Physics 346 – Spring 2021
Project # 1: FIRST images of 3C radio sources

The Faint Images of the Radio Sky at Twenty-cm (FIRST) survey (Becker, White, & Helfand, 1995, ApJ, 450, 559) was conducted using the Very Large Array (VLA) over a period from 1993 through 2011, and over a combination of two areas on the sky:

- right ascension $7.0 \leq \alpha \leq 17.5$ and declination $-8.0 \leq \delta \leq +57.6$ (B1950)
- right ascension $20.4 \leq \alpha \leq 4.0$ and declination $-11.5 \leq \delta \leq +15.4$ (B1950)

The images produced by the survey have $1.8'' \times 1.8''$ pixels, $\sim 5''$ resolution, and a typical 1σ RMS noise of 0.15 mJy. Full information about the survey and tools for accessing its images are available at `http://sundog.stsci.edu/`.

For this project, you will be examining FIRST observations of a subset of the "revised 3C" (Third Cambridge) catalog of bright northern radio sources. The 3CR catalog was published by Bennett (1962, MNRAS, 125, 75) on the basis of 178 MHz mapping, and contains 328 objects in total; it is also available through the VizieR database at `http://vizier.cfa.harvard.edu/viz-bin/VizieR-3?-source=VIII/1A/3cr`. Using these online resources, you should do the following:

1. Determine which of the 3CR sources fall within the area covered by FIRST.
2. For the subset of 3CR sources with FIRST data, identify a "fair" working subsample of at least 40 sources that you can use for the objective investigation of the questions listed below.
3. For your working sample, use the "Retrieve Image Cutouts" tool to download FITS files of the FIRST images. (You will need to set "Image Type" to "FITS File," and you may need to change the "Equinox" to B1950, depending on which columns you are using from the VizieR catalog.)
4. For each source in your working sample, determine whether its FIRST image shows (a) a spatially resolved detection, (b) a spatially unresolved detection, or (b) a non-detection. For sources with spatially resolved detections, determine whether you can identify any notable morphological classes (e.g., compact doubles vs. jets vs. lobes).
5. For each FIRST *detection* in your working sample, determine its total 1.4 GHz flux density. To do this, you will need to add up the brightness values of all of the pixels that you feel show emission, then divide that sum by the number of pixels per (synthesized) beam, which is
$$\frac{\pi}{4\ln 2}\frac{a \times b}{\Delta x \times \Delta y} \tag{1}$$
in terms of beam major axis a, beam minor axis b, and pixel size $\Delta x \times \Delta y$ (all information contained in the FITS file header). For each FIRST *nondetection* in your working sample, assign $3\times$ the RMS noise of the image as an upper limit to the 1.4 GHz density, where the RMS noise is as reported by the image cutout server.

6. Using the 178 MHz flux density from the 3CR catalog and the 1.4 GHz flux density you have measured (or determined an upper limit for), calculate the spectral index $\alpha_{0.178}^{1.4}$ for each source in your working sample, assuming that $f_\nu \propto \nu^{\alpha_{0.178}^{1.4}}$ over the range $0.178\,\mathrm{GHz} \leq \nu \leq 1.4\,\mathrm{GHz}$.

7. Determine whether there are any patterns or relationships among 178 MHz flux density, 1.4 GHz flux density, spectral index $\alpha_{0.178}^{1.4}$, and 1.4 GHz morphology within your working sample. (This question has deliberate open-ended phrasing — there may or may not be patterns or relationships that emerge when you do a little exploring!)

8. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How might light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?

Physics 346 – Spring 2021
Project # 2: FIRST sources in the COSMOS field

The Faint Images of the Radio Sky at Twenty-cm (FIRST) survey (Becker, White, & Helfand, 1995, ApJ, 450, 559) was conducted using the Very Large Array (VLA) over a period from 1993 through 2011, and over a combination of two areas on the sky:

- right ascension $7.0 \leq \alpha \leq 17.5$ and declination $-8.0 \leq \delta \leq +57.6$ (B1950)
- right ascension $20.4 \leq \alpha \leq 4.0$ and declination $-11.5 \leq \delta \leq +15.4$ (B1950)

The images produced by the survey have $1.8'' \times 1.8''$ pixels, $\sim 5''$ resolution, and a typical 1σ RMS noise of 0.15 mJy. Full information about the survey and tools for accessing its images are available at http://sundog.stsci.edu/.

For this project, you will be examining FIRST detections within the footprint of the Cosmic Origins Survey (COSMOS; Scoville et al. 2007, ApJS, 172, 1), which used the *Hubble Space Telescope* to image a $1.4° \times 1.4°$ area on the sky centered at right ascension 10:00:28.60 and declination +02:12:21.0 (J2000). Because the FIRST image cutout server does not deliver images larger than 1024×1024 pixels, to examine the FIRST detections over a substantial fraction of the COSMOS field, you will need to extract four separate images and analyze them jointly. Using these online resources, you should do the following:

1. Determine the coordinates of the four positions at which you would need to extract 1024×1024 pixel FIRST images in order to cover the inner $1° \times 1°$ of the COSMOS field. (This inner region represents about half of the total area of the COSMOS field.) Make sure not to forget the $\cos\delta$ correction for separations in right ascension.

2. For these four positions, use the "Retrieve Image Cutouts" tool to download FITS files of the FIRST images. (You will need to set "Image Type" to "FITS File," and you need to make sure to set the "Equinox" to J2000. Warning: this tool can be finicky. Even if you are confident in the coordinates you selected for your four positions, the output images may have an unexpected appearance. If this happens, set "Image Type" to GIF so that can quickly view the output images in-browser and increment your RA and dec by a few arcminutes multiple times and see how the extracted image responds.)

3. Within the inner $1° \times 1°$ of the COSMOS field, identify every radio source whose peak flux density is $\geq 3\times$ the RMS noise in the field, and determine whether it is (a) spatially resolved, or (b) spatially unresolved. For sources with spatially resolved detections, determine whether you can identify any notable morphological classes (e.g., compact doubles vs. jets vs. lobes).

4. For each FIRST $\geq 3\sigma$ detection, determine its total 1.4 GHz flux density. To do this, you will need to add up the brightness values all of the pixels that you feel show emission, then divide that sum by the number of pixels per (synthesized) beam, which is
$$\frac{\pi}{4\ln 2}\frac{a \times b}{\Delta x \times \Delta y} \tag{1}$$
in terms of beam major axis a, beam minor axis b, and pixel size $\Delta x \times \Delta y$ (all information contained in the FITS file header).

5. For each FIRST $\geq 3\sigma$ detection, determine the distance on the sky (in angular units) to its closest neighbor among your other FIRST $\geq 3\sigma$ detections.

6. Determine whether there are any patterns or relationships among 1.4 GHz flux density, 1.4 GHz morphology, and distance to nearest 1.4 GHz neighbor within the COSMOS field. (This question has deliberate open-ended phrasing — there may or may not be patterns or relationships that emerge when you do a little exploring!)

7. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How might light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?

Physics 346 – Spring 2021
Project # 3: FIRST sources in the MUSYC 1030+05 field

The Faint Images of the Radio Sky at Twenty-cm (FIRST) survey (Becker, White, & Helfand, 1995, ApJ, 450, 559) was conducted using the Very Large Array (VLA) over a period from 1993 through 2011, and over a combination of two areas on the sky:

- right ascension $7.0 \leq \alpha \leq 17.5$ and declination $-8.0 \leq \delta \leq +57.6$ (B1950)
- right ascension $20.4 \leq \alpha \leq 4.0$ and declination $-11.5 \leq \delta \leq +15.4$ (B1950)

The images produced by the survey have $1.8'' \times 1.8''$ pixels, $\sim 5''$ resolution, and a typical 1σ RMS noise of 0.15 mJy. Full information about the survey and tools for accessing its images are available at http://sundog.stsci.edu/.

For this project, you will be examining FIRST detections within the footprint of the 1030+05 field of the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006, ApJS, 162, 1), whose public data release can be found at https://www.physics.rutgers.edu/~gawiser/MUSYC/ . MUSYC used the CTIO4m+MOSAIC to image four $30' \times 30'$ fields. The FIRST image cutout server does not deliver images larger than 1024×1024 pixels, so you might need to extract multiple images and analyze them jointly. Using these online resources, you should do the following:

1. Determine the coordinates of the position(s) at which you would need to extract 1024×1024 pixel FIRST images in order to cover the $30' \times 30'$ MUSYC 1030+05 field. You might need to use the $\cos\delta$ correction for separations in right ascension.

2. Use the “Retrieve Image Cutouts” tool to download FITS files of the needed FIRST image(s). (You will need to set “Image Type” to “FITS File,” and you need to make sure to set the “Equinox” to J2000. Warning: this tool can be finicky. Even if you are confident in the coordinates you selected, the output image(s) may have an unexpected appearance. If this happens, set “Image Type” to GIF so that you can quickly view the output images in-browser and increment your RA and dec by a few arcminutes multiple times and see how the extracted image responds.)

3. Within the MUSYC 1030+05 field, identify every radio source whose peak flux density is $\geq 3\times$ the RMS noise in the field, and determine whether it is (a) spatially resolved, or (b) spatially unresolved. For sources with spatially resolved detections, determine whether you can identify any notable morphological classes (e.g., compact doubles vs. jets vs. lobes).

4. For each FIRST $\geq 3\sigma$ detection, determine its total 1.4 GHz flux density. To do this, you will need to add up the brightness values all of the pixels that you feel show emission, then divide that sum by the number of pixels per (synthesized) beam, which is

$$\frac{\pi}{4\ln 2}\frac{a \times b}{\Delta x \times \Delta y} \tag{1}$$

in terms of beam major axis a, beam minor axis b, and pixel size $\Delta x \times \Delta y$ (all information contained in the FITS file header).

5. For each FIRST $\geq 3\sigma$ detection, determine the distance on the sky (in angular units) to its closest neighbor among your other FIRST $\geq 3\sigma$ detections.

6. Determine whether there are any patterns or relationships among 1.4 GHz flux density, 1.4 GHz morphology, and distance to nearest 1.4 GHz neighbor within the MUSYC field. (This question has deliberate open-ended phrasing — there may or may not be patterns or relationships that emerge when you do a little exploring!)

7. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How might light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?

Physics 343 – Spring 2021
Project # 4: Galaxy Colors in the MUSYC 1030+05 Field

In the early 2000s, the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006, ApJS, 162, 1), used the CTIO4m+MOSAIC to image four $30' \times 30'$ fields in the $UBVRIz$ optical filters, with additional data gathered from other telescopes and instruments. Full information about the survey and links to its images are available at `https://www.physics.rutgers.edu/~gawiser/MUSYC/`.

For this project, you will be using the SExtractor (pronounced "ess-extractor") package to create source catalogs and galaxy color magnitude diagrams for one of the MUSYC fields. Documentation for SExtractor (as well as the package itself) can be found at `https://www.astromatic.net/software/sextractor`; it will be installed on a publicly accessible computer for those of you who cannot install it on your own. Using these online resources, you should do the following:

1. Download the images of the MUSYC **SDSS1030+05** field. You will need to click on the "Data Release" link at the main website and then grab the appropriate files.

2. Choose a suitable "detection" image and run SExtractor on it to generate a catalog of sources. Compare the resulting catalog of sources to the original image to assess whether your extraction parameters worked as you expect, and tweak as needed. (Note that no matter how you tweak the input parameters for SExtractor, there may be some "sources" — e.g., near the edges of the image — that are clearly not real.)

3. For each object in the catalog, determine on the basis of its "stellarity index" (which can be calculated by SExtractor) whether it is a galaxy or a star/quasar.

4. Once you are satisfied with the quality of your detected catalog, run SExtractor in dual-image mode with your chosen detection image but now using the R-band image as the measurement image. This will generate R-band photometry for your catalog.

5. For all sources identified as galaxies, generate a histogram showing number of objects vs. magnitude (in bins that are 1 mag wide). Are there any noteworthy patterns in this plot?

6. Use SExtractor in additional dual-image mode runs to obtain U and V-band photometry for the same catalog of objects. Make a UVR color-color diagram and a $U - R$ vs. R color-magnitude diagram. Do the stars and galaxies separate clearly on either plot? Are any other interesting patterns present?

7. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How might light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?

Physics 343 – Spring 2021
Project # 5: Galaxy Colors in the MUSYC ECDF-S Field

In the early 2000s, the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006, ApJS, 162, 1), used the CTIO4m+MOSAIC to image four $30' \times 30'$ fields in the $UBVRIz$ optical filters, with additional data gathered from other telescopes and instruments. Full information about the survey and links to its images are available at `https://www.physics.rutgers.edu/~gawiser/MUSYC/`.

For this project, you will be using the SExtractor (pronounced "ess-extractor") package to create source catalogs and galaxy color magnitude diagrams for one of the MUSYC fields. Documentation for SExtractor (as well as the package itself) can be found at `https://www.astromatic.net/software/sextractor`; it will be installed on a publicly accessible computer for those of you who cannot install it on your own. Using these online resources, you should do the following:

1. Download the images of the MUSYC **ECDF-S** field. You will need to click on the "Data Release" link at the main website and then grab the appropriate files. (Note that most of the optical images of this particular field were reprocessed by MUSYC from publicly released GaBODS images taken with the ESO 2.2m+WFI.)

2. Choose a suitable "detection" image and run SExtractor on it to generate a catalog of sources. Compare the resulting catalog of sources to the original image to assess whether your extraction parameters worked as you expect, and tweak as needed. (Note that no matter how you tweak the input parameters for SExtractor, there may be some "sources" — e.g., near the edges of the image — that are clearly not real.)

3. For each object in the catalog, determine on the basis of its "stellarity index" (which can be calculated by SExtractor) whether it is a galaxy or a star/quasar.

4. Once you are satisfied with the quality of your detected catalog, run SExtractor in dual-image mode with your chosen detection image but now using the R-band image as the measurement image. This will generate R-band photometry for your catalog.

5. For all sources identified as galaxies, generate a histogram showing number of objects vs. magnitude (in bins that are 1 mag wide). Are there any noteworthy patterns in this plot?

6. Use SExtractor in additional dual-image mode runs to obtain U and V-band photometry for the same catalog of objects. Make a UVR color-color diagram and a $U - R$ vs. R color-magnitude diagram. Do the stars and galaxies separate clearly on either plot? Are any other interesting patterns present?

7. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How might light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?

Physics 346 Project 6

Measuring the Transit of an Exoplanet

Text Reference: *Birney, Gonzales, & Oesper* Chapter 10†

Purpose: The discovery of planets that orbit other stars is one of the most exciting recent discoveries in astronomy. One powerful technique to discover and determine the properties of exoplanets is to measure the dimming of a star as a planet transits in front of it. Such measurements can be carried out with modest-sized telescopes like the 0.5m Schommer Observatory telescope on the roof of Serin.

*For this remote course, we have preserved the observing checklist (**sections I and II**) in these instructions to give you some feel for the process involved in obtaining your exoplanet transit data. This will provide you with some background resources for exoplanet observation and will give your data files some context. <u>To begin your data analysis, proceed to **section III**.</u> Although this project appears long, the process of extracting photometric data from a series of images is quick and straightforward with RUPhAst; the intention is for you to spend most of your effort interpreting the exoplanet transit light curve (**section IV**).*

I. Preparation for Observing:

The observing for this lab is time-critical since your chosen transit occurs at a specific time and ideally we want observations before, during, and after the transit. Thus, it is very important that you show up for your lab period on time and well prepared. This will require some collaborative effort with your lab-mates *before* the lab period. Since the transits typically last from 1 to 3.5 hours, if there are two periods that night, the two groups should work together in choosing the target star and taking the data.

1. Use the Exoplanet Transit Database website (http://var2.astro.cz/ETD/ − also linked to the class website) and use the menu near the top to go to the *Transit predictions* page. Select the date of your observing night. You will probably be asked for the east longitude (285.5 degrees) and latitude (40.5 degrees) of our observatory. The page will then display the transits happening that night for our location. In collaboration with your lab-mates, chose the star that you will observe using the following criteria. You may have to compromise on some of the criteria – life is rarely perfect! In your report you should discuss the reasons for selecting your target.
    a. The transit occurs during your period. Note that EDT = UT – 4 hours; thus, 23:00 UT is 7:00 PM EDT.

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†OPTIONAL text: *Observational Astronomy, 2nd edition* by Birnet, Gonzalez, & Oesper, Cambridge University Press, ISBN 978-0-521-85370-5

b. The star is bright enough to measure an accurate brightness with exposure times of about two minutes or less. This means V < 12.5 or so. Brighter is better.

c. The transit depth is 0.01 magnitude or larger. Even when the target star is bright, various systematic errors (such as the quality of our flat-fields and darks) will probably limit the accuracy of individual measurements to about 0.005 magnitude.

d. The altitude during the transit is (mostly) above 45 degrees. Observations at low altitude look through more air and are more susceptible to clouds and telescope tracking problems. Unfortunately, stars that cross the meridian during the transit (which is when they are highest in the sky!) also cause problems since the telescope needs to move over the pole when this happens to avoid running into the pier. This means that the guiding has to be re-established and with a different star, since the CCD field of view has rotated by 180°. It is usually possible to follow a star for about 20 minutes after it crosses the meridian without the telescope running into the pier. If you have a candidate transit where this would be helpful, discuss it with myself or the TA.

2. Determine how you will point at your chosen target. If the name of the star is its number in the Henry Draper (HD) catalog, then you are in luck. You can use *Find* in The Sky to locate and slew to your target. Most of the targets are too faint to be in the HD catalog. Then you will have to determine the Space Telescope Guide Star Catalog (GSC) number of the star using its RA and Dec and the finding chart provided by the Exoplanet Transit Database (click on the name of the star on your predictions page). Start *The Sky*, set the time and date to the beginning of your lab period, and click on a star with an RA and Dec close to that of your target (or use the *Move To* feature in the *Orientation* tab to go to the epoch 2000 right ascension and declination). Center that star and zoom in. The zoomed-in display will show more stars and you will be able to click on a star still closer to your target and zoom in some more. Keep this up until your see the "footprint" of the main CCD and guide CCD of our camera. You should then be able to match up the stars in the finder chart with those in The Sky and identify your target. Click on it and record its name (probably its number in the GSC).

3. Examine the stars displayed in The Sky around your target. Using the camera footprint, check that there is at least one other star in the main field of view that is similar in brightness to your target (or somewhat brighter) and so can be used as a comparison star for doing relative photometry. If no such star is available, you will have to choose a different target. Then decide what star you will use to guide with by moving the field-of-view indicator around. Remember that the guider orientation is 90° if you are observing east of the meridian and 270° if you are observing west. With the guide-star in the guide CCD, your target and comparison star should be not too close to the edge of the field of the main CCD. Good guide stars are about 10^{th} magnitude or brighter, but you may have to use a fainter one because of the small field of view of the guide CCD. If conditions are good (clear, dark skies) then stars as faint as 11^{th} magnitude will work. If no acceptable guide star is available, you will again have to choose a different target. Finally, chose a 7^{th} to 8^{th} magnitude star within a degree or so of your target with which to focus the CCD.

II. Acquisition of the Data:

In broad outline, the procedure is to set up the telescope and camera, initialize the telescope pointing, focus the camera near your target star, set up the autoguider on your chosen guide star, and then take a continuous series of images for the expected duration of the transit. The lab is written to take flat-field data at the end of the observing, but it can be taken at the beginning if time permits. Most of the steps are similar to those in the previous labs, but reminders of some of the details are provided below. Do become familiar with the steps before your observing session since getting set up on your target tends to take longer than you expect and so is hectic. To obtain a good estimate of the brightness of the unobscured target star and because the predicted start and end times can be in error, try to start taking images at least 15 minutes before the predicted start of the transit and continue until at least 15 minutes after the predicted end. Exposures will use 2×2 binning (shorter readout time) and AutoDark subtraction (more convenient) unless otherwise noted. (Multiple dark exposures are not necessary because noise from the dark current is much smaller than from photon statistics.) We will observe most of the transits through the V-band filter since the CCD is more efficient at these wavelengths than at the B or I bands and the sky is darker than in the R band. An exception is any target star brighter than about magnitude 7.5, for which exposure times are around 5 seconds or shorter. These short exposures suffer from brightness fluctuations due to atmospheric scintillation. Using the I band reduces these fluctuations (the index of refraction of the atmosphere decreases with increasing wavelength) and also slightly lengthens the exposure times due to the lower CCD efficiency.

1. Turn on the CCD system and start the *CCDSoft* program, *IDL*, and *RUPhAst* as in previous labs. On the *Setup* tab in *CCDSoft*, connect to the CCD and set the temperature 35 to 40 °C cooler than the ambient. Set up the *AutoSave* tab to save your images in a subdirectory named with the date and your initials in Astrolab:/home/ph344/lab5 (e.g., oct23tpjh). Set the *starting number* to 1 and choose a reasonable filename prefix.
2. While the CCD is cooling, open the dome and turn on the telescope controller box. Get the telescope ready to observe. The stepper-motor controller on the observing desk is used to focus the telescope by moving the secondary mirror. Turn on the encoder readout above these controls with the green button. Use the focus motion buttons on the panel below to set the encoder to a reasonable first guess at a good focus: about 0.000 mm unless your night is much warmer or cooler than previous ones (the best focus increases by about 0.100 mm for every 5 °C *decrease* in temperature).
3. Do the usual telescope initialization procedure: home the telescope, point at the zenith with the bubble levels, sync on a star near the zenith and to the right (west) of the meridian. Then slew to a bright star and refine the pointing. Center the star first in the finder with the joystick and then in the CCD field of view by taking 1-second exposures. Move the star in the CCD field using motion controls in *The Sky*. You can estimate the size of motions needed by remembering that the long axis of the CCD is oriented north/south and is about 32 arcminutes across. Don't forget to do a final *Sync* to save your pointing.
4. Slew the telescope to a 3rd magnitude or brighter star near your target star. Take a 1 second exposure and, if necessary, re-center this star and sync the coordinates.

5. Slew to your focus star and use the same procedure as in Labs 3 and 4 to focus the CCD using 1×1 binning, 5-second exposures, and a filename prefix of “focus”. Start with a full frame (*without* AutoDark subtraction to avoid the second long readout) and then click and drag a selection box in the *CCDSoft* image display to define a subframe including the focus star and a few others. Take a set of 7 exposures reading out just the subframe (*with* AutoDark subtraction), starting with the focus 0.150 mm less than the estimated optimum value and increasing the focus value in steps of 0.050 mm between exposures. Set the focus to the best value. Remember to record the value and the temperature so that it can be included in your report.

6. Slew the telescope to your target star. Set *Subframe* off, binning back to 2×2, change the filename prefix to something other than focus, and take a 5 to 20 second exposure (depending on how faint your target and surrounding stars are). Identify the field around your target star to make sure that your pointing is correct. Use aperture photometry of your target and comparison star in this test images to decide on an exposure time that will keep both at no more than 40,000 ADU (about 60% of the saturation value) at the center of their profiles. The cushion is to allow for higher central pixel values if the seeing improves. However, do not use an exposure longer than 2 minutes since this would result in loss of time resolution.

7. To set up the guider, select and move the red field-of-view indicator in *The Sky* to match the location of your test image – stars near the edge of the image are particularly helpful for this. Then use the telescope *Motion Controls* (in *The Sky*) to move your chosen guide star into the field of view of the guide CCD. This is a finicky process because of the small field of view of the guide CCD. If the star does not appear in the guider when you think it should be there, take another exposure with the main CCD and refine the location of the field of view indicator. Once you have acquired your guide star, do not immediately start guiding but instead do the next step.

8. Take a test image with your chosen exposure time to confirm that both your target and the comparison star are in the field of view (and preferably not in one of the vignetted corners of the field) and that the signal levels are what you expect. This also gets the autodark exposure taken, which is important for not disrupting the guiding, particularly for longer exposure times. This is a good time to set up a filename prefix for you transit data. Once you are satisfied with the field placement and exposure time, start guiding. The guider exposure times should be between 3 seconds, for brighter stars, to 6 seconds or so for fainter ones. Guider exposures shorter than 3 seconds tend to cause the telescope to fruitlessly chase rapid seeing-induced image motion. Exposures longer than 6 seconds make it harder for the guider to keep up with tracking errors and lengthens the gaps between images (see below).

9. Start taking blocks of 10 exposures. Use enough *Delay* between exposures so that the guider can take two images between the readout ending and the start of the next exposure. This will help the guiding settle down after the cessation of guiding during the readout of the main CCD. Continue taking blocks of images until at least 15 minutes after the transit is expected to end. Monitor the guiding to make sure that it is working OK (that clouds have not dimmed the star, for example). Remember to periodically move the dome so that the slit does not occult the telescope. Also check to be sure that the telescope does not run into the pier if the target star approaches the meridian.

10. **Acquisition of CCD Calibration Data:** Once you are done taking data for your transit, send the telescope it to the home position. Drop the link with the computer and turn off the black telescope interface box. Point the telescope horizontally by hand and close the dome shutter.
11. Turn on the dome white lights and point the telescope to a region of the inside of the dome that is unshadowed and as free of "structures" as possible.
12. Select the *AutoSave* tab. Turn *AutoSave* on and choose a filename of flat*V,* for example, if we are observing with the V-band filter.
13. **Flat field images:** Select the *Take Image* tab. Set the *Exposure Time* to 7.5 seconds, *Series of* to 7, and *Reduction* to AutoDark. Click the *Take Series* button to take seven sequential images. During these exposures, no one should move in the dome, since this can change the illumination pattern on the dome. Use the cursor on the displayed image to verify that the exposure has produced an intensity of roughly 30,000 ADU per pixel.
14. **Gain and read noise measurement:** Change *Reduction* to None and *Frame* to Bias. Take a series of two bias (zero exposure time) images.
15. Cover the telescope and point it to the zenith. End the *CCDSoft* program and turn off the power to the CCD at the plug strip in the telescope base (if this is the last data that you are taking in your lab period).
16. Finally, cover the telescope and shut everything down. Remember to fill out the log.

III. Data Analysis (differential photometry in RUPhAst):

We will use a customized version of PhAst, *RUPhAst*, on the Astrolab server to measure the brightness of the target star and a few comparison stars in all of the images. The basic steps in the process are the following:

a) Make a "flat-field" image from images taken of the inside of the illuminated dome.
b) Read science images into *RUPhAst* and use it to divide them all by the flat-field image. This removes the effect of vignetting in the camera and pixel-to-pixel sensitivity variations in the CCD.
c) Read the "flattened" images into *RUPhAst* and use its aperture photometry tool to measure the brightness of the target star and two or more comparison stars in all of the images and to write the results in a file.
d) Use a tool of your choice (Python code, spreadsheet program, etc.) to calculate the magnitude difference between your target & comparison stars and plot this *versus* time.

0. Your data were obtained by undergraduates Harry Oslislo and Adrian Casper at the Schommer Observatory on the night of Friday, 4 November 2016. They had selected the target WASP-58b beforehand from the Exoplanet Transit Database (see the entry below). Browse the *Transit Predictions* for tonight using the Schommer Observatory coordinates 40.52318 N latitude 285.53502 E longitude. Notice how many there are to choose from!

Take a look at a raw image of the target with RUPhAst, these are located in the folder */home/ph346/project6* and labeled “scienceSeries.00000###.FIT” From the image header, record the exposure time and filter Harry and Adrian selected.

OBJECT		BEGIN (UT/h,A)	CENTER (DD.MM. UT/h,A)	END (UT/h,A)	D (min)	V (MAG)	DEPTH (MAG)	Elements Coords
WASP-58 b	Lyr	23:04 59°,NW	**05.11. 0:58** **41°,NW**	2:52 23°,NW	227.81	11.66	0.0156	55183.9335+5.01718*E RA: 18 18 48.25 DE: +45 10 19.1

What time (in UT) was their first image taken? Did they manage to get the telescope on-target before the transit began? What time was their first image taken in EDT? (daylight savings ended Sunday, November 6th that year). Harry and Adrian had precious little time from the moment the first bright star was visible in the sky until the transit began!

What time was their last image taken? Did they manage, in theory, to capture the entire transit event?

Locate the finding chart for WASP-58b in the Exoplanet Transit Database (you will have to follow the link labeled “Show transit predictions for the next 365 days”). Identify WASP-58b in your image. (Hint: our 30’ × 20’ images may be rotated relative to the 15’ × 15’ finding chart. The giveaway feature for me was the distinctive “loop” of stars one-quarter from the top of the finding chart; the brightest star in the finding chart is not in our field).

Select at least two comparison stars – change Mouse Mode to *ImExam* and click on some stars that are reasonably close to your target WASP-58b and similar in brightness (brighter than the target, if possible). Record the brightness and coordinates of your target and comparison stars in your notes, you will need these soon.

1. Copy all of the CCD images from the folder */home/ph346/project6* to a project6 folder in your home area and work on these copies. Also copy the file */home/ph346/project6/ phast.conf* into your project6 folder. This configuration file initializes certain quantities in *RUPhAst*, most notably the CCD gain and readnoise. Examine the contents of this file.
2. Create a subdirectory in your *project6* folder called *flat* and move the dome flat-field images into it. The only images in your project folder should be those of the science field. This will make automatic loading of the many images possible. Note that extraneous images (i.e., focus images, set-up images, …) from the observing night have been removed, which is why the science sequence doesn’t begin at number 001. Your science and flat images have had dark exposures automatically subtracted from them during observations.

   Examine one of these flat-field images in RUPhAst with color mode. It was taken by exposing the telescope on a uniformly-bright patch of the inside of the dome. You should see darkening around the edges, this vignetting is caused by shadowing from the internal structure of the telescope. You should see “donuts” of a couple similar sizes, these are from dust particles sitting in the path of the light, most likely on the filter window. Often these features can be seen in images of the sky; we will soon learn how to remove these features.

What is the brightness near the center of the flat-field image? Henry and Adrian were aiming for a brightness of 30,000 ADU/pixel, halfway to saturated. How does the brightness near the center compare to the brightness near the darker edges? How long did they have to expose this image for their chosen filter? Does this filter match the filter they took their science data with? Record these in your notes.

3. Start IDLDE and then change the path to the folder with your flat-field files using the IDL *cd* command:

   cd, "/home/yourusername/project6/flat"

   These quotes are important, as is the comma. Use the IDL program *mkflatru* to combine your images into an average flat-field image, scaled to be close to one at its center. Call the output image something like FlatV.FIT. When combining the images, *mkflatru*, measures the average signal in the central half of each image, divides the image by this number, and then takes the median of all of these normalized images to eliminate cosmic-ray events (and stars, if these flat-fields were taken with twilight-sky).

4. At the IDL command line, cd back to your *project6* folder (*cd, ".."* will do this; the .. is a shorthand for the folder above the current one). Start *RUPhAst* and agree to the request to create an "output" directory. This directory will be created in your *project6* directory – we will make use of it shortly. Examine your final flat-field image with *RUPhAst* to check that it looks reasonable. If it does not, return to step 3 and determine what went wrong.

5. Remove all of the images loaded into *RUPhAst* (such as the final flatfield you just looked at) with *File -> Remove -> Remove all images*. Then use the menu item *File -> Read -> Read FITS directory* to load the images in your project6 folder. You should be able to just select "." in the navigation window that pops up (this is shorthand for the current directory). Adjust the brightness and contrast using the *Color* Mouse Mode and then examine the images; you can simply cycle through the images using the arrowed buttons in the upper left. Are they all well-aligned with each other? Do they all have satisfactory image quality? Why might the brightness of the sky appear to change through the series? Delete any bad images from your project6 folder and then again remove and re-read the directory of images. Record in your notes the images removed and the reasons for each removal.

   If the position of the stars in your images shift part-way through the sequence, you will need to put the sets of images with the same alignment in different subdirectories so that you can read and photometer them easily. However, wait to do this until after dividing the images by your flat-field image in the next step. For the now, just note which ranges of image sequence numbers are aligned with each other. Changes in the positions of the stars will have occurred if the observers lost and reacquired the guide star, say because of a passing cloud or because the star crossed the meridian and the telescope had to be moved to the other side of the pier.

6. Use the *Pipeline -> Batch calibrate* to bring up the "Batch image processing" window. Make sure that the "Current images" radio button is pushed and then push the *Flat* button

and select your flat-field image created in step 3. Push the *Start* button – after some time a pop-up window will announce that batch processing is complete (an hourglass cursor should appear while the processing occurs). Push the *Done* button to dismiss the batch processing window. The processing will have written the flattened images in the *project6/output/images* folder. They will be named using their original sequence numbers. Remove your original images from *RUPhAst* and then load those in the *project6/output/images* folder. The sky level in the flattened images should look reasonably uniform (at least, more uniform than the raw images). If it does not, determine what you did wrong and repeat steps 5 and 6.

7. Change back to the *ImExam* Mouse Mode. Identify the target and comparison stars and left-click on your target star to again bring up the aperture photometry tool. Look at the FWHM of the star. Set the aperture radius to twice this value (rounding up to the nearest integer). Remember to hit return in the boxes to actually enter the new value. Set the inner sky radius to a value 5 pixels larger than the aperture radius and the outer sky radius to a value 10 pixels larger than the inner sky radius. You should actually set them in the order outer-, inner-, and then aperture-radius, since *RUPhAst* insists on having these values in decreasing order. Push the button to choose the *Centroid* centering method and then bring up the *Photometry settings* window. Select output units: *Arcsecs-Magnitudes*, magnitude system: *Instrumental*, and calculate photometric errors?: *Yes*. Check that the CCD Gain is set to 1.8e^-/DN and the read noise to 15.5 e^-. Push the *Apply Settings* button to apply the new values and dismiss the window.

   Back in the aperture photometry tool, push the *Write results to file…* button and pick a reasonable name to store your photometry results in. Then push the *Do all* button. The radial profile plot will successively show the profile of your target star in all of the images. Watch to make sure that the photometry has been successful in every image (in particular, that the star does not change position so much that the centering algorithm fails). Then click on the next star you wish to photometer in the image. This will create an extra entry in your ouput file, but it is easily ignored or deleted. Push *Do all* again. Repeat this process for every star you wish to measure. Once you have photometered your target and comparison stars, close the output file by pushing the *Close Photometry File* button.

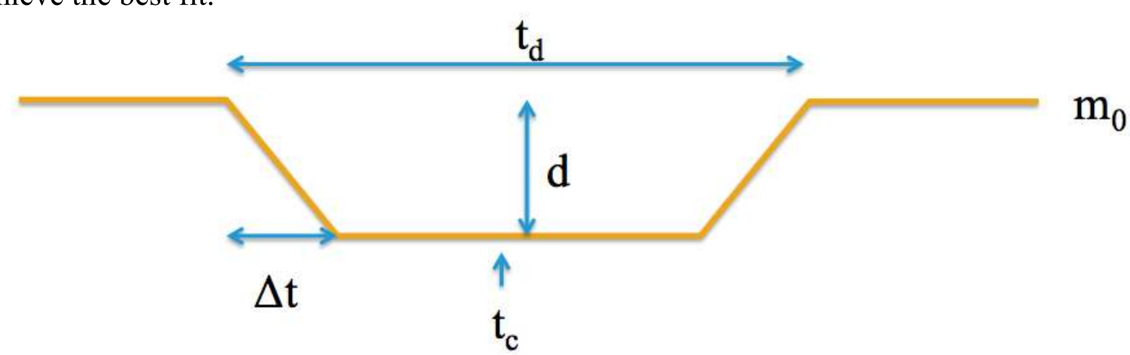
8. Examine the photometry file. The first column is the image in which the star was measured, with 0 being the first image in the *RUPhAst* stack, 1 the next, *etc*.. The next column is the Universal time of the middle of that image, calculated by adding half of the exposure time to the start time in the file header. There follows the name of the filter, the (x,y) of the centroid of the star, and the radii of the apertures used to do the photometry. Finally come the results of the photometry: the measured brightness of the sky in instrumental magnitudes per square arcsecond, the instrumental magnitude of the star, the uncertainty in the stellar magnitude, and the FWHM of the stellar profile. The instrumental magnitude is calculated with $m = 20.3 - 2.5\log((\mathrm{C/t}))$, where C is the number of counts in the aperture and t is the exposure time. The value 20.3 was chosen to make the instrumental magnitudes approximately correct for images taken in the V band with our telescope.

IV. Data Analysis cont'd (analyzing the exoplanet transit light curve):

9. Plot the magnitude of your target star and comparison stars versus time. Include the plot in your lab and comment on possible causes for any trends and features.

10. Calculate the difference between the magnitude of your target star and your comparison stars. Plot these one or more differences versus time. Do your results for each comparison star agree (you may need to add a constant to one, or more, of the differences to make the comparison)? This is one way to check whether a comparison star is itself a variable and also gives an indication of the level of any systematic errors present in the photometry (as a function of position in the image, for example). Produce a final best estimate of the *light curve* (magnitude difference *vs.* time) for the transit, by averaging your results from different comparison stars (if you have more than one).

11. Does your data show the dimming of the star caused by the transit of the planet? Estimate the depth, duration, and mid-time of the transit. Be as quantitative as you can and include your estimate of the uncertainties in these quantities. Plotting a running mean of 3 or 4 points can aid in making your estimates (be careful though, the times of observation may not be evenly spaced). Another approach is to use the simple function of time shown below and determine the parameters by least squares or by adjusting them by hand to achieve the best fit.



12. How do your values compare with those predicted by the Exoplanet Transit Database? How do they compare to results found by other observers?

13. The depth of the eclipse is a measure of the ratio of the cross-sectional area of the planet to the cross-sectional area of the star. Convert your measured depth from a difference in magnitudes into a ratio of the brightness of the star during and outside of the transit. Use this to find the ratio of the diameter of the planet to that of the star assuming that both are spherical and that the disk of the star is of uniform brightness. What is your uncertainty in this ratio? Compare your value to the ratio calculated from the stellar and planetary diameters listed for your system in the Extrasolar Planet Encyclopedia (http://exoplanet.eu/catalog/).

14. **Multiwavelength astronomy:** What data from other wavelengths would be scientifically interesting to add to the data you have analyzed here? How may light from other wavelengths help or hinder the collection and analysis of your data? What multiwavelength analyses would you like to undertake?