
LABORATORY MANUAL

—
PHYSICS 327L/328L

ASTRONOMY LABORATORY

EDITED BY

DAVID S. MEIER

DANIEL KLINGLESMTIH

PETER HOFNER

New Mexico Institute of Mining and Technology

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NMT — PHYSICS

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Chapter 1

Introduction

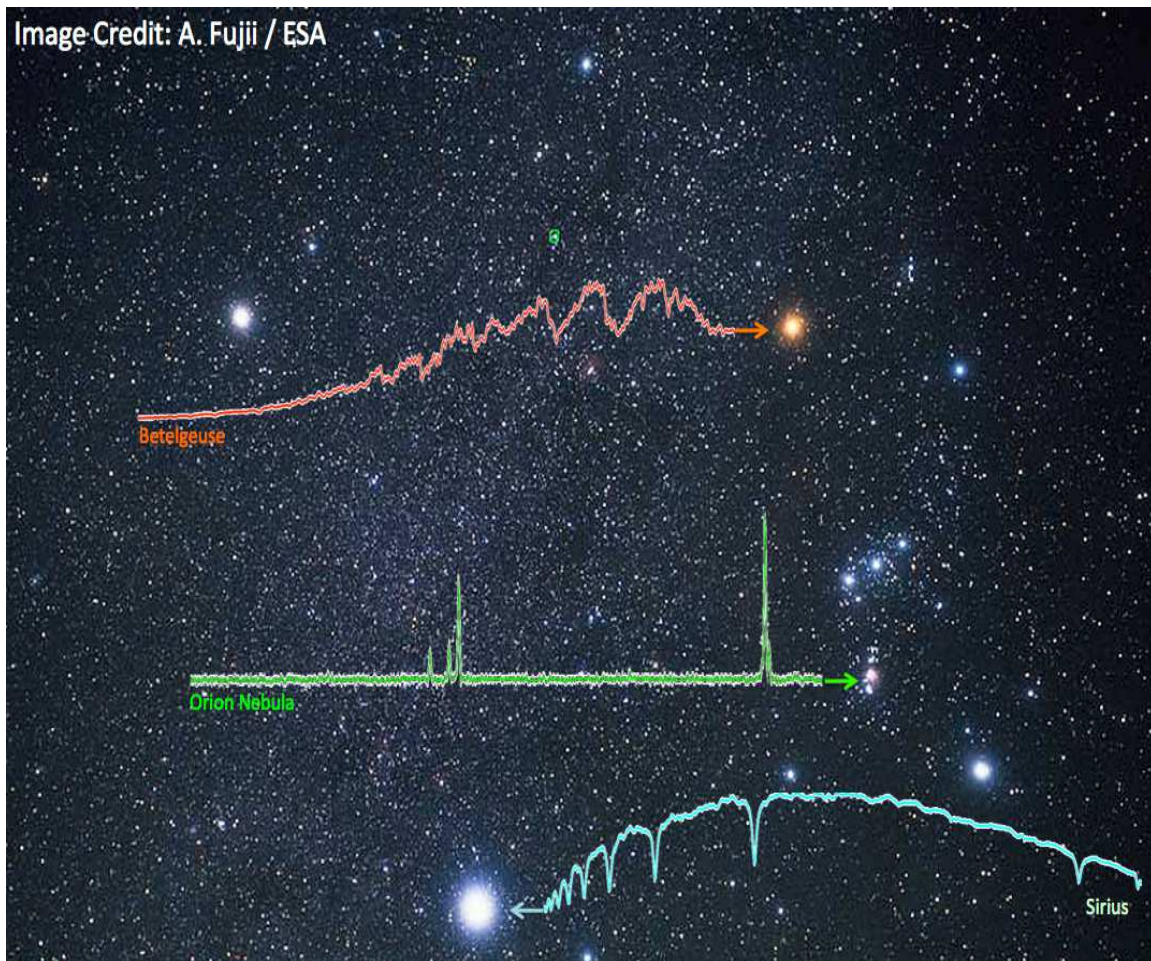


Figure 1.1: Winter Sky with optical spectra. Image credit: Hubble — A. Fujii / ESA, with optical spectra from Etsorn.

1.1 Introduction to Astronomy Laboratory

Whether one plans to be an observational, theoretical or computational astrophysicist it is important to develop skill and experience observing the sky. Observing the sky has been important not only in its own right but also in guiding the development of theoretical physics throughout history. From Babylonian times through the classical period of Greece, observations of the sky set a societies cosmology, both mythological and secular. The prediction of a solar eclipse by Thales of Miletus in the 6th century BCE was one of the cornerstone developments leading to the explanation of nature in terms of purely natural phenomena.

In the 15th - 17th centuries, scientists including Copernicus, Brahe, Kepler, Galileo, Decartes and Newton made and used observations of the heavens to begin to pin down the physical laws that govern both the terrestrial world as well as the Universe as a whole. Since this time there has been a steady and continual interplay between astronomy and physics to delineate the nature of physical law. This promises to continue to be true into the future, with the current insight that the matter that makes up the standard model accounts for only $\sim 5\%$ of the Universe.

Because of this intimate connection, even purely theoretical astrophysicists need to understand the observation process. It is vital for such students to develop experience regarding the capabilities and limitations imposed by the observing process. Without such it would be difficult to present testable predictions — the life blood of the scientific method.

In this Laboratory you will obtain an understanding of the apparent motions of the heavens by direct observation. These motions will be put in context of the true underlying motions of the Earth, Moon and solar system bodies. Once a feel for the motions of the planetary bodies and their governing laws are obtained, you will proceed to investigate astronomical aspects of these and more distant bodies. To gain further knowledge of these objects telescopes are needed. You will next be introduced to the basics of optics, imaging, CCD detection, both black & white and color, and spectroscopy. This class will not focus heavily on research-level data calibration / analysis, however basic data calibration, analysis and statistical interpretation procedures will be covered.

1.1.1 The Laboratory Manual

The Laboratory manual includes a number of different types of experiments, each requiring different equipment setups¹. Laboratory assignments overlap in material content. Therefore, it is expected that the Instructor will pick and choose assignments based on topic preference. Once expertise is acquired on the telescopes, students will push astronomical studies to fainter, more distant objects including stars and galaxies. In all assignments, the Laboratory strives to maintain a physics-based focus. That is, we must remember that our observations are in service of testing astrophysical principles. The Laboratory expects that students already have a firm freshman-level understanding of general physics and astronomy but are simultaneously developing at least a junior-level understand of astrophysics. By the end of Laboratory, it is expected that the student will have the basic skills necessary to suggest interesting astronomical observing projects, assess their instrumental demands and feasibility, and then, ultimately, be able to carry out the observations

¹The [...] after each lab in the Table of Contents indicates whether the lab includes an indoor component, [i], an outdoor component, [o], or both, [i/o].

with a minimum of 'hand-holding'.

Generally it is assumed that the student has access to a mounted, tracking, 10" - class telescope equipped with a modern amateur-astronomy quality CCD and a standard set of optical astronomical filters. Some assignments require a spectrometer. It is important when working the assignments to keep a well maintained laboratory notebook. In this notebook, the student should carefully document the observational conditions, setup, and execution strategy, as well as the actual measurements. At the top of each laboratory assignment, additional information on laboratory logistics is provided, including in particular, statements on which parts may be done in groups and which should be done individually.

Besides access to a suitably equipped telescope, a number of other astronomical resources are helpful, including smaller portable telescopes, a Sunspotter solar telescope, and optical binoculars. Other material that is worthwhile for the student to provide themselves include:

1. *Stars and Planets (current edition)* — Jay M. Pasachoff; or any equivalent sky guide
2. A red flash light
3. A compass (your cellphone may have this already)
4. A protractor (the big hobby ones are best but a standard small one and a ruler will work)
5. A notebook/pens & pencils
6. (*Recommended*) if you have a smart device, installing a planetarium app is worthwhile; there are several good ones that are free

1.1.2 Rules/Etiquette

You are responsible for the care of the equipment you use during the observations. Be respectful and careful with all equipment but especially the sensitive optics/cameras. When finished return everything back to their proper place. If you are taking your car to the observatory, please dim the lights to a low (but still safe to drive) level as you approach the observatory.

Chapter 2

Naked Eye Astronomy



Figure 2.1: Van Gogh's *The Starry Night*. Source: Wiki Commons — public domain.

2.1 Lab I: Constellations and Stellar Magnitudes [o]

For this assignment, working in small groups is permitted for the observations, however each student should do their own measurement of the constellation position and brightness and create their own sketches. Reminder: For the naked eye observations please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; time/date of the observation.

2.1.1 Constellations

The purpose of this assignment is to teach you how to find your way around the night sky. This will be done by asking you to identify several constellations and draw their locations in the sky when you observe them. This assignment may be repeated a couple of time throughout the year as the constellations that are visible changes.

2.1.2 Exercises

1) Find the following constellations in the night sky for the corresponding season (you may consult a star chart or planetarium app to help you recognize and locate the constellation, but once found you must put it away and not consult it until problems 2 - 3) are fully completed):

FALL: Cygnus, Lyra, Aquila, Cassiopeia, Pegasus and Sagittarius

SPRING: Orion, Auriga, Canis Major, Gemini, Ursa Major, and Leo

2) Draw a sketch of the constellations (only sketch the main backbone of the constellation, but attempt to include at least six stars) listed above in their correct locations at the time you observe them, on the provided sheet (Figure 2.2). Be sure to note the exact time of your observations and carefully identify the direction corresponding to North. You will use the same map for all six constellations. Pay particular attention to the relative position in the sky, the angular separations of the stars and the apparent brightness of the stars. Use the 'hand method' for estimating angular separations¹.

3) For each constellation number the six brightest stars in order of their decreasing apparent brightness. Pick the brightest star in all six constellations listed and call this star 'zeroth' magnitude. Next adopt 'fifth-magnitude' for the faintest stars you can discern. Estimate the stellar magnitudes of the other stars by extrapolating between 0th through 5th magnitude. Compare each star to the other stars and to the two limiting cases. Do not use catalog or star chart magnitudes when doing this problem. The purpose of this problem is to help you understand how to estimate stellar magnitude based on stars in the field.

¹The hand method is crude but useful tool for estimating angular separations. Hold your hand out at arms length and close one eye. The angular size projected by the width of your pinkie fingernail is $\sim 1^\circ$. 2° corresponds roughly to the width of a non-pinkie finger, 10° to the width of your fist, and 25° to the width from thumb tip to pinkie tip of a fully spread hand. Intermediate angles can be built up from combinations of these measures.

4) Once you have completed sketching the constellations and estimating magnitudes based solely on your observations consult a star chart to see how well you did. Do you notice a correlation between the naming convention of stars in the star chart and their apparent magnitude? What is it?

5) Take a piece of standard letter paper and cut out an 8"×8" square. Hold this 'window' at arms length perpendicular to the direction your are looking. Count the number of stars you are able to see through this window towards a random location in the sky. Record the number of stars and the location you are looking on the chart you drew the constellations. Repeat for at least two other random locations on the sky. Record these on the chart (Figure 2.2). Average the number of stars you see in the three measurements. Next calculate the solid angle your window projects on the sky (you will need to measure the distance from your eye to the aperture and use elementary geometry to calculate this). This will give you a measure of the stellar surface density, $\Sigma_* = (\# \text{ of stars visible}) / (\text{solid angle of the window})$. Scale this number to the 4π steradians of the full sky to obtain an estimate of the number of visible stars in the night sky; only half of which are potentially viewable at any given time of the year (if you live on the equator; fewer otherwise). Compare your numbers to the true number (look up online) and discuss differences / uncertainties.

6) The constellations that you are being given are from the western European tradition which are derived from Greek and Roman cultures. Each culture has its own stories about the sky. Find a story associated with one of the above star groups from a different culture and describe.

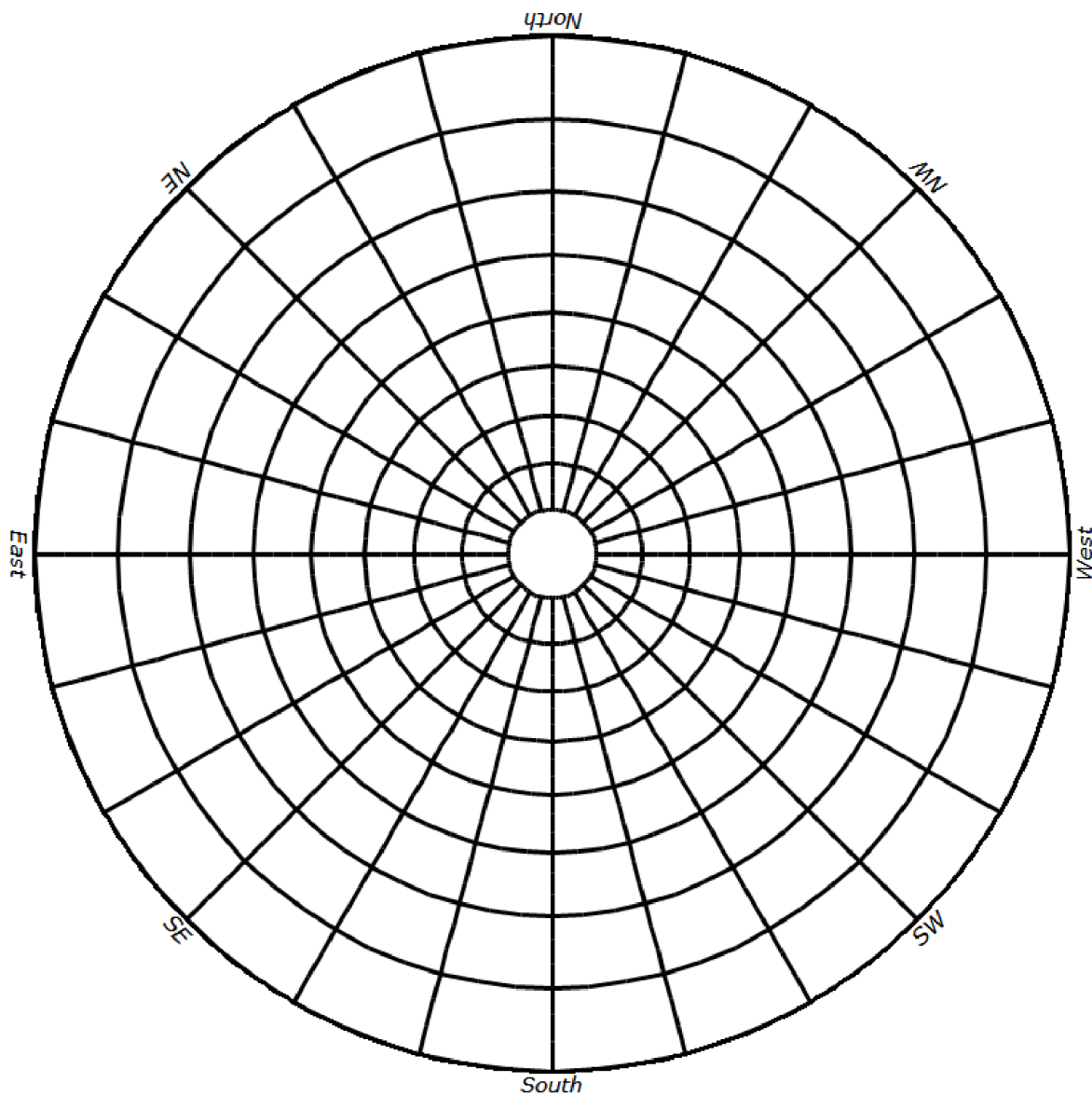


Figure 2.2: Blank sky chart onto which you are to sketch your constellations. The outer ring corresponds to the horizon. Each successive inner ring corresponds to 10° higher in altitude (see Lab 2.3). Zenith (altitude = 90° ; straight overhead) is at the center of the chart. 'Radial' lines correspond to 'hours', or 15° increments at the horizon. The separation of these lines decrease with the cosine of the altitude as you move toward zenith (e.g. these rays are converging).

2.2 Lab II: Naked Eye Constellations [i/o]

Please answer the questions in section 2.2.1 on this assignment sheet. For section 2.2.2 please attach a separate sheet(s) of paper. For the observing section (section 2.2.3) please use your notebook. *For this assignment, working in groups is not permitted.*

2.2.1 Constellation Trivia

1) Name two constellations that are visible in the evening sky (dusk - midnight) this week?

2) What constellation contains the position: Right Asc: $12^h 34^m 56^s$; Dec: $-01^\circ 23' 45''$?

3) Name a constellation that lies *directly* south of Sagittarius? (*There may be more than one correct answer.*)

4) Name one constellation that borders Andromeda?

5 - 7) The 'Summer Triangle' is an asterism that is composed of the stars Altair, Deneb and Vega. In which constellations do each of these three stars reside?

Altair _____

Deneb _____

Vega _____

8 - 9) Sirius is the brightest star in the night sky. What constellation does it reside? Sirius is often called the 'Dog Star'. Why does this 'make sense'?

10 - 13) Determine the constellation in which each of the following objects reside:

Messier 31 (M31) _____

Messier 45 (M45) _____

NGC 7000 _____

PKS 2000-330 _____

14) Suppose you are born on February 1st (birth sign: Aquarius), in what constellation does the Sun reside on that day? (*Hint: trick question.*)

15) If you look high in the sky at midnight on your birthday (assume February 1st), name at least one visible constellation.

16) In what constellation does Saturn reside on November 1st of the current calendar year?

17) From Campus, can you ever see any part of the constellation, Horologium? (Assume viewing conditions permit you to see the full hemisphere above the horizon.)

2.2.2 Constellation Report

18 - 20) Write a ~1 page report on the constellation of your choice. Include in the discussion: Where is it in the sky? When is it visible from Campus (if it is)? Does it contain any especially interesting/famous astronomical objects? If so what are they, if not what is the visual magnitude of the brightest star in the constellation? What is the history of the constellation? What is a mythology associated with the individual/object represented by the constellation (it need not be exclusively the 'Greek' myth).

2.2.3 Naked Eye Observing

Reminder: For naked eye/binoculars observations please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; and time/date of the observation.

21) Using a star chart determine what the constellation Cygnus looks like and where to look for it in the sky. Go outside on a clear evening and locate the constellation

Cygnus. Using 'hand measurements'². estimate the size of the constellation in degrees. Does your answer make sense? *Hint: Based on the number of constellations that cover the area of the celestial sphere, what would you guess is the typical constellation size.*

22 - 25) Testing your limiting magnitude: Find a location where you can (comfortably) view the constellation Cygnus for a sustained period. Carefully draw the constellation of Cygnus (or a part of it) as you see it in the sky. Draw the bright stars as well as the faint stars. Focus your attention on the stars that are just barely visible to your unaided eye. Record their positions, relative to the bright stars (which form a 'cross'), carefully so that you may identify them on a star chart afterward. I expect you to record at least a *dozen* faint stars in the Cygnus area so that you have good statistics. Once you have sketched the faint stars (please include your sketch / notebook with the assignment) consult the sky guide, a star chart or an online database to determine the visual (V) magnitudes of your faint stars. On your sketch label the name of the star and its V band magnitude. Determine what is the magnitude of the faintest stars you identify. (*Suggestions: 1) Let your eyes dark adapt for ~10 minutes before beginning; 2) try to choose a reasonably dark site to observe from; 3) a red flashlight may be helpful to see the paper to sketch; 4) the more carefully you sketch the position the more likely you will correctly identify them on a star chart.*)

²The hand method is crude but useful tool for estimating angular separations. Hold your hand out at arms length and close one eye. The angular size projected by the width of your pinkie fingernail is $\sim 1^\circ$. 2° corresponds roughly to the width of a non-pinkie finger, 10° to the width of your fist, and 25° to the width from thumb tip to pinkie tip of a fully spread hand. Intermediate angles can be built up from combinations of these measures.

2.3 Lab III: Celestial Sphere / Coordinates [o]

For this assignment, working in small groups is permitted for the observations, however each student should do their own measurement of the stellar position. Reminder: For these naked eye/binoculars observations please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; time/date of the observation.

2.3.1 Coordinate Systems

The usefulness of a coordinate system on the surface of a sphere is apparent to anyone trying to navigate the surface of the Earth. As such it makes sense to generate coordinate systems for the 'virtual' spherical surface of the sky (the celestial sphere). There are any number of ways to accomplish this but here we focus on two, the altitude-azimuth and equatorial systems.

◇ Altitude - Azimuth System:

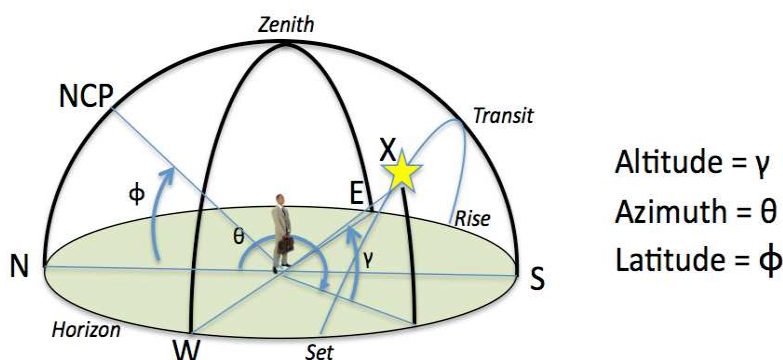


Figure 2.3: The Altitude-Azimuth system of coordinates.

The altitude-azimuth system is perhaps the simplest from the perspective of a local observer. It defines two angles on the 2-D celestial sphere (Figure 2.3). The first, altitude = γ , is the angle directly up from the nearest point on the horizon to the object (X). The second angle, azimuth = θ , is the *eastward* angle from the great circle incorporating the north celestial pole (NCP: the projection of the Earth's north pole onto the sky) and the zenith (the point directly overhead) to the objects' nearest horizon point used to determine the altitude. While this coordinate system has the advantages that it is simple and already 'in your reference frame', making it easy to locate the position of an object, it has the two main disadvantages that different observers at different locations on the Earth will assign different (γ, θ) to the same object and the stars' coordinates would change with time. It can be appreciated that this is rather problematic for the universal applicability of such a coordinate system.

◆ Equatorial System:

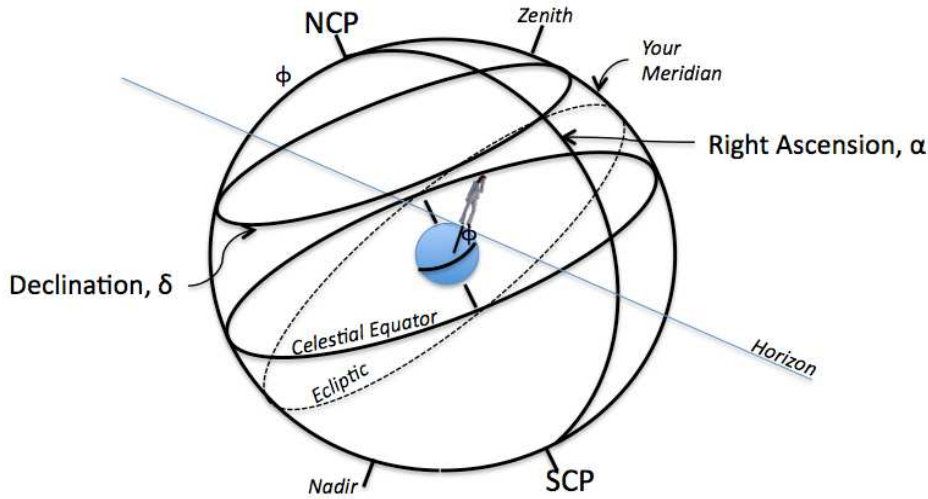


Figure 2.4: The Equatorial system of coordinates.

The other commonly used alternative is to select a coordinate system permanently attached to the celestial sphere. Here we project Earth's latitude - longitude system upward to the celestial sphere (Figure 2.4). The longitude equivalents (or meridians) are given the name right ascension, α , and are reported in hours:minutes:seconds from 0 hr - 24 hr (for reasons that will become apparent momentarily). α are great circles running through the NCP and the SCP, with the particular one running through zenith referred to as your meridian (sometimes just meridian). An object passing your meridian is said to be transiting. Also from the geometry of Figure 2.4, the altitude of the NCP (roughly the star Polaris [α UMi]) is equal to the observer's latitude, ϕ , along this meridian. Just as the zero point of the longitude system on Earth is arbitrary (currently the longitude line running through Greenwich, England), so to is the zero point of right ascension. It has arbitrarily been chosen to be the observed location of the Sun on the vernal equinox. [Note: remember that unlike the stars, the Sun appears to move across the celestial sphere. At the vernal equinox, roughly noon on March 21st (not counting DST), the Sun is at the location where the ecliptic intersects the celestial equator (Figure 2.5).] When viewed from above the north pole, α increases in the counter-clockwise (eastward) direction. Because of the Earth's rotation, the celestial sphere appears to rotate east to west in a regular fashion. Hence right ascension ticks by your meridian like a clock, hence the units (Figure 2.5, *right*).

The clock metaphor is quite good, with the following two caveats, 1) unlike typical dial clocks you are used to (if you are old enough), the hour hand (your meridian) remains fixed and the dial (right ascension on the sky) rotates clockwise (when facing south) past the hand, and 2) the clock dial has 24 hours instead of 12 hours. From this we can define a couple of time related concepts. The first is hour angle, H , which is the difference between the $\alpha(\textit{your meridian})$ and $\alpha(\textit{object})$ (– if east of your meridian, + if west). The second is local sidereal time, LST , ('star time'). LST is defined as:

$$LST = \alpha + H, \quad (2.1)$$

and corresponds to either the $\alpha(\textit{meridian})$ or the hour angle of the right ascension = 0 line. Know-

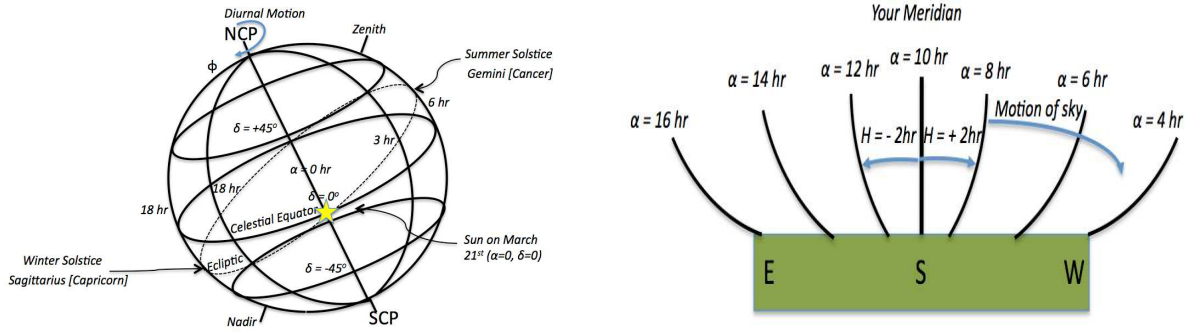


Figure 2.5: *Left)* The zero of the Right Ascension. *Right)* The right ascension system is a good metaphor of a clock, except in this case the hour hand (meridian) is stationary and the dial (the sky) rotates.

ing your *LST* and your latitude uniquely defines the appearance of the night sky.

The latitude equivalents for the sky are given the name declination, δ . They represent the projection of the Earth's latitude lines onto the celestial sphere. The projection of the Earth's equator, fittingly enough called the celestial equator, marks the zero of declination. Declination lines are parallel to the celestial equator (and hence are not great circles), with + for the northern hemisphere and - for the southern. The apparent path of the Sun across the celestial sphere is called the ecliptic and is inclined $23.^\circ5$ from the celestial equator (Figure 2.5). Therefore the position of the Sun on the vernal equinox is $(\alpha, \delta) = (00:00:00, 0)$.

2.3.2 Converting Between Systems

Since alt-az coordinates are often simpler to work with from an observational perspective, it is worthwhile gaining experience converting between the two coordinate systems. By measuring (γ, θ) and knowing ϕ , we can convert alt-az coordinates to equatorial by use of spherical trigonometry. Figure 2.6 illustrates the relevant geometry. From spherical trigonometry, with the following assumptions: 1) a triangle, with interior angles a, b, c , lying on the surface of a unit sphere, 2) all (angular) sides ABC are great circles, and 3) all sides and angles are expressed in angular units, then we can use the spherical cosine law:

$$\text{Side } B : \quad \cos(B) = \cos(A)\cos(C) + \sin(A)\sin(C)\cos(b)$$

$$\text{Side } C : \quad \cos(C) = \cos(A)\cos(B) + \sin(A)\sin(B)\cos(c).$$

Or given that $A = 90 - \phi$, $B = 90 - \delta$, $C = 90 - \gamma$, $a = \text{parallactic angle}$, $b = 360 - \theta$, and $c = H$:

$$\sin(\delta) = \sin(\phi)\sin(\gamma) + \cos(\phi)\cos(\gamma)\cos(\theta), \quad (2.2)$$

and

$$\cos(H') = \frac{\sin(\gamma) - \sin(\phi)\sin(\delta)}{\cos(\phi)\cos(\delta)}, \quad (2.3)$$

where H' is the hour angle expressed in angular units. Equation 2.2 can be used to obtain the declination, δ , once you have measured the altitude and azimuth of the object (γ, θ) . Once you have

δ , equation 2.3 can give you H (H'). Next you can get LST , by remembering that $LST=00:00:00$ at noon on March 21st and shifts forward $(24/365)$ hr per day and 1 hr per hr on a given day. [Example: $LST(\text{Nov 4th @ 6 pm}) = (227/365) \times 24 \text{ hr} + 6 \text{ hr} = 20 \text{ hr } 56 \text{ m}$ — do not forget to account for daylight savings time if applicable.] Equation 2.1 can then be used to find α given H and LST . Using other spherical trigonometric relations it is possible to develop the reverse conversions (get γ, θ from α, δ) but we will not focus on it here. (If you care to try to calculate the relations, use eq. 2.3 to solve for γ instead of H , and use the sine rule to get θ in terms of H, δ and γ).

2.3.3 Exercises

Given this long-winded introduction, the goal of the assignment is to measure the γ, θ of a star at a given (sidereal) time and from that derive the α, δ and compare to catalogs to verify your accuracy.

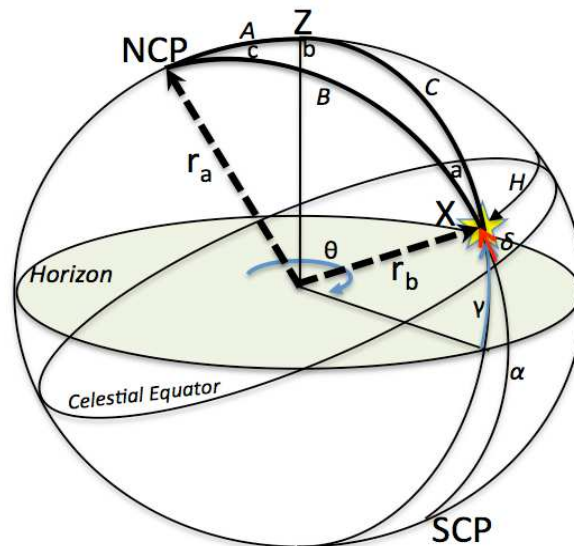


Figure 2.6: The spherical trigonometry relevant for converting between alt-az and equatorial coordinate systems.

- 1) **Locate Polaris (the tail star of the Little Dipper).** Measure the angle from the northern horizon to Polaris. Assume this gives ϕ , the latitude of the observations. To do this you will need a compass to locate north-south so that you may determine your meridian and a protractor (angle measuring device) in order to determine ϕ . Compare to the true value (Google Earth is very convenient for this).
- 2) **What is δ for an object at zenith?**
- 3) **Locate some object in a sky chart that appears to be on your meridian.** Record its (α, δ) . Calculate the α of the meridian given the LST . Is α of your object equal to the α you calculated? Discuss any discrepancies.

- 4) Locate a bright star towards the southern sky. Identify the star, then measure and record its altitude, γ and its azimuth θ at a given time. Draw a sketch similar to Figure 2.3, for your star and label your measured angles.
- 5) Calculate the right ascension and declination of your chosen star from your measurements. Look up its α, δ and discuss any discrepancies (both measurement and associated with incorrect/inaccurate assumptions.)
- 6) Calculate the azimuth of the chosen star's rise. Assume α and δ are [now] known quantities (hint: what is γ for an object just rising?). Determine the clock time of its rise (hint: since it is up in the sky your answer should be before the current clock time.)

2.4 Lab IV: Earth - Sun - Moon System [o]

For this assignment, working in small groups is permitted for the observations. Reminder: For these naked eye / binoculars observations please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; times/dates of the observation.

The coupled motions of the Earth and Moon lead to a number of important observed effects for the Earth-Sun-Moon system. These motions are of fundamental importance for wide range of subjects, including the appearance of the day/night sky, our place in the solar system, Earth's seasons/weather, our system of timekeeping, and even to humanity's socio-political structure. In this assignment you will mix theoretical calculations with careful observations of the Sun/Moon/Stars to better understand the important Earth-Moon cycles.

2.4.1 Sidereal vs. Synodic Period

The apparent motions of the Sun and stars across the sky are due to the complex motion of the Earth, including rotation, revolution and precession of the axis. To reasonable approximation orbits are circular. The subtleties come from the coupled nature of the motion. Because of this there are multiple definitions of key times like the day, month and year, depending on the point of view adopted. Take the day for example. There are (at least) two different definitions of the day, 1) the sidereal day — the time it takes for the Earth to rotate 360° on its axis relative to the distant stars, and 2) the solar day — the time it takes the Sun to go from on the meridian back around to the meridian again. Since the Earth revolves while it is rotating, these two times differ. The hour is defined as $1/24$ th of a solar day, so a solar day is exactly 24 hours long. For the Earth, both rotation and revolution are counter-clockwise as viewed from above the north pole. Hence the Earth must rotate through a little bit extra angle to get a given spot on the surface of the Earth pointing back toward the Sun (Figure 2.7). By geometry the extra amount of time required to cover this extra angle is, $\Delta t = (1 \text{ day}/365.2422 \text{ day}) * 24 \text{ hr} = \simeq 4 \text{ min}$. Therefore the sidereal day is shorter than the solar day by Δt or $\simeq 23^h 56^m$.

Since our clocks are synchronized to repeat (twice) after 24 hours, if we return to look at the sky at the same exact clock time the next day, the stars will appear to have moved 4 minutes westward. Or stars in the sky appear to rotate at a sidereal rate of 1° (well more technically $\frac{360}{365.2422}^\circ$) westward per solar day. This is in comparison to the apparent rotation rate of stars on a given day due to Earth's rotation of $(1 \text{ hr}/24 \text{ hr}) * 360^\circ = \simeq 15^\circ$ per hour.

Similar effects influence the other cyclic times when multiple sources of rotation are coupled. For the Moon, the sidereal month is, again, the time it takes for the Moon to complete one orbit relative to the distant stars. The Synodic or Lunar month is the time for the Moon to cycle through its phases (e.g. return to the same Earth-Moon-Sun relative geometry).

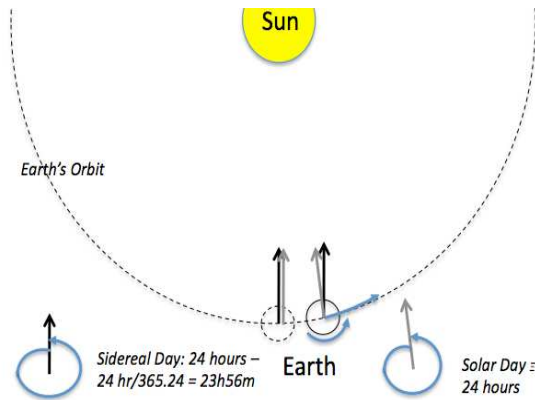


Figure 2.7: Due to the extra counter-clockwise revolution of the Earth around the Sun, the Earth must rotate an extra $\simeq 1/365$ fraction of a circle ($\simeq 4$ min) to return the Sun to the meridian.

2.4.2 Moon Phases

We are all aware that the position of the Sun in the sky is a (reasonably) accurate clock (in fact, historically, the first good clock). This clock is not exact (consider the solar analemma), but sets the basis of the day. Moon phases result from the relative geometry of the Earth - Sun - Moon system (Figure 2.8). A combination of the position of the Moon and its phase will tell you where the Sun is and hence can be used to tell time (even at nighttime).

As a simple example consider the Full Moon. The fact that the phase of the Moon is full indicates that the Sun is 180° away from the Moon. So if the Full Moon is on your meridian, then it is local midnight (e.g. the Sun is at the Nadir). This, of course, does not include humanity's changing of clock time, for example Daylight Savings Time, and other subtle effects you are to contemplate in problem 9). For the case when the Moon is not at your meridian then you must remember the rate at which the Moon (and stars) appear to 'rotate' across the sky. For example, in our Full Moon case, if the Full Moon was at an hour angle of -2 hours (towards the east) then

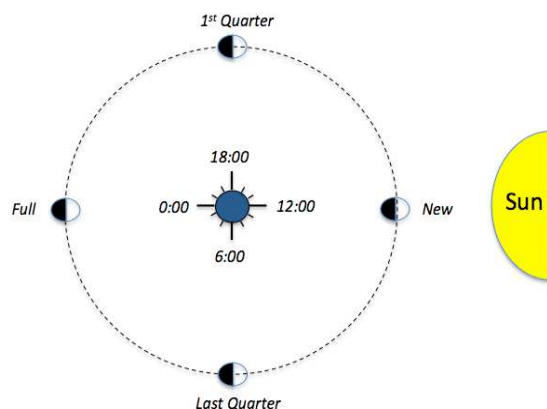


Figure 2.8: The geometry of the Earth - Moon - Sun system for determining Moon phases. If you are standing on the Earth's surface at the location of the tick mark and the corresponding Moon phase is on your meridian, then the clock time is given.

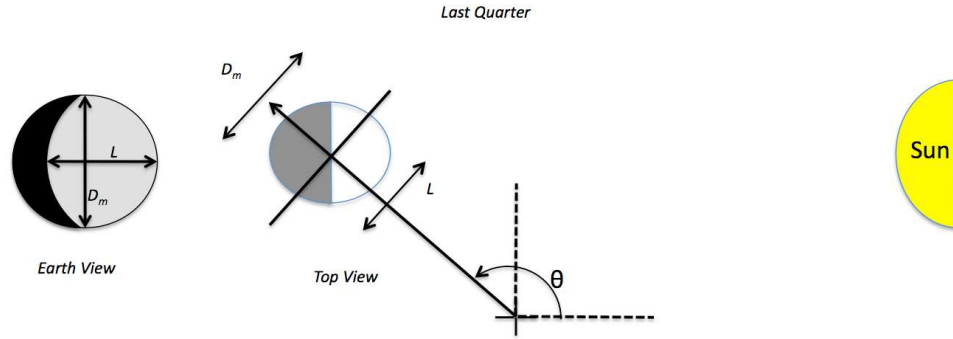


Figure 2.9:

the Moon is 2 hours from reaching meridian, hence the Sun is 2 hours from reaching Nadir. So your clock time must be 10pm.

2.4.3 Exercises

In this assignment you will observe the sky to confirm the above discussed motions.

1) Find a bright star on your meridian. (How do you know if the star is on the meridian?) Record your ground position and exact clock time/date. Now wander off and have a good time. Return to your spot *exactly* 1 hr later, find the star and measure the angle off your meridian, including direction and an estimate of your uncertainty, (this is the Hour Angle: + to West, - to the East). From your measurements estimate by how much the stars appear to move in a 1 hour period due to the rotation of the Earth? Discuss whether your answer conforms to what you expect given your uncertainties. You will need to be cognizant of the declination of the source in this measurement. A choice of a star with $\delta \simeq 0^\circ$ will generally make the measurements easier.

2) Find a bright star on your meridian — it makes sense to use the same one you adopted in problem 1). Record your ground position and exact clock time/date (or use those from problem 1). Now come back to this exact same spot at the same time between 2-4 days later (depending on weather for example) and measure the angle off the your meridian. Repeat the above after waiting between 8 - 12 days and after approximately one month. From your measurements estimate by how much do the stars appear to move in a 24 hr period, due to the difference between the sidereal and solar day? Discuss whether your answer conforms to what you expect given your uncertainties.

3) Following arguments analogous to the sidereal / solar day, sketch the geometry of the Earth-Moon-Sun system necessary to calculate the synodic (lunar) month, given that the sidereal month is **27.3217 days**. Include at least two (important) positions of the Moon in the diagram (as is done in Figure 2.7 for the day). The Moon also revolves counter-clockwise when viewed from above Earth's north pole.

4) Using your sketch calculate the length of the synodic (lunar) month. Do you best to get four significant digit accuracy, so you will need to carefully think about the geometry.

5) Use two lunar eclipses, which to good approximation meets the requirement of the Moon having the exact same phase, to determine the Synodic month. (You may find lists of lunar eclipses in a sky guide or online. Try selecting lunar eclipses that are roughly a year apart.) Also look up the true Synodic month in a reference. Discuss the accuracy of your measurement and possible reasons for any discrepancies between the three numbers.

6) The Moon is tidally locked to the Earth (the same 'face' of the Moon always points toward Earth). What is one 'lunar' day on the Moon (analogous to a 'solar day' on Earth; e.g. Sun directly overhead to the next time the Sun is directly overhead when standing on the Moon)? Explain why.

7) If you go out (in the northern hemisphere) at 3 am and see a gibbous moon high in the southern sky, is it a Waxing or Waning gibbous? Explain your reasoning.

8) Observe the Moon's phase over a period of at least one lunar month. You need not observe every night but you should have at least *six* measurements dispersed throughout this period. For each observation make sure to record the time you did the observation, the position of the Moon in the sky (altitude-azimuth) and the phase (percent illuminated). Be as precise as you can for the Moon phase. Here binoculars might be helpful in seeing precisely where the terminus of the shadow occurs on the Moon. But this is not required (your answer for the the next part will be more precise if you are careful). Sketch the phase of each observation in your notebook.

Figure 2.9 assists you in determining the relative phase/geometry for case when the Moon is not in an obvious phase, like first or third quarter. If you carefully locate the shadow terminus on lunar features then you can consult a Moon map to accurately determine the angular extent of the illuminated portion, L , as compared to the true angular diameter, D_m . The ratio $L/D_m = \frac{1}{2}(1 - \cos\theta)$. This gives θ , the angle from the New Moon geometry as illustrated in Figure 2.9 (noon if the New Moon is at your meridian).

9) For *two* of your measurements, use the phase of the Moon together with its position on the sky to calculate the clock time (do not forget to account for daylight savings time if applicable). Compare this to your recorded clock time. Discuss any discrepancies.

2.5 Lab V: Lights and Light Pollution [o]

For this assignment, working in small groups is permitted for the observations, however each should turn in their own list. Please record the members of your observing 'team' and their individual responsibilities.

2.5.1 Lights

One of the key culprits for decreased enjoyment of the splendor of the night sky is light pollution. Because so many of us live in cities light pollution is a major concern. However, some things can be done to minimize light pollution by controlling the type and shielding lights have.

In this assignment we will judge the quality of lights on the campus from a perspective of light pollution. The provided "Night Spectra Quest" packet contains a small diffraction grating that will allow you to determine the type of light source you are observing. The types of lamps that you might find around campus are listed on the back of the card. You might want to make a copy of the that list so you don't need to keep turning the card over and over. By the time you are done with this project you should have memorized the spectra of the various lamps. In order to see a spectrum when looking through the grating you need to hold the card horizontal, length parallel to the ground, and look through the hole at the light. The spectrum will appear either to the left or the right.

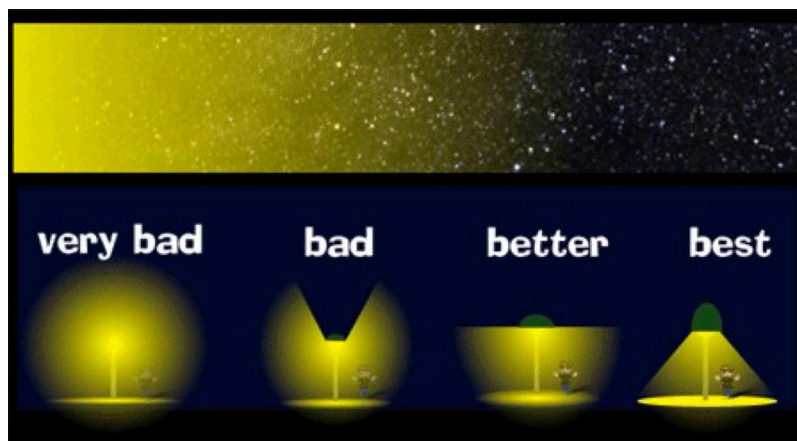


Figure 2.10:

You will be given map of campus with a selected portion highlighted. Your mission, if you accept (and if assigned you have no choice), is to count the number of each type of light source either on a pole or attached to a building in your selected territory. You do not need to count light sources coming from inside a building. Looking at the spectra on the back of the card you can see that the lights that gives off the least amount of light are the low pressure Mercury and Sodium vapor lamps. Basically they have no continuum light. The other important factor in reducing light pollution is how the light is projected. Figure 2.10 gives you examples of different quality light projection schemes.

A number of locations have lighting requirements on the books that mitigate against light pollution. Sometimes they are because you live in an astronomically sensitive environment. But having lighting that does not pollute are preferred for reasons beyond just their benefits to astronomers. For example, they are much more efficient at illuminating the ground (and not the sky), so they are better from both an economic and public safety perspective.

2.5.2 Exercises

1) The goal of this assignment is for each student to develop a list of the types of lights, how many of each kind and the quality of the shield in their designated region. Mark locations on the map for each light source. Label each light source with the following label (a-j)/(1-4). The letters a - i would come from the card. And the letter "j" would stand for other types of light not on the card. For the shield parameter, "1" is the worst and "4" is the best. For a light source on a building that is not pointed down you could use "5". If you have a cell phone camera, documenting the lights, particularly the worst culprits, may be done

2) Include a short ($\sim 1/2$ page) summary of the lights in your section of campus. Review, briefly, what the local regulations are for lighting / light pollution in your area. What are the commonest types of lights in your region? Are they well designed or bad light polluters? Do they generally conform to the regulations? Which lighting types do you personally feel do the best job of safely illuminating the area? Are areas overlit? Underlit? For those who live off campus, you might briefly try the same experiment in your neighborhood. Are the results different from campus? How so?

Chapter 3

Telescopic Techniques



Figure 3.1: Etscorn Observatory.

3.1 Lab VI: Introduction to Telescopes / Optics [i/o]

For this assignment, working in small groups is permitted for the observations. Reminder: For any naked eye/binoculars/telescope observations done, please record the details of your observation in your Laboratory Notebook. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; time/date of the observation; telescopic/eyepiece parameters; and the members of your observing 'team'.

3.1.1 Simple Astronomical Refracting Telescope

Simple astronomical telescopes are (can be) built of two converging lenses, typically one of long focal length known as the 'objective, (with focal length, f_{ob}) and the second of short focal length known as the eyepiece (with focal length f_{ep}), separated by a distance, $f_{ob} + f_{ep}$. (Note: The so-called 'Galilean telescope' design is made of one converging and one diverging lens.) Figure 3.2 displays the geometric setup of a simple astronomical refracting telescope. We see that this lens combination acts to angularly magnify and invert the image of a object, with angular magnification given by:

$$m \equiv \alpha' / \alpha,$$

where α and α' are the angles given in Figure 3.2.

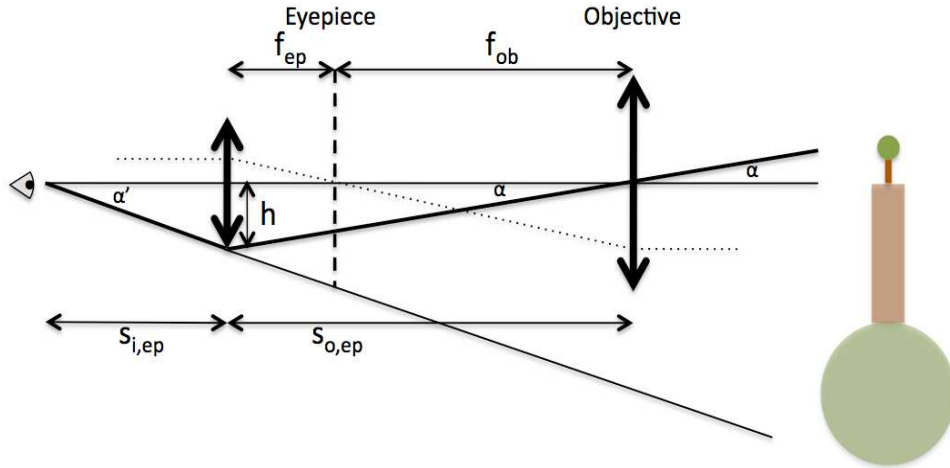


Figure 3.2: A simple astronomical refracting telescope. The $\updownarrow$ is a shorthand notation for a converging lens. The simple astronomical telescope is an inverting instrument.

From the leftmost triangle we see that in the small angle approximation $\alpha' \simeq h/s_{i,ep}$. From the central triangle we further see that $\alpha \simeq h/s_{o,ep} \simeq h/(f_{ob} + f_{ep})$. Making use of the basic lensmaker's equation: $1/f_{ep} = 1/s_{i,ep} + 1/s_{o,ep}$, it can be demonstrated that $m = f_{ob}/f_{ep}$. Namely for a given eyepiece focal length, f_{ep} , a long objective focal length, f_{ob} leads to high magnification, while for a given objective focal length, a short eyepiece focal length leads to high magnification. Furthermore, the 'f-ratio' (written f/N) can be defined as, $f/N \equiv f/f_{ob}/D_{ob}$, where D_{ob} is the diameter of the objective lens. The f/N is solely of function of the design of the objective lens. For example, if $f_{ob} = 1.0$ m, $f_{ep} = 10$ mm and $D_{ob} = 0.1$ m, then the objective has an f-ratio of "f/10". For a given D_{ob} , bigger

f/N imply high magnification, while for a given f_{ob} , bigger f/N imply smaller light grasp (see below).

3.1.2 Schmidt-Cassegrain Telescopes

Many of the telescopes you will use are not simple refracting telescopes, but the above concepts can be fairly easily adapted to apply. For simple (Newtonian) reflecting telescopes the focal length of the objective is just the distance from the mirror to the focus point of the converging (or diverging) rays. The most commonly used 10"-class telescopes are Schmidt-Cassegrain telescopes. The focal path of Schmidt-Cassegrains are folded and so a bit more complex. *Here we just use its reported focal length as f_{ob} .* However it can be determined from the optics of the mirrors, with f_{ob} corresponding to extending the converging rays from the secondary lens back along the line until they reach the diameter of the telescope, D_{ob} . Geometry (not derived here) gives $f_{ob}^{SC} \simeq f_m f_b / (f_m - d)$, where f_m is the focal length of the primary mirror, f_b is the distance between the secondary mirror and the focal plane, and d is the distance from the secondary mirror to the primary mirror.

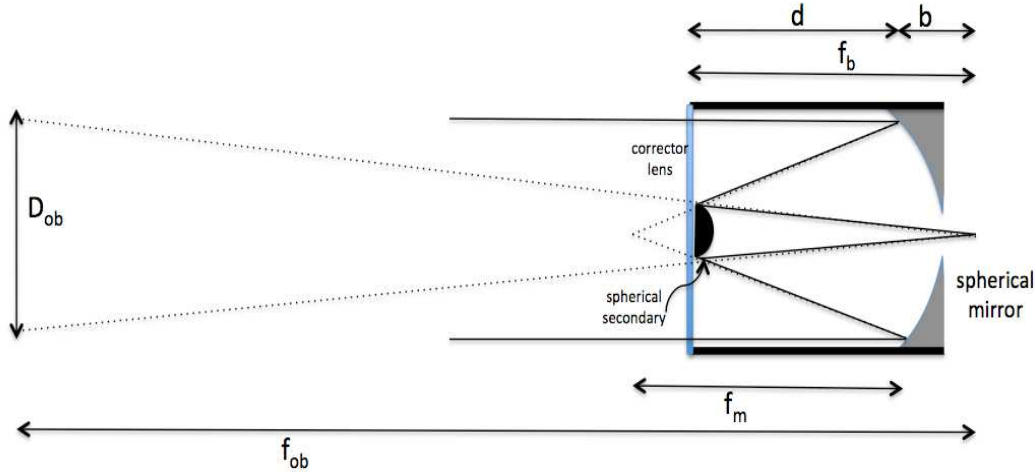


Figure 3.3: Schematic of a Schmidt-Cassegrain, with its focal length drawn.

3.1.3 Important Optical Parameters

There are a number of optical parameters that are important to the understanding of how successful telescopic observations are executed. These are discussed in turn.

Field of View: The field of view (FOV) of a telescope depends on its optics, both the objective and the eyepiece. To a crude approximation the FOV of the simplest eyepieces are, $FOV_{ep} \sim D_{ep}/f_{ep}$, where D_{ep} is the diameter of the eyepiece lens (or more properly any limiting aperture stops inside). However, modern eyepieces have become quite complex optically and so nominally we take the FOV_{ep} (often referred to as 'apparent FOV') of an eyepiece as a given from the manufacturer. They are often written on the eyepiece directly. Low quality eyepieces, like the Huygens, Ramsden and Kellner types typically have a $FOV_{ep} \simeq 25 - 45^\circ$. Very high quality, wide field eyepieces, such as Erfles and Naglers have $FOV_{ep} \simeq 65 - > 82^\circ$. However the most commonly used eyepieces, such as Plössl and Orthoscopes, have intermediate $FOV_{ep} \simeq 50^\circ$. Due to magnification the FOV

of the telescope system, FOV_{tel} , is much smaller. The telescopic magnification 'zooms in' on the FOV_{ep} by a factor equal to the total magnification. So telescopic FOV (often referred to as 'true FOV') is given by:

$$FOV_{tel} = \frac{FOV_{ep}}{m}.$$

The larger the FOV the larger fraction of extended astronomical objects that can be viewed simultaneously. The projected angular drift rate of an object on the sky is $15^\circ/hr \times \cos \delta$, ($\delta = \text{declination}$) (see Lab 2.4). So for simple telescopes without tracking motors, larger FOVs also mean longer times for the object to be viewed without readjusting the pointing of the telescope. However, larger FOV naturally imply low magnifications.

Resolving Power: In the wave theory of light, the point source response function (or point spread function; PSF) is the Fourier transform of the aperture function (the shape of the aperture). For circular apertures of size, D_{ob} , the PSF is an 'Airy disk'. From the central peak to the first null of an Airy disk is:

$$\theta_{1/2} = 1.22\lambda/D_{ob},$$

so a star viewed in the visible ($\lambda \simeq 5500 \text{ \AA}$) will exhibit a full width zero intensity (FWZI) size of $2 \times \theta_{1/2}(\text{''}) \simeq 280/D_{ob}(mm)$. Objects spaced by less than this cannot, theoretically, be fully separated. Small telescopes, with perfect optical systems, well focused, on sturdy mounts, and in very stable atmosphere can reach close to this theoretical limit. But since these are difficult conditions to obtain, practical resolving power of an aperture rarely is this good. For larger apertures, the atmosphere limits resolving power to about $1\text{--}2''$. A typical (though fairly conservative) approximation to estimate the ability to resolve two point sources (up to the atmospheric limit) is to assume one FWZI PSF separation between the two nulls. With this assumption, point sources (stars) that are separated by $\theta_{res} \simeq 4\theta_{1/2} = 560/D_{ob}(mm)$, ought to be resolved by an objective of size D_{ob} . This corresponds to slightly worse than '20/20' vision in daylight. ('20/20' vision is approximately the ability to resolve separations of 1.75mm at 6.1 m [20 ft], or $\theta_{res} \simeq 1$ arcminute, so for $D_{ob}(\text{eye}) = 4 \text{ mm}$, we would have $\theta_{res} \simeq 240/D_{ob}(mm)$.)

Maximum Useful Magnification: The eye's aperture at night ranges from 5 - 7 mm, so from $\theta_{res} \simeq 560/D_{ob}(mm)$, we obtain the resolving power of the unaided eye to be roughly $^{eye}\theta_{res} \sim 100''$, or about $\frac{1}{18}th$ of the size of the Full Moon. This practical limit of the eye implies a maximum useful telescope magnification. Any telescopic magnification that magnifies the maximum theoretical limit of the aperture ($\simeq 140/D_{ob}(mm)$) greater than $100''$ is of no practical use. Doing so would just result in zooming in on the unresolved blob of light limited by the telescope optics and not lead to seeing any finer detail (also would just make it appear fainter — see the Surface Brightness subsection). Inserting numbers, one obtains:

$$m_{max} \simeq 0.75 - 1.0 \times D_{ob}(mm),$$

or phrased in terms of the eyepiece focal length: $f_{ep}(\text{min}) \simeq f/N(\text{objective})$. Therefore for small hobby telescopes ($D_{ob} \sim 100 - 150 \text{ mm}$ [4 - 6 inches]), the maximum useful magnification is $\sim 100 - 150\times$. The larger, stably-mounted campus telescopes can support 2 - 3 $\times$ this magnification. Note: these numbers are approximate and depending on the observer, site and quality of the telescope. Furthermore they relate to the properties of a human eye as a detector, and are not the situation when a CCD or electronic camera is attached (see Lab 3.2 for those cases.)

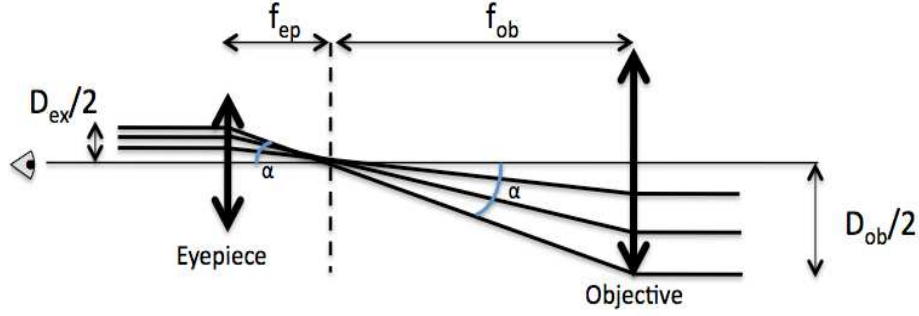


Figure 3.4: The geometry for determining exit pupil.

Exit Pupil: The exit pupil, D_{ex} , is the physical size of the image of the objective as seen through the eyepiece. From Figure 3.4 it can be seen that $\alpha = (D_{ex}/2)/f_{ep} = (D_{ob}/2)/f_{ob}$, hence the exit pupil size is given by $D_{ex} \equiv (f_{ep}/f_{ob}) \times D_{ob}$ or $D_{ex} = D_{ob}/m$. The higher the magnification for a given objective focal length, the smaller the exit pupil. This is why it often takes some effort to get your eye aligned properly to see the image when working at high magnification.

Minimum Useful Magnification: The exit pupil also controls the minimum useful magnification of a system. If the exit pupil gets bigger than 7 mm, then the entire light collected by the telescope is not focused down tight enough to completely enter the eye. For a completely dark-adapted eye aperture of 7 mm, this implies a $m_{min} = D_{ob}(mm)/7$. Incidentally, this is the reason that most astronomical binoculars tend to be manufactured such that the ratio of the magnification to the objective is ~ 7 (such as 7×50 , 12×70 , 15×80), and 'terrestrial' binoculars/opera glasses have the above ratio being ~ 4 (D_{eye} in daylight; such as 8×25 , 10×42).

Light Grasp / Surface Brightness: Light grasp, G_L , represents how much more light an objective collects relative to the eye. It is given as the ratio of the area of the objective to the area of the eye, and hence is roughly $G_L = (D_{ob}(mm)/7)^2$. Light grasp is the main benefit of large telescopes, not so much magnification, as seen in the previous section.

When magnifying by m , a scope spreads (roughly) the same amount of light over a surface area m^2 larger. Hence the surface brightness, SB , of an object is m^2 fainter. However, a scope also collects more light, in proportion to G_L . So the surface brightness of an object when viewed through a telescope is:

$$SB_{tel} = SB_{eye} \times \frac{G_L}{m^2} = \frac{\left(\frac{D_{ob}}{D_{eye}}\right)^2}{\left(\frac{f_{ob}}{f_{ep}}\right)^2}$$

(as long as $D_{ex} < D_{eye}$), where SB_{eye} is the surface brightness the object would have with the unaided eye. The maximum SB_{tel} corresponds to the case when the magnification is minimum, $m = m_{min}$, so $SB_{max} = SB_{eye}$ (assuming $f_{ob}/f_{ep} > 1$). The best surface brightness a telescope can provide is that of the unaided eye! A telescope just makes that surface brightness cover a larger area. (Note: this does not account for 'integration time'. Surface brightness sensitivity can be improved by 'integrating' longer than the eye does or by using more efficient photon detectors like

CCDs — more on this in Lab 3.2.) We define SB_{eye} as 100%. Thus:

$$SB_{tel}(\%) = 100\% \times \frac{G_L}{m^2} = \frac{\left(\frac{f_{ep}}{D_{eye}}\right)^2}{(f/N)^2} = 2\% \times \frac{f_{ep}(mm)}{(f/N)^2}.$$

High magnification makes objects large but dim. Low magnification keeps objects bright but compact.

3.1.4 Limiting Magnitude (Telescopic)

The limiting magnitude of a telescope, $^{tel}m_{V_{lim}}$, (in this case m_V is the V-band apparent magnitude, not the magnification — apologies for the collision in notation) is the faintest magnitude seen by the eye, through a telescope. Since:

$$^{tel}m_{V_{lim}} - ^{eye}m_{V_{lim}} = -2.5 \log\left(\frac{I_{lim}}{^{eye}I_{lim}}\right) = -2.5 \log(G_L),$$

then:

$$^{tel}m_{V_{lim}} = -2.5 \log(G_L) + ^{eye}m_{V_{lim}} \simeq 5 \log(D_{ob}(mm)) - 4.2 + ^{eye}m_{V_{lim}}.$$

If the site you are observing from has a limiting V-band magnitude with the unaided eye of 6.0, then $^{tel}m_{lim,6} \simeq 5 \log(D_{ob}(mm)) + 1.8$.

The Teaching/Lab assistant will demonstrate the use of the Schmidt-Cassegrain telescopes at the campus facilities, including use of the domes, checking the collimation of the telescopes, focusing the telescope and pointing the telescope using the telescope software.

3.1.5 Exercises

1) Using a pair of binoculars, observe β Cygnus (Alberio). Determine whether you should be able to resolve this binary given the D_{ob} of the binoculars? Do you? If yes, please sketch. If not, and your calculation indicates you should, suggests reasons why you do not.

2) Repeat your limiting magnitude experiment Lab 2.2, using a small telescope or binoculars. Observe M 45 (Pleiades) and use the following reference chart (Figure 3.5) to determine stellar magnitudes. Sketch the (six) 'backbone' bright stars then add a number of faint stars to the sketch based on your telescopic view. Identify the stars and their magnitudes, and determine your limiting magnitude. How does the determined m_{lim} compare to $^{eye}m_{lim}$? Is this consistent with the theoretical expectations from §3.1.4?

3) Select two eyepieces, one with as long a focal length, f_{ep} , as is practicable, and one with a short f_{ep} , (preferably near m_{max}). Attach each eyepiece to a telescope. Measure and record the exit pupil of each eyepiece (your will need a ruler for this). This does not require outside observing and, in fact, can best be done during daylight or inside a room/dome with lights on. Calculate the magnification of each eyepiece for the telescope setup you

use. Calculate the expected exit pupil, D_{ex} , and compare to your measurement. Alternatively, if you have two binoculars with significantly different objective / magnification properties, you may use them to answer this question.

Table 1 displays a collection of famous astronomical objects. Category A contains selected double/multiple stars. Category B contains selected bright objects with interesting structure amenable to high magnification. Category C contains a collection of faint, extended, diffuse nebulae/galaxies amenable to large collecting area telescopes and wide FOVs.

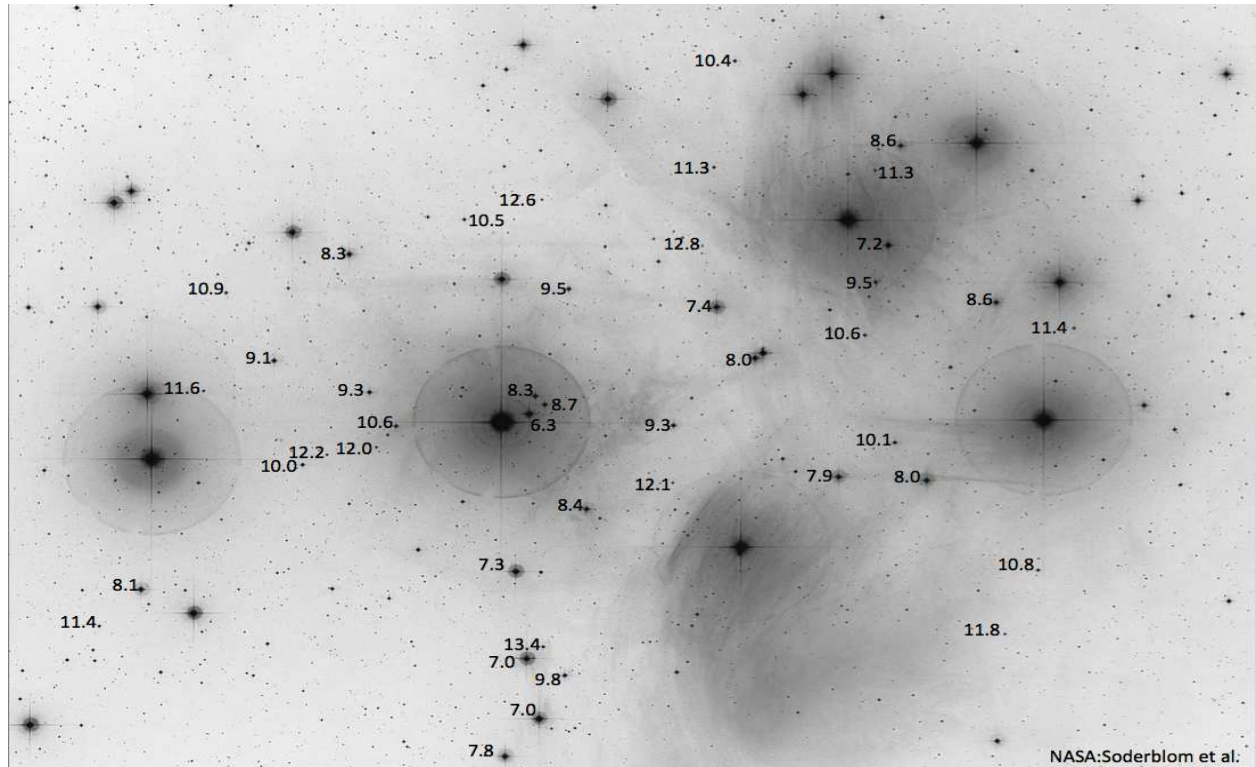


Figure 3.5: A close up view of the Pleiades (M45) with associated stellar magnitudes (NASA).

4) Select one object from each category (**bold/italics** gives you hints as to the time of year each object is visible). Sketch the view through each of the above two eyepieces. Include comments on brightness, color and orientation. For each category describe which eyepiece gives you the preferred view and why?

5) For the category A object (double star), turn off the telescope tracking and let the star drift across the *center* of the FOV of the eyepiece. Time the interval required for it to drift across. Calculate expected drift time given m , FOV_{ep} , and δ , and compare to your findings.

Table 3.1: Astronomical Objects

Category A	Category B	Category C
β Cygnus	Moon	M 8
γ Andromeda	Jupiter	M 31
β Scorpius	Saturn	M 57
ϵ Lyra	Venus	<i>M 42</i>
α Hercules	M 45	<i>M 81</i>
β <i>Monoceros</i>	NGC 869/884	<i>M 49</i>
ι <i>Cancer</i>	M 13	
α <i>Gemini</i>	<i>M 3</i>	
γ <i>Leo</i>	<i>M 44</i>	
$\theta^{1,2}$ <i>Orion</i>		
variable	summer/fall	<i>winter/spring</i>

3.2 Lab VII: Introduction to CCD Observing [o]

For this assignment, working in small groups is permitted. Reminder: For these telescope/CCD observations please record the details of your observation. Include: the weather/sky conditions; time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

3.2.1 Introduction to CCDs

Charge coupled devices (CCDs) are devices that convert individual photons of light into electric current. CCDs have revolutionized astronomy, allowing even small 'amateur astronomy' telescopes to generate images of the quality of >1-meter class telescopes using film. As a feature of the 1970s semi-conductor revolution, CCDs have the great advantage of being nearly linear and highly efficient photon detectors. The quantum efficiency, Q_e , of CCDs are typically $\sim 75\%$, compared to the $\sim 1\%$ offered by film.

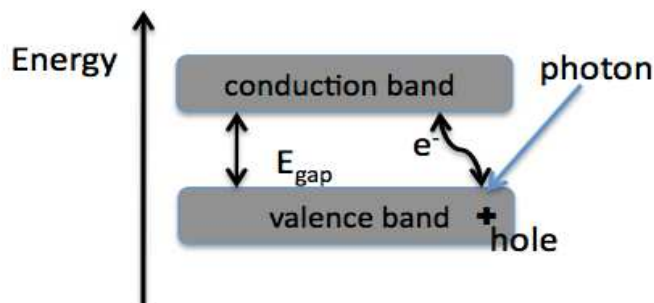


Figure 3.6: Left) The energy band structure of a semi-conductor.

CCDs are made from a large array of pixels (often millions of pixels). The pixels within a CCD convert photons to electrons by a process similar to the photoelectric effect (though the electron do not leave the material). When a photon strikes an atom in a semi-conductor an electron can be knocked out and promoted into a weakly bonded (free to flow) 'conduction band'. These electrons can then be trapped by a electric potential and steered to a counting device (Figure 3.6). Pixels are read out in a 'bucket brigade' ('pass the bucket along') fashion, with rows of electrons containing pixels being passed across the array by sequential change of electrode potential. The end pixels pass their electrons to a serial register, which are then shifted down the serial register one-by-one to a read out amplifier (Figure 3.7). By keeping careful track of the timing, one can reconstruct the location on the array that is currently being read out.

3.2.2 CCD Properties

There are a number of important properties associated with CCDs. Some of these are reviewed here.

Pixels (Plate scale / Field of View): It is important to be able to tell how big an object will appear on the CCD and how small of detail it will be sensitive. The physical size of the pixel and

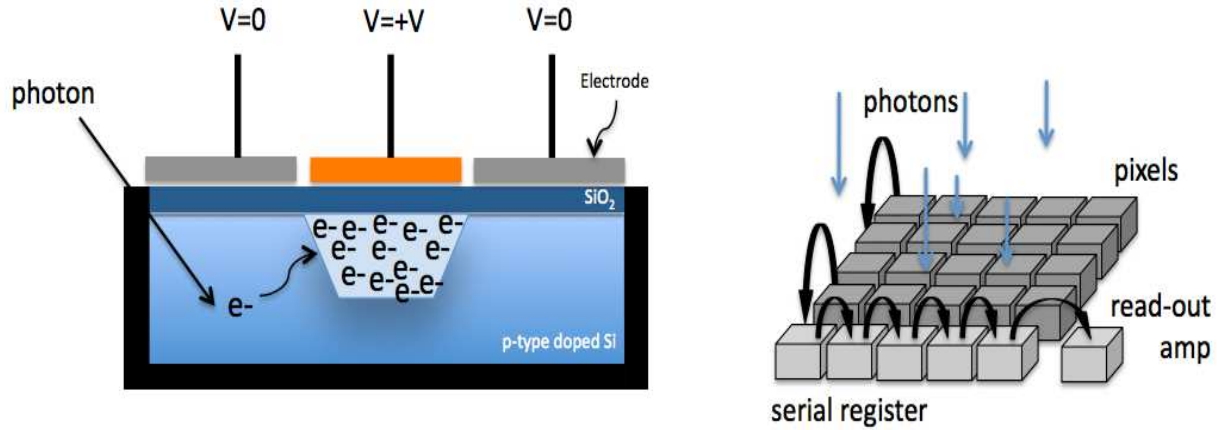


Figure 3.7: Left) A schematic of a simplified CCD pixel. Right) Schematic of the 'bucket brigade' read out of a CCD chip.

the telescope optics are important for setting the resolution of the CCD. Pixels are typically about $10\mu\text{m}$ in size for CCDs available to 'amateur' astronomers / university students, but vary from maker to maker. When coupled with the optics of the telescope, it is possible to determine the 'plate scale', ps , of a CCD/telescope setup. The ps is the ratio of angular distance off of center to the physical distance off of center on the focal plane. Figure 3.8 shows the optics diagram relevant for determining plate scale. β is the angle an object is off the optical axis of the telescope, while Δ is the resultant physical distance that shifted object appears off the center of the CCD. The plate scale is the relation between β and Δ in pixel units. From the figure, in the small-angle, paraxial

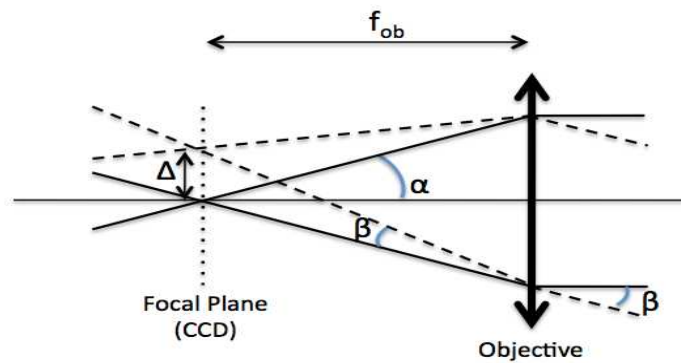


Figure 3.8: A schematic of the optics used to determine the plate scale. The solid lines ray trace an object on the optical axis of the telescope, while the dashed line shows the ray traces for an object at an angle, β , off the axis. The plate scale is the relation between β and Δ , the physical shift on the focal plane.

approximation, $\tan \beta \simeq \beta \simeq \Delta/f_{ob}$. So:

$$ps(rad/mm) = 1/f_{obj}(mm) \quad - or - \quad ps(" /mm) = 206265/f_{obj}(mm), \quad (3.1)$$

or in terms of pixel size:

$$ps("/pxl) = [206265/f_{obj}(mm)][s(mm/pxl)], \quad (3.2)$$

where s is the physical pixel size. Thus if a CCD chip has a pixel size of, $s = 10 \times 10^{-3}$ mm, and an $f_{ob} = 2000mm$, then $ps("/pxl) \simeq 1$. The field of view of the CCD can be determined simply from $ps \times N_{pxl}$ along each dimension.

Quantum Efficiency: The fraction of photons falling on the detectors that are actually registered and result in production of an electron is given by the quantum efficiency, Q_e . Obviously, higher sensitivities are better. Typical Q_e are ~ 75 % for quality CCDs. Q_e usually is somewhat better at the red end of the spectrum than the blue. The Q_e of the human eye is between 5 - 10 % depending on whether you are using the rods or cones. Film is typically less efficient than the eye.

Errors/Uncertainties: CCDs have sources of noise/uncertainties:

- *Bias:* The e^- in a pixel when no light is shining on it. It can be calibrated out by taking a zero second 'exposure'. Sometimes, bias also refers to any constant offset value applied to all pixels by the software.
- *Dark Current, D_c :* Thermal energy can also cause e^- to be excited into the conduction band. This thermally generated signal is called dark current. Dark current is a strong function of temperature, so cooling CCDs greatly reduce dark current. In efficiently cooled CCDs, dark current is often very low, with values of order $D_c = 1e^-/sec/pxl$. Dark current is calibrated out by taking an exposure of exactly the same integration time as the target, but with the shutter closed, and then subtracting it off the target observation. Because of this, the length of time to complete a single observation will always be at least twice the integration time, if dark frames are taken.
- *Read Noise, RN :* Read noise is the amplifier noise associated with reading out each pixel. It is not a Poisson process and hence its S/N ratio does not reduce with the number of counts, CNT .
- *Flat Fielding:* The Q_e of every single pixel is not the same. Different pixels have different sensitivities or different illumination by the optics (vignetting). To normalize out this effect, we need a uniform (white) source to image that can be used to determine the relative response of each pixel. Taking the corresponding flat, white image is called flat fielding. Generally this is done by observing a portion of the interior of the dome when its lights are on. Note: this step can be done before night falls.
- *Saturation ('Full Well Capacity'):* There is a maximum number of e^- that a pixel can hold. If the pixel reaches this level then a new incoming photon will not be able to produce a measurable e^- . Integrating longer will not result in any more e^- being detected, and so saturation sets constraints on the length of time you can integrate for a given brightness source. CCDs become increasingly non-linear in their photon response as saturation is approached and so it is best to have count rates stay well below saturation values for quantitative work. Adjust integration time, filters, or apertures such that you do not reach such high counts.

- *Gain, g* : An image count (CNT) need not be equal to one e^- . In fact, it is generally not. The conversion between e^- and CNT (or ADU) in an image is given by the gain, g .

3.2.3 CCD Observing

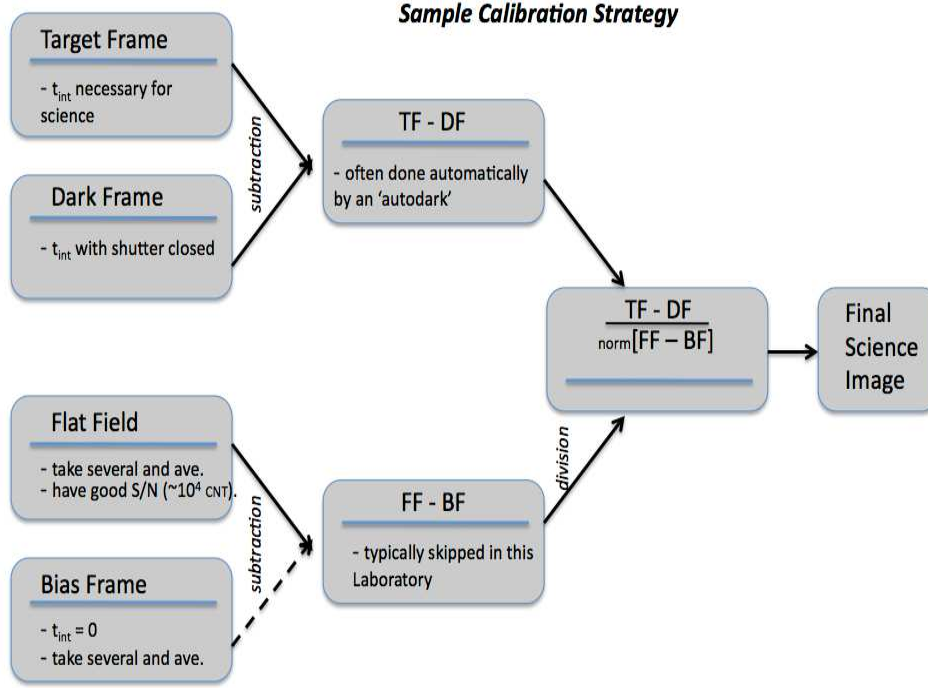


Figure 3.9: A basic CCD calibration strategy.

Calibration: Figure 3.9 shows a basic calibration strategy for CCD imaging. Based on the accuracy demands, this strategy can be made more or less complicated. One obtains several flat field frames (aim for high S/N but not near saturation and then average to make a master 'flat'). Then one obtains (optionally) several bias frames ($t_{int}=0$ sec), then average to get a master 'bias' — or alternatively subtracting a dark frame from the flats can be used to effectively bias subtract. Then one integrates on the target for the needed time, t_{int} , and on the 'dark' for the same time. The 'dark' is subtracted from the 'target', and the 'bias' from the 'flat' and normalized. Then these two outcome files are divided to give the final image.

Sensitivities: It is also good to have some idea of the amount of integration time you will need to image an object at the required sensitivity. In this Laboratory you will generally determine this by experimentation, but in the long run it will be useful to be able to estimate this ahead of time. Given here is an approximate 'CCD equation' for determining sensitivity requirements. The signal-to-noise per pixel, $S/N|_{pxl}$, of an object of brightness, m_V , can be given as:

$$S/N|_{pxl} = \frac{P_{tar} Q_e t_{int}}{(P_{tar} Q_e t_{int} + P_{sky} Q_e t_{int} + D_c t_{int} + R N^2)^{1/2}}, \quad (3.3)$$

where P_{tar} (P_{sky}) is the rate of photon arrival per pixel per sec for the target (sky) and t_{int} is the integration times in seconds. P_{tar} is often looked up in tables for a given telescope but can be

roughly estimated (see below). Since the collecting of photons (or electrons) is a random process, the standard deviation increases as the $\sqrt{CNT}$, so that S/N increases roughly as the $\sqrt{CNT}$ (in the 'photon noise' limit). When the signal CNT gets low, then the D_c and RN terms become significant and alter the S/N evolution behavior. Once the S/N is determined, it is possible to use it to determine the error bar on the measured magnitude. In magnitudes, the error bar is $\pm\Delta m \simeq 1.09/(S/N|_{pxl})$ (see Lab 4.5).

We can estimate the expected brightness given knowledge of the telescope and known fluxes of a zeroth-magnitude star. A useful rule of thumb to remember is that a V-band, $m_V = 0$ magnitude star generates a photon rate, P' , of $1000 \gamma s^{-1} cm^{-2} \text{\AA}^{-1}$. A 14 inch Schmidt-Cassegrain telescope has an aperture of roughly $10^3 cm^2$, while the width of the V band filter is $1000 \text{\AA}$. So a photon rate of $P(m_V = 0) \sim 10^9 \gamma s^{-1}$ is obtained. However, this flux of photons (or e^- in the pixels) is not focused into one pixel. Normally you will try to have several pixels across a resolution element (either the resolution of the telescope optics or the atmospheric seeing). So crudely estimating a star is spread over 10 (uniformly illuminated) pixels, then $P_{tar}(m_V = 0) \sim 10^8 e^- s^{-1} pxl^{-1}$ (note: the image is normally spread over closer to 100 pixels and not uniformly illuminated, so this is a bit of an optimistic estimate). One can find the $P_{tar}(m_V)$ for any V band magnitude by: $P_{tar}(m_V) = P_{tar}(m_V = 0) * 10^{-0.4m_V}$.

The sky is not, in general, completely dark. At a decent site, the sky has a V band surface brightness of $\sim 20 mag/arcsec^2$ and the flux associated with it contributes to the noise budget. We can estimate the photon (or e^-) rate associated with the sky, by a similar analysis as above, except that because the sky is extended, we have the count rate per pxl without the further flux to surface brightness correction done for the star. For a CCD with a plate scale of, say, ps is $\sim 1''/pxl$, $m_{sky}(mag/pxl) = m_{sky}(mag/'^2) - 2.5\log(ps^2) \simeq 20$. Therefore, if we assume the sky brightness is $\sim 20 mag/pxl$, then $P_{sky} \simeq (10^9 e^- s^{-1} pxl^{-1}) * 10^{-0.4*20} \simeq 10 e^- s^{-1} pxl^{-1}$. Using this sky background and $D_c = 1 e^- /pxl/sec$, $Q_e = 0.7$ and RN $10 e^- /pxl/sec$, we obtain that in a $t_{int} = 1$ sec integration on a $M_V=0$ magnitude star, we have a S/N $\simeq 8700$ (does not include issues related to saturation). Likewise for the same t_{int} , $m_V = 5, 10$ and 15 mags correspond to peak S/N per pixel of 870, 99, and 7, respectively.

3.2.4 Differential Photometry

Often one wants to determine the magnitude of an object in the sky. To determine this by doing absolute photometry (measuring relative to an absolute reference calibrator like an A0 star) can be rather tricky and we do not discuss the subtleties here (see Lab 6.3 for an introduction to some of the details of absolute calibration). However, if you have multiple sources in a single image and one can be considered constant and of known reference magnitude, then comparison of its relative count rate to the targets can be used to calibrate the target magnitude. This process is known as differential photometry. Since $m_1 - m_2 = -2.5\log(F_1/F_2)$, then it can be seen that $m_{tar} = m_{ref} - 2.5\log(F_{tar}/F_{ref})$. You may then measure F_{ref} and F_{tar} from the image [$F_{tar} = {}^{on} CNT_{tar} - {}^{off} CNT_{tar}$, that is the total CNTs in a small aperture centered on the object subtracted from the total CNTs in an identical small aperture just off the object; and then likewise for F_{ref}]. By knowing the magnitude of the reference, you can then determine the magnitude of the target star from the above equation. The differential nature of this photometry is important. Because you are looking through the same patch of atmosphere at the same time you eliminate

most of the (time-dependent) atmospheric-related corruptions.

In this assignment you will become familiar with the techniques needed to execute CCD imaging with the campus observatory. The Teaching / Lab assistant will lead you through the steps to operate the dome, telescope and software on site.

3.2.5 Exercises

1) A basic observations should begin with turning on the dome, telescope and software systems. Establish a working directory on the computer. Focus the telescope. Choose the V band filter from the filter wheel. Obtain several 'flat field' frames by observing the inside of the dome. Do not forget to record the instrumental set up parameters for each file taken. The header of the .FIT (Flexible Image Transport System) files do include some of this useful information.

2) Locate the RR Lyrae star AV Peg (see Figure 3.9 for information on its position, magnitude and ephemeris). Take target frame-dark frame pairs at a number of roughly log spaced t_{int} . Say something like 0.3s, 1s, 3s, 10s, 30s etc. or whatever turns out to be relevant for the source (you should figure this out). Calibrate each frame, determine the target count rate for each frame and plot the target count rate vs. t_{int} . (The calibration can be done directly with the telescope software and the measurements of the CNTs can be done in a number of packages. 'fv' is an extremely simple one, 'ds9' is a very common and somewhat more sophisticated one, and IRAF, IDL or Python may be used for publication-quality data reduction / analysis.) Discuss the meaning of the result.

3) The figure caption of Figure 3.9 gives information about the stars in the AV Peg field. Two stars, of magnitude 9.34 (labeled 93) and 9.53 (95), are near AV Peg. Their distances from AV Peg are given. By measuring the number of pixels between either star and AV Peg in the image a plate scale can be determined in ("/pxl). Compare this to that expected theoretically for the telescope / CCD system.

4) Choose just the best t_{int} for AV Peg (high S/N but not with the CNT near saturation values) and repeat integrations with that t_{int} on AV Peg once every 1/2 hour (or so) for at least three hours. Note: the members of the group [or groups] can split up the 3 hours and have one group do the early observations (plus flat fields) and another the later observations (and shut down) if necessary.

5) Determine the V band magnitude of AV Peg for each measurement from differential photometry on each of the '93' and '95' reference stars, and average. Plot the apparent V band magnitude, $m_V(AV Peg)$ (with error bar) vs. time. Do you see it vary? At the level it should have? (<http://www.aavso.org/vsp> may be useful here.)

6) RR Lyrae stars have roughly constant peak absolute magnitudes of $M_V \simeq 0.75$. This makes them useful (and famous) as 'standard candles' for determining distances to astronomical objects [e.g. globular clusters and galaxies]. Derive the distance to

AV Peg assuming its peak absolute V band magnitude is the standard $M_V = 0.75$. See the top left hand corner of Figure 3.10 for the peak m_V of AV Peg.

7) Select any two deep sky objects (see for example the Messier and Caldwell Catalogs in *Stars and Planets*) that do not completely fill the FOV of the CCD. Obtain and report a V band calibrated image of each. Once you get comfortable, these may be done quickly between your 1/2 hour waits for AV Peg.

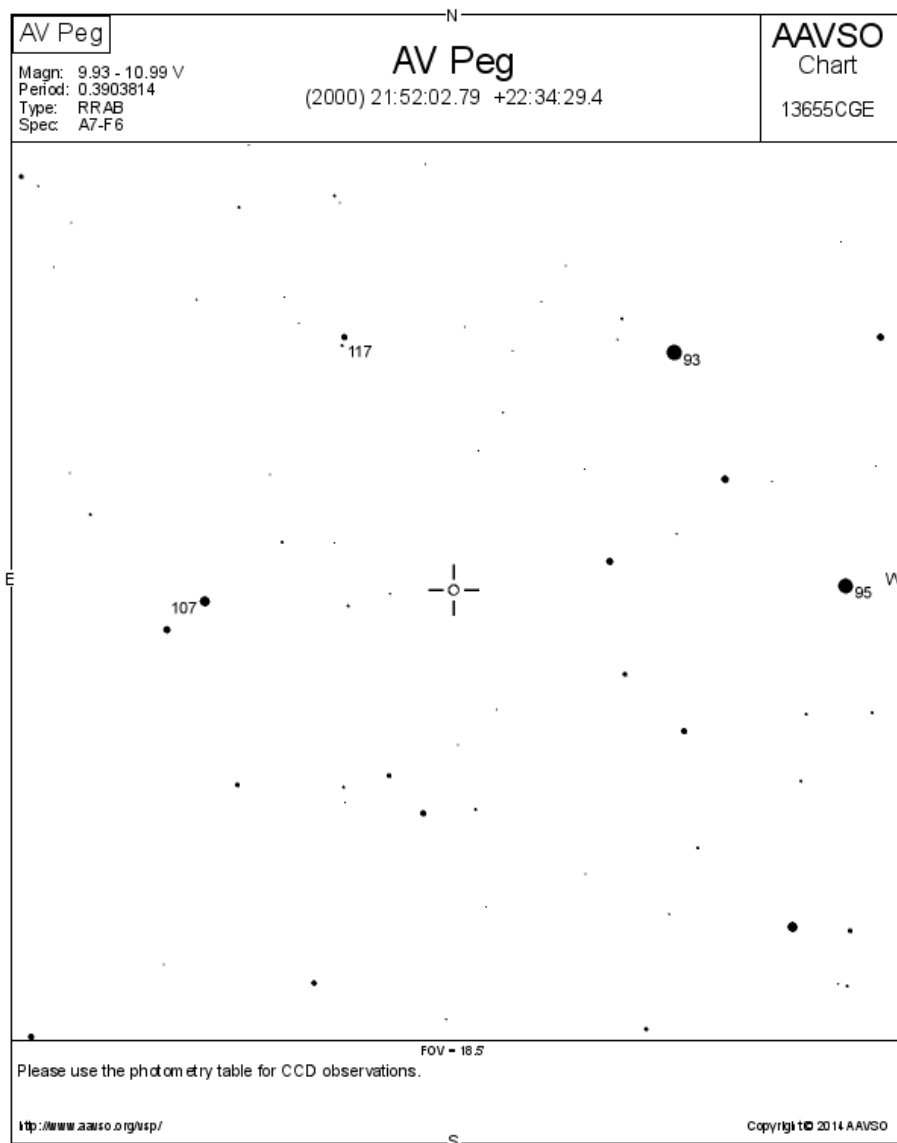


Figure 3.10: A finder chart for the AV Peg area from the AAVSO. The coordinates, V band apparent magnitude range, and variability period are shown. (At least) two reference stars useful for differential photometry are labeled. The star labeled 93 has a V magnitude of 9.34 and is separated by 419" from AV Peg. The star labeled 95 has a V magnitude of 9.53 and is separated by 532" from AV Peg.

3.3 Lab VIII: Introduction to CCD Color Imaging [o]

For this assignment, working in small groups is permitted. Reminder: For these telescope/CCD observations please record the details of your observation. Include: the weather/sky conditions; time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

3.3.1 Introduction to CCD Color Imaging

Color information is one of the best tools we have as astronomers to understand the physics occurring in an object (whether 'color' be 'broadband' or 'spectral line'). Different radiation mechanisms emit at different wavelengths and so by comparing different wavelengths we can constrain the relative importance of the different emission mechanisms (or other properties such as temperature).

In a previous lab (Lab 3.2) you became familiar with basic CCD / telescope operation and simple reduction / analysis. The goal of this lab is to extend this so that you can obtain color images (and begin to contemplate the science associated with that color). Color imaging is done by making a number of single wavelength (filter) images and then combining them in post-processing. Typical astronomical filters available in the optical include U, B, V, R, and I. Figure 3.11 shows the transmission fraction as a function of wavelength for the standard filter sets along with a representative Q_e of the CCD. Nominally the B (Blue) filter peaks around $4450\text{\AA}$ and has a width of $\sim 1000\text{\AA}$, while V ('visual' or green) peaks around $5500\text{\AA}$ and has a width of $\sim 900\text{\AA}$, R (red) peaks around $6600\text{\AA}$ and has a width of $\sim 1400\text{\AA}$, and I ('infrared') peaks around $8000\text{\AA}$ and has a width of $\sim 1500\text{\AA}$. Another 'filter' is the L or luminance "filter", which is clear — that is it is equivalent to no filter or just the black line in Figure 3.11. A CCD does not have the same sensitivity in each filter. The relative sensitivity of a CCD in a filter is the integral of the transmission weighted by the CCD response. Notice that the combination of the CCD response and the bandwidth of the filter makes CCD generally most sensitive in R. Because the sensitivities are unequal you will need different integration times (or to take more images of the same integration time) to achieve equivalent sensitivities in each filter. [Of course the color of the object also influences the brightness in each band, but that is the science we are after.]

The basic strategy behind color imaging is to proceed to a *final* image just as you did for a single filter observation, but then repeat those steps individually for each filter (typically at least three filters are used so that you can build an RGB color image, and an L 'filter'). Make sure to obtain a separate flat field frame for each filter.

The Teaching / Laboratory assistant will provide a more detailed explanation of how to create color images with the available software at the telescope.

3.3.2 Exercises

In this class you will want to image in the B, V, R and L bands. The first three will give you the red - green - blue RGB components and the last, through no filter, gives you the overall white light response.

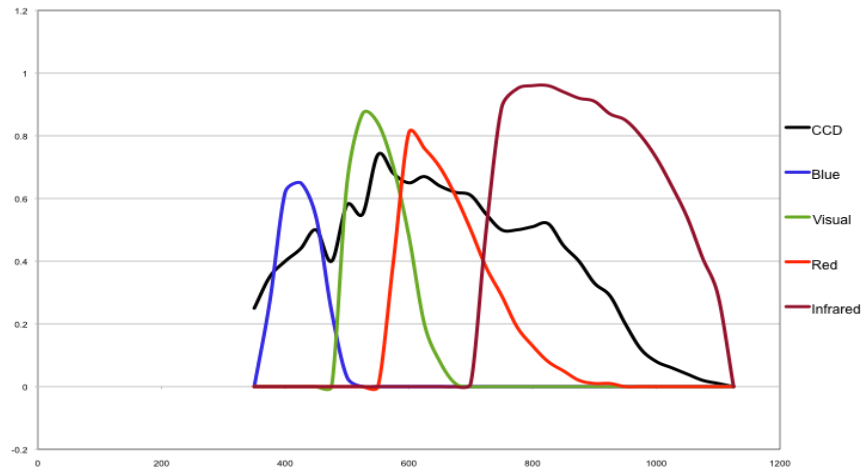


Figure 3.11: The filter response (transmission fraction) vs. λ in nm ($10\text{\AA}$) for a typical set of astronomical filters, B, V, R, and I, and the quantum efficiency of a SBIG ST-1001E.

1) Pick a relatively bright deep sky object (the Messier or Caldwell catalogs are a good place to start) of interest to you (preferably one that has significant color differentiation to it). Observe it to obtain the best color image you can. Selection of several candidate objects that you expect to be interesting (and bright enough to be doable), should be done ahead of time. Come prepared!

2) Summarize your observing strategy and details of the success/problems associated with getting a good color image (particularly at the combination stage).

3) Once you have obtained a nice color image of the object, describe the image in careful detail (please include both a printout of the image and a copy of the electronic image file). It should take you at least a paragraph to describe suitably quantitatively. Note features such as overall colors and shapes, as well as fine detail like wisps, dust lanes, voids, etc... [Do not just say 'It's round and blue' or the something similar.]

4) Find an online color image of the object and compare to yours [cite its reference]. Include the four component images (BVRL), the color image (printed in color) and the online reference image (also printed in color) Do they agree? How does the observational/instrumental differences between the telescope you use and the one used to take the comparison online image impact any differences you see?

5) Write an at least one page typed report on the *astrophysics* of your chosen object. Make sure that a major component of the write up focuses on the reasons for the colors you observe. This should be written in a fairly formal 'report style', including citation to all referenced literature. Here I demand that you include at least one peer-reviewed research journal article in your discussion. (Do not just use encyclopedia/textbook/wikipedia descriptions.) Important reference webpages that will help you with peer-reviewed literature include the NASA Astrophysics Data System [NASA-ADS: http://adsabs.harvard.edu/abstract_service.html] to find the literature articles, the SIMBAD Astronomical Database [SIMBAD: <http://simbad.u-strasbg.fr/simbad/>] for detailed information on Galac-

tic sources including lists of references, and the NASA Extragalactic Database (NED: <http://ned.ipac.caltech.edu/>) for extragalactic objects.

3.4 Lab IX: Introduction to Spectroscopy [o]

For this assignment, working in groups is permitted for the observations. Reminder: For all Spectroscopy/CCD observations you do, please record the details of your observation. These include: the weather/sky conditions; time/date of each observation; integration time/filters/telescope/spectral line set up etc. [if applicable]; and the members of your observing 'team'. *This assignment assumes that the Laboratory has access to an SBIG-SGS spectroscope or its equivalent. This assignment is not possible without this equipment.*

3.4.1 Introduction

The light from astronomical objects is extremely rich, carrying vital information on the object's composition, temperature, densities, internal structure, and dynamics. Spectra from these objects are a complex mix of continuum emission, absorption lines and emission lines. The nature of the emission mechanism depends on the part of the spectrum one observes. In the optical, emitted light tends to be associated with hot ionized gas and stars, which exhibit temperatures of thousands of degrees K. The continuum emission of most bright objects are (very roughly) thermal blackbody emission associated with hot ($\sim 3000 - 30,000$ K) objects. Absorption and emission lines are related to quantum electronic transitions between atoms (both neutral and ionized) and molecules as these are transitions have characteristic transition energies of $\sim$ few eV ($1 \text{ eV} = 11,600 \text{ K}$ in temperature units).

3.4.2 Stellar Spectroscopy

With a spectroscope, the incoming optical light can be split into its constituent wavelengths and the student can begin to investigate the information carried in the spectrum. Here focus is on stars and ionized gas nebulae (HII regions), as they are the brightest objects in optical spectra. Most of the emission from stars are continuum in nature. The emission originates from the hot, opaque interiors of the star. As it leaves the star it passes through a more diffuse, transparent stellar atmosphere, which imprints a series of absorption lines atop the continuum. Because of hydrostatic equilibrium, the more massive the star, the higher the pressure and hence the hotter and bluer the continuum. The strength of the spectral lines seen in the atmosphere depend both on the excitation and temperature of the atmosphere. We know that the atmosphere of stars are mainly H (and some He), but these lines are not always the strongest (in absorption). At very hot temperatures ($> 30,000 \text{ K}$) H is primarily ionized, making neutral H abundances small and Balmer H lines weak. As temperatures drop too low then little H is excited out of the ground state and the Balmer ($n=2$) lower state is unpopulated. The optimal temperature of Balmer absorption lines occur at about $10,000 \text{ K}$. At cool temperatures of a few thousand degrees, the small excitation gaps between energy levels of metals and even molecules come to dominate. Figure 3.12 gives a very schematic view of the expected stellar spectral properties as a function of temperature.

The stellar temperature axis is often characterized by *spectral classification* rather than temperature. The standard spectral classification goes as O, B, A, F, G, K, M [Oh Be A Fine Girl/Guy, Kiss Me]. For even cooler brown dwarfs, L & T classifications have been added recently. The earlier in the alphabet the more prominent the H Balmer series, so A stars have the most prominent Balmer lines and hence have temperatures around $10,000 \text{ K}$. The spectral classifications are further

subdivided by arabic numerals from 0 - 9, with 0 being hottest and 9 coolest. Finally a luminosity classification, marked by Roman numerals is included. Important categories include "V" for dwarf or "main sequence" stars, "III" for giant stars and "I" for supergiants. The spectral classification of the Sun (a 1 solar mass main sequence star) is G2V. Spectral lines in the atmosphere are pressure broadened and so linewidths are related to the stellar atmospheric pressure. Giants and supergiants are very large stars with puffy, low density / pressure atmospheres and hence narrower spectral lines. However, given the available spectroscope's resolution, this can be difficult to distinguish.

3.4.3 Ionized Nebular Spectroscopy

Diffuse ionized clouds of gas (HII regions — the 'II' $\equiv$ singly ionized, while 'III' $\equiv$ doubly ionized, 'IV' $\equiv$ triply ionized, etc.) are different from stars in a number of respects of which two are noted. These differences result in qualitatively different spectra. Firstly, the HII regions are generally hot, low density and free from (optical) continuum emission. Therefore, by Kirchoff's laws, we expect the HII regions to have a pure emission line spectrum. Secondly, for typical solar metallicity environments, it happens that heating and cooling rates conspire to keep HII region at a roughly constant electron temperature of about 10,000 K. The temperature of the nebula is set by balancing heating rates associated with energetic photons from the massive stars' radiation and cooling rates from recombination line emission. The hotter the star the higher the heating rate. But the higher the heating rate, the more transitions / species are available to recombine and emit photons that carry energy away from the cloud. In solar metallicity gas, abundances of trace species like C, N, O, S, Ne and their partially ionized forms, are enough to cool the gas down to $\sim 10,000$ K even for much hotter stars. Because of these two points, we expect that the observed spectra to reflect gas abundances for a plasma of about 10,000 K. Lines such as the Balmer lines of H, plus low ionization states of C, N, O and S (e.g. CIII, NII, OI-OIII, SII etc.), and HeI are common.

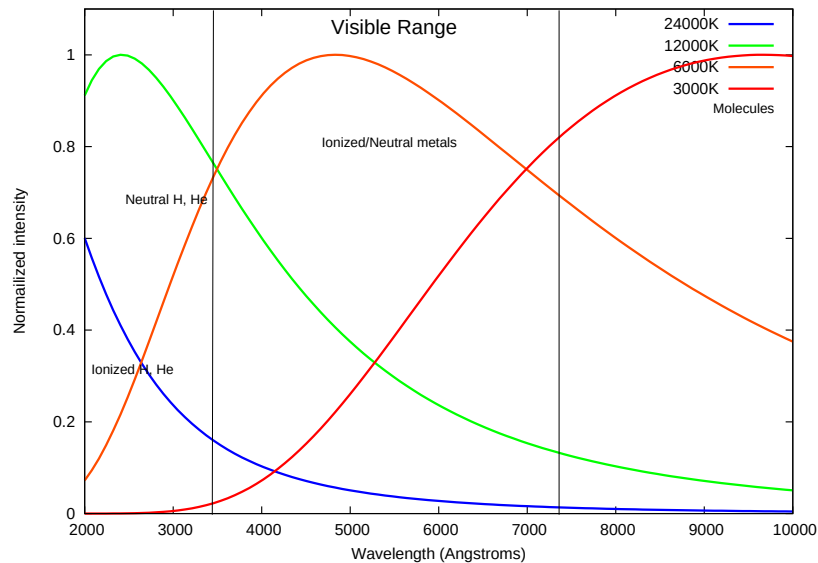


Figure 3.12: Normalized blackbody curves for four temperatures shown for wavelengths' somewhat larger than the visible range (marked). Typical sources of emission/absorption lines at varying temperatures are also indicated.

3.4.4 The Spectroscope

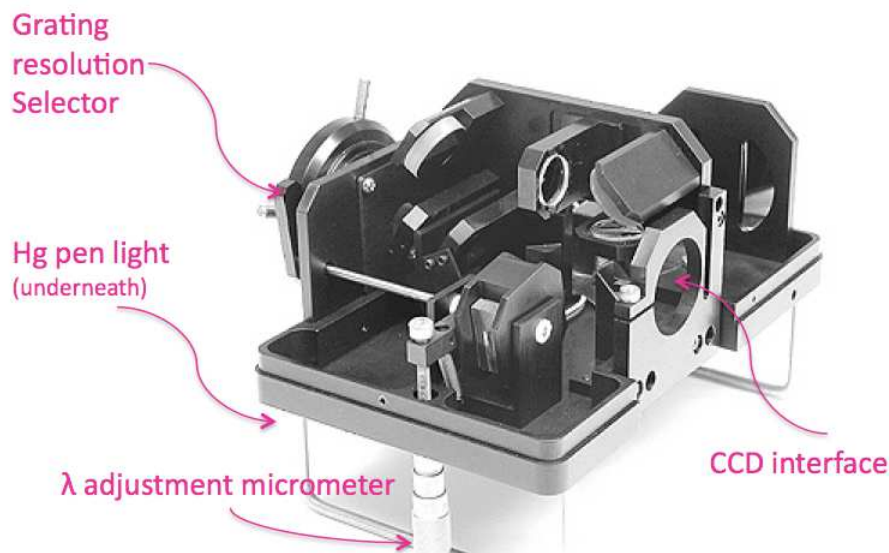


Figure 3.13: The interior of the SBIG Spectroscope. (Image: SBIG)

In this assignment requires the use of an SBIG - SGS spectroscope + SBIG ST-7 CCD camera to image spectra of a number of the brightest available astronomical objects. The SGS spectroscope/CCD system contains two CCDs. One is a small square chip, known as the autoguider. This CCD gives a normal image of the sky in the direction of the slit. It is this camera that you will use to place and keep your object of interest centered on the slit. The slit, aligned vertically, can normally be identified as a dark stripe across the object, when properly centered. An LED can be turned on inside the spectroscope to illuminate the slit, if you are having difficulties locating it. (Don't forget to turn it off before making your science exposures.) The second chip is used to obtain the object spectrum. It is a rectangular chip of width 765 pixels. The spectrum should appear roughly horizontal on this CCD. The more horizontal the better in terms of wavelength calibration.

Also provided is a mercury (Hg) pen light for wavelength calibration. (Two important notes with this light source. 1) *Minimize your exposure to the light source as much as possible because it emits a fair amount of UV radiation that can 'burn' the skin and eyes with prolonged exposure.* 2) *Do not slew the telescope while the pen light is plugged in. The cable is short and a slew can pull it apart.*) Plugging in the Hg pen light will illuminate it and project a Hg spectrum on the CCD (use a short exposure so as to not saturate the chip). The wavelength axis (the horizontal axis of the chip) can then be calibrated given the known wavelengths of the mercury vapor lines (see Table 3.4.5).

The CCD is controlled by *CCDSOft* and the telescope by *Sky6.0*, while the calibration/spectral analysis is done by the computer program, *Spectra* available with the instrument. The spectroscopy is quite flexible, though we will not use all the modes due to time constraints and because they can

be tedious to set up. Modes available include two slits, a broad $72\mu\text{m}$ width and a narrow $18\mu\text{m}$ width. The broad width slit gives up spectral resolution for increased sensitivity. The narrow slit gives higher spectral resolution but is best suited for bright (naked eye) objects. This assignment will exclusively use the narrow slit. There are two diffraction gratings inside the spectroscopy. One (the low resolution grating) has 150 rules/mm and gives a dispersion of $4.27 \text{ \AA}/\text{pxl}$, (for the ST-7 $9\mu\text{m}$ pixels). The spectral resolution is approximately twice the dispersion. The bandwidth of this grating is $\sim 3300\text{\AA}$. The second grating has 600 rules/mm and therefore has four times the dispersion/spectral resolution ($1.07\text{\AA}$ dispersion), but $1/4$ the bandwidth (it can cover only about $750\text{\AA}$ at once). A micrometer on the bottom of the spectroscopy can be used to change the central frequency of the spectrum projected onto the CCD. For this assignment we will use the low resolution grating exclusively. It is currently set to accept a wavelength range of about 3600 - 6800 $\text{\AA}$. This should be acceptable and therefore adjusting the micrometer likely will not be needed.

In this assignment you will become acquainted with the spectroscope and the spectra of bright stars / nebulae. We will not make use of all the features of the spectroscope, but will use enough to see its power. The Teaching / Laboratory assistant will train the student on the use of the software.

3.4.5 Exercises

1) Obtain broad band ($\sim 3600 - 6800\text{\AA}$) spectra in low resolution mode for a range of bright stars of different spectral classifications. The following stars are recommended: γ Orion (Bellatrix) — B2III, β Orion (Rigel) — B8I, α Canis Major (Sirius) — A1V, α Canis Minor (Procyon) — F5V, α Auriga (Capella) — G6III, β Gemini (Pollux) — K0III, α Taurus (Aldebaran) — K5III, and α Orion (Betelgeuse) — M2I. Display these spectral along a spectral classification sequence so that you can see how the spectrum changes with class.

2) Identify the main spectral features you see in each of the above stars' spectrum. (You need not identify all of them but do identify the most obvious features). Table 3.4.5 includes an (incomplete) list of the more prominent and likely to be detected lines. Describe which features are found in which spectral classification. Do they follow what is alluded to in §3.4.2 and Figure 3.12?

3) Comment on the meaning of the shape of the underlying continuum emission in each spectral class. Does your observed continuum profiles match those shown in Figure 3.12 for the appropriate temperature/spectral class (blackbodies)? If not explain why not.

4) The luminosity class of the brightest apparent magnitude red stars you observe tend to be giants (III) or supergiants (I). Explain, in terms of "observation bias", why this might be.

5) Estimate the strength of the $6563\text{\AA}$ Balmer $H\alpha$ line versus spectral classification and plot. Normally optical (absorption) spectral line strengths are reported as 'Equivalent Widths' (EW). EW has units of wavelength and is the width of a rectangle having the height of the continuum at the line wavelength and the area of the line. That is:

Table 1 — Selected Spectral Lines (Incomplete)

Line	λ	Line	λ	Line	λ
OII	3726	HI1	3771	HI10	3798
HI9	3825	NeIII	3869	HI8 / HeI	3889
CaII [K]	3934	NeIII	3967	CaII [H]	3968
HI ϵ	3970	NII	3995	HeI	4026
MnII	4030	FeI	4045	CIII	4068
SrII	4077	HI δ	4101	HeI	4144
CaI	4226	Fe/Ca/CH [G]	~ 4300	HI γ	4340
OIII	4363	HeI	4388	HeII	4541
CaI	4454	HeI	4471	MgII	4481
HeI	4541	CIII	4647	HeII	4686
HeI	4713	HI β	4861	HeI	4922
FeI	4958	OIII	4959	OIII	5007
FeI / MgII [b]	5167-5183	MgH band	5210	FeII	5217
OI	5577	NeII/NII	5754	HeI	5876
Na [D]	5890-6	TiI	6260	OI	6300
CrI	6330	FeI	6400	CaI	6440
FeI /CaI	6494	NeII	6548	NII	6549
HI α	6563	NeII/NII	6583	HeI	6678
SII	6717	SII	6731	s CaII	8500
CaII	8544	CaII	8664		
TiO band edge: 4750, 4800, 4950, 5450, 5550, ~ 5870 , ~ 6180 , 6560, 7050, 7575					
VO band: 5230, 5270, 5470, 7800-8000, 8400-8600					
CaH band: 6385, 6900, 6950					
O2[terr.]: 6870, 7600 H2O[terr.]: 7150					
Planets: CH ₄ band: 5430, 6200, 6680, 7250					
NH ₃ bands (narrow): 5530, 6470					
Hg Calibration lines: 4046.57, 4358.34, 5460.75, 5769.60, 5790.66					

$EW = \int (1 - I_{\lambda}/I_{cont})d\lambda$, where I_{λ} is the intensity of the line profile and I_{cont} is the (extrapolated) continuum intensity at the wavelength of the line. However, since we have not calibrated the intensity axis in this Laboratory, for this part of the assignment you may simply plot $(1 - I_{\lambda_o}/I_{cont_o})$ vs. spectral class, where I_{λ_o} is the count value at the deepest point on the line and I_{cont_o} is the extrapolated count value of the continuum at the same wavelength.

6) Take a spectrum of a planet if available (Jupiter or Venus is best) in the same spectral setup. Carefully describe its spectrum. Does it look like a stellar spectrum? If so what spectral class? What modifications from this class do you observe? Why does the planet's spectrum look this way?

7) Take a spectrum of M 42 (the great Orion Nebula). Do your best to get both some of the Trapezium stars (θ^1 Orion A-D) and the nebular emission (easy to get) on the slit simultaneously. Identify the brightest spectral features from both the stars and the nebula. Describe the spectrum of this object. Are there emission / absorption / continuum lines from the stars? From the nebula? (That is does the type of spectral feature change with vertical position [spatial dimension] along the slit?) What spectral class would you give for the trapezium stars based on your work in problems 1 - 4? Does this make sense from the perspective of them being the ionization source of the Orion Nebula? Are the HII region lines the same as the stellar lines?

Chapter 4

Planetary Science Labs



Figure 4.1: Moon — © Daniel Meier (reproduced with permission).

4.1 Lab X: Introduction to the Sun and its Cycle [i/o]

For this assignment, working in small groups is permitted only for the Sunspotter part of the assignment. Please record observational details of the Sunspotter part of the assignment. Otherwise, make sure to appropriately document all of the Mt. Wilson Observatory images you use to complete the "indoor" portions of the assignment.

4.1.1 Introduction

The Sun is the nearest star and hence provides us a close up look at the nature of a stellar photosphere (visible light surface). The surface of the Sun is a boiling caldron of gas that is laced by magnetic fields and blemished by dark patches known as sunspots. These sunspots are regions of enhanced magnetic field strength that are carried across the apparent surface of the Sun by differential rotation. Since the Sun is the prime source of energy for the Earth, the changing properties of the solar surface have an important impact on life on Earth.

In this assignment you will investigate a number of surface properties by 'observing' (both by you and by others) the Sun over a period of time.

Observing the Sun without proper protection can lead to dire consequences — like blindness. Do not observe the Sun in any way other than directly instructed (either observing through an appropriate filter, projecting the sunlight onto a viewing screen or using a specifically designed telescope, like a Sunspotter scope).

4.1.2 The Solar Sunspot Cycle

Sunspots, while having a degree of randomness, exhibit clear evolutionary trends that yield important information about the properties of the Sun. The first important thing to note is that the amount and location of sunspots follow a cycle. The number of sunspots rise and fall in cyclic pattern with a ~ 11.2 year cycle (well 22.4 year cycle [more below]). Figure 4.2 shows the sunspot number versus time for the last ~ 75 years, along with predictions for the next ~ 25 years. The sunspot number, N , is defined as:

$$N = k(10 \times g + t) \quad (4.1)$$

where k is a constant that is observer dependent and established by 'calibration' (just assume $k = 2$ [to account for the back side of the Sun]), g is the number of sunspot groups, and t is the total number of individual spots discernible.

The distribution and number of sunspots are determined by the behavior of the Sun's magnetic field. Figure 4.3 shows the distribution of sunspots with solar latitude versus time. The diagram is referred as a 'butterfly' diagram because of the distinctive butterfly wing pattern of the sunspots. It is noticed that as a new solar cycle begins the sunspots are preferentially seen towards the high latitudes ($\sim \pm 30^\circ$) of the Sun. As the cycle progresses the sunspots appear closer and closer to the solar equator. This behavior stems from the wrapping up of the magnetic field in the differentially rotating solar disk.

The Sun rotates on its axis (tilted by $\sim 7^\circ$) just like the Earth. However, unlike the Earth, the fact that the Sun is not a rigid object means that the poles and equator of the Sun do not rotate

at the same rate. To good approximation, a sunspot's positions on the surface of the Sun is fixed, and rotates east to west with the Sun's rotation rate, maintaining its given latitude. This also makes sunspots a useful probe of the rotation rate of the Sun. Since we are rotating around the Sun as we watch it rotate, there is a distinction between the Solar rotation period determined from a stationary distant platform (e.g., stars; the 'sidereal' period) and that observed by calculating the period it takes a sunspot to appear to complete one revolution (synodic period).

4.1.3 Exercises

In this assignment you will observe the Sun once with the Sunspotter solar telescope. The Sunspotter is a specially designed simple refracting telescope that projects a $56\times$ magnified image of the Sun onto a platform, where you can lay a piece of paper and sketch the Sun, without doing damage to your eyes. Instructions for its use is written on the side of the device.

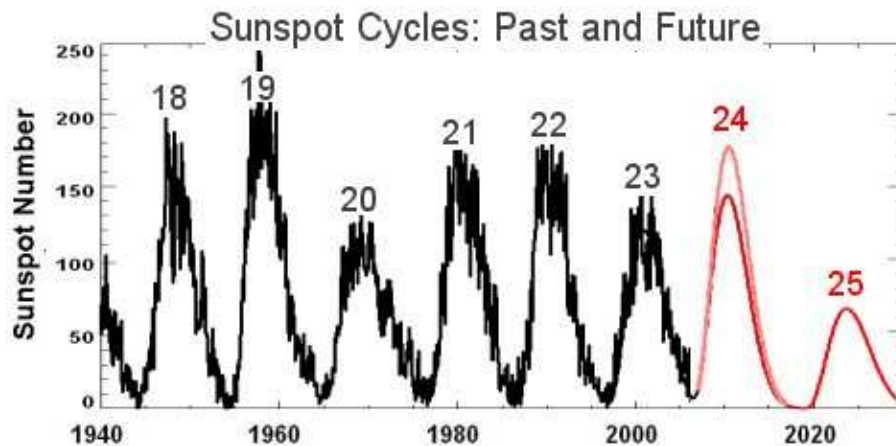


Figure 4.2: The sunspot number versus time for the last ~ 75 years, along with predictions for the next ~ 25 years. Image from NASA; David Hathaway.

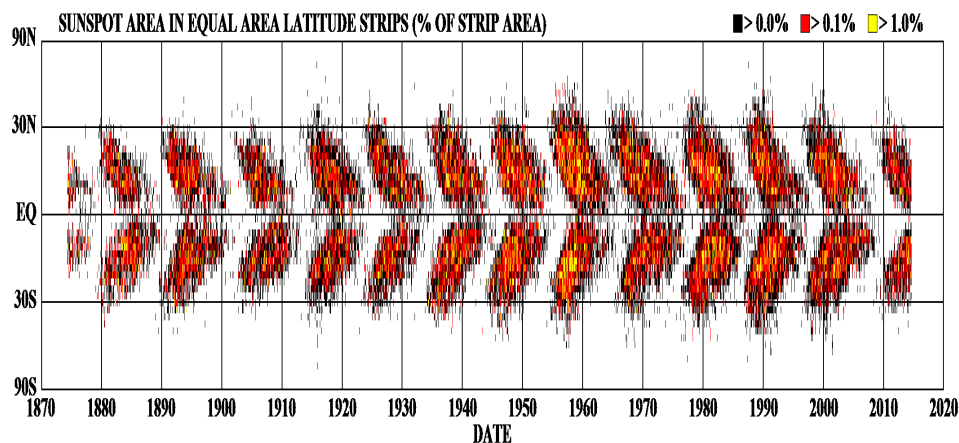


Figure 4.3: The sunspot 'butterfly' diagram. Image courtesy Mt. Wilson Solar Observatory.

1) Explain physically way sunspots appear dark relative to the rest of the Solar photosphere.

2) Using the Sunspotter, sketch the image of the Sun carefully. Note the sunspot positions and any other features you see. Compare your sketch to that taken the same day (weather permitting) by the Mt. Wilson Solar observatory daily sketches found at http://obs.astro.ucla.edu/cur_drw.html. How does your sketch compare?

The Mt. Wilson Solar Observatory (MWSO) has been sketching the distribution and magnetic properties of the Sun (semi-)continuously since 1917! The sketches are a wonderful solar resource and for the remaining quantitative work, we will make use of this database. (We do this not just because sketches produced are of the higher quality than we could produce, but because, depending on the year the Laboratory is occurring, there may not be enough [any] visible sunspots to complete the assignment.) The sketches are found at http://obs.astro.ucla.edu/cur_drw.html ("Previous Drawing Archive (via FTP)" link near the bottom of the page). Figure 4.4 illustrates an example of one of the sketches (June 25th, 2000). The plots include the time (UT), date, observing conditions, the sunspots visible, their solar coordinates (degrees latitude and longitude — 0° longitude point being the point on the Sun directly above Earth), and when available the magnetic field strength and polarity. Each sunspot is labeled by R or V to indicate the direction of the **B**-field (R = North or '+' and V = South or '-'), and a number which gives the **B**-field strength in units of 100 Gauss.

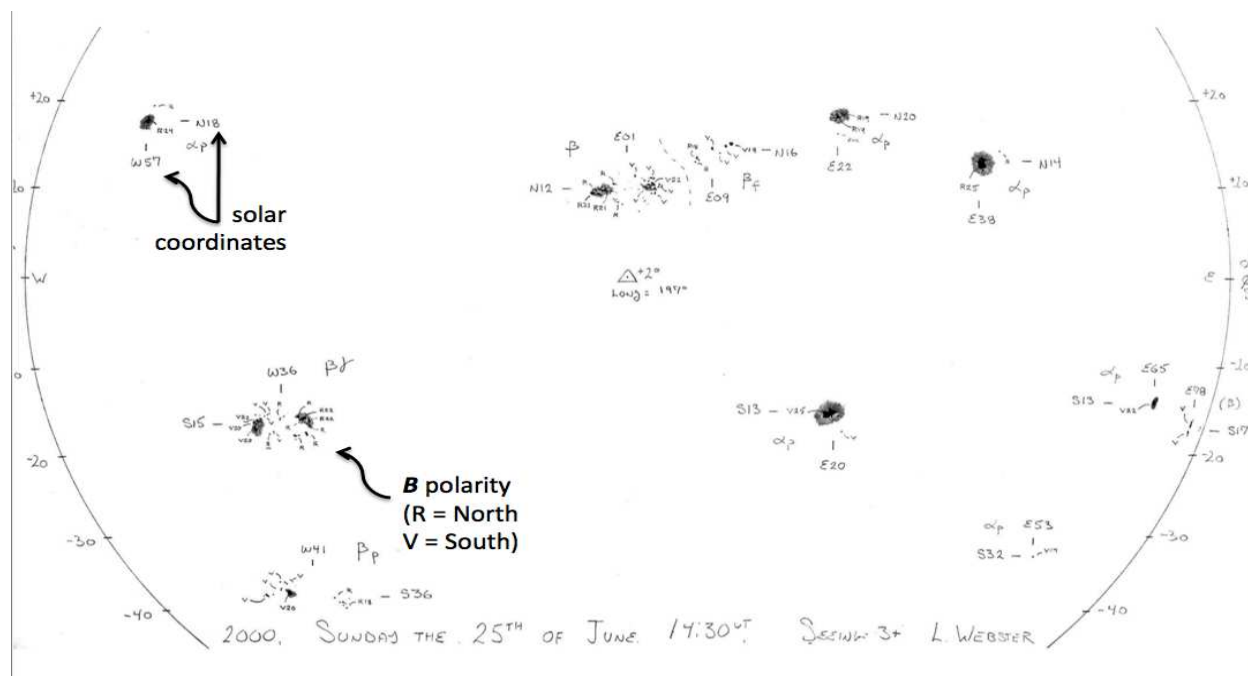


Figure 4.4: A sample Mt. Wilson Solar Observatory sketch of the Sun. See http://obs.astro.ucla.edu/cur_drw.html

3) Making use of the MWSO sketches, determine the synodic rotation period of the

Sun. To do this you will need to pick a sunspot in one of the sketches and then track its motion across the surface of the Sun. Recording the solar latitude, longitude and date/time at two times as widely spaced as feasible is the best way to get accuracy. Calculate the rotation period for (at least) two sunspots, one with a solar latitude $< 5^\circ$, and one with a solar latitude $> 35^\circ$. You are free (encouraged) to pick any time in the past 75 years of sketches (as long as they include the necessary information). *Hint: You might wish to consult Figure 4.2 to determine when the Sun has a lot of sunspots, and Figure 4.3 to determine when you might expect sunspots at the appropriate latitudes.*

4) Compare your determined synodic period to the 'official' values. Discuss any discrepancies. Compare the determined period from the $< 5^\circ$ data with the $> 35^\circ$. Are they the same?

5) Select a MWSO sketch (it can be one of the same ones as used in problem 3) and calculate the sunspot number using eq. 4.1). Compare it the expected number displayed in Figure 4.2 for that date. (Note: Expect a fair degree of uncertainty in this calculation given the subjective nature of the estimation.)

6) Select three MWSO sketches from three consecutive solar maxima. For each sketch inspect the polarity (direction) behavior of the sunspots in both the northern and southern solar hemispheres. Do you notice any regularities when compared to the rotation direction of the Sun/sunspots? If so what is it? How does the northern hemisphere behavior compare to the southern hemisphere? How does one 11 year cycle compare to the next. Use this to give a reason why 22 years is a better indicator of a complete solar cycle.

7) Qualitatively explain/sketch, in terms of the deforming of the magnetic field lines due to differential rotation, why you see the sunspot polarity behavior that you do.

4.2 Lab XI: Lunar Topology [o]

For this assignment, working in small groups is permitted for the lunar observations only. Reminder: For the observations you do (telescope/CCD) please record their details. Include: the weather/sky conditions; the location of the Moon in the sky; time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

4.2.1 Introduction

In this assignment, following in the spirit of Galileo, you will determine that the surface of the moon exhibits a mountainous topology on the same scale as Earth's geology. By making CCD observations of the Moon, you will be able to determine the height of its mountains, ridges or crater walls. This will be accomplished by measuring the length of the shadow of lunar features. To do so you will need to understand the Earth-Sun-Moon geometry, as that controls how the shadow will appear. For a general orbital configuration the geometry can be somewhat complex. However, by suitable choice of observing geometry we can simplify the trigonometry significantly, keeping the focus most directly on the science not the math.

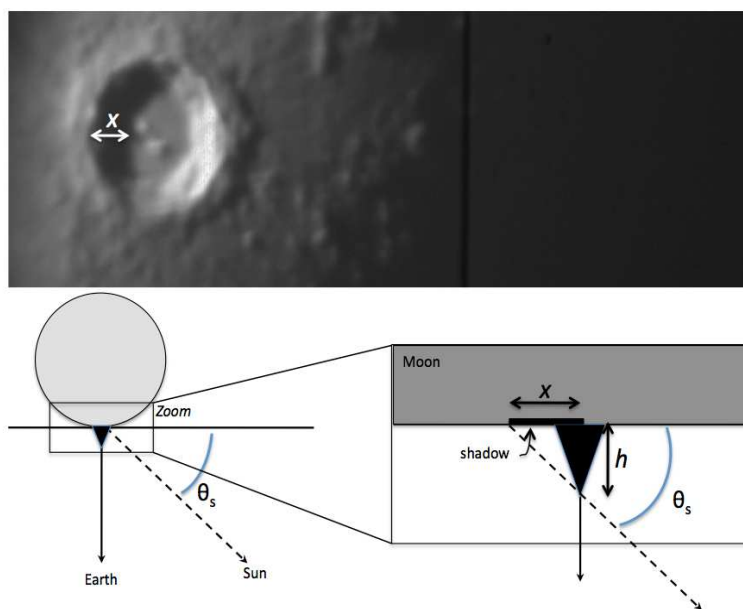


Figure 4.5: *Top)* A slice of the moon, showing a crater. The shadow cast by the crater wall is marked. *Bottom-left)* The geometry of the Earth-Sun-Moon system during the gibbous phase, assuming that we are looking at a mountain feature on the meridian of the moon (point on the Moon where the Earth would appear on its meridian). *Bottom-right)* A zoom in on the mountain, showing the height/shadow geometry.

Figure 4.5 shows the geometry relevant to the project, with two simplifying assumptions. Firstly, the assignment will concentrate only on measurements of geologic features that lie on the central north-south meridian of the Moon. This guarantees that the surface of the Moon is locally perpendicular to our line-of-sight. Hence you can ignore the geometry of a skewed Earth-Moon viewing angle. Secondly, the observations are to be confined to the gibbous phase of the Moon, illustrated

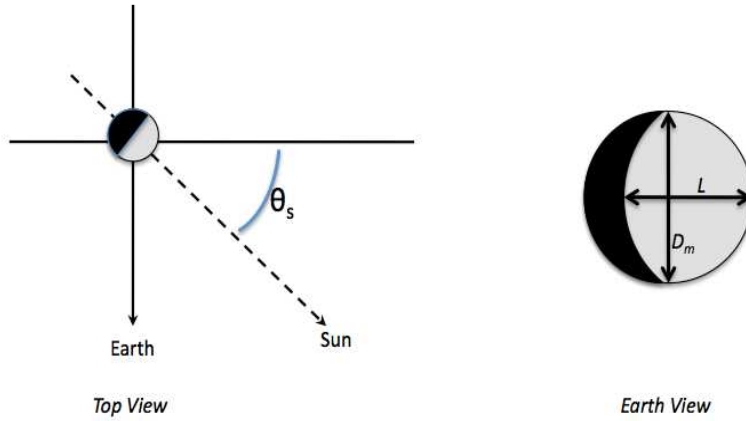


Figure 4.6: *Left)* Inspired by Figure 2.9, the orientation of the Earth-Sun-Moon system (θ_s) is correlated with the Moon phase. *Right)* θ_s (which is $\theta - 90^\circ$, where θ is defined in Figure 2.9) can be determined by measuring L and D_m .

in Figure 4.5. The angle between the sky plane and the Sun is defined as θ_s (see Figures 4.5 & 4.6). The gibbous phase is optimal both for having pronounced shadows and for determining the Moon phase, as done in Lab 2.4. Measurement of the diameter of the Moon, D_m , and the 'diameter' of the lit portion of the Moon, L , allows for the estimate of the θ_s . Following the discussion associated with Figure 2.9 (see Figure 4.6):

$$\theta_s = \sin^{-1}\left(\frac{2L}{D_m} - 1\right). \quad (4.2)$$

Once θ_s is known, then the height of the topological feature, h , can be determined from the geometry of the triangle shown in Figure 4.5:

$$h = x \tan \theta_s, \quad (4.3)$$

where x is the physical length of the shadow along the surface of the Moon.

4.2.2 Exercises

1) Determine θ_s by measuring L and D_m for your given observation period. Caveat: Things to note that might complicate your observations:

- The Moon is bright. You may need to stop down or filter the aperture of the telescope in order to obtain a quality image of the Moon that does not saturate the CCD.
- Depending on the size of your CCD / telescope setup, you may not be able to get the full Moon within one image. You may have to take multiple images to cover the full extent of the Moon and thus be capable of determining L and D_m .

2) Choose a topological feature to measure that lies on the meridian of the Moon. Measure x . To determine x , first measure the size of the shadow in number of pixels,

x_{pxl} , then convert first to arcseconds using the plate scale (see Lab 3.2) and finally to physical length via the distance to the Moon, d_{em} (3.84×10^5 km), e.g.:

$$x(km) = \frac{x_{pxl}(pxl) \text{ } ps(^{\circ}/pxl) \text{ } d_{em}(km)}{206265(^{\circ}/rad)}.$$

3) From Eq. 4.3, determine h . Compare your answer to the true value (typically this can be found on Wikipedia) and discuss sources of error. Include at least one possible source error besides 'measurement error'. Also discuss how this size compares to selected famous geological features (of your choice) on the Earth.

4) From your data, calculate what is the minimum physical size, ℓ_{min} in km, that you resolve on the Moon.

5) The Apollo 11 lunar excursion module (LEM) is about 5 meters in size. How close would you have to bring your CCD / current telescope system to the Moon to have ℓ_{min} equal this size?

4.3 Lab XII: Lunar Eclipses and the History of Astronomy [i/o]

For this assignment, working in small groups is permitted for the lunar eclipse observations only. Reminder: For the observation please record the following details: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; time/date of the observation; the members of your observing 'team'. Note: This assignment has the most 'impact' when done on a 'live' lunar eclipse and without the aid of fancy '21st century' technology. However, it can be done as a purely indoor exercise, with lunar eclipse timing and geometry looked up online / in tables.

4.3.1 Lunar Eclipses and the Distance to the Moon

In this assignment you will get a chance to observe a total lunar eclipse and derive from it the basic geometry of the Earth - Sun - Moon system. We will follow the methodology originally used by the great Greek astronomer/polymath of the 3rd Century BCE, Eratosthenes, so that you may also get a taste of an important moment in the history of astronomy.

Eratosthene of Cyrene was a Librarian working at the famous Library of Alexandria circa 245 - 200 BCE. He was one of the greatest of ancient scientists, being a member of the great triumvirate of ancient scientists of 3rd century BCE, along with Aristarchus and Archimedes. He is most famous for determining the size of the Earth to a few percent accuracy, using only a stick (gnomon) and a royal pacer (walker), by comparing the shadow cast by the stick in Alexandria on June 21st to the fact that at the same time in Cyene (modern Aswan, Egypt) the Sun was directly overhead (shined down to the base of a deep well). But he did not stop there. By knowing the latitude of Alexandria (and hence Cyene, latitude = +23.5°), [how did he know this?], and the fact that the Sun was directly overhead there only once a year, he was able to determine that the rotation axis of the Earth is inclined with respect to the Ecliptic by 23.5°. From this fact he was the first to correctly explain the physical cause of the seasons as due to the changing elevation of the Sun.

He also made use of his accurate determination of the size of the Earth in order to determine the distance between the Earth and the Moon. This was done by timing a lunar eclipse together with basic Euclidian geometry. With current lunar eclipses it is possible to reproduce his basic derivation.

4.3.2 Exercises

1) Observe a total lunar eclipse progress starting at least from shortly before the above start of partial eclipse through till after totality ends (assuming one is available). Carefully record the times when you believe partial eclipse begins, and when totality begins and ends. As the eclipse progresses, sketch and describe, in detail, what you view roughly in steps of 30 mins. Since the total lunar eclipse phase lasts a fairly long time, you may work in small groups, splitting the 1/2 hour observations amongst the group. However be sure that the overall timing measurements are accurate.

Figure 4.7 gives a crude approximation to the geometry of a lunar eclipse, assuming the Sun is infinitely far away and all orbits are circular. The Moon's velocity in its orbit, v_m , can be found

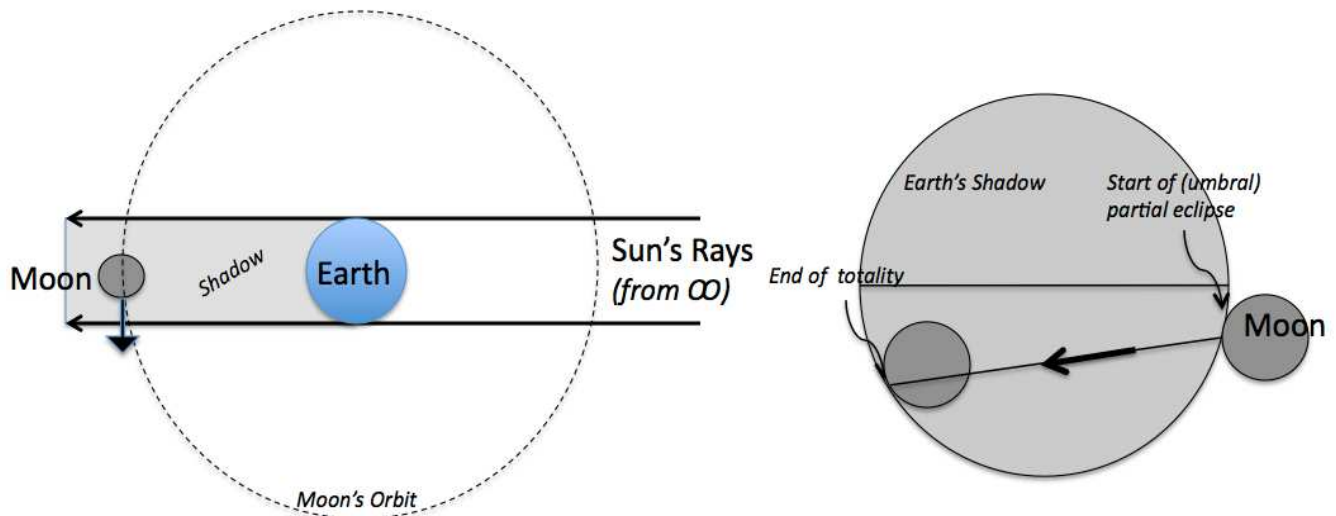


Figure 4.7: *Left*) —The approximate trigonometry for calculating the time that the moon is eclipsed by the Earth's shadow assuming the Sun is infinitely far away and all orbits are circular. *Right*) An example of a particular geometry of the Moon passing through the Earth's shadow relevant for the eclipse analysis in problem 2).

from the length of a month and the distance to the Moon, d_m . Also v_m can be found from timing the eclipse, together with the diameter of the shadow, D_{sh} . In the infinitely distance Sun approximation, D_{sh} equals the diameter of the Earth, D_e . But D_e was known from Eratosthenes' gnomon experiment. (You may use modern values for D_e .)

2) Derive the relation for d_m in terms of T_{ecl} (defined below) and D_e for the crude geometry in Figure 4.7. T_{ecl} is the period of time it takes the Moon to traverse the full Earth's shadow; e.g. from the start of (umbral) partial eclipse to the end of totality, then corrected for the fact that the Moon doesn't cross the shadow through the exact middle. See Figure 4.7 for an example geometry. You should attempt to determine this geometry from your observations.

3) From your eclipse timing measurements, determine T_{ecl} and hence your experimental value of d_m . Compare your value to the true d_m . Your results should be of the correct order of magnitude, but will not be precise.

This is because, in reality, the Sun is not infinitely far away so the Sun's rays are not parallel like they appear in Figure 4.7.

Advanced Questions:

4) Why does the Moon remain visible during totality, unlike the case for total solar eclipses?

5) Why do total lunar eclipses last much longer than total solar eclipse (for a stationary observer)?

6) Sketch the geometry and rederive an equation for d_m for the true solar configuration. In this case you will need the distance and diameter of the Sun, d_s and D_s , respectively. Eratosthenes (and his immediate predecessor Aristarchus had determined d_s [and hence D_s], though with significantly less precision [see problem 8]).

7) From your eclipse timing and the new equations derived in problem 6, calculate a better d_m . Again you may use modern values for d_s and D_s . Discuss any remaining discrepancies from the true value for d_m .

8) While Aristarchus/Eratosthenes' estimate of d_s was only accurate to an order of magnitude, the precision was enough to realize that the correct calculation in problem 6) was necessary. Discuss possible ways that they were able to determine d_s , using only 3rd century BCE technology. Hint: it is a very difficult measurement based on Moon phases.

4.4 Lab XIII: Kepler's Law and the Mass of Jupiter [o]

For this assignment, working in groups is permitted. Reminder: For any work you do (telescope / CCD) please record the details of your observations. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); time/date of each observation; integration time/filters/telescope/etc. [if applicable]; the members of your observing 'team' and their individual responsibilities during the observing program.

4.4.1 Introduction

In this assignment you will tackle, in earnest, deriving experimental physics results from a series of astronomical observations.

The four brightest moons of Jupiter, discovered by Galileo with the 'invention' of his telescope, are in order of increasing distance from the planet, Io, Europa, Ganymede and Callisto (I Eat Green Cheese). These moons hold a privileged place in astrophysics. Galileo demonstrated that these objects orbit Jupiter and not the Earth. The fact that these objects orbited Jupiter like a mini-solar system helped undermine the pre-Copernican belief that the Earth was the center of the Cosmos.



Figure 4.8: Example of what the image of Jupiter's moons might look like through a telescope. I = Io, E = Europa, G = Ganymede and C = Callisto.

With Newton's explanation of Kepler's law for orbiting bodies, we now know that for circular orbits (which the orbits of the Galilean moons can be considered at the level of sophistication of this Laboratory) with the central object's mass much greater than the orbiting bodies, then gravity supplies the needed centripetal force holding the moons in orbit:

$$\frac{m_m v_m^2}{r_m} = \frac{GM_J m_m}{r^2}, \quad (4.4)$$

where m_m and M_J are the masses of one of the moons and Jupiter, respectively, v_m is the orbital velocity of the moon and r is the distance from Jupiter's center to the moon. The orbital velocity is:

$$v_m = \frac{2\pi r}{P}, \quad (4.5)$$

where P is the orbital period of the moon. Hence:

$$P^2 = \left[\frac{4\pi^2}{GM_J} \right] r^3. \quad (4.6)$$

So by determining the period, P , and the radius, r , of the moon's orbit we may measure the mass of Jupiter, M_J . This is the primary goal of this assignment. You will set up and undertake

an observing strategy that lets you measure P and r .

You are allowed three 'knowns':

- *the distance to the Jupiter/moons system*
- *the angular size of Jupiter's disk*
- *you may use webpages (see below) to locate which moon is Io at the beginning of your observations, [but you may not use the webpages to determine orbits of the moons.]*

(Note: the first two values change with time since both Jupiter and the Earth are revolving around the Sun at different rates. You will want to obtain values for a given day that you observe by consulting a planetarium program.)

Such observations sound, in principle, simple to do. Simply observe the Jupiter / moons system repeated and watch the 'merry-go-round' of motion take place, timing P and measuring off the position (Figure 4.8). However there are a few subtleties, that you as a budding observational astronomer must consider:

- You need to convert angular separation to a physical scale.
 - Physical scale: You will need to be able to measure the positions of the moon accurately. The obvious reference given the knowns you are provided is the disk of Jupiter, itself. Because you have the distance to the system and the angular size of the disk, you will be able to determine the physical distance covered by one pixel at Jupiter's distance. From that you can measure separations in numbers of pixels and convert.
- You will need the maximum possible spatial resolution to get precision measurements, while at the same time not losing field-of-view, so that you can keep as many of the moons in view as possible.
 - High resolution: Since you will reference based on Jupiter's disk, you need as many pixels across the disk of Jupiter as possible. Use the CCD in its maximum resolution mode. However still read out the full array, so that you still maintain the maximum field of view because the moons extend several arcminutes away from the disk. [This will make your file sizes large. Make sure you have the disk space for the files.] Also work hard to get the best focus of the telescope possible, since a blurry disk will compromise your measurements. Make sure optimal focus is maintained throughout the observing run.
- Jupiter is very bright and can easily saturate the CCD for integration times optimized to show the moons.
 - Brightness: Using the maximum resolution mode should decrease the rate at which you saturate the detector (you have made your 'light bucket' smaller), but Jupiter is so bright that it likely will saturate the CCD even at the shortest possible exposure time, t_{int} . Select the filter with the narrowest bandwidth (Blue) and t_{int} at its minimum value. This should give you a small enough count rate such that you can accurately measure the size of Jupiter's disk, and still detect the moons. (You will need to play with the image contrast to see the moons.)

- Orbits are such that they take more than one night to cover an appreciable fraction of an orbit.
 - You will need to track the positions of the moons for a whole night (and perhaps back-to-back nights) to get a good fraction of a cycle (enough to determine r and P accurately). Use Io to do the analysis as its orbit is the shortest, but you can try the other moons since they should also be in the frame. The following webpages/applets allow you to plot the configuration of the moons at a given time. This will help you identify which moon is Io. [<http://www.shallowsky.com/jupiter/> -or- <http://www.12dstring.me.uk/jovianmoons.htm>]. *I recommend that you take measurements across the entire night and possibly back-to-back nights. So that this doesn't become too oppressive, I recommend the following observing scheduling: the class splits into groups, each with 3-4 students. On each night one of the groups observe. During that night each student within the group observes for about ~1.5 hours and then is relieved by another group member. Subsequent groups relieve the previous group when they finish. This is continued based on the number of groups, until completing the observations. All images are then shared amongst everyone in the Laboratory so that each student has access to a 9-18 hours of tracking, while only being required to be actively observing for a total of ~1.5 hours.* [Note: Like 'real' astronomical observing you will be at the telescope for a while but will only need to take a ~0.1s image once every 15mins or so. So you will have plenty of free time on your hands. Bring something to fill the downtime.]

4.4.2 Recommended Methodology

You will need to measure r and P so that you can determine, M_J . There are several possible methodologies to do this. I list some variations on the basic theme below (assuming to you will use Io as the moon of choice). I recommend that the students gets together when scheduling and adopts one methodology for everyone, since data will be shared.

1) Image the location of the moon (relative to Jupiter's disk) on ~15 min intervals for ~1/4 of a cycle starting at the time when the moon transits/is occulted by Jupiter till it reaches its maximum separation. This will directly give r (the maximum separation) and P (e.g. $4\times$ the time it takes to go 1/4 of a cycle).

2) Measure the time it takes the moon to transit (cross) Jupiter's disk, Δt . Combining Δt and D_J will allow you to calculate v_m (remember the Lunar Eclipse / History of Astronomy Lab [Lab 4.3]). Then observe at sparser time intervals to determine the maximum separation of the moon (r) (or have the other groups continue this part). Coupling v_m with r will give you P (see eq. 4.5).

3) Observe in regularly spaced time increments for as long as feasible. Then plot the separation vs. time. The plot should exhibit a sinusoidally varying pattern. If you observe long enough to be able to fit a sinusoid to the data and predict the maximum separation (and when it occurs) then you will have obtained r and P . This method works best if you observe the moon on either side of its maximum separation.

You can determine when transits and occultations occur by consulting the following webpage: <http://www.skyandtelescope.com/observing/a-jupiter-almanac/>

Important: Given the nature of the CCD / mount setup, the position on the CCD chip flips 180° when the object crosses the meridian. So if you track Jupiter's moons on different sides of the meridian throughout an observing run (which given the length of time needed, is almost guaran-

teed) you will need to account for this flip is the data analysis.

4.4.3 Exercises

- 1) Given d_J and θ_J , determine the diameter of Jupiter's disk, D_J , in meters.
- 2) Observe Jupiter and its moons repeatedly and regularly over an extended time period. For each observation accurately record the time. After collecting data from everyone, (individually) measure the separation of the moon from the center of Jupiter's disk for each observation together with the time. Plot or tabulate the separation [pixels or physical separation — see problem 1)] vs time.
- 3) Using some version of the above methodologies, determine, r and P for Io. If you wish to attempt to determine the r and P for another moon in addition to Io then repeat. Extra credit will be given.
- 4) Determine M_J from your r and P . Compare this to the known value of M_J (cite the source you use to get this information). Please do not look up the mass of Jupiter, or a given moon's orbital period, before completing the scheduled observations. Discuss, quantitatively, any errors between your determination and the correct value. Specifically focus on what piece of the calculation / observation was the cause limiting the precision of your determination. *Again for extra credit:* If you happened to have determined P and r for a second moon, then determine M_J from that moon and compare to your original determination. Do they agree? Should they?

4.5 Lab XIV: Transiting Exoplanets [o]

For this assignment, working in small groups is permitted for the observations. Reminder: For the telescope/CCD work please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

4.5.1 Introduction

Life in the Universe is one of the most exciting and profound possibilities to contemplate. But for life (as we know it) to exist it must have a home on which to arise. Thus we need planets. Our understanding of planet formation (fragmentation of the residual accretion disk associated with the formation of the star) suggests that it should occur approximately as commonly as does star formation. As such planets should be ubiquitous throughout the Galaxy. But because they are very faint ($10^6 - 10^9 \times$ fainter than the host star in the visible), detection of their existence, historically, has been challenging.

Early to mid 1990's technology reached the point where detection became possible. The first exoplanets detected, by Wolszczan & Frail in 1992, were around pulsars. The first exoplanets around sun-like stars were detected three years later by Mayor & Queloz. Since then thousands of exoplanets have been discovered.

The two main methods for exoplanet detection are the radial velocity method and the transit method. The radial velocity method makes use of the fact that by Newton's 3rd law, as the star pulls on the planet, the planet pulls on the star. As the planet orbits the star, the star is tugged back and forth in phase with the planet. This back and forth wobble, while small (typically at about jogging pace), is enough to be detected as a periodically changing doppler signal. The second method is the transit method, where the presence of a planet is betrayed by a drop in the apparent flux of the host star due to the planet eclipsing part of the stellar disk. The disadvantage of the transit method is that the Earth - Star - Planet system must have a special (edge-on) orientation, so these systems are rare. But the transit method has the advantage that the method is indirect, with the signal being measured being that of the star (so it is bright). It turns out that the dip in the signal associated with the eclipse can be of a size (for Jovian-like planets) that they can be detected with modest university student-class equipment.

4.5.2 Background

In this lab the student will detect an exoplanet using the transit method. The transit method can be visualized in Figure 4.9. The transit method is analogous to eclipses of our Sun, except that it is another solar system's sun being eclipsed. When the planet passes in front of the star's disk as viewed from Earth (primary eclipse/transit; Fig. 4.9-*top*), an area of the stellar disk corresponding to the area of the planetary disk is blocked. Thus the total light received from the system is decreased by $F_*(1 - A_p/A_*) \simeq F_*(1 - (R_p/R_*)^2)$, where F_* (F_p) is the total un-eclipsed flux of the star (planet) and R_* (R_p) is the radius of the star (planet) at that wavelength. Since the visible light of the planet is negligible, we drop F_p compared to F_* .

By studying the properties of the light curve one not only 'discovers' an exoplanet, but can learn a great deal about the properties of that planet / solar system, including, for example, size, orbital parameters, masses, densities, surface gravities and even implications for composition. Given the equipment available for this lab, not all these parameters are within reach, however the student will be able to measure a number of parameters of the chosen system and thus learn interesting facts about that planetary system. From this the student will get a taste of the power of modern exoplanet studies. Likewise, similar types of studies of eclipsing binary stars also allow for a detailed understanding of the nature of stars.

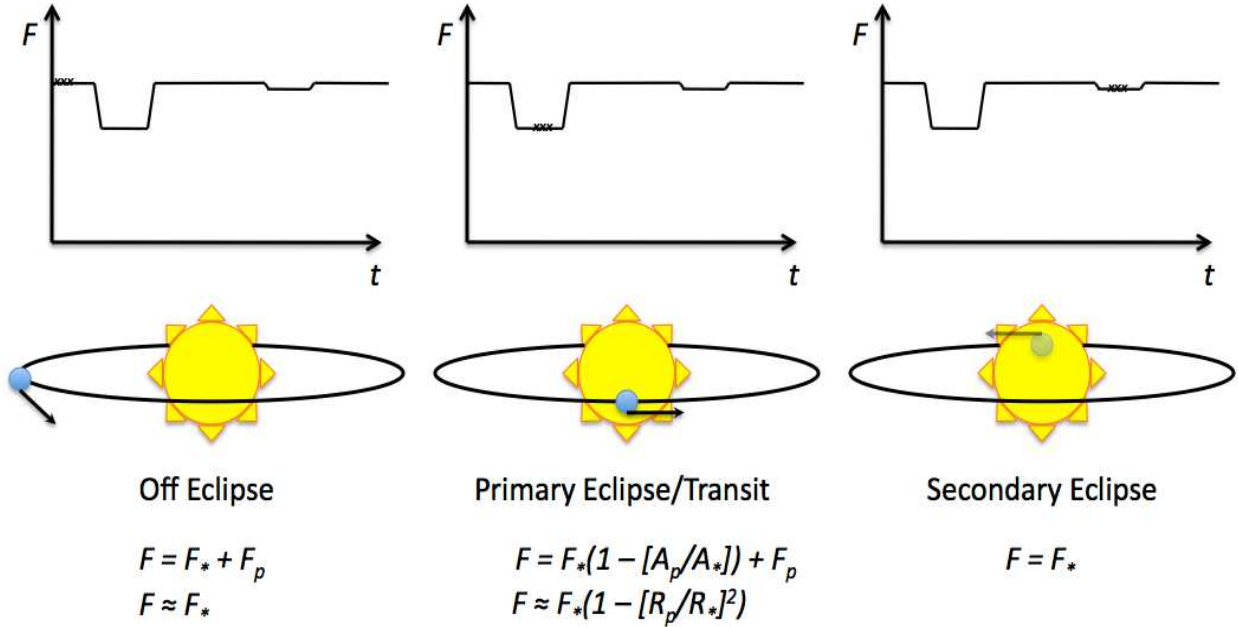


Figure 4.9: *Top)* Light curve of the star - planet system. 'x' marks indicate the part of the light curve corresponding to the orbital configuration displayed below it. *Middle)* The star - planet geometry at three times throughout the orbit. *Bottom)* The name and amount of flux received for each of the three labelled configurations.

The fractional decrease in flux during primary eclipse is:

$$f \equiv \frac{F_{off} - F_{ecl}}{F_{off}} \equiv \frac{\Delta F}{F_*} \simeq \left(\frac{F_* - F_*(1 - (\frac{R_p}{R_*})^2)}{F_*} \right) \simeq \left(\frac{R_p}{R_*} \right)^2. \quad (4.7)$$

From this one can see that by measuring the transit depth, information on the size of the planet may be obtained. The bigger the planet the larger the drop in flux. If we reference numbers to our solar system we find:

$$f \simeq 0.010 \left[\frac{R_p(R_J)}{R_*(R_\odot)} \right]^2$$

or:

$$R_p(R_J) \simeq 10\sqrt{f}R_*(R_\odot).$$

Note: In this lab we assume that the properties of the host star system (e.g R_* , M_* and L_*) are completely known. Also it should be mentioned here, specifically, that f is the fractional change in flux, whereas often the dip will be displayed in magnitudes rather than flux (for example Figure 4.10). As such one must remember to either convert all magnitude measurements to flux units first (can be arbitrary flux units), or more likely, convert the measured Δm to ΔF directly, e.g.:

$$\Delta m \equiv m_{ecl} - m_* = -2.5 \log \frac{F_{ecl}}{F_*},$$

thus:

$$\frac{F_{ecl}}{F_*} = 10^{-0.4\Delta m}$$

or:

$$f \equiv \frac{\Delta F}{F_*} = \frac{F_*}{F_*} - \frac{F_{ecl}}{F_*} = 1 - 10^{-0.4\Delta m}.$$

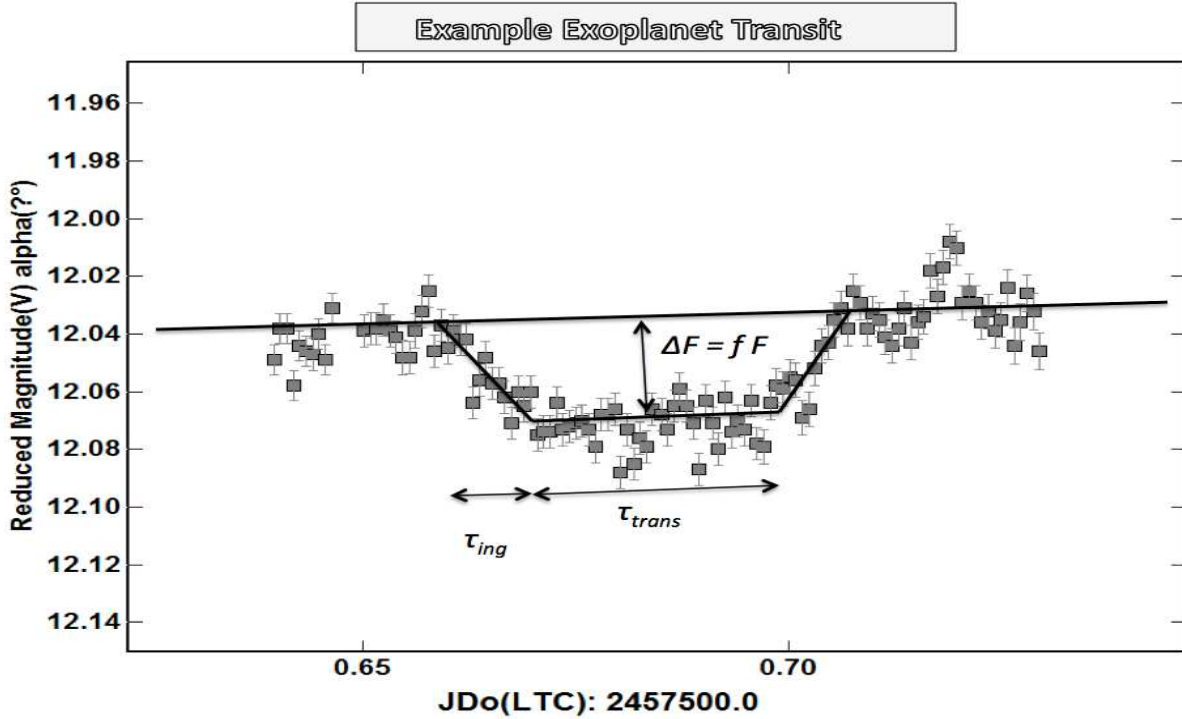


Figure 4.10: An example of an exoplanet detection made with Etscorn Obs. Useful measurables of the light curve are indicated. (Note: ΔF is the dip measured in flux units, even though the light curve here happens to be displayed in magnitudes.)

An example of an exoplanet transit is displayed in Figure 4.10. The figure labels the measured dip as well as timing measurables, τ_{trans} and τ_{ing} . The elapsed time of full eclipse of the star, τ_{trans} (when the planet lies entirely within the bounds of the stellar disk), and the ingress (or egress) elapsed time, τ_{ing} (the time from 'first contact' of the planet with the stellar disk till completely within the stellar disk), also provide useful information. In what follows it is assumed that the planet orbits its host star on circular orbits. (This assumption can actually be tested but elliptical orbits will not be considered here.) Under this assumption, eclipse timing leads directly to orbital

parameters (see the Lunar Eclipse History of Astronomy Lab [Lab 4.3] for an example in our own solar system). τ_{trans} tells the time it takes to cross the stellar disk and hence the orbital speed or semi-major axis, a (orbital radius), of the planet. For a moment, imagine that the planet transits the host stars' equator (we will discuss relaxing this assumption momentarily), then:

$$\begin{aligned} \frac{\tau_{trans}}{P} &\simeq \frac{\frac{2(R_* - R_p)}{v_{orb}}}{\frac{Circum_{orb}}{v_{orb}}} \simeq \frac{R_*}{\pi a} \\ \Rightarrow \quad a &\simeq \frac{R_* P}{\pi \tau_{trans}} \simeq \left(\frac{GM_*}{4R_*} \right) \tau_{trans}^2, \end{aligned} \quad (4.8)$$

where P is the orbital period of the planet (time between to different primary transits; Table 4.1). Thus given host star parameters, the planet's orbital radius can be determined from τ_{trans} . Crudely, the ingress time, τ_{ing} , is the time for the orbital motion to take the planet through one *planetary* diameter. So:

$$\frac{\tau_{ing}}{P} \simeq \frac{\frac{2R_p}{v_{orb}}}{\frac{Circum_{orb}}{v_{orb}}} \simeq \left(\frac{R_*}{\pi a} \right) \left(\frac{R_p}{R_*} \right) \simeq \left(\frac{R_p}{R_*} \right) \tau_{trans}.$$

Equation 4.8 is only approximately correct since it assumes the planet transits the full diameter of the star. It is rare that one is this lucky. Typically the planetary orbit will not be perfectly edge-on and thus will traverse the stellar disk along a chord, with impact parameter, b (see Figure 4.11-*left*). In such conditions the observed τ_{trans} will be less than the relevant τ_{trans} for eq. 4.8. Defining $2\gamma R_*$ as the length of the chord across the stellar disk, then in general $0 < \gamma < 1$ and can be described geometrically by, $b = (1 - \gamma^2)^{1/2} R_*$. Figure 4.11-*right* schematically illustrates the change in the observed light curve as the star transits at increasingly large impact parameters. The signal-to-noise ratio (SNR) likely to be obtained in this Lab is not high enough to tightly constrain γ , however some limited constraint is possible, enough to mention first order corrections to eq. 4.8 and equation below it.

Repeating the line of reasoning that lead to eq. 4.8 except letting $b > 0$, we correct the above equations to read:

$$a \simeq \frac{\gamma R_* P}{\pi \tau_{trans}} \simeq \left(\frac{GM_*}{4\gamma^2 R_*} \right) \tau_{trans}^2, \quad (4.9)$$

and because R_p/R_* is known from eq. 4.7:

$$\gamma \simeq \sqrt{f} \frac{\tau_{trans}}{\tau_{ing}}. \quad (4.10)$$

Thus in this assignment, by measuring the light curve depth and comparing it to the ratio of τ_{trans}/τ_{ing} , it is possible to constrain γ , and hence 'improve' the a estimate.

So far we have seen how to determine the planetary radius and orbital distance from the host star, plus finer precision statements about the inclination of the planetary orbit. However, with some complementary data outside what can be obtained in this assignment, it is possible to constrain the mass and hence structure of the exoplanet. Since transiting exoplanets are, a priori, known to be in basically edge-on orbits, adding radial velocity measurements provide powerful constraints on a system's mass. A star-planet system orbits around its center-of-mass. From

standard orbital mechanics $|M_* {}^{cm}r_*| = |m_p {}^{cm}r_p|$, with ${}^{cm}r_{*,p}$ being the star/planet distances from the center-of-mass. But:

$$v_* \simeq \frac{2\pi {}^{cm}r_*}{P} \quad - \text{ and } - \quad v_p \simeq \frac{2\pi {}^{cm}r_p}{P},$$

$$\Rightarrow \quad \frac{v_*}{v_p} \simeq \frac{{}^{cm}r_*}{{}^{cm}r_p} \simeq \frac{m_p}{M_*},$$

where v_* is the reflex motion of the star in response to the planet orbiting it and is the variable radial velocity studies measure. Since $v_p \simeq (2\pi a)/P$:

$$m_p \simeq \frac{M_* v_* P}{2\pi a}. \quad (4.11)$$

By deriving a and P from the transit, v_* from radial velocity studies and M_* from the stellar properties (spectral type and class), it is possible to determine the mass of the exoplanet, m_p . Together with the radius determined from transits, the planetary density, surface gravity and by extension the nature of its composition can be ascertained. *Combining transit studies with radial velocity studies will permit understanding of the type of world you have, whether gas-giant Jovian world or an Earth-like terrestrial world [maybe habitable for life]!*

4.5.3 Observational Strategies

It is quite impressive that even a small aperture telescope with a quality CCD can 'discover' exoplanets and enable such exciting science. The key requirement is the ability to obtain accurate differential photometry capable of identifying changes in the stellar light at the $\sim 1\%$ level (eq. 4.7).

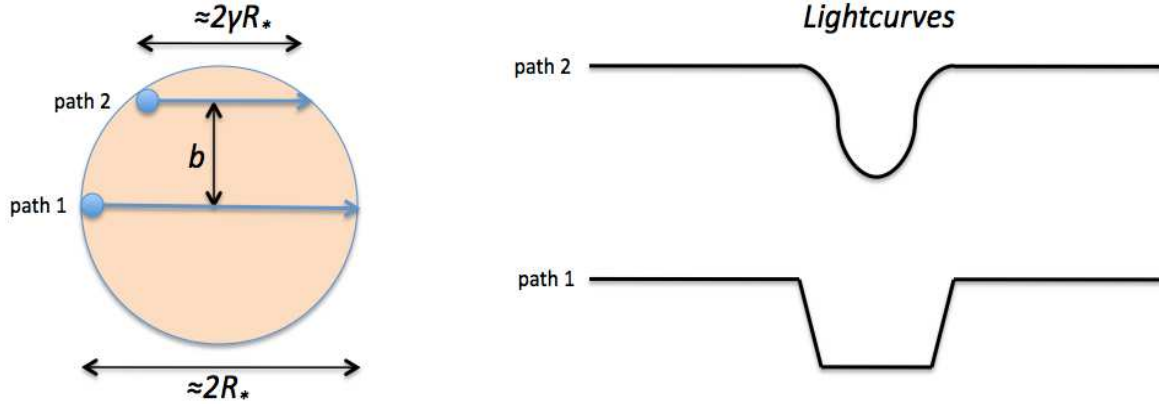


Figure 4.11: *Left)* Transits do not always cross the stellar equator and thus the path of eclipse is in general less than the stellar diameter. Two example paths are shown and the geometric parameters labelled. *Right)* The light curve from the two different paths are different. Typically the fraction of time spent in ingress (egress) relative to total eclipse is larger for larger impact parameter, and thus the light curve spends less time in the total eclipse phase.

In this assignment the student will not attempt to discover an exoplanet, that is (a very popular) research endeavour beyond the scope of this Laboratory. Instead the student will observe known exoplanets suitable for detection, confirm their transit measurables and constrain some of their parameters. This will be done by repeated careful imaging throughout the night, covering the eclipse. Differential photometry (see the CCD Lab [3.2] for a refresher) will be used to measure the magnitude of the host star vs. time. (We will assume that stars elsewhere in the frame have constant (known) magnitudes on this time scale and therefore can serve as reference stars.) Table 4.1 presents a list of candidate exoplanets that surround bright enough stars, have sufficiently deep and short transits to be completely studied in one night, and have suitable reference photometry stars in the field-of-view. Exoplanets will be chosen from this list based on observing session constraints. The clock time of a given transit can be determined from the "The Extrasolar Planet Encyclopaedia" (exoplanet.eu/catalog/) or (<http://www.exoplanets.org>) prior to the scheduled observing run. Also the Swarthmore College astronomy department has created a very useful 'app' to display exoplanet transit schedules: (<https://astro.swarthmore.edu/transits.cgi>)

4.5.4 Exercises

1) Based on the up times and transit times (requires preparation before the scheduled run), select an exoplanet to observe. Estimate the required integration time necessary to detect the transit dip at (at least) 3σ in one observations (see below). After setting up the observations (filter selection, focussing, flat-fielding, etc.) observe the target star for the calculated integration time. Locate the host star and any appropriate reference star(s) and measure their SNR to confirm the appropriate integration time and check for saturation. Once satisfied with the integration time, repeatedly take images of the field, covering the full primary eclipse. Several issues should be kept in mind while observing:

- Observations should be taken once every few minutes for the entire length of the session.
- In order to have an accurate 'baseline' against which to compare, the student will need to observe at least as much off-eclipse phase data as on-eclipse phase; twice as much is even better.
- It is important to have both deep enough integrations and enough of them to accurately trace the light curve. Figure 4.10 is an example of about the minimum number of observations necessary. The student will want individual observations deep enough to detect 1% dips at the $\sim 3\sigma$ (SNR=3) level. Here I give a quick reminder on estimating required SNRs (see eq. 3.3 in the CCD Lab [3.2]). Neglecting sky, dark current, and read-noise contributions to the error budget, a 12th magnitude host star in, for example a 14" - Schmidt-Cassegrain telescope, will have an SNR in a $\simeq 1000\text{\AA}$ -band filter:

$$SNR(12mag) \simeq (P_{tar}(12mag) Q t)^{1/2} \simeq 35t^{1/2}$$

(if you use the clear filter instead of the V filter then the SNR is $\simeq 2\times$ better.) To determine the associated error on a photometric data point it is assumed that the noise is gaussian random noise and independent of position on the chip, thus it adds in quadrature. The error on the target is:

$$err|_{tar}^{mag} \simeq \frac{1.09}{SNR_{tar}},$$

where SNR_{tar} is the measured (host star signal)/(rms noise over an adjacent background) and the 1.09 is a factor that converts SNR in flux units to SNR in magnitude units. The error on the reference star is:

$$err_{ref}^{mag} \simeq \frac{1.09}{N} \left[\left(\frac{1}{SNR_{ref1}} \right)^2 + \left(\frac{1}{SNR_{ref2}} \right)^2 + \dots N \text{ times} \right]^{1/2}.$$

While not required in this Lab, this equation shows that by measuring N reference stars within the field the reference star errors can be beaten down. Here the expectation is that the student will use one ($N=1$) reference star for the differential photometry. Finally, the total error on a measurement (measurement = value(mag) $\pm$ err_{tot}^{mag}) is:

$$err_{tot}^{mag} \simeq \left[(err_{tar}^{mag})^2 + (err_{ref}^{mag})^2 \right]^{1/2}.$$

Therefore, assuming the reference star is brighter than the host star, so err_{ref}^{mag} is small compared to err_{tar}^{mag} , to reach a 3σ level for a 1% dip on a 12th magnitude star requires an $err_{tar}^{mag} \sim 0.004$, $SNR_{tar} \sim 275$ or $t \sim 1$ min. Hence if the host star is $\simeq 12$ th magnitude then you can expect required integration times to be of order a minute.

- The student will perform differential photometry following the CCD Lab [3.2] on each of the images obtained, recording both the target flux / off-source noise and the reference flux / off-reference noise. This is straightforward but a rather tedious and time consuming step of the process. From this you will calculate host star magnitudes and errors for each image.

2) The student will then plot a light curve of time vs. mag($\pm$ error), for all measurements.

3) From the plotted light curve, measure τ_{trans} , τ_{ing} and the magnitude dip, Δm , from which f can be calculated.

4) a) Using eq. 4.7 determine R_p . b) Using eq. 4.8 along with the known orbital period (Table 4.1) determine the semi-major axis, a , or the planet's orbit.

5) If the planet crosses the the stellar equator then eq. 4.10 states that the ratio of τ_{ing} to τ_{trans} should be approximately equal to $\sqrt{f}$. Is this so? If not crudely estimate γ .

6) Look up in the literature (or online — see above listed links), the known values of the parameters, R_p , and, a , and compare to your measured values. If you can find a radial velocity measurement for the chosen exoplanet in the literature, look up v_* . Determine m_p , the planet's density, ρ_p , and based on this density comment on whether the planet is likely to be a rocky terrestrial or gaseous Jovian planet.

Table 4.1: *Potential exoplanet primary transit observable with $\delta > -20^\circ$ [J2000], transit duration < 3 hours, transit depth > 0.013 and known $m_V > 14$ host star.*

Object	RA [J2000]	Dec [J2000]	m_V^* [mag]	$T_{transit}$ [hrs]	Period (P) [days]	Depth (f)
HAT-P-19 b	00h38m04.012s	+34°42'41.5"	12.9	2.84	4.009	0.02011
HAT-P-32 b	02h04m10.278s	+46°41'16.2"	11.4	3.11	2.150	0.02274
Wasp-50 b	02h54m45.135s	−10°53'53.0"	11.6	1.81	1.955	0.01970
HAT-P-25 b	03h13m44.500s	+25°11'50.6"	13.2	2.82	3.653	0.01626
Wasp-35 b	05h04m19.626s	−06°13'47.3"	10.9	3.07	3.162	0.01540
HAT-P-54 b	06h39m35.520s	+25°28'57.0"	13.5	1.80	3.800	0.02470
Wasp-84 b	08h44m25.713s	+01°51'36.0"	10.8	2.75	8.523	0.01672
Wasp-36 b	08h46m19.298s	−08°01'37.0"	12.7	1.82	1.537	0.01913
Wasp-43 b	10h19m38.008s	−09°48'22.59"	12.4	1.15	0.8135	0.02550
Wasp-104 b	10h42m24.584s	+07°26'06.0"	11.3 ^a	1.76	1.755	0.01490
HAT-P-36 b	12h33m03.909s	+44°54'55.1"	12.3	2.22	1.327	0.01407
HAT-P-12 b	13h57m33.480s	+43°29'36.7"	12.84	2.34	3.213	0.01977
HAT-P-27 b	14h51m04.189s	+05°56'50.5"	12.2	1.68	3.040	0.01430
XO-1 b	16h02m11.840s	+28°10'10.4"	11.2	2.94	3.942	0.01758
HAT-P-18 b	17h05m23.151s	+33°00'44.9"	12.8	2.71	5.508	0.01863
TrES-3 b	17h52m07.020s	+37°32'46.2"	12.4	1.35	1.306	0.02739
HAT-P-37 b	18h57m11.058s	+51°16'08.8"	13.2	2.33	2.797	0.01899
TrES-1 b	19h04m09.844s	+36°37'57.5"	11.8	2.51	3.030	0.01844
Wasp-80 b	20h12m40.178s	−02°08'39.1"	11.7	2.11	3.069	0.02933
Qatar-1 b	20h13m31.615s	+65°09'43.48"	12.8	1.61	1.420	0.02117
TrES-5 b	20h20m53.251s	+59°26'55.6"	13.7	1.85	1.482	0.02062
HAT-P-23 b	20h24m29.724s	+16°45'43.7"	11.9	2.18	1.213	0.01367
Wasp-69 b	21h00m06.193s	−05°05'40.1"	9.9	2.23	3.868	0.01796
Wasp-52 b	23h13m58.760s	+08°45'40.6"	12.0	1.81	1.750	0.02710
Wasp-10 b	23h15m58.299s	+31°27'46.2"	12.7	2.23	3.093	0.02525

Note: a. Indicates R-magnitude.

Chapter 5

Galactic / Extragalactic Science Labs



Figure 5.1: Orion Nebula (M42) from Etsorn Obs.

5.1 Lab XV: Narrowband Imaging of Galaxies [o]

For this assignment, working in groups is permitted. Reminder: Please record the details of your observation. These include: the weather/sky conditions; time/date of each observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

5.1.1 Introduction

We have seen that the spectra of different objects are different. When observing extended objects such as nebulae and galaxies it is often tedious to try and slide a slit across the whole object to determine spectral make up. Narrow band imaging permits a rapid characterization of the distribution of an individual spectral line. Then the overall spectrum can be built up by observing through a number of narrow band filters.

In this lab you will use the narrow band filters available to image the ionized gas in galaxies of different types. The available filters, in addition to the broadband clear filter, are the [SII] (6720Å), $H\alpha$ (6563 Å), [OIII] (5007 Å) and $H\beta$ (4861 Å). The $H\alpha$ and $H\beta$ lines are the Balmer recombination lines of hydrogen and thus trace ionized hydrogen gas that is in the process of recombining; so called HII regions. The ratio of the $H\alpha$ to $H\beta$ line generally has a constant ratio depending on the radiative transfer in the HII region. Differences in the $H\alpha/H\beta$, tend to be reflects the presence of dust extinction. This is because $H\alpha$ and $H\beta$ occur at widely separated wavelengths and extinction is wavelength dependent. [OIII] and [SII] are higher excitation lines and therefore requires more energetic photons to excite. Often the [OIII]/ $H\beta$ and [SII]/ $H\alpha$ ratios (ratios that are each relatively free from extinction effects) are used to gauge the level of excitation in an ionized region. A particularly common use of these ratios is for identifying/characterizing AGN (accretion onto a black hole) emission (high ratios) versus normal stellar ionization (low ratios). Careful analysis of multiple transitions of individual species can allow for determination of that element's abundance.

5.1.2 Exercises

In this assignment, you will use narrow band filters to image a couple of galaxies and look for changes in their line emission properties. Given the sensitivity expected in these observation, detailed line ratios are not the focus. Qualitative comparisons between the stellar (clear filter) and ionized emission will be the focus. You are to observe the galaxy, M82 (a starburst dwarf), and choose one from the following list (M 51 (spiral), M81 (spiral), M101 (spiral), or NGC 4449 (giant irregular)).

1) Obtain narrow band images in each of the four narrow bands ($H\alpha$, $H\beta$, [OIII], [SII]) for the two galaxies of choice. Follow the procedure used to obtain color images (Lab 3.3) up through the alignment stage, except with each narrow filter replacing each color image. (It is not necessary to create an RGB 'color' image from the narrow bands.) Don't forget to take flats for each filter. The $H\alpha$ and [SII] are in the red while $H\beta$ and [OIII] are in the blue, so the number of images taken and combined should roughly follow a B:R = 5:1 or 5:2 pattern. Make sure to save the four final combined and aligned narrow band filter images as .fits files for later analysis. Also obtain a

clear filter image of each galaxy.

2) Compare the different filter images to the clear image. Do you see differences? Mark and explain where the narrow band filters are relatively brighter. These correspond to ionized gas regions. How do they relate to position in the galaxy? It is potentially likely that for the spiral galaxies you will not see extensive [OIII] and [SII] emission (aside from the continuum you see in the clear filter). Is this true? If you do detect the emission, compare the [SII] to $H\alpha$ and the [OIII] to $H\beta$ images. If there is no extra emission in the [SII] and [OIII] images aside from the continuum, they can serve as 'off' spectra to compare to $H\alpha$ and $H\beta$ 'on' positions. One easy way to compare images is to use the *ds9>frames* option to blink aligned .FIT images. If there is additional emission in the O and S lines, describe how it differs from $H\alpha$. Does the nucleus of the spiral galaxies stand out in emission lines?

5.2 Lab XVI: Galaxy Morphology [o]

For this assignment, working in small groups is permitted for the observations, however each should turn in their own analysis. Reminder: For any telescope / CCD observations you do please record their details. These include: the weather/sky conditions; time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

5.2.1 Background

Galaxy morphology is perhaps the most obvious characteristic of galaxies and is important for revealing information about a galaxy's internal structure. Internal structure, in turn, influences star formation properties and hence how a galaxy will evolve in time. Thus studying galaxy morphology and its changes throughout the life of a galaxy is vital to understand cosmic evolution.

5.2.2 Galaxy Classification

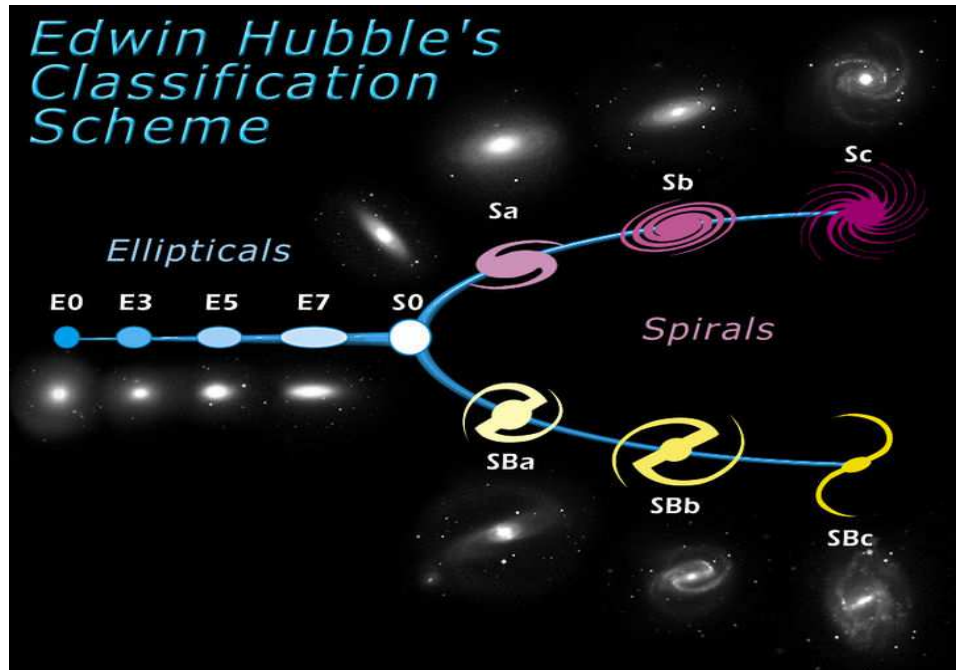


Figure 5.2: The Hubble tuning Fork. Source: NASA and ESA — Wiki Commons

A cursory look at any collection of galaxies show that each is different, but that there are two basic types that appear regularly. The first is spiral / disk galaxies. These have a flattened distribution of stars suggestive of a spinning disk supported by angular momentum. Often (though not always) these disks have superposed on them a spiral pattern (the cause of which remains a topic of research). The second main class are ellipticals, which appear as just blobs of stars. Edwin Hubble was the first person to really quantitatively study the nature of galaxies. After all he was the one credited with both first demonstrating that 'spiral nebulae' were outside of our Galaxy, and to determine how far away they were. Hubble devised a fairly simple classification system for the structure of galaxies.

◇ Hubble 'Tuning Fork':

Hubble's classification system, which he originally thought of as an evolutionary sequence, is shown in Figure 5.2. As we now know today, his evolutionary sequence was incorrect (in fact it is closer to backwards of what he thought), but the basics of the classification has stuck. The classification can be summarized as a 'tuning fork'.

The 'stem' of the tuning fork subdivides the elliptical galaxies (which today are often referred to paradoxically as 'early-type' galaxies — a hold-over from his incorrect evolutionary sequence). Along the stem the degree of flattening of the ellipticals increases, characterized by the parameter, $10(1 - \frac{b}{a})$, where a is the semi-major axis — [one-half the longest] and b is the semi-minor axis — [one-half the shortest]), respectively, of the galaxy. For example, an elliptical with a minor:major axis length ratio of 0.7 would be listed as E3.

The 'tongs' of the tuning fork subdivide the spiral galaxies (paradoxically often referred to as 'late-type') — one tong for galaxies with barred stellar distributions (SB) and one for pure spirals (S). Along the tongs spirals are classified with lower case letters ranging from a to c . The $a \rightarrow c$ classification is based on the nature of the spiral structure. Specifically it is a sequence of the following (there are quantitative distinctions but we will not be concerned with them here):

- bulge:disk ratio — a : large bulge, small disks $\rightarrow c$: small / faint bulge and a dominant disk
- tightness of spiral pattern (pitch angle) — a : tightly wound, nearly circular arms $\rightarrow c$: loosely wound 'S'-shaped spiral arms
- arm clumpiness — a : smooth spiral arms with little substructure $\rightarrow c$: clumpy spiral arms with signs of a lot of star formation / clusters

Finally, those galaxies that are left over, not resembling either spiral disks or fuzzy balls of stars are classified as irregulars. This catch-all category is dominated faint irregular stellar distributions and 'train-wrecks' (multiple galaxies that have 'collided' and disrupted their initial smooth stellar distributions).

◇ de Vaucouleurs 'Barrel':

While a popular classification, it is clear that the labeled distinctions fail to capture much of the morphological diversity of galaxies. As such new, more sophisticated classification schemes have been developed. Probably the current standard is the scheme created by Gerard de Vaucouleurs in the late 1950's and 1960's, known as the de Vaucouleurs 'pitchfork' or 'barrel' (see Figure 5.3). It is the typical reported classification scheme in most places today — see for example NED: NASA/IPAC Extragalactic Database; <http://ned.ipac.caltech.edu/>. The elliptical and irregular classification strategies remains essentially Hubble's (except he added letters 'd' [dwarf] and 'm' [magellanic] to further divide up the irregulars), however he significantly expanded the spiral category. Firstly, he added a third 'tong' to make a trident or pitchfork. This middle tong is for galaxies with an intermediate degree of barred-ness (renaming the tongs: SA - pure spiral; SAB - intermediate bar; SB - strongly barred). Secondly, he rotated this pitchfork about its axis to create a 3-D classification scheme. For each letter category of Hubble's, the axial dimension separately characterizes the structure of the inner part of the galaxy (often different than the outer parts of the disk). Here designations are given r , rs and s , for ring, ring-spiral, and spiral, respectively.

Thus, for example, an intermediately barred spiral with loose, open, clumpy spiral arms and a nuclear barred spiral might receive the classification: SABc(s). While this classification scheme is somewhat open to interpretation, it is much easier to guess the basic structure of a galaxy by simply seeing its classification in a catalogue.

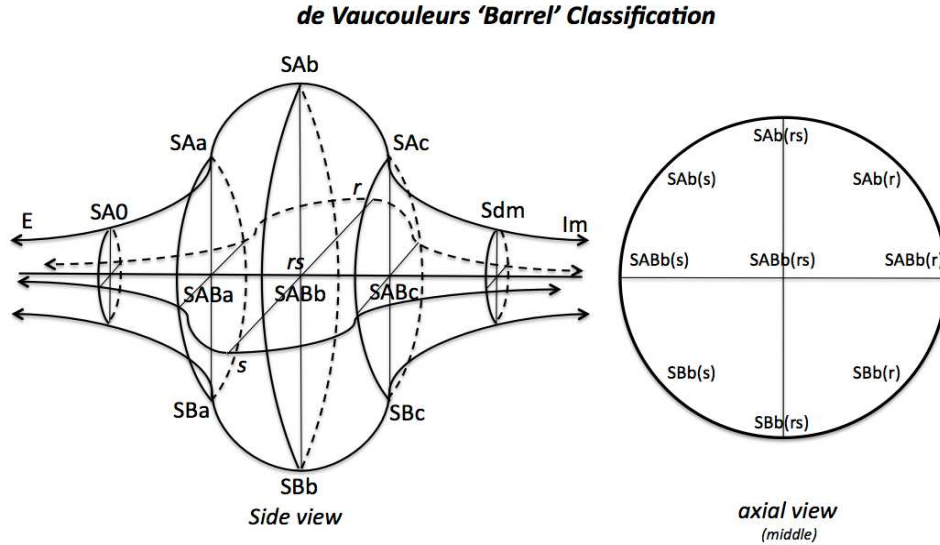


Figure 5.3: A schematic showing the added dimensions of classification developed by Gerard de Vaucouleurs [the 'de Vaucouleurs Barrel'].

5.2.3 Exercises

In this assignment you will image, with the telescope / CCD, a number of galaxies with different morphological structures and classify them by their properties. Using the Messier and Caldwell (and NGC if necessary) catalogues, select one galaxy from each of the main subdivisions of de Vaucouleurs' classification [E , SA0, SAa, SAb, SAc, SABa, SABb, SABc, SBa, SBb, SBc, I]. Choose the brightest galaxies up at the scheduled time so as to minimize the length of integration time. It is recommended to pick a back up as well, just in case there is some reason why you cannot observe your first choice. *Also note that galaxies are not uniformly distributed across the sky (see Lab 5.5), so this assignment may be difficult to execute at certain times of the year.*

1) Record your galaxy choices along with their coordinates, full de Vaucouleurs classification and V-band apparent magnitude, m_V , in a table in your notebook.

2) Obtain a sensitive CCD image of each galaxy in the the clear (L), V and B band filters. You may wish to work in groups, splitting up the galaxies between groups. If so data should be shared amongst the groups.

3) Identify the galaxy (should already be done before the observing run), carefully describe its morphology in both filters, with an eye towards the above itemized galaxy properties. Do you find consistency with the given classification of the galaxy? Does the classification depend on the filter used? Can you say something about the star

formation properties of the galaxy? (Hint: if you are not sure how you might do this, take a look at the Narrowband Imaging of Galaxies assignment; Lab 5.1.) **Does it have alot? Where is it within the galaxy? Does it vary with galaxy class?**

4) Look up each galaxy's distance (remember to always cite your sources). Measure the angular size of the galaxy (for those that fit within the CCD field-of-view). The angular size, together with its distance, will allow you to calculate the physical size of the galaxy. Calculate this value. Compare it to the Milky Way (diameter approximately 50 kpc). Does the size of the galaxies also vary with different morphology classification?

5.3 Lab XVII: Hertzsprung-Russell Diagram and Stellar Evolution [o]

For this assignment, working in small groups is permitted for the observations, however each should turn in their own list. Reminder: For any telescope / CCD observations you do please record their details. These include: the weather/sky conditions; time/date of the observation; integration time/filters/telescope/etc.; and the members of your observing 'team'.

5.3.1 Hertzsprung-Russell Diagram

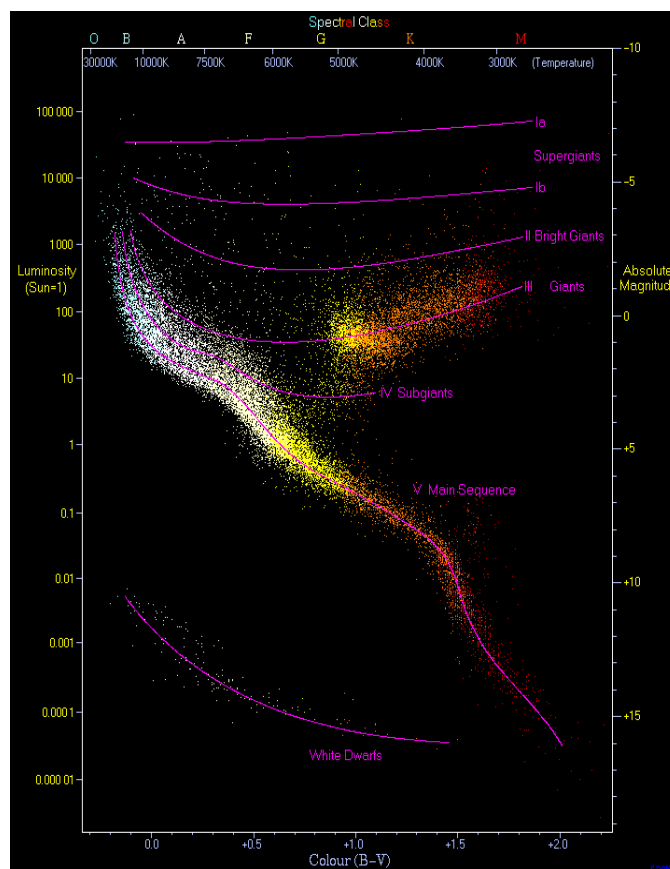


Figure 5.4: The Hertzsprung-Russell diagram in both observational units (B-V color vs. [absolute] magnitude) and theoretical units (temperature vs. luminosity). Luminosity classes are also labeled. Source: Wiki Commons — Author: Richard Powell.

The Hertzsprung-Russell (HR) diagram is the foundational diagram characterizing stellar properties. Depending on whether expressed in observational or theoretical quantities, it is a plot of stellar color vs. stellar magnitude, or stellar temperature vs. stellar luminosity (see Figure 5.4). Stars are nuclear furnaces that burn hydrogen to heavier elements in their core. The high energy radiation (gamma rays) percolate out of the dense interior, taking 100,000s years to escape. By the time they do they have cooled to about 5800° K. The emission seen from a star's surface is approximately a blackbody and thus color / temperature and magnitude / luminosity are inter-

changeable quantities. From Wien's displacement law, peak wavelength (color) and temperature are directly proportional. Likewise, the more luminous a star, the brighter its magnitude at a given distance.

When stars are plotted on this diagram they fall in only specific locations, revealing something about the evolution of stars. Most stars live of a diagonal path running from the top-left to the bottom-right of this diagram. This band of points is known as the "main sequence" (luminosity class V). It represents the stable adulthood of a star when it is burning hydrogen to helium in its core. Because of the Stephen-Boltzmann law, hotter temperatures imply higher luminosities, thus the slope of this band. The more massive the star the more internal pressure exists in the core of the star. As a result the hydrogen atoms collide with each other at higher energies leading to more rapid nuclear reactions (nuclear reactions are extremely sensitive to temperature / pressure). More intense nuclear reactions imply higher luminosity, so stars at the top-left end of the main sequence (O stars) are (much) more massive than stars at the cool bottom-right end of the diagram (M stars). Stars spend about 90 % of their lifetime in this phase (which is why most stars selected at random appear there).

From stellar structure modeling, it is known that as stars age and 'die' they leave the main sequence in a roughly perpendicular direction. This locus of stars leaving the main sequence is known as the "giant branch" (luminosity classes, IV [subgiant] $\rightarrow$ III [giant]). During this phase the outer envelope of the star puffs up to a very large size, the core is degenerate (inert) helium and nuclear burning occurs in a shell around this inert core. Giant stars can have radii that approach the size of Earth's orbit around the Sun. Once the core has heated up enough helium can begin to fuse to form carbon (and oxygen), retriggering core nuclear fusion. But since there is less helium and helium-to-carbon nuclear reaction ('triple- α ' process) is less efficient, this new stable phase, known alternatively as the 'horizontal branch', 'helium main sequence', or the 'red clump' phase is much shorter lived than the main sequence. After exhausting helium the star rapidly grabs any nuclear reaction it can get its hands on in a desperate struggle to stave off gravitational collapse. In the process it swings violently back-and-forth to the giant branch. Evolved stars returning to the giant branch after main helium burning phase is known as the 'asymptotic giant branch'. Ultimately gravity wins out and the star implodes, leaving behind a white dwarf + planetary nebula or a supernova remnant + neutron star/black hole, depending on the mass of the original star.

5.3.2 Stellar Evolution and Clusters

One of the methods used to discover this life cycle of stars was to study the HR diagram of individual clusters. Clusters form as (nearly) bound objects so it is expected that they are approximately coeval. Therefore, clusters give a snapshot of a collection of different mass stars that are all the same age. Since different mass stars live different lengths (more massive stars have shorter lifetimes), a cluster of some age will have some fraction of its stars evolved to the point of leaving the main sequence. As a cluster ages the location this 'turnoff' from main sequence to giant branch progresses to successively lower mass (redder) stars (see Figure 5.5). The age of the cluster corresponds to the main sequence lifetime of the most massive (bluest) star remaining on the main sequence. Main sequence lifetimes can be approximated as:

$$\tau_{life} \simeq \tau_{ms}(M_{\odot}) \left(\frac{M/M_{\odot}}{L/L_{\odot}} \right) \simeq 10Gyrs \left(\frac{M}{M_{\odot}} \right)^{-5/2} \simeq 10Gyrs \left(\frac{L}{L_{\odot}} \right)^{-5/7}. \quad (5.1)$$

Thus by measuring the color of the turnoff stars, the spectral class and hence mass or luminosity of the turnoff star determined and τ_{life} calculated.

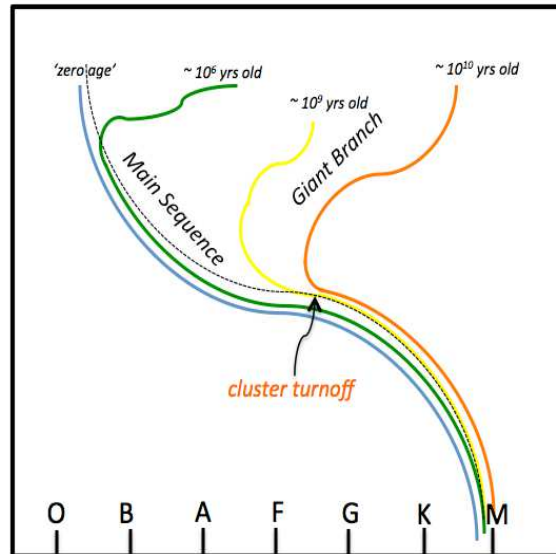


Figure 5.5: A schematic showing the the evolution of stars in a cluster as the cluster ages. As the cluster ages increasingly lower mass stars exhaust their hydrogen fuel and move off the main sequence to the giant branch. The most massive star left on the main sequence within a cluster marks its turnoff point. The lifetime of this star marks the age of the cluster.

5.3.3 Exercises

In this assignment you will create an HR-diagram for the open cluster, M 67. M 67 is one of the oldest, (fairly) nearby open clusters which hasn't completely dissolved (see Figure 5.6). Thus a significant fraction of the stars have evolved off the main sequence onto the giant branch. This makes the cluster especially amenable to the cluster turnoff method and as a visual probe of stellar evolution.

1) Take B and V band images of the M 67 cluster. The images should be as deep as possible without saturating the brighter cluster members. Since stars that you need to calibrate will cover all of the CCD chip, it is key for you to carefully flat field the data.

2) Following the strategy in Lab 3.2, execute differential photometry on as many of the stars in the cluster as possible. (This workload should be split up amongst the team members.) The Instructor will give you one star to treat as a known reference magnitude against which all the other star's magnitudes will be referenced. This will save you from having to do absolute photometry. **Tabulate the B-V color ($m_B - m_V$) vs. the V-band magnitude, m_V , in your notebook (or a spreadsheet). Plot a color-magnitude version of the HR diagram. On the plot label the main sequence, the main sequence turnoff and the giant branch.** Note: as a word of caution, your HR diagram will not likely look exactly like Figure 5.4 because you will not have the sensitivity to detect all stars down to M spectral classes, so be careful in your identification of the corresponding features.

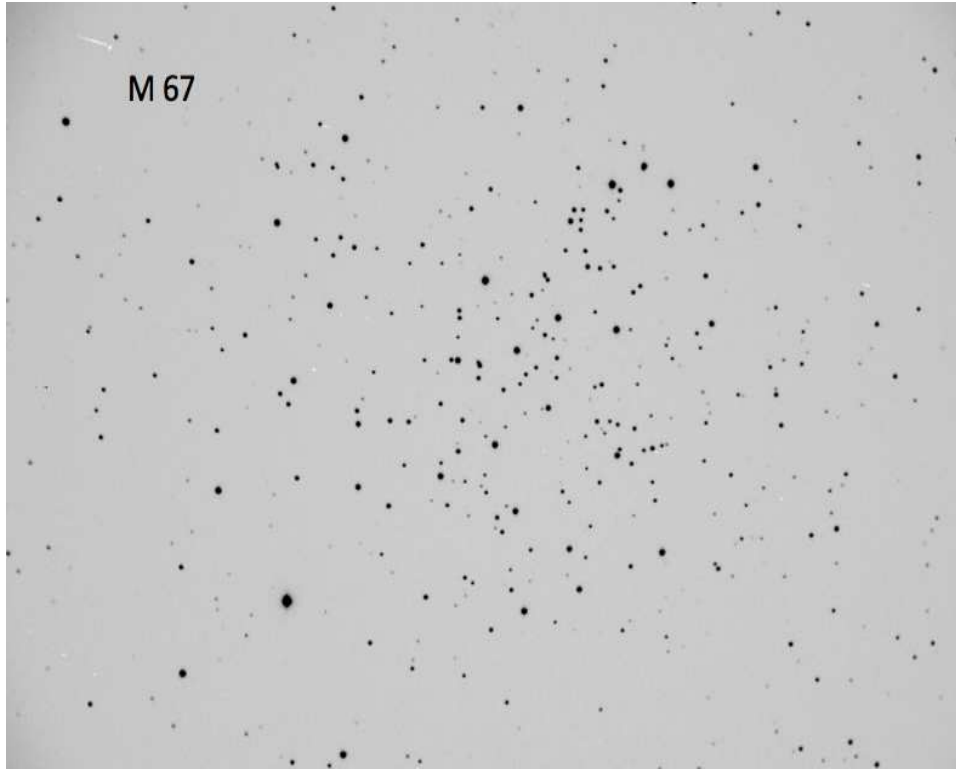


Figure 5.6: An image of the inner portion of M 67.

3) Identify the color of the most massive (bluest) stars remaining on the main sequence. Look up the mass (or luminosity) corresponding to this color. Using eq. 5.1 calculate the age of the cluster. Compare this to the literature value (cite your source for the literature value).

4) Find a main sequence star with the same color as the Sun ($B-V|_{\odot} \simeq 0.65$). This means that star is approximately equal to the Sun in spectral class (G2V) and hence can be assumed to have approximately the same luminosity and temperature as the Sun. **Compare the apparent magnitude of this star to its implied absolute magnitude (that of the Sun — $M_V = +4.8$) to determine the distance to M 67.** This method of distance determination is known as 'main sequence fitting'.

5) What is the spectral class of the faintest stars you can measure?

6) Comment (qualitatively) on the number of stars you detect of each spectral type. You may adopt the following color ranges for each spectral type:

O stars: $B-V < -0.31$

B stars: $-0.31 < B-V < -0.05$

A stars: $-0.05 < B-V < +0.27$

F stars: $+0.27 < B-V < +0.57$

G stars: $+0.57 < B-V < +0.79$

K stars: $+0.79 < B-V < +1.39$

M stars: $+1.39 < B-V < +2.20$

This quantity is known as the 'mass function' (initial mass function = number of stars formed per unit mass bin) and is a very important topic of research in star formation.

5.4 Lab XVIII: Stellar Distribution Assignment [i]

For this assignment, working in small groups is not permitted. A lab write up is required for this assignment. Please tabulate the information in the table and chart provided or in your Laboratory notebook, if too little space is available. Make sure to list the references you use.

5.4.1 Introduction

In this exercise, you will use equatorial and galactic coordinate systems to explore how stars of different spectral types (specifically classes O and G) are distributed in the Milky Way galaxy. You will be given two lists: one of 24 O-type stars, and one of 24 G-types. You will investigate whether the distribution of these two types of stars in the Galaxy is different, and if so, characterize and explain the distribution.

1) Using the SIMBAD database system at <http://simbad.u-strasbg.fr/>, find the coordinates for each star in the lists and record both the *equatorial* and *galactic* coordinates in the corresponding table (Table 5.1 for G stars and Table 5.2 for O stars). Also record the actual spectral class (O# or G#) and luminosity class (I - V). For example, a main sequence O9.5 star should be recorded as O9.5V. Finally record the apparent V-band magnitude (m_V) of the star. Since SIMBAD does not readily provide the absolute V-band magnitude, M_V , for each star, so those values has been provided in the tables.

2) Next plot right ascension (α) / declination (δ) for these stars on the chart below (Figure 5.8), using 'O' for the O stars and 'X' for the G stars. Describe what you see from the distribution in this graph. For assistance, look up images of the coordinate system on the web and try to get a good sense of how our Galaxy is distributed across the celestial sphere in the equatorial coordinate projection shown in Figure 5.8. **Sketch the path of the Galactic plane on the Figure, along with your 'O's and 'X's.** You will need to be careful in analyzing your data. Remember that the coordinate grid displayed is a (aitoff-hammer) projection of the celestial sphere and as such the grid elements are not a square. Degrees near the poles are much smaller on the projection than at the equator.

3) Galactic coordinates offer an angular grid to measure an object's position with respect to the Galactic center and the Galactic plane, as measured from our point of view. Now make another plot, this time of Galactic longitude, ℓ (the azimuthal direction along the Galactic plane, + to the left, - to the right), vs. Galactic latitude, b (the direction perpendicular to the Galactic plane, + above, - below). You may use a square grip (graph paper) for this if you wish. Again, explain what the graph of the O stars and G stars shows. Though you won't need to calculate galactic longitude and latitude from RA & Dec, as they are given in SIMBAD entries for a given star, it is sometimes useful to understand the mathematical relationship between equatorial and galactic coordinate systems. You will find the equations below. Note carefully that, if you do use these equations in calculations of ℓ and b in the future, be sure to carefully consider the quadrant of the output, because (co-)sinusoids are quadrant degenerate.

5.4.2 Converting Between Equatorial and Galactic Coordinates

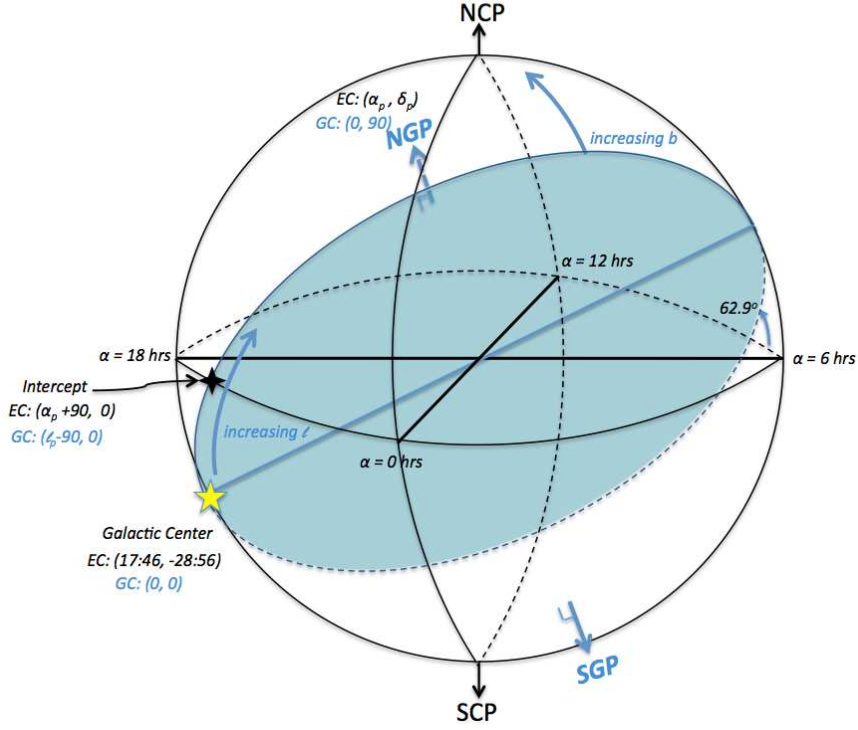


Figure 5.7: A schematic showing the inter-relation between Equatorial coordinates (labeled in black) and Galactic coordinates (labeled in blue). Dashed lines represent parts of the sphere's surface that are 'behind the plane of the page' (so from the reader's perspective the near side of the Galactic disk (blue disk) is the top side). Values with a subscript P refer to those of the north Galactic pole (see text).

It is possible to derive conversions between different coordinate systems on the celestial sphere. You have seen an example in Lab 2.3. There you learned to convert between Altitude-Azimuth and Equatorial coordinate systems. A similar analysis can be used to derive conversion equations between Equatorial and Galactic coordinate systems. Since the Equatorial coordinate system is geocentric (remember it was effectively an extension of the Earth's coordinate system onto the sky), it is often not especially handy when referring to sources outside of the solar system. Figure 5.7 shows the relative orientations of these two coordinate systems, with a few key locations and coordinates listed. From this geometry it is possible to determine the equations of transformation, as we did in Lab 2.3. However, here we will not set up the details of the derivation, just report the relevant equations. (If you wish to try and derive it for yourself, set up a spherical triangle that has the north Galactic pole [NGP; the direction the Galaxy's north rotation axis points towards], the north celestial pole and the target as the three vertices.) The conversions found are:

$$\sin b = \sin \delta_P \sin \delta + \cos \delta_P \cos \delta \cos(\alpha - \alpha_P) \quad (5.2)$$

$$\tan(\ell_P - \ell) = \frac{\cos \delta \sin(\alpha - \alpha_P)}{\cos \delta_P \sin \delta - \sin \delta_P \cos \delta \cos(\alpha - \alpha_P)}, \quad (5.3)$$

where the subscript P on the variables refers to α , δ and ℓ of the NGP, given by:

$$\begin{aligned}\alpha_P &= 192.9^\circ \\ \delta_P &= 27.1^\circ \\ \ell_P &= 122.9^\circ.\end{aligned}$$

4) Create a histogram (number of objects within a given interval, or "bin", of a certain variable) by plotting the number of stars in a given Galactic latitude interval vs. different bin sizes of b . This should give you a sense of the angular offset for these stars in the direction perpendicular to the Galactic plane.

Stellar distances may be obtained by comparing the apparent magnitude of a star to its absolute magnitude. Remember that the absolute V-band magnitude of a star, M_V , is the V-band magnitude the star would have if it were 10 pc away. So:

$$m_V - M_V = -2.5 \log \left(\frac{F_*}{F_*(10pc)} \right),$$

but:

$$\frac{F_*}{F_*(10pc)} = \frac{\left(\frac{L_*}{4\pi d_{pc}^2} \right)}{\left(\frac{L_*}{4\pi 10^2} \right)} = \frac{100}{d^2(pc)}$$

so:

$$m_V - M_V = -5 \log \left(\frac{10}{d_{pc}} \right) \quad - \text{ or } - \quad d_{pc} = 10 \times 10^{0.20(m_V - M_V)}. \quad (5.4)$$

5) The tables provide the absolute magnitude for each star. From this and equation 5.4 calculate the physical distance to each star and record it in the tables. Once you know the distance to the star, you can deduce from trigonometry and the Galactic b coordinate, how far above or below the Galactic plane the star resides. Recreate the histograms from part 4), this time as a function of physical distance above or below the plane.

6) Interpret your data: Why is the distribution of O-type stars in the Galaxy different from that of G-type stars? Come up with reasons why certain types of stars, based on their masses, luminosities, makeups, etc.. might exist only in certain parts of our galaxy (if that is what you observe). As a hint, consider their very different main-sequence lifetimes, given by the approximate formula:

$$\tau_{ms} \simeq 10^{10} \text{ years} \frac{M}{M_\odot} \frac{L_\odot}{L} \quad (5.5)$$

and the fact that stars are born with a given random velocity, σ , and will then travel through the galaxy throughout their life.

7) Comment on the connection between absolute magnitude and the luminosity class of the stars (both for O and G types). Do you see a pattern? What is it?

Table 5.1: List of G Stars

Star	Spectral Type	R.A. / Dec. Coord. ($hh : mm ; ^\circ : \iota$)	Galactic Coord. ($^\circ : \iota ; ^\circ : \iota$)	m_V (mag)	M_v (mag)	Dist. (pc)
Alpha ¹ Centaurus					4.45	
Alpha Auriga					-0.51	
Beta Cetus					-0.34	
Beta Corvus					-0.51	
Eta Bootes					2.38	
Mu Velorum					-0.05	
Eta Draco					0.50	
Beta Hercules					-0.53	
Beta Draco					-2.47	
Beta Hydra					3.43	
Zeta Hercules					2.68	
Epsilon Virgo					0.37	
Beta Lepus					-0.64	
Beta Aquarius					-3.47	
Gamma Perseus					-1.58	
Eta Pegasus					-1.19	
Alpha Aquarius					-3.88	
Epsilon Leo					-1.48	
Gamma Hydra					-0.09	
Epsilon Gemini					-4.16	
Delta Draco					0.61	
Zeta Hydra					-0.22	
Zeta Cygnus					-0.13	
Epsilon Ophiuchus					0.61	

Table 5.2: List of O Stars

Star	Spectral Type	R.A. / Dec. Coord. ($hh : mm; ^\circ : l$)	Galactic Coord. ($^\circ : l; ^\circ : l$)	m_V (mag)	M_v (mag)	Dist. (pc)
Zeta Orion					-5.15	
Delta Orion					-4.84	
Zeta Puppis					-5.96	
Zeta Ophiuchus					-3.24	
Iota Orion					-5.30	
Lambda Orion					-4.05	
Xi Perseus					-4.73	
Sigma Orion					-3.75	
Alpha Camelopard.					-7.39	
Tau Canis Major					-5.11	
10 Lacerta					-2.71	
29 Canis Major					-5.11	
68 Cygnus					...	
Delta Circinus					-6.46	
Lamda Cepheus					-3.47	
19 Cepheus					-6.06	
Mu Columba					-2.84	
14 Cepheus					-5.22	
9 Sagittarius					-5.05	
16 Sagittarius					...	
9 Sagitta					-6.99	
Theta ¹ Orion					...	
15 Monoceros					0.32	
Theta ² Orion					-0.57	

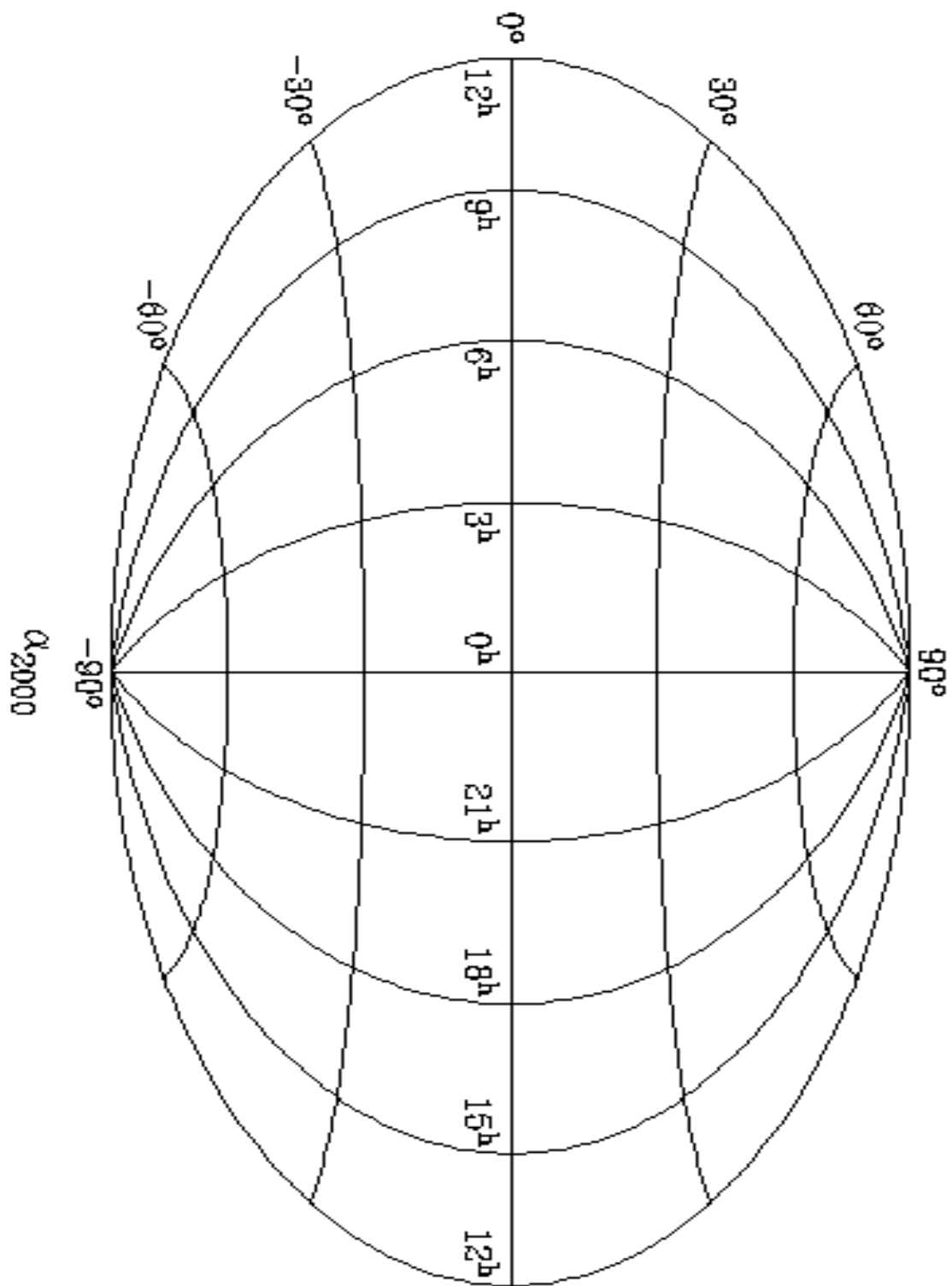


Figure 5.8: Aitoff-Hammer projection of the celestial sphere.

5.5 Lab XIX: Galactic Structure Assignment [i]

A short lab write up is required for this lab. Please plot the data on the given coordinate grid. Make sure to list the references you use. *For this assignment, working in small groups is not permitted.*

5.5.1 Introduction

The Universe is characterized by structure on all scales ranging from subatomic to cosmological. In this assignment you will investigate the structure on 1 - 1000 kpc scales (without having to do extensive outdoor observations). The Messier and Caldwell Catalogs are two well known catalogs of deep-sky (non-stellar or non-planetary) objects. The catalogs each list 109 of the bright nebulae, star clusters, galaxies and other detritus visible. These catalogs represent a good inventory of the brightest Galactic non-stellar objects and the closest galaxies, therefore are excellent for observationally determining the structure of the Galaxy and the local Universe.

5.5.2 Exercises

1) Find a copy of the Messier and Caldwell catalogs listing at least (α, δ) and type of object [e.g. *Star & Planets* or find them online]. On the attached sky coordinate grid (Figure 5.9), mark the position of the every galaxy with an open circle (O), the position of every globular cluster with an asterisk (*) and everything else with a cross (X). You need not be exact but you should place the mark within a few degrees of accuracy. Also remember that the coordinate grid displayed is a (aitoff-hammer) projection of the celestial sphere (α vs. δ) and as such the grid elements are not square. Degrees near the poles are much smaller on the projection than at the equator. Also the projection of a disk will not appear exactly as a circle, but instead will appear more like an (american) football, with a side partial smashed in.

2) Upon completing problem 1), inspect your plot and identify trends in the structure of the sources. a) Mark with a line through the rough midplane of any bands/strips of similar sources. Label what these bands correspond to (e.g. celestial equator, ecliptic, Galactic plane, Super-Galactic plane, etc.). What is the significance of each 'band' structure seen on this plot? Globular clusters (your '*') are known to reside in a large roughly spherical halo centered on the center of the Galaxy. Historically, Harlow Shapley used just this fact to locate the center of the Milky Way (and hence the fact that we are not at its center). b) From your distribution of globular clusters roughly locate and label the center of the Galaxy. How does this 'center' correspond to the other distributions you observe (particularly the X's)? c) Do the other galaxies (O's) appear randomly distributed across the sky? If so, does this make sense? If not, then what astrophysical process might be at work to cause the distribution to not be uniform. d) Briefly describe the astrophysics mechanisms that control all other observed bands.

3) Mark the approximate region of the sky visible to you for the current evening (state what time you have adopted).

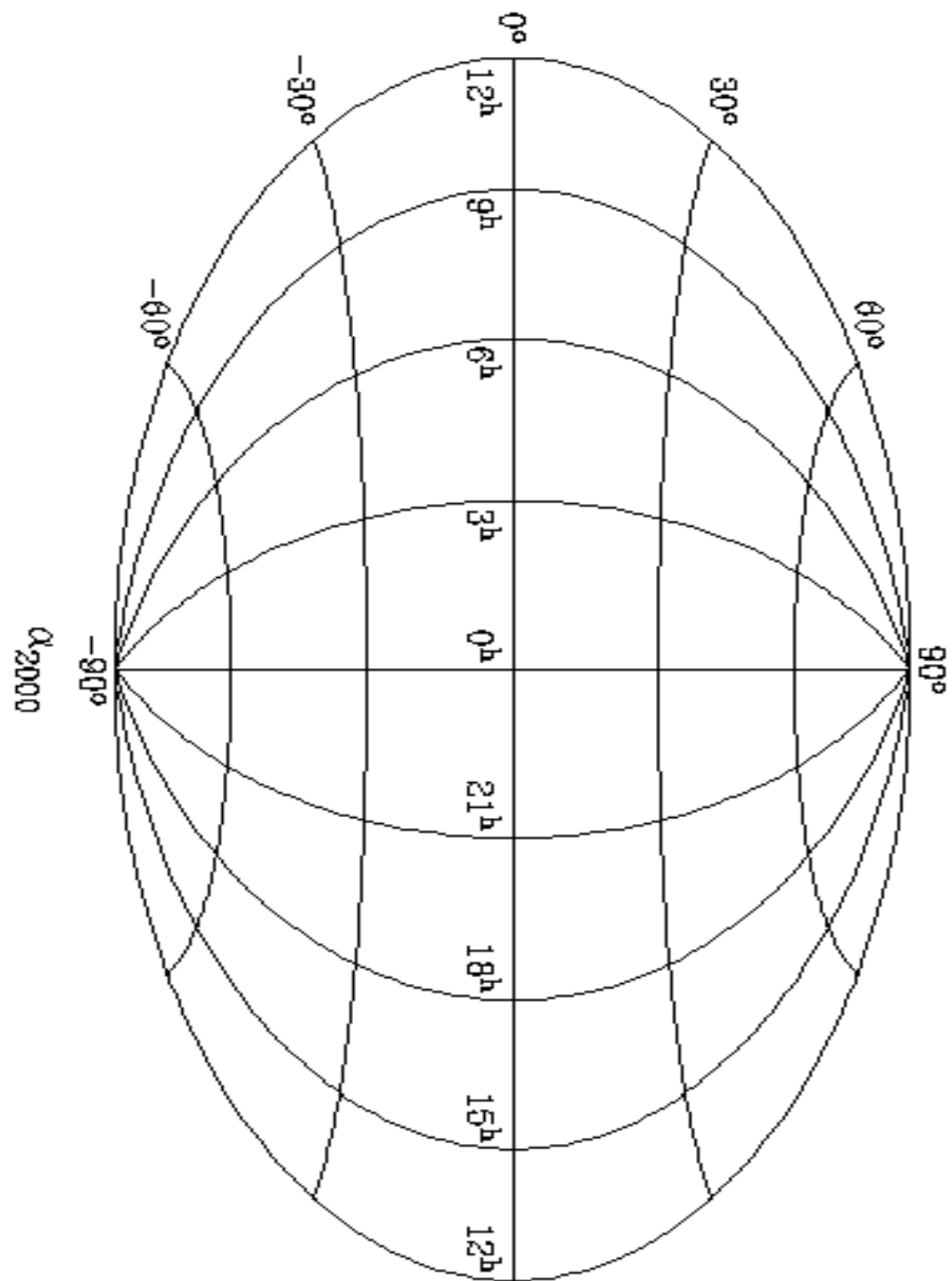


Figure 5.9: Aitoff-Hammer projection of the celestial sphere.

5.6 Lab XX: Counting Galaxies [i]

For this assignment, working in small groups is not permitted. Do not forget to cite your sources used to answer the questions.

5.6.1 Counting Galaxies in Clusters

Since trying to count all of the stars in our galaxy would take a little too long, you will count all of the galaxies that appear to be in the Leo Cluster of galaxies. The number of galaxies in a cluster is important for a number of reasons, of which three are mentioned here. Firstly, it is important for estimating the mass and density of the cluster, since galaxies with similar brightnesses tend to have vaguely similar masses, and so counting galaxies $\Rightarrow$ counting (visible) mass. Secondly, measuring the velocities that the galaxies move with inside the cluster, via the Doppler effect, gives constraints on the dynamics of the cluster and hence its mass and evolutionary state. The more galaxies a cluster has the more accurate the measurement of this dynamics. Thirdly, the number tells us something about cosmology and how structure forms in the Universe. Structure forms in the Universe by the gravitational collapse of early Universe overdensities. Richer clusters (those with more galaxies), mean they started off as more extreme perturbations in the early Universe. Therefore rich cluster abundances tell astronomers about how (not) smooth and uniform the Universe started out, which can be directly compared with theoretical cosmological models.

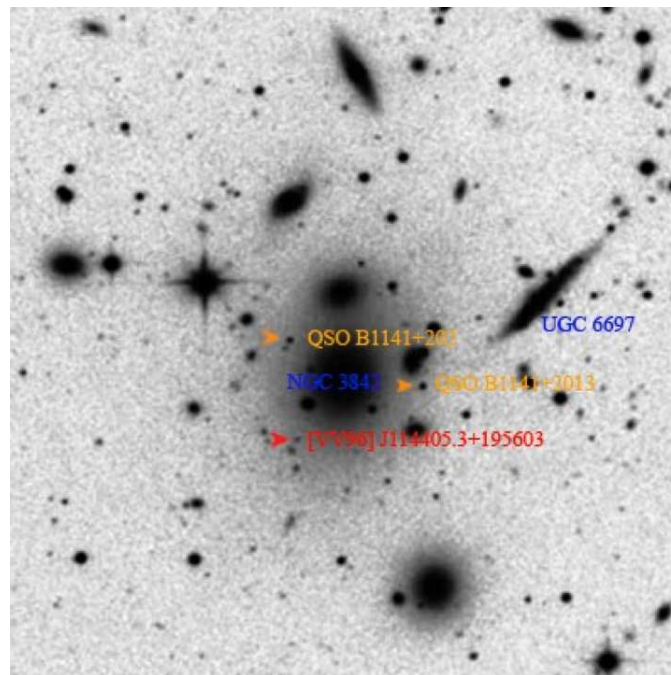


Figure 5.10: Image of the inner portion of the Leo Cluster.

In this assignment, you will count the number of galaxies in a 'nearby' cluster. The cluster you will choose is the Leo Cluster (Abell 1367 — (11 : 44 : 36; +19 : 45 : 32); Distance $\approx$ 100 Mpc; Figure 5.10). To do the counting you will make use of Palomar Sky Survey (POSS) photographs. While this survey is now digitized and online, we will use the copies of the actual photographs, as

the digitized images of the relevant field of view would be too large to be practically manageable. The POSS survey plates may be checked out from the instructor.

5.6.2 Exercises

1) Who is George Abell and what does he have to do with clusters. And the Leo Cluster, in particular? Also include at least one interesting factoid about the Leo Cluster.

2) Count and record the number of galaxies in the Leo Cluster. Abell has created a system for ranking the richness of a cluster. It is based on the number of galaxies within certain magnitude ranges. The technical definition is: 1) find the apparent magnitude of the third brightest galaxy in the cluster; 2) go two magnitudes fainter; 3) then count all galaxies with at least this magnitude; 4) give a richness classification based on the following subdivision: 0: 30-49 galaxies; 1: 50-79 galaxies; 2: 80-129 galaxies; 3: 130-199 galaxies; 4: 200-299 galaxies; 5: >299 galaxies. Now we do not have an effective way of measuring magnitudes off the POSS plates, so we will count galaxies in the following way:

1. Take a piece of paper and cut out an aperture that is a square of sides 10 cm. Since the POSS plate scale is 67.14 arc seconds/mm you will be looking at an area of 1.8 square degrees on the sky.
2. Find the brightest galaxy in the cluster on the POSS plate. Center your aperture on this galaxy.
3. Now count all galaxies lying inside that aperture that are somewhat comparable to this galaxy in brightness. Basically count all 'smudges' that look more prominent than a point source. Notes: 1) if the object has 'diffraction spikes' then it is a foreground Galactic star — do not count those, 2) there is obviously going to be a fair amount of uncertainty here, so different student's answers may vary significantly from each other, and 3) *do not write on the POSS plates!* — so you will have to develop a method of counting that both, doesn't mark up the chart and doesn't double-count or miss galaxies. Perhaps using a piece of transparency acetate to overlay might be useful.
4. Also count the number of these galaxies that look *clearly* like spiral galaxies [e.g. they are edge-on disks or have obvious spiral structure].

Record both numbers (total and spirals) in your notebook. Determine the richness classification of the Leo Cluster from your numbers.

3) Can you be sure all of the galaxies that you counted really members of the cluster? Why?

4) Estimate the mass of the cluster by using the virial theorem. Remember from mechanics class that the virial theorem states that for equilibrium (which you may assume the cluster is in), $|U| \simeq |2K|$, where U is the gravitational potential energy and K is the kinetic energy of the object. Therefore, $(GM_{cl}^2)/R \simeq M_{cl}\Delta v^2$, or:

$$M_{cl} \simeq \frac{(\Delta v)^2 R}{G}.$$

For this assignment, adopt R based on the size of your aperture (and the distance to the cluster) and Δv , the average velocity of a galaxy within the cluster, to be ~ 1000 km/s (e.g. *Dickens & Moss 1976, MNRAS, 174, 47*).

5) Estimate the cluster mass by counting galaxies. Assume that the mass of each counted galaxy is approximately that of the Milky Way. The (total) mass of the Milky Way is $\sim 5 \times 10^{11} M_{\odot}$ — note: this measure includes dark matter (at least for the inner halo). Compare the mass of the cluster calculated this way to that obtained in problem 4). Discuss any discrepancies. (Hint: agreement is not necessarily guaranteed even if our counting method was precise.)

6) Estimate the fraction of total galaxies counted that are spirals. Compare it to the value of our Local Group, which is a fairly low density intergalactic environment. Discuss any differences. For our Local Group, we have three bright galaxies, the MW, M31 and M33, all of which are spirals. Hence in the Local Group the fraction of bright galaxies [those we would count if in a distant cluster] that are spirals is 100 %.

Chapter 6

General Observing Labs



Figure 6.1: Triangulum Galaxy (M33) from Etscorn Obs.

6.1 Lab XXI: Visual Dark Sky Scavenger Hunt [o]

Working in groups is permitted for the observation portion of this assignment. You will not be required to write a report for this assignment. Instead, you must work with your group members and share your drawings and documentations of the objects you observed, and do some research to discover the official name of each object (NGC and Messier numbers are fine where applicable). Each of you will turn in the following information for each object: Telescope, eyepieces, a photocopy of others or your original drawings, and descriptions (completely labeled with object coordinates, name and number).

6.1.1 Set Up

This experiment is designed to help you get acquainted with objects that are best observed on a very dark, clear night, as well as to aid you in becoming proficient at finding objects using their equatorial coordinates.

First, decide within your group what telescope you will use for the observations. Next, obtain two eyepieces: one of low magnification ($\gtrsim 30$ mm focal length), and one of high magnification (5 – 20mm focal length). Set up your telescope and make sure the collimation of your telescope is okay. Once your telescope is properly collimated, look at a bright star and focus. Then begin your observations.

6.1.2 Make Observations

1) Using the sets of coordinates in the lists below, use your field guide or star charts to find the object at those coordinates. You may need to refer to more than one star chart in order to get the best sense of the position of a given object, in reference to surrounding constellations/bright stars. Work your way down the list sequentially, and make the following observations. HINT: It is best to use low-magnification eyepieces to find your objects, then switch to higher magnification for your observations. Groups should be no larger than four students. Divide the list approximately equally amongst group members.

2) Observe each object using the highest magnification of the eyepieces you chose, so long as most of the object fits within the field of view. Draw what you see (in your notebook), and take the time to let your eyes adapt to the finer details of the object you are looking at, and make sure the drawing is as detailed as possible (you should spend at least between 5 and 10 minutes observing a given object at high magnification). Be mindful of the time you take: you don't need to attain artistic perfection in your drawing, just make sure it is *accurate* and contains as much information as you can perceive. Make sure each member of a given group gets a photocopy of all of that groups' sketches before identification begins (other than the coordinate list information).

3) For each drawing, include the following information: A description of the object, details in color and structure, relative sizes, and what you believe the object actually is (i.e. if it is a galaxy, which galaxy specifically?). If applicable, note any other objects surrounding the one in question within the same field of view, identify them and also describe their properties. For objects which you know the common name of, include

the classification name (i.e. Messier number or NGC number) where applicable. Your descriptions should be as detailed as possible. For example, when looking at a distant galaxy, just describing it as "fuzzy" is not acceptable.

Fall List of Object Coordinates (RA ; Dec)

1. 18:18:48 ; -13:47:50
2. 18:51:06 ; -06:16:00
3. 18:53:35 ; +33:01:47
4. 18:44:23 ; +39:36:46
5. 19:59:36 ; +22:43:18
6. 00:42:44 ; +41:16:08
7. 01:33:52 ; +30:39:29
8. 02:19:04 ; +57:08:06
9. 03:47:00 ; +24:27:00
10. 05:34:32 ; +22:00:52 *
11. 05:35:17 ; -05:23:28

Spring List of Object Coordinates (RA ; Dec)

1. 05:34:32 ; +22:00:52 *
2. 05:35:17 ; -05:23:28
3. 05:41:42 ; -01:50:43
4. 08:51:24 ; +11:49:00
5. 09:55:54 ; +69:40:59
6. 10:47:49 ; +12:34:52
7. 11:20:15 ; +12:59:24
8. 13:23:56 ; +54:55:31
9. 14:03:12 ; +54:20:58
10. 16:41:41 ; +36:27:36

* These objects can be very difficult to find.

6.2 Lab XXII: Blind CCD Scavenger Hunt [i/o]

(Working in groups is permitted for the observations portion of this assignment.) You will not be required to write a report for this lab. Instead, you must work with your group members and share your images and documentations of the objects you observed, and do some research to discover the official name of each object (NGC and Messier numbers are fine where applicable). You will need to turn in all of the following information: Observing conditions, time/date, telescope, CCD settings, calculations of altitude, descriptions (completely labeled with object coordinates, name/number/identifier, type of astronomical object, nature of object), and images of each.

6.2.1 Set Up

This experiment is designed to help you get acquainted with astronomical objects that are suitable for quality CCD imaging, as well as to aid you in becoming proficient at finding objects using their equatorial coordinates. It will also re-enforce your ability to determine if an astronomical object is up at a given observing session, as you learned in lab 2.3.

6.2.2 Exercises

First, decide upon your group. There are a maximum of 4 people to a group. Next, mutually decide upon an observing date and time. It is okay if your date is uncertain by a few days, however adopt a local time that you are likely to observe and do not let this time slip.

1) Calculate the altitude, γ , of the object for *each* of the (α, δ) coordinates listed below. The goal is to determine whether that object is high enough in the sky that it can be observed. You must determine which objects are up before you go to observe — you will not be allowed to begin until you should the teaching assistant / instructor all your calculations. Adopt a minimum acceptable altitude of 30° . [It is not acceptable to consult a star chart or application to determine if the object is up. All calculations should be shown.] It is possible to split the list up amongst the group, so that each person in the group does a subset of the calculations. It is, perhaps, helpful to make a quick computer code to do the calculations. (If you do this well it will be a very valuable code to have around for future use.) It is also allowable to state that an object is not above the horizon without calculating a specific altitude if you can make a clear and precise explanation of why it cannot be visible, based on its coordinates or on similarity in coordinates to an object you have already determined was below the horizon.

The following methodology might be useful to you (following from lab 2.3). First determine H (the hour angle — it might be helpful for differentiating rising sources from setting sources) from the LST and α using eq. 2.1. Then from the side 'C' spherical cosine law applied to figure 2.6, we have: $\sin(\gamma) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(H)$. So knowing your latitude, ϕ , δ and H allows you to determine γ . If γ is greater than 30° at your time, then it should be observed.

2) Once you have obtained a list of objects that you conclude are above 30° on the date/time of your observations. You will go to the observatory at that time and obtain a CCD image of all objects that are up for that calculated time. Note: the sky appears to move throughout the night. So depending on how fast you are at getting quality CCD images of objects, some objects may set before you get through the entire list. As such, you will need

to plan your observing strategy to make sure you get the objects that are setting early in the session.

3) For each CCD image, you will report the following information (which can be written on the printout of the image directly): A description of the object, including what is its name/catalog ID (e.g., M 31, NGC 1234), details of shape and structure, its approximate angular sizes (if it completely fits in the field of view), and what the object actually is (i.e. a double star, planetary nebula, open cluster, globular cluster, diffuse nebula, elliptical galaxy, spiral galaxy, irregular galaxy, etc.).

4) As you observe the object, record its the altitude from the telescope software at the time you made the observation. Compare the value with what you calculated. Compare and discuss causes for any discrepancies.

Note: Your grade will be based primarily on the ability to correctly identify all the objects that are up at your given observing time and obtain quality CCD images from them. Think of this as a 'true' astronomical observing run, where you have been allocated a certain amount of telescope time and you must complete your target list before your time runs out or an object sets.

List of Object Coordinates (RA [h:min]; Dec [$^{\circ}$, '])

- 1) 01:33.2 ; +60:42
- 2) 01:36.7 ; +15:47
- 3) 01:42.4 ; +51:34
- 4) 02:03.9 ; +42:19
- 5) 04:03.3 ; +36:25
- 6) 05:34.5 ; +22:01
- 7) 05:52.4; +32:33
- 8) 06:28.8 ; -07:02
- 9) 07:29.2 ; +20:55
- 10) 07:36.9 ; +65:36
- 11) 09:55.8 ; +69:41
- 12) 11:14.8 ; +55:01
- 13) 12:30.8 ; +12:24
- 14) 12:39.5 ; -26:45
- 15) 12:56.0 ; +38:19
- 16) 12:56.7 ; +21:41
- 17) 13:29.9 ; +47:12
- 18) 15:05.7 ; -55:36
- 19) 16:41.7 ; +36:28
- 20) 18:18.8 ; -13:47
- 21) 18:44.3 ; +39:39
- 22) 18:51.1 ; -06:16
- 23) 20:34.8 ; +60:09
- 24) 21:30.0 ; +12:10

6.3 Lab XXIII: Atmospheric Extinction [o]

For this assignment, working in small groups is permitted for the observations, however each should turn in their own list. Reminder: For any 'observation' you do (naked eye / binoculars / telescope / CCD) please record the details of your observation. These include: the weather/sky conditions; rough estimate of the stability of the seeing (twinkling); location of object in the sky; location and nature [city lights? trees blocking part of the view? etc.] of the ground site where you observe from; time/date of the observation; integration time/filters/telescope/etc. [if applicable]; and the members of your observing 'team'.

6.3.1 Extinction

The effects of the atmosphere must be accounted for to obtain accurate photometric calibration of the brightness of a star as it would appear above the atmosphere. Examples of these effects include twinkling, extinction and differential extinction (reddening). In this assignment you will learn about atmospheric extinction. You will take a series of images of a Landolt Standard Star field — SA 112 (Figure 6.2). There are 20 standard (known and calibrated magnitudes) stars in this field. We will pick the bluest and the reddest and compare the amount of extinction. You will need to take a series of images in each of four filters (B, V, R, L) starting when SA 112 is highest in the sky. This corresponds to the starlight passing through a minimum amount of the atmosphere or the lowest air mass. For a simple plane-parallel, uniform density atmosphere, air mass is given by:

$$X \simeq \sec z, \quad (6.1)$$

where z is the zenith angle, $z = 90^\circ - \gamma$, with γ the altitude. So $X = 2$ corresponds to a $z \simeq 60^\circ$ or $\gamma \simeq 30^\circ$. More complicated formulae for the true atmosphere may be found online.

6.3.2 Exercises

1) Observations will continue throughout the night as the field gets lower in the sky. Observe at least until the field's air mass is greater than 2. This will likely take at least three hours of continual observing. The class may be divided into groups and take different portions of the time, so that an individual need not stay up for the full time. Make sure to record the altitude of each observation. Observations should be carried out on nights that are photometric. This means the sky will need to be clear and stable, i.e. no clouds and not much wind or humidity.

In order to cover the largest amount of air mass we need to start as soon as it gets dark enough. So one team will need to get there as early as possible to start taking the flat-fields. You will need a set of flat-fields for each of the 4 filters. Then start taking $\sim 2 - 3$ minute exposures, in a sequence of B, V, R, L. Be sure to test that your integration time does not saturate any of the key stars in the field. A sequence of exposures will take about 15 minutes or four per hour for at least three hours. This should give a minimum of twelve air mass samples permitting good fitting.

The data processing steps will be to follow the usual multi-filter CCD calibration (see Lab 3.3).

2) Then you will need to use DS9 or fv to obtain:

- Determine the total counts in a circle centered on the star and how many pixels in the circle.
- Measure the median of the counts in an annulus or equal size aperture adjacent, but not including the star, to determine the background.
- To get the net star counts subtract the (median background) $\times$ (number of pixels in the circle) from the total within the circle.
- Convert this to magnitudes via $-2.5 \log (\text{net star counts})$

3) Plot the measured magnitude for each filter vs. the air mass. You will find the air mass value listed in the .FITS header.

4) Calculate the air mass from the above equation (eq. 6.1) and compare to the value listed in the header.

5) Fit a straight line to the data plotted in 3) and find the slope and intercept. The slope is the extinction in magnitudes per unit air mass and the intercept is the magnitude of the star outside the atmosphere (when the airmass is zero). Is there a good straight line fit to the data? If not, why not? Is there a difference in the slope between the red star and the blue star in the field? Which has the largest amount of extinction? Why?

6.3.3 SA 112

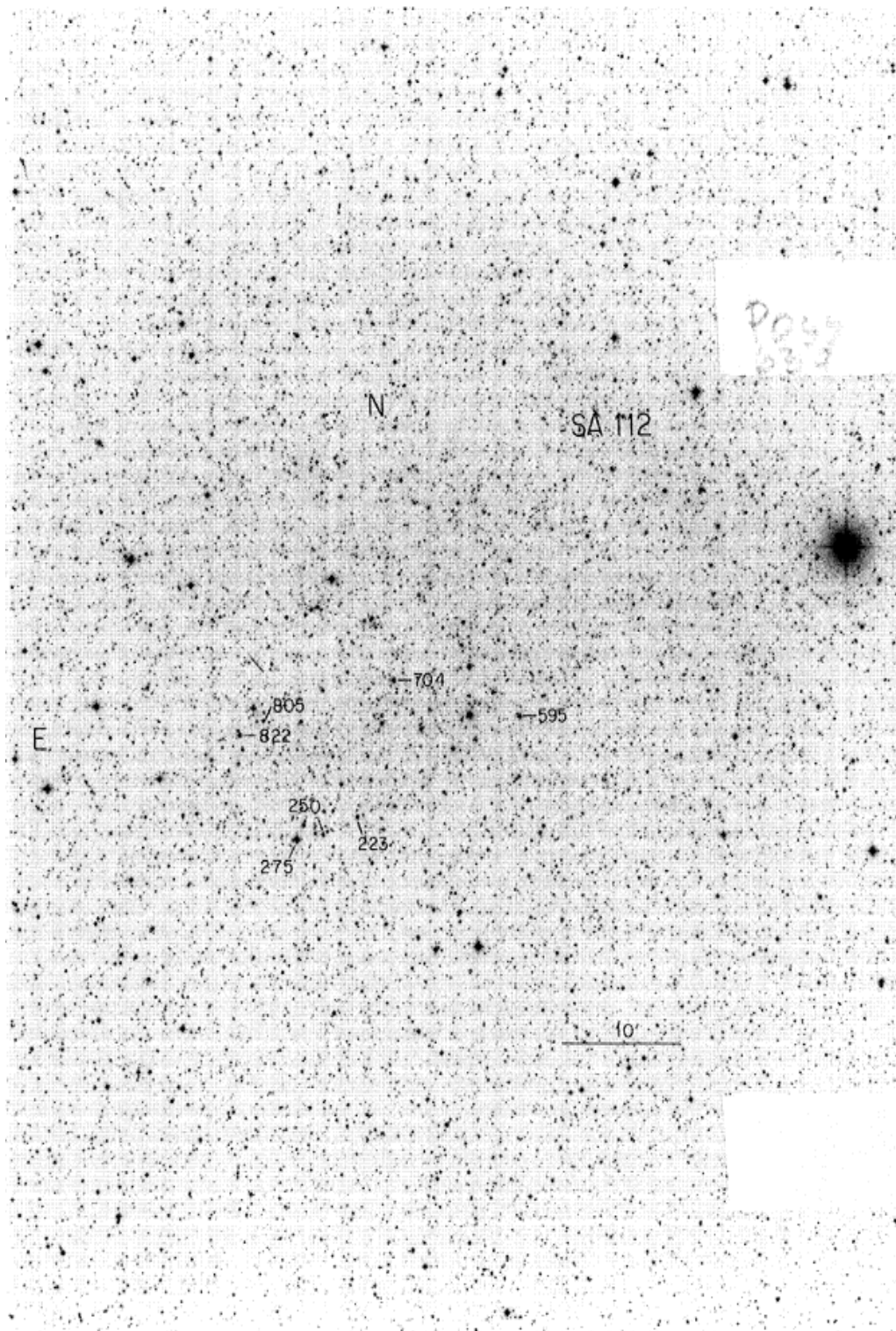


Figure 6.2: The SA 112 field, with data given in Table 6.1.

Table 6.1: SA112 Field Data

Star	RA2000	DEC2000	V	B-V	U-B	V-R	R-I	V-I	n	m	e_V	e_B-V	e_U-B	e_V-R	e_R-I	e_V-I
	h:m:s	d:m:s	mag	mag	mag	mag	mag	mag			mag	mag	mag	mag	mag	mag
112-595	20:41:19	+00:16:11	11.35	1.601	1.993	0.899	0.901	1.801	46	37	0.0022	0.0016	0.0061	0.0009	0.0012	0.0015
112-704	20:42:03	+00:18:53	11.45	1.536	1.742	0.822	0.746	1.570	19	12	0.003	0.0023	0.0076	0.0021	0.0018	0.0025
112-223	20:42:15	+00:08:44	11.42	0.454	0.010	0.273	0.274	0.547	45	37	0.0012	0.0009	0.0021	0.0012	0.001	0.0016
112-250	20:42:27	+00:07:25	12.10	0.532	-0.025	0.317	0.323	0.639	18	12	0.0021	0.0019	0.0042	0.0019	0.0019	0.0026
112-275	20:42:36	+00:07:03	9.91	1.210	1.299	0.647	0.569	1.217	63	48	0.0001	0.0009	0.0025	0.0008	0.0005	0.0009
112-805	20:42:47	+00:15:51	12.09	0.152	0.150	0.063	0.075	0.138	51	42	0.001	0.0011	0.0028	0.0011	0.0015	0.0021
112-822	20:42:56	+00:14:47	11.55	1.031	0.883	0.558	0.502	1.060	36	27	0.0012	0.0015	0.004	0.0008	0.001	0.0012

see <http://www.cfht.hawaii.edu/ObsInfo/Standards/Landolt/> for more information.

Chapter 7

Appendix

7.1 Facilities for Astronomy Laboratory

Much of the telescope experience will be gained through the use of the equipment provided to the department. The main site of the telescopic work will take place at the Frank T. Etscorn Campus Observatory, housed on the New Mexico Tech Campus. This facility (described below) is a well-equipped, research-grade astronomical facility, particularly well-suited to the Lab.

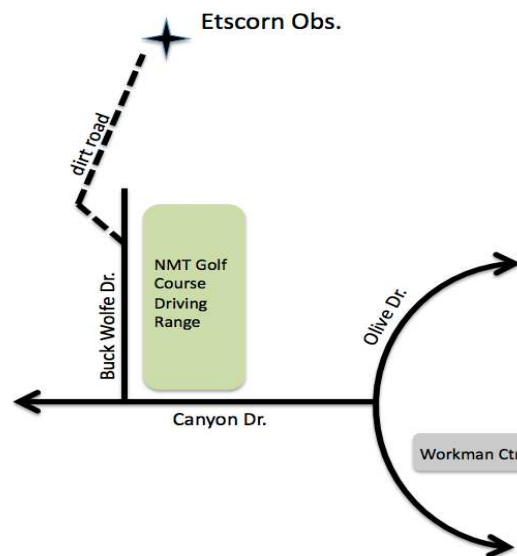


Figure 7.1: A basic map giving directions to the Frank T. Etscorn campus observatory.

We are lucky to live in a location that maintains relatively dark skies, where observations of the night sky are still impressive. NMT has its own campus observatory, the Frank T. Etscorn Campus Observatory (FTEO), that capitalizes on this feature. FTEO is equipped with a number of telescopes and control room space that may be used in this Laboratory (Figure 7.2). Located north of the NMT golf course driving range (figure 7.1), this observatory is impressively equipped for both rigorous scientific research and 'amateur astronomy'. The main building contains a control center, student work space, storage space and a resource room. FTEO includes three enclosed 14" Celestron Schmidt - Cassegrain telescopes, one in the 'Tak dome' controlled from the 'Tak control room' in the main building, a second in the 'roll-off' dome north of the main building, and one

in the 'Sheif' dome, which is not generally used for the Astronomy Lab. FTEO also includes the flagship visual telescope, a permanently mounted 20-inch Tectron Dobsonian telescope, mounted on a equatorial platform inside a 15-foot diameter dome. It gives spectacular views of the moon, planets and many, many extended objects. It is used at all of our local star parties.

7.1.1 Technical Details of Instrumentation

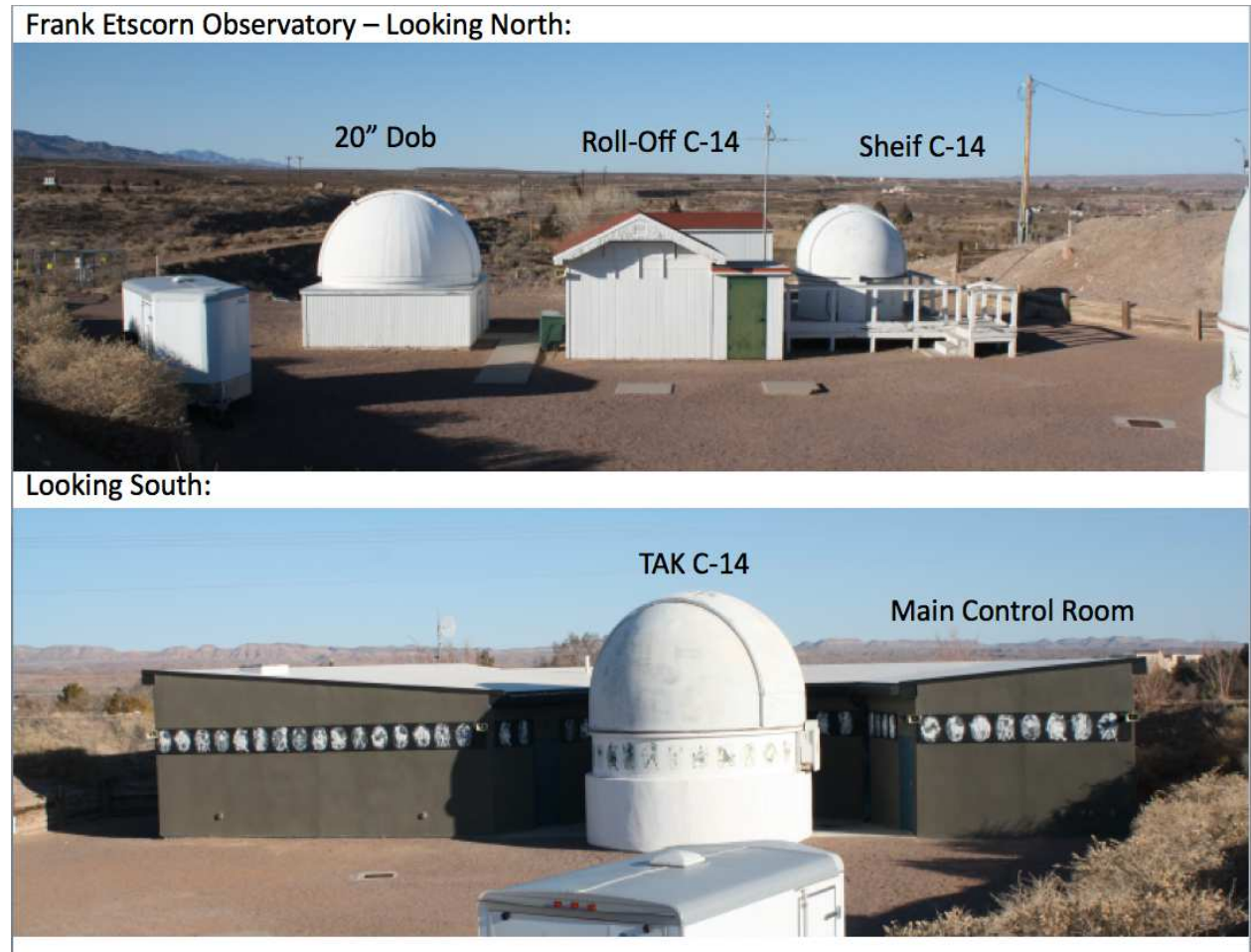


Figure 7.2: An overview of the Frank T. Etscorn campus observatory with the main building labeled.

The most commonly used telescope for Astronomy Lab is the 'Tak C-14' (Figure 7.3). The Celestron C-14 is housed in the large dome that can be seen in the 'looking south' image. Combined with the SBIG STL-1001E CCD (Table 7.1.1 for its specifications) and the Software Bisque Paramount ME mount, it gives excellent image quality with ~ 1.2 arcsecond plate scale and a field of view of $\sim 21'$. There is an integrated CFW8A filter wheel that has V,B,R,I and clear filters allowing scientific multi color imagery. The TAK control center is located in the central portion of the main building. The computer system is the same as those in the Etscorn Control center, a computer and two monitors running Software Bisque's TheSky V6 and CCDsoft V5. We also have a SBIG-SGS high resolution spectrograph that can be use on either the TAK or either of the

C-14s.

TAK Control Room



TAK C-14



Figure 7.3: The inside of the control room and dome of the 'Tak C-14'.

The original Etscorn building has a 'roll-off roof' that houses a Celestron C-14 with a SBIG STL 1001E CCD mounted on a Software Bisque Paramount ME (Figure 7.4). The internal 5 position filter in the STL1001E houses a B, V, R, I and clear filter set. The scope also includes a set of narrow band filters, including H_{α} , H_{β} , [SII] and [OIII]. The control room for the roll-off roof enclosure actually houses two control computers. One for each of the Celestron C-14s. In this image the computer and two monitors on right side of the image control roll-off roof C-14. The monitor on the left side is of each control space displays Software Bisque's TheSky6 which controls the telescope pointing and tracking. The monitor on the right side has Software Bisque's CCDSoft V5 which controls the taking and saving of our CCD imagery.

The entire facility is built behind an earthen berm that is high enough to partially keep out most of the city lights.

Table 1: Tak Dome CCD (SBIG STL-1001E)

Parameter	Value
CCD	Kodak KAF-1001E
# of Pixels	1024×1024
Pixel Size	24 μ m square
Full Well Capacity	~200,000 e ⁻
Peak Q_e	72 %
Dark Current	9 e ⁻ /pxl/sec at 0°C
A/D gain	2e ⁻ /CNT
Read Noise	14.8e ⁻ /pxl RMS
Cooling	2 stage, H ₂ O-assisted thermoelectric fan
T regulation	0.1 °C
Anti-blooming	No

Roll-Off Control Room



Roll-Off C-14



Figure 7.4: The inside of the control room and dome of the 'Roll-Off C-14'.

7.1.2 Etscorn Observatory B&W CCD Imaging Tutorial

Here is a very short summary of an example observing session at the Etscorn Observatory 'Tak' dome 14" SCT. The Teaching / Laboratory assistant will give more details on the CCD observing with the telescope at Etscorn. (Subject to change.)

Start Up:

- Turn the computer on (and login) in the control room (CR)
- Open up the *SkyX* application on the computer (telescope and CCD control)
- Open telescope control, focus control, camera control and find windows
 `>display>[telescope control, camera, focuser, find]`
- Remove the white sheet and the lens cap from the telescope
- Turn the telescope, the mount, and the CCD camera on in the dome
- Create subfolders `< flats >`, `< raw >` and `< final >` in working directory
- Connect *SkyX* to the telescope
 `>telescope>startup>connect telescope`
 - find home? = yes

Flat Fielding:

- Connect *SkyX* to the camera
- In *SkyX* camera control set the camera to cool down:
 `>camera>temp setup — select  $\Delta T$  to cool CCD`
- While cooling, turn on white light at base of telescope mount, position dome so telescope points to the wall
- In *SkyX* set the camera exposures (odd number):
 `>camera> — Select filter`
 `>camera> — Select exposure time`
 `>camera> — Toggle subframe=on (full field)`
 - Take exposures till you are happy with the # of counts in the flat
 `>camera> — Toggle autosave=on, set path to < flats > folder`
 `>camera>setup>autosave; [when happy with the setup]`
 - Take odd # of exposures to median
- Open up the *CCDSOft* application on the computer
 - (In *CCDSOft* do not 'connect' to the camera.)
- In *CCDSOft* make a master flat:
 `>image>combine>combine folder of images`
 select path `< flats >`
 select all flat .FIT files
 `>median>combine>combine [highlight image window] >file>save as> < flats > folder`
 — Save combined master flat as a .FIT file.

Focusing:

- Turn on focus paddle
- Focus the telescope with the hand paddle/mask (the software should hold focus as the temperature changes).
 - select star to focus on:
 `>find>slew`

- Open and align dome slit to new position (the dome slit 'overshoots' so go slowly when almost fully open)
- Click off all dome lights
 - >*camera*> — Select exposure time
 - >*camera*> *Take Photo* — take exposure, find star in image
- In dome, put focus mask on telescope
- Check focus
 - >*camera*> *Take Photo* — take exposure, note the starburst pattern on all stars
 - >*focus*> — change focus in steps, take exposure
 - take exposure
 - >*focus*> — Adjust focus setting till you observe the middle spike centered between the other two spikes
 - repeat exposure till happy with focus
 - >*focus*> *add datapoint*
 - >*focus*> *activate*
- In dome, remove focus mask from telescope

Observing:

- You are now ready to take science images.
 - >*find*> enter name; or select lists
 - >*slew* to slew
 - Select integration time, filter, turn autosave=on (if you wish to save image); autodark=on
- In *SkyX* set image path to < *raw* >, adopting a rememberable nomenclature
- [Alternatively you can leave autosave off and save manually. But if so be careful to not forget to save all needed files!]
- take images
 - >*camera*> — Select exposure time
 - >*camera*> *Take Photo* — take exposure
- Save dark corrected files as .FIT files in < *raw* > (if not autosaved).

Data Reduction:

- Reopen the *CCDSOft* application on the computer
- Apply the master flat field to images:
 - In *CCDSOft* apply flat:
 - >*image*>*reduce*>*flat field*
 - choose master flat from < *flats* > folder and image to flat field from < *raw* > folder
 - >*okay*
 - save corrected image as .FIT in < *final* > folder
 - Repeat for all science images

Shut Down:

- In *SkyX* 'home' the telescope and disconnect:
 - >*telescope*>*startup*>*find home* to slew to home
 - >*telescope*>*shutdown*>*disconnect* to disconnect telescope once homed
 - >*camera*>*disconnect* to disconnect camera
- Close *SkyX*
- Close *CCDSOft*

- Power off the mount, telescope and CCD camera
- Put lens cap on the telescope and white sheet completely over the telescope
- Close up the dome slit (the dome slit 'overshoots' so go slowly when nearly closed)
- Turn off any dome lights and lock dome
- Save you data somewhere that you can take with you
- Shut off computer and monitor

7.1.3 Etscorn Observatory Color CCD Imaging Tutorial

Here is a very short summary of an example color observing session at the Etscorn Observatory 'Tak dome' 14" SCT. The Teaching / Laboratory assistant will give more details on the CCD observing with the telescope at Etscorn. (Subject to change.)

Begin:

- Create a file directory tree logical to handle four copies of all images. For example:

```
< name >
  < clear >
    < flats >
    < flatfielded >
    < raw >
    < aligned >
```

- then repeat for all filters plus create a separate 'final' directory:

```
< final >
```

- Follow the imaging strategy laid out in §7.1.2 for *each* filter until you have a 'final' calibrated image for each band.

Make Color Image (In *CCDSOft*):

- Move the four final, individual filter images to a new < color > folder
- Open four images in < color > folder
 - Align the images:
 - click the star/tack icon on top of main window
 - select the same star in each image
 - click >Image>Align>Align Centroid
 - Combine the images to make a color image:
 - click >Image>color>color combine
 - Correctly associate the B filter with the blue channel, V with the green, R with red and L with luminance
 - click 'reset' and 'show preview'
 - Adjust the histograms for each color until the image in the preview window makes a good color image:
 - >Histogram Editor>adjust sliders
 - Your goal is to adjust the histograms such that the background is black and the majority of the stars are white (or close to it)
 - When you are happy with the preview click >combine
- Save your beautiful color image somewhere, again with a understandable naming convention e.g. M57_rgb. Note: The resultant image will be a bitmap and not a .FIT file.

7.1.4 Etscorn Observatory Spectroscopy Tutorial

You will be led through the basic observing strategy at Etscorn Observatory by the instructor/TAs, but a rough outline is included here:

1. Initiate the usual set up for using the C-14
2. Slew to a bright object.
3. In *CCDSOft* image the object with the 'autoguider'. Exposures should be very short (~ 0.1 for these bright objects).
4. Using fine motion control, move the object to sit on the slit.
5. Save the autoguider image as an .SBIG file.
6. Plug in the Hg pen light and take a short exposure with the 'imager'. Check to see that you see the characteristic spectrum of Hg. Bright lines include: 4046, 4358, 5461Å and a pair at 5770/5791 Å.
7. Make a subimage of your calibration image that is ≤ 20 pixels in the vertical direction.
8. Save this calibration lamp image as an .SBIG file.
9. **Unplug the Hg pen light.**
10. Open up the *Spectra* program.
11. Click the 'Load Cal' spectrum, and input the Hg .SBIG file.
12. Select one of the Hg lines near the red end of the spectrum (the left), e.g. either one of the 5770/5791 pair or the 5461. Center it between the green vertical lines in the display. Identify its wavelength and select it from the 'Identify Spectral Line (Angstroms)' menu. Select 'Mark line 1'. Using the slide bar on the display, move to a Hg line on the blue side of the spectrum (e.g. the 4358Å), center it, select it from the 'Identify Spectral Line (Angstroms)' menu, and click 'Mark Line 2'. At which point *Spectra* will calculate the dispersion (the number should come out near 474Å/mm) and calibrate the wavelength axis.
13. In *CCDSOft* take 'imager' observations of your object. You will need to test different integration times.
14. Make a subimage of your object image that is ≤ 20 pixels in the vertical direction.
15. Save this object image as an .SBIG file. And as a .FITS file if you wish to load it into other data packages like fv or ds9 at a later time.
16. Click the 'Load Spectrum' button, and input the object .SBIG file. The spectrum should be calibrated. Peruse the spectrum with the slidebar in the display. Verify that you can identify spectral features. *I recommend starting with Sirius because it is very bright and has an obvious spectral pattern.* If your calibration with the Hg is not great then you can further 'self cal' if the object has the bright Balmer series. You can select two Balmer lines and repeat the 'Mark Line' step to calibrate again on the 'science spectrum'.
17. When happy with the spectrum, click 'Write text file' and the program will save your calibrated object spectrum to a .txt file, on which you can perform subsequent analysis.
18. Slew to a new object, Goto #13 and repeat. *Spectra* should remember your calibration. If the slit does not produce a perfectly horizontal spectrum then the wavelength calibration will be somewhat dependent of the position of the object (vertically) along the slit. To optimize calibration accuracy, try to put the stars in the same vertical position on the slit.