entire field. Do you find any other lenses? Be vigilant. If you find something suspicious, what kind of additional data would you like to have to determine if it was a lens, or not? This is the kind of discussion you could include in your lab book, if you find something interesting.

14. Measuring the properties of the lens galaxy

What is the centroid position, angular size and morphology of the lens galaxy? You should describe size and morphology in your lab report. In this lab we will skip measurements of integrated magnitude, surface brightness and position angle, though you are welcome to determine any of these quantities. For example, the sky direction North is NOT in the +Y direction.

The lens galaxy's centroid position is needed so that you can subtract a model galaxy and also to measure the angular separations between galaxy and Einstein rings.

For morphology, you make take various line cuts, and you could also create an isophote map. In DS9 try the top menu item ANALYSIS->Contours

In IRAF you can try the package *contour*

One visual way to see the low surface brightness, extended morphology of the galaxy is to bin the data, such as by creating a new image that sums or averages 4x4 pixels, or 8x8 pixels. In IRAF, you can try *blkavg*.

15. Model and subtract the galaxy

No problem, you just need to make a galaxy today. IDL might have some packages, and in the literature I found a software package called GALFIT. However, IRAF is also used for this task. Try the package *mkobjects*. You can see from the help file that this can take a long time to learn. If you wish, limit your experiment to a De Vaucouleur model. To get this package to work, you need to create and edit a text file where each line has the input parameters of the object to be created [xc yc magnitude model radius ar pa]. For example, I made a file called dv1.txt with the following:

```
200 200 0.0 devauc 20 1.0 45

400 200 0.0 devauc 20 0.5 45

600 200 0.0 devauc 20 0.25 45

200 500 0.0 devauc 40 0.25 45

400 500 0.0 devauc 40 0.25 90

600 500 0.0 devauc 40 0.25 135
```

Then I execute the mkobject command:

```
cl> mkobject  galaxies1.fits objects=dv1.txt  ncols=1515 nlines=1495 backgro=0
```

Note that I do not want to add simulated noise or have a background level because in the subtraction of the model galaxy from the real data I wouldn't want to add noise.

The test above should create an image called *galaxies1.fits* which will immediately show you what happens when you vary the input parameters.

You should notice that a single De Vaucouleur model galaxy is insufficient for modeling the real galaxy. You may have already seen that the galaxy isophotes twist. Roughly speaking, the isophotes have one position angle out to about x arcseconds radius, then change position angle by ~y°.

You can therefore superimpose or add together two or more galaxy models to get a more satisfactory fit. The process used here and in the literature is iterative.

If you are running out of time, you can submit for your lab report a single model galaxy. *The important part is to describe your model galaxy, the parameters used, and how well it works in a given region, and how poorly it works in other regions for x number of reasons*.

16. High Pass Filtering

After putting you through the trouble of making a model galaxy and subtracting it from the data, you might try a quick experiment that demonstrates high pass filtering. This is also called unsharp masking in photography. The filter will "pass" structure on high spatial scales, or "high resolution" scales. If it were a "low pass filter" then the "low resolution" angular scales are passed, or the broad features.

IDL and IRAF probably have various packages, but here is a quick way to do it manually. First you want to blur your image such as by convolving it with a gaussian function. Then you subtract the the blurred imaged from your original image, thus achieving a high pass filter since you just subtracted the information on long "wavelength" scales.

In IRAF

ecl> *gauss f3.fits f3.g5.fits sigma=5*

ecl> *imar f3.fits - f3.g5.fits f3-g5.fits*

ecl> *disp f3-g5.fits 2 zr- zs- z1=-0.01 z2=0.1 ztrans=log*

You can play around with adjusting the *sigma* parameter of the gaussian. As you can see, extended portions of the galaxies are subtracted, emphasizing sharp structure. You might want to take a few minutes to study other galaxies in your field.

17. Astrometry

Measure and report the radial angular separations between the lens galaxy and the ring features. In IRAF you could try various cuts across the image using *implot* or *graph*. Is the lens, in the radial direction, equal to the FWHM image quality of the data, or is it extended?

[Note that steps 15 and 16 above give you two different versions of the processed image. The two different results should allow you to comment in you lab writeup on how much the astrometry depends on the method used to subtract the galaxy.]

18. Find the mass of the lens galaxy

Report your calculation for the mass of the galaxy (in units of solar masses) in the lab report, and add a discussion on what uncertainties influence the outcome.

For the calculation we need the angular separation between the galaxy and the first ring. We also need the redshifts measured for the galaxy and the first ring. The second ring has no measured redshift because it is too faint.

θ_{E1} = the angular separation that you measured for the first ring, convert it to radians
Galaxy lens (SDSS J0946+1006) at redshift z_L = **0.222**
Inner ring at redshift z_{S1} = **0.609**

Based on Einstein's 1936 paper that you read in Step 6, the angular deflection of light in radians for an Einstein ring is a function of the galaxy mass:

$$\theta_{E1} = \sqrt{\frac{4GM(d_{S1} - d_L)}{c^2(d_{S1}d_L)}}$$

Solve for the mass M. A helpful version of G is G = 0.0043 [pc (km/s)^2 / $M_\odot$]

Here you will encounter a difficulty in converting redshift to Mpc due to the assumptions and uncertainties in cosmology. For students with a good cosmology background, feel free to proceed as you see fit. For low redshifts (z < 2) you could try the formula:

$$d \approx \left(\frac{c}{H_0}\right)\left(\frac{(z+1)^2 - 1}{(z+1)^2 + 1}\right)$$

In case you encounter h^{-1} in your research, note that h = H_0 / 100

19. Did you discover dark matter?

After determining the galaxy mass in $M_\odot$, estimate how bright the integrated light from the galaxy would be if all of that mass were in stars like the Sun. Compare this apparent magnitude to the known integrated magnitude of the galaxy in the bandpass: m_{606W} = 17.78 mag

What is the mass to light ratio? Discuss the various uncertainties and assumptions that brought you this far that would make the mass-to-light ratio a lower limit, or an upper limit.

20. Draw the geometry of the entire system.

Good luck. Time to get your hands on the glassware from Crate & Barrel.

Your figure should show a line connecting an observer with a galaxy (lens plane). However there are two rings, which means that there are two sources behind the galaxy, and one source, the source farthest away from the observer, will be lensed twice. First by the source between it and the lens galaxy, and then by the lens galaxy itself.

21. Your Reward

By now you have observationally tested General Relativity, finding that mass warps spacetime, that you can easily estimate the mass of a galaxy, when most of it cannot be directly seen, and that the HST data archive is at your disposal to satisfy your curiosity about the Universe.

22. CHECKLIST

Don't forget to turn in by noon, December 7, 2010, at our 7th floor lab, the following:

1) Your drawing of Fig. 1 for Einstein 1936

2) Your lab report

3) A <2 page answer to the questions for your "research ethics" homework. This homework has the following parts:

A. In the J.R. Minkel article (SciAm) there is an error concerning gravitational lensing in the 5th paragraph (beginnning with the word "If"). What is the error? Explain.

B. Read Section V of Dyson et al. 1920. What is the stellar displacement measured with the 4-inch lens at Sobral? Look at the "probable error", and then write down your opinion on how well the observation matches the prediction of Einstein.

C. In Section V of Dyson et al. 1920 you will find a figure. Explain in words what it shows (explain the axes, the points, the lines) and what is missing.