The Astronomy Teaching Assistant's Handbook

I. Introduction

This is a textbook for a course in amateur and educational astronomy. Its main purpose is to

- bring teaching assistants up to scratch in the practical astronomy
- provide a source book of related data
- provide a first introduction to observational astronomy for students who wish to take advanced astronomy courses later.

It is assumed that the reader has read the textbook of *J. Bennett et al: The cosmic perspective,* installed the SkyGazer CE software that comes with it, and is sufficiently familiar with its use. However, there are exercises in this book to ensure the reader has really has acquired the skills in the necessary depth.

The book concludes with a review of the suggested assignments and tests of such a course.

Contents

II. Familiarization with the sky

This section assumes that the reader has already studied Chapter 2 (Discover the Universe for Yourself), and Chapter S1 (Celestial Timekeeping and Navigation) in *J. Bennett et al: The cosmic perspective*. All of the theory is not repeated here, we only expound on those issues that have immediate practical applications.

II.1. Constellations

The most often quoted reason a student chooses to take introductory astronomy is that they are impressed with the stars in the sky. Truly, the zillions of stars and the bright Milky Way we see from a dark location are fascinating. When we address laypeople we must capitalize on this common experience, and for that reason it is imperative that we know how to find our way in the sky.

Constellations in the popular mind represent collections of stars we know are unrelated. Actually, the 88 constellations are areas in the sky, delineated by the IAU (International Astronomical Union). Any point in the sky belongs to a constellation. For example, many people mistakenly think the Seven Sisters (the Pleiades) are a constellation – they are not. The Pleiades' stars are physically related, form an open cluster, and the whole cluster is only a small part of the constellation of Taurus (the Bull).

The 88 constellations all have official Latin names, and some of them have traditional English names as well (we do not expound on other cultures' traditions here). In the astronomical literature a three-letter short is used to designate them, and it is quite useful to remember these. Most names are based on Greek mythology, with more added in the Middle Ages. An interesting example is Serpens, which originally came on the shoulders of Serpentarius (the Serpent-bearer[*]). Another tradition saw Ophiuchus in the same stars, and the IAU accepted the Ophiuchus version. Now we ended up with the two ends of the Serpent without the middle, which are still considered one constellation but called Serpens Cauda (the Serpent's Tail) and Serpens Caput (the Serpent's Head) respectively. So, for example, α Ser is in Serpens Caput, and η Ser is in Serpens Cauda (see Fig. 1).

---

[*] Ascelpius, the son of Apollo, concocted a potion from the Serpent's venom and herbs to heal the sick and revive the dead. Worried that he would upset the order of life Zeus killed him but placed him in the sky as a constellation.

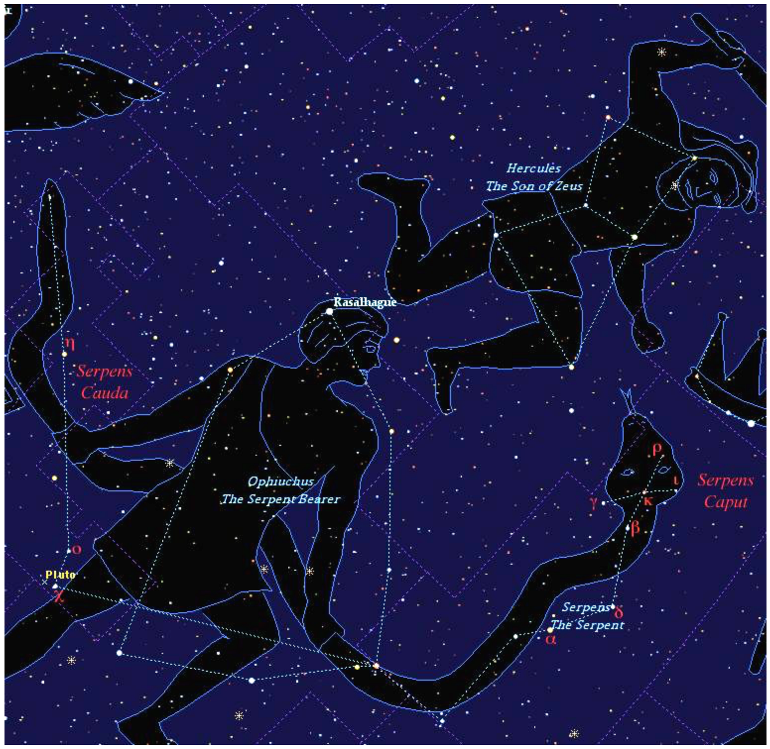


Fig. 1: The constellation of Serpentarius has been broken up by the IAU into Ophiuchus and Serpens, which is a discontinuous constellation consisting of Serpens Caput (the head) and Serpens Caput (the head).

Not all constellations are visible at all times. In its yearly motion Sun proceeds along the ecliptic, and crosses thirteen constellations. They are, starting with January: Sagittarius, Capricornus, Aquarius, Pisces, Aries, Taurus, Cancer, Gemini, Leo, Virgo, Libra, Ophiuchus, and Scorpius. These thirteen constellations roughly correspond to the twelve astrological signs of the Zodiac, so called because many are named for animals. It is interesting to note that the Sun does not spend exactly one month in each constellation (they are not regularly shaped), nor is it in the constellation that is traditionally assigned to each month. These assignments were made thousands of years ago, and precession has slowly moved the constellations. For example, the spring equinox, traditionally assigned to Aries, actually is located in Pisces.

As the Sun proceeds among the constellations of the Zodiac, different constellations are visible in each season of the year. Here is a list of the constellations that are most conspicuous early night in each season, around 9 pm, at Mississippi's latitude:

August – October:	Sagittarius, The Summer Triangle, Hercules, Cepheus, Pegasus
November – January:	Cassiopeia, Pegasus, Andromeda, Perseus, Auriga, Taurus, Orion
February – April:	Perseus, Auriga, Taurus, Orion, Gemini, Canis Maior
May – July:	Leo, Virgo, Bootes, Ursa Maior, Hercules, The Summer Triangle, Scorpius, Sagittarius

Constellations at high declination, such as the Summer Triangle (consisting of Lyra, Aquila and Cygnus), are visible for many months, while those down south (such as Sagittarius) need to be viewed close to their transit time*. The constellations close to the North Pole, such as Ursa Minor, which contains Polaris, are visible all year. They are called "northern circumpolar" constellations. These are Ursa Maior and Minor (the two Dippers), Draco, Cepheus, Cassiopeia and Camelopardalis.

Another important principle to select constellations of interest is related to their galactic latitude. Obviously, the Milky Way is a fine view, but it is also true that bright stars in the sky are strongly concentrated in the plane of the Milky Way. For example, Orion includes seven stars of second magnitude or brighter, while the equally large Eridanus has none. The Milky Way touches the following bright constellations, in order: Scorpius and Sagittarius, Aquila, Cygnus, Cassiopeia, Perseus, Auriga, Taurus, Auriga, Gemini, Orion, Canis Maior and Canis Minor. It is very important to be familiar with these constellations.

The tradition behind many of the officially accepted constellations goes back to Greek mythology. There are two detailed sets of legends that gave birth to large numbers of constellations, the Perseus legend, and the story of Orion.

Orion was the son of Poseidon, the ancient Greek god of the sea. An extremely handsome but wild titan, he fell in love with Merope (one of the Seven Sisters) and was to hunt down the wild beasts in her island. He became a skilled hunter, but Merope's father would not give her to him. He rather cursed Orion with blindness for his violence, and it took Orion a long and hard quest to gain a glimpse at the goddess of dawn, Aurora, who gave him back his eyesight.

According to Greek legend, the ever-virgin Artemis, goddess of Hunt, fell in deep love with Orion. Her twin brother Apollo, jealous and afraid that her sister would lose her power and standing due to his love, sent the Scorpion to kill Orion. In another, Roman version of the legend, Juno (the Roman name for Artemis) took umbrage at Orion's bragging as a better hunter than she, and she sent the Scorpion. Orion fled to his father's realm, the sea, but before he reached the shore the scorpion stung him to death. The famous healer Aesculapius (the original Serpent Bearer), son of Apollo, was called to bring Orion back from the dead. On Hades' request, Zeus killed the revived Orion with his thunderbolt, stoke to death Aesculapius as well, but allowed both to be placed in the sky as constellations. The Scorpion, guarded by Sagittarius the Archer (there is even a tiny constellation Sagitta - the Arrow - inside the Summer Triangle), was also placed in the sky. Orion is opposite in the sky from Scorpius. Whenever Scorpius rises in the southeast, Orion, fearful of his nemesis, speedily sets in the west.

Orion's famous hunting dogs, Canis Maior and Canis Minor, have also been put in the sky. They are east if Orion, and as Orion moves in the sky, they follow. (This is a nice way to show that the sky turns from left to right.) They both contain one bright star each. Sirius, α Canis Maioris, is the brightest star in the sky at *–1.6 mg*, and it is often called the Dog Star. The star's proper name though comes from the Greek word Seirios, which means *shining*; a proper name for the brightest star in the sky, but it has nothing to do with a dog.

The other legend most prolific in producing constellations recounts how Perseus saved Andromeda from the sea monster. Perseus was one of the great Greek mythological heroes. The son of Zeus, he was brought up by Polydictes, king of the island of Sephiros. Polydictes fell in love with Perseus' mother Danae, and decided on an intrigue to send Perseus away. He gave Perseus the

* Transit is when a star crosses the meridian, that is, when it is straight south. Transit is the time when the star is highest up in the sky.

dangerous task to retrieve Medusa's head. The Gorgons were fearful monsters whose eyes turned anyone looking at them immediately into stone. Perseus, with the help of Athena's advice and shield, Hermes' sword and flying sandals, flew to Libya where he found the cave where the Gorgons lived. He watched Medusa's reflection in the shield and cut his head off with a sway of his sword.

Flying back home through Ethiopia to Greece (?!), mounted on his winged horse Pegasus, he found Andromeda, the beautiful daughter of the King Cepheus, chained to a rock on the seashore. Her mother Cassiopeia had offended the gods claiming that Andromeda was more beautiful than any goddess. To appease the gods, she was to be sacrificed to Poseidon and to be eaten by the sea monster Cetus. Perseus, holding up the still-murderous Medusa head, showed it to the monster, which turned into stone immediately. He saved Andromeda, and received her hand in marriage and they lived happily ever after.

When Perseus and Andromeda died, they were raised to the sky by Athena and Poseidon, together with Cepheus and Cassiopeia, the sea monster Cetus, Pegasus the flying horse. In Perseus' raised hand is the Medusa head, the ghoulish Algol[*]. It may be coincidence that Algol, the Medusa Head, petrified the astronomer Geminiano Montanari, who in 1667 discovered that it changes its brightness! It fades every *2.9 days* by *1.3 mg* for a few hours. Algol, β Persei, is the first eclipsing variable ever discovered.

Exercises

1. Which constellation is the spring equinox in?
2. The equinoxes are defined as the intersection of what?
3. What is the Zodiac? (Give a definition.)
4. Is Pleiades a constellation? If so, is it circumpolar or what season is it associated with? If no, what is it and in which constellation is it?
5. Use a ruler and measure the size of the Pleiades and/or a bright constellation that is visible now. State your results in degrees.
6. What is transit?
7. What is the meridian?
8. Which are the twelve signs of the Zodiac?
9. What are the most conspicuous constellations along the Milky Way? Which season is each one associated with?
10. What are the most conspicuous circumpolar constellations?
11. Recount (i) Orion legend, (ii) Perseus legend, without the use of a book or notes. Indicate which constellations have their origin in these legends, and which season is each one associated. What culture's legends are these, and how old are they?
12. What are the names of the three stars that form the Summer Triangle (give the proper name and the official Greek letter name for each), and what constellations is each one in (give the Latin and the English name for each)? Give the same information for Aldebaran, Betelgeuse, Rigel, Sirius, Capella, Arcturus and Polaris.

---

[*] Middle age astronomers first learned this legend from Arabic sources. Medieval Baghdad, of the Thousand and One Night fame, was the cultural center of the world at the time, and transmitted much of classical culture to medieval Europe. Al-Ghoul is Arabic for "the monster" (the Medusa head). This same Arabic word is preserved as "ghoul" in the English language.

13. Go to a dark location at night, and learn how to identify all the conspicuous constellations, and also the names of the brightest stars that are visible at the time. Point out the celestial equator and the ecliptic in the sky.

II.2. Naming schemes

There are about 6,000 stars in the sky visible to the naked eye. The brighter of these have a *Bayer designation*, which consists of a Greek letter and the name of the constellation in genitive. (For a list of the names of the constellations and the Greek alphabet, see the Appendix.) For example, the star α Orionis is the brightest in Orion, while λ Orionis is not as bright. The constellation names are often abbreviated using three letters, such as in λ Ori or γ UMa. Fainter stars may not have a Greek letter left for them. For these, we use the *Flamsteed designation*, which consists of a number (usually 1 – 100) and the name of the constellation in genitive, also covering all of the Bayer stars. For example, λ Orionis = 39 Orionis. Also, the brightest hundred or so stars also have a proper name. So, α Ori = 58 Ori = Betelgeuse. Fainter stars go by their numbers in various catalogs, most notably the Henry Draper (HD) catalog, the Smithsonian Astrophysical Observatory (SAO), the Hipparchos catalog, the Hubble Guide Star catalog (GSC) and the US Naval Observatory's (USNO) catalog. Much of the SAO catalog is contained in the Meade telescopes LX200 mount, so the SAO numbers make it quite easy to find these stars with these telescopes (up to about 9 magnitudes). The USNO catalog contains stars up to 18 – 20 magnitudes (depending which part of the sky we are looking at).

The brightest 100 deep sky objects (star clusters, nebulae and galaxies) are contained in the Messier Catalog: for example, M31 is the Andromeda Galaxy. The NGC and IC catalogs are huge collections of deep-sky objects. The NGC catalog is also included in the LX200 library.

Exercises

1. What does the *M* stand for in *M 31*? How many of such entries exist?
2. M 77 could conceivably be any of the following except which two? A galaxy, a star, a star cluster, a gas nebula, a planet.
3. What does NGC stand for, and what does it contain? NGC 891 is most probably a what?
4. The name τ Velorum, because of its structure, must be a what?
5. Why is Vega called α Lyrae, while the name of the constellation is Lyra?
6. What is the full name of star λ in Canes Venatici?
7. How deep is the SAO catalog?
8. Which star catalog would you use to find a faint star with the Meade telescopes' GOTO feature?
9. How deep does the deepest-going star catalog go? (Choose from those that cover the whole sky.)
10. Memorize the names and shapes of the Greek letters.
11. Memorize the correct spelling of the Latin names of each constellations, both in the nominative and the possessive case.
12. List and memorize the names of the most conspicuous constellations, in each of the five categories of Circumpolar, Summer, Spring, and Fall. Mark the twelve zodiacal ones, three per season.
13. Read a book on Greek mythology and write a book report with special emphasis on those aspects that come up in the naming of constellations and stars.

II.3. The magnitude scheme

The brightness of stars is usually expressed as its “magnitude”. It does not refer to size (all stars look like dots only), but rather brightness. Traditionally, the brightest stars in the sky have been designated 1st magnitude, fainter ones 2nd etc. Those stars barely visible for the human eye in dark conditions are 6th magnitude. The smaller the number, the brighter the star.

The scale has been extended in both directions and has been precisely defined. With the color sensitivity of a standardized human eye, the visual magnitude of a star is defined as $m_V = 2.5 \times \log I_{star} / I_{Vega}$, where *I* is the intensity of the star’s light, and Vega (= α Lyrae) is a bright white star defined to have $m_V = 0mg$ for brightness. With this definition, one magnitude of *difference* will correspond to an intensity *ratio* of $2.52\times$, or 5 magnitudes of *difference* correspond to a *ratio* of $100\times$. Note that a few magnitudes of difference mean a huge difference in intensity: the *14.3 mg* Pluto is $2.52^{14.3}$ = 500,000 × fainter than the *0 mg* Vega.

On the bright end of the scale, the brightness of the Sun is *-26.8 mg*, the full Moon is *-12.7 mg*, Venus is very bright at *-4 mg*, and the brightest star is Sirius at *-1.6 mg*. On the other hand, stars fainter than *6 mg* can be seen only through telescopes. Binoculars in a dark location can see *10 mg* stars, while Pluto with its *14 mg* needs a large amateur instrument to be observed. In Kennon Observatory, the faintest star ever pictured was *19 mg*, on an image with an hour of light collection. Professionals routinely image stars up to 26 magnitudes, and the deepest image ever taken with the Hubble Telescope showed stars of *31 mg*.

When small differences in brightness are considered, this definition of magnitudes becomes quite convenient, because 2.5 is close to e=2.718. For this reason, for small *x*, an *x*% relative change in brightness almost exactly corresponds to 0.01*x* magnitudes of difference. For example, the fact that visual estimations of brightness usually have a precision as bad as ±10%, we may translate this to an error estimate of $\pm 0.1^{mg}$.

The faintest star still visible with the naked eye is the “limiting magnitude”, and it depends on the weather and on light pollution from city lights. The three contributing factors are: (1) the transparency of air, compromised by moisture and/or dust in the air, (2) the brightness of the sky due to scattered city lights, (3) that humans eye do not completely adapt to darkness when the environment is not completely dark. On the Ole Miss campus all the three factors contribute about equally, each costing a magnitude in the winter (the limiting magnitude is lowered from *6 mg* to *3 mg*), and moisture in the air costs another magnitude in summer (the limiting magnitude is *2 mg*, only a few stars are visible at all). The limiting magnitude on a clear winter night away from Oxford is about *5 mg*, one magnitude is lost due to Mississippi’s low elevation.

The magnitude scheme is based on the intensity of the light of stars as felt by the human eye. Of course, this ‘felt’ intensity depends on the sensitivity of the human eye. The eye’s sensitivity is color dependent, and this color dependence varies slightly (within about 20%) from person to person. For this reason, visual magnitudes are not really precisely defined and vary according to the definition by as much as $\pm 0.2^{mg}$. A more precise definition requires the specification of the sensitivity of the instrument-filter-telescope-atmosphere system. One set of such definitions, based on well-defined color filters, is the much-used UBVRI system. Each star has a different magnitude in each of these colors, and the conversion between these magnitudes depends on the color (more precisely, the spectrum) of the star. For example, Vega – by definition – has $U=B=V=R=I=0^{mg}$, but a red star may have, for example, $U=6.0^{mg}$ (faint in ultraviolet), $V=2^{mg}$ (bright in yellow, also called *visual*), and $I=0^{mg}$

(very bright in near-infrared). Obviously, B and R correspond to a well-defined type of blue and red filters respectively.

When it comes to observing extended objects, such as galaxies or nebulae, the total magnitude is often quite misleading. The appropriate concept is surface brightness, which is the brightness of light reaching us from every $1\ as^2$ of the object. While this concept is inapplicable to stars, the surface brightness of the face of the Sun is $-10.5\ mg/as^2$, and the face of the full Moon is $+3.5\ mg/as^2$, the bright disk of Venus is $+2.2\ mg/as^2$, Jupiter is $+5.5\ mg/as^2$, while the Milky Way glows at $+20\ mg/as^2$. Light pollution on campus is about at $+18\ mg/as^2$, so the only time we can really see the Milky Way is during a power outage. However, skyglow is about at $+21\ mg/as^2$ away from Oxford, and $+23\ mg/as^2$ at the best locations on Earth.

For comparison, the central bulge of galaxies glow at 19 -$20\ mg/as^2$, their spiral arms are 3 - $4\ mg$ fainter. There is no chance to see the spiral arms by visual observation; they are always hidden in skyglow. Telescope optics cannot increase surface brightness, as we will discuss below. Only by artificially removing the skyglow from pictures can spiral arms be detected.

Exercises

1. Which one is brighter, a 3^{mg} star or a 5^{mg} star? How many times?
2. How bright are the following objects: The Sun, the full Moon, Venus, Jupiter, Saturn, Sirius, Vega?
3. How bright is the faintest star visible to the naked eye at Ole Miss? And at a dark site on a high mountain? And with a 12-in telescope? And with a decent professional telescope (say, the 5 m Hale telescope on Mount Palomar)? And on the deepest pictures ever made with the Hubble Space Telescope? Give only approximate estimates, do no calculations.
4. How many times is Pluto (14.3^{mg}) fainter than Betelgeuse (1^{mg})?
5. Star A is $100\times$ brighter than star B, which is 6.3^{mg}. How bright is star A? (Do not use a calculator.)
6. A star is moved $2.5\times$ farther. How many magnitudes does it get fainter?
7. Sedna, a distant asteroid, is at $40\ AU$ away now, and is only 21.2^{mg}. It has an elliptic orbit, which slowly carries it to a distance of about a $100\ AU$. How bright will it be then? (Do not forget that asteroids reflect sunlight!) Based on your calculation, tell what power of the distance from the Sun is a planet's brightness proportional to?
8. Give a ballpark number for the surface brightness of the Moon, of Venus, of the Sun, of the daylight sky, of the Milky Way, the light pollution on campus, the bulge of the Andromeda Galaxy, of the spiral arms of the Andromeda Galaxy, and of the natural skyglow in a dark location.
9. The Dumbbell Nebula, M27, is 7.3^{mg}. It would appear that it should be an easy target for a small telescope. Given its apparent diameter, *7.5 arc minutes*, calculate its average surface brightness in mg/as^2. Is that brighter than the Milky Way's band of light in the sky or fainter? Will a telescope help making it brighter?
10. The Sun's brightness changes, due to hydrostatic pulsations, with an amplitude on the order of a few milli-magnitudes. What percent change is that?
11. The precision of brightness measurements of stars on CCD camera images is, when a careful job is done, about ±1%. How many magnitudes is that error bar?
12. The Ring Nebula (M27) is 8.8^{mg} in visual brightness and $1.2\ as$ in diameter. Calculate its surface brightness. How does the result compare with the surface brightness of the Milky Way?
13. Knowing that skyglow is $+21\ mg/as^2$ calculate the total magnitude of skyglow from all of the sky. Does your result explain why it is not fully dark on a cloudless night?

14. The pulsating variable star with the largest amplitude of visual change is χ Cygni, brightening to 2^{mg} and dimming to 14^{mg} with a *~400 day* period. How many times is it brighter in maximum than in minimum?
15. At night, estimate the limiting magnitude by finding the faintest star you can still see.
16. Using a 12-inch Meade, find four moons of Saturn (other than Titan). Find appropriate comparison stars using the TheSky astronomy software, and estimate each satellite's brightness.
17. Find a bright, and a 10^{mg} asteroid with a 12-inch Meade. Use the laboratory resources and the TheSky software to locate the asteroid, and read off its coordinates. Find appropriate comparison stars and estimate the asteroids' magnitudes by visual comparison.
18. Use a SkyMeter device to determine the sky brightness (i) on campus at night, with the parking lot lights on, (ii) on campus with the parking lights off, (iii) at the Dark Site, (iv) during the day.

II.4. Daily and yearly motion

The motion of stars in the sky is not as mysterious as many people think. We can safely neglect the *parallax* and the *peculiar motion* of stars relative to each other. We must imagine the sky as a solid glass sphere with a large radius, with all the stars simply glued on it. The sky simply turns as a whole, once in 23^h56^m.This is the true rotational period of Earth. That means that a star *transiting* (i.e. crossing the *meridian*, the south line) at 9:00 pm tonight will transit four minutes earlier, at 8:56 tomorrow. The constellations rise, transit, and set *4 min* earlier each day, so that they rise, transit, and set *2 hours* earlier each month. This adds up to a full day per year. The difference is due to the fact that Earth revolves around the Sun once a year, and our timekeeping is fixed to the Sun. The Sun takes 24^h00^m (on average) to make one circle around the sky.

The daily motion (called sidereal motion) of stars is a steady revolution around the North Pole – South Pole axis. In fact, the axis of Earth misses Polaris by a half a degree. Note that, contrary to popular belief, Polaris is not a particularly bright star, it only happens to be close to the point where the axis of Earth is pointing. Facing south, the sky seems to be is moving from left to right (from east to west) at a rate of 15^o*/hour*. This is actually correct only for stars on the equator; other stars "move" slower by a factor of $\cos\delta$ (δ is their declination). For example, the North Pole ($\delta=90^o$) is not moving at all. Facing north, the sky appears to be turning around the North Star.

This sidereal rate means that the ½ °-sized Moon and Sun take 2 minutes to set or rise. When we watch the sky in a telescope, the sidereal rate is sped up by the amount of magnification. It is absolutely necessary to use a sidereal clock to follow the stars: in $100\times$ magnification, the rate appears to be 25^o*/min*, so the object will go out of the field within a minute. At high magnification any misalignment of the right ascension axis with the axis of Earth will result in that the stars slowly drift out of the field.

The *2 hours/month* difference results in that different constellations are visible in different seasons. As the Sun proceeds around the ecliptic, the constellations close to it are only up during the day when they cannot be seen. The constellations located opposite to the Sun are high up in the sky at midnight. In a few months however, they will be setting after sunset and in another month they disappear in the dusk. The constellations are called winter, spring, and summer and fall constellations according to the season when they are high up early night. For example, the three constellations in the Great Summer Triangle (Lyra – Cygnus – Aquila) are summer constellations, Andromeda is a fall constellation, Orion is a winter constellation, and Leo is a spring constellation.

Constellations at high declination, $\delta > 90^\circ - l$ (*l* is the geographical latitude), are always up and are called circumpolar. A famous circumpolar constellation is the Little Dipper (Ursa Minor). The constellations around the South Pole never rise and are invisible from our latitude (southern circumpolar region).

Exercises

1. A star rises exactly in the east. Where will it transit, E, W, S or N, and how many hours after it rises? Where and when will it set?
2. A star rises in the southeast. Where will it transit, E, W, S or N, and how many hours after it rises? Where and when will it set? (No calculations, give an estimate.)
3. What is the declination of the celestial North Pole, and of the equator, and of Zenith?
4. What is the declination of a star that is on the horizon in the south? How long will that star be over the horizon, and how long will it be under the horizon?
5. Facing south, you see a star in the sky. How many degrees will it would a star move in an hour, and in which direction?
6. A star with $\delta = 0°$ is centered in a telescope with a 44° eyepiece, magnification 100 ×, no clock drive. How soon will the star leave the field? How does your answer change when you look at a star in Zenith, or at Polaris?
7. How large does the Moon appear in the sky? Give the answer in degrees and in radians as well.
8. Imagine making observations at the same hour every Monday, facing south shortly after sunset. Describe how a constellation just rising in the East would change its position week by week. Quantify your answer in degrees per week. After how many months will this constellation become unobservable, and where in the sky will it be last seen? (Neglect the fact that the time of the sunset changes with the seasons.)
9. Orion rises at 7 pm tonight. At what time will it rise in two months?
10. Jupiter sets 3.5 hours after sunset. When will it set in three weeks?
11. Imagine a telescope is centered on Venus two hours after sunset, no cock drive. The telescope is a simple refractor with no star diagonal, which gives an inverted image. Which way in the field will Venus move due to sidereal motion? Which of the following are correct? (A) From east to west. (B) From west to east. (C) From northeast to southeast. (D) From bottom right to top left. (E) From top left to bottom right. (F) From top right to bottom left.(G) From bottom left to top right. (H) From left to right. (I) From right to left. (K) Straight up. (L) Straight down.
12. In the previous question, which way in the field will north be?

II.5. Main circles

A few technical concepts of spherical astronomy are so commonly used that it is necessary to repeat them here, even though they are quite clearly explained in *The Cosmic Perspective*.

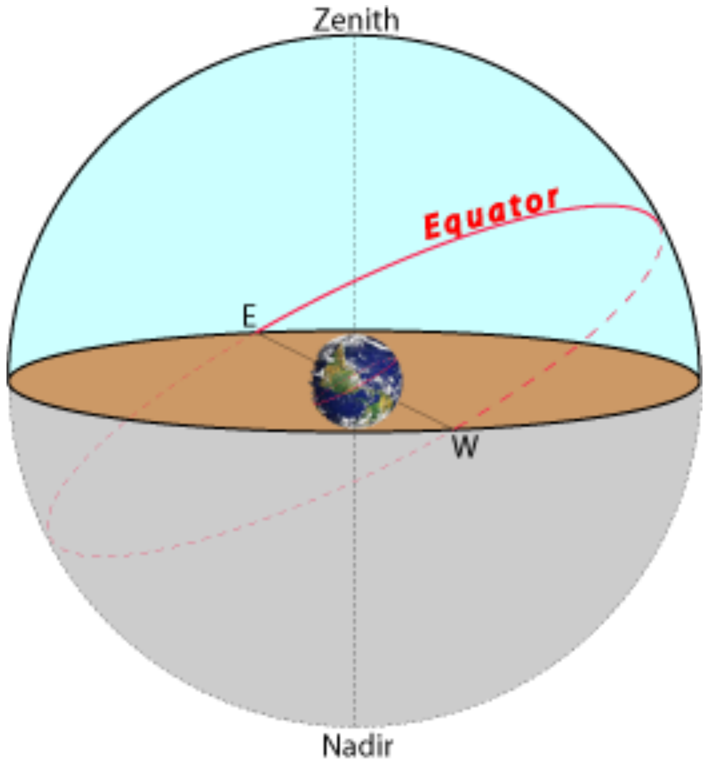


Fig. 2: The celestial equator is the projection of Earth's equator onto the sky.

The celestial equator is the circle in the sky that corresponds to the equator on Earth (see Fig. 2). It "rises" exactly at the east, transits at 56^o ($=90^o$-l) altitude over the horizon and "sets" exactly in the west. The Sun crosses the equator at the time of the two equinoxes (March 21 and Sept 21). Stars on the celestial equator have $\delta = 0$. The poles corresponding to the celestial equator are the North Pole ($\delta = +90^o$), close to the North Star, α Ursae Minoris in the Little Dipper, and the South Pole ($\delta = +90^o$), where there is no bright star in the vicinity.

The ecliptic is the circle that the Sun follows among the stars. Its plane is inclined 23.5^o to the equator. The equator intersects the ecliptic at two points: in the spring equinox (where the Sun is located on March 21) and the autumn equinox (where the Sun is located on Sept. 21). Note that the word "equinox" is used in two senses: it designates the two places in the sky *where* the Sun crosses the equator, and also the *two times of the year* when that happens (see Fig. 3).

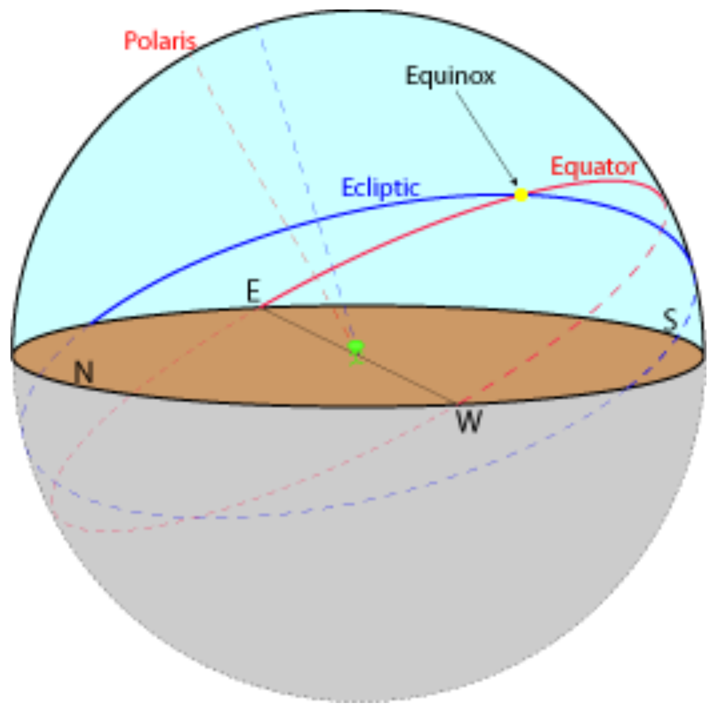


Fig. 3: The vernal (Spring) equinox is the intersection of the ecliptic and the equator.

In the summer the Sun is on the half of the ecliptic "above" (north of) the equator, having $\delta>0$. The Moon and the planets, typically observed on the other side of the ecliptic, are on the half of the ecliptic that is "below" (south of) the equator, having $\delta<0$. They are low over the horizon for this reason, and usually hard to observe. In the winter it is the opposite: the Sun is at $\delta<0$, low, but the observable part of the ecliptic (at night) is high up, a good time for the planets.

The north pole of the ecliptic is located in the constellation of Draco at $\delta = 66.5^o$. Eventually, the (equatorial) North Pole precesses around this point with a period of 26,000 years.

The twelve constellations along the ecliptic are called the Zodiac, although not all of them are named for animals. Each month of the year corresponds to the constellation of the Zodiac in which the Sun is located in that month. However, the correspondence is inaccurate because (i) the constellations are not equal in size, and (ii) precession shifts the correspondence by one constellation every 2,000 years. Tradition has not incorporated this shift and astrologists are still using the position of the Sun, as it had been as if we lived in old Babylonian times.

The meridian is the half a circle that starts with the North Pole, crosses our local Zenith, continues straight down south, reaches the horizon at the South point and continues to the South Pole. It is of course not fixed to the stars. Stars cross the meridian once a day (the "transit"), and that is the time when they are highest up over the horizon.

The galactic equator is the (projection on the sky of the) plane of the Milky Way. It is also a full circle, and its pole is located in the constellation of Coma Berenices, not very high over the equator ($\alpha = 12^h 50.5^m$, $\delta = 27.5^o$). When the galactic pole is high up (as early night in May) the Milky Way is low in the sky, and few clusters or nebulae are visible. It is a good time for galaxies, which cannot be seen along the Milky Way due to interstellar absorption. However, when the galactic pole is close to the horizon (rising or setting), as it happens early night in August and December, the Milky Way rises very high up in the sky. This is why spectacular areas of Cygnus in August and Orion in December are look so great at those times.

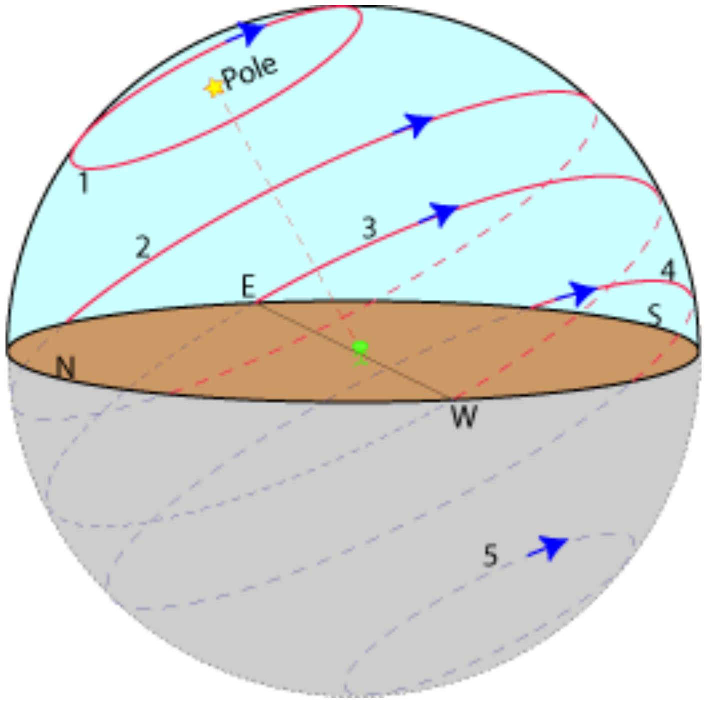


Fig. 4: The daily motion of the stars is parallel to the equator. Star 1 is circumpolar (never sets; δ>56º), star 2 rises in the NE and sets in the NW (δ>0º), star 3 follows the equator from east to south to west (δ=0º), star 4 rises in the SE and sets in the SW (δ<0º), and star 5 is southern circumpolar (never rises, δ<–56º).

Exercises

1. What is the proper name of α Ursae Minoris?
2. What is the declination of the Sun on Dec. 22, on June 21, on Sept. 22, and on March 21?
3. What main circle does the Sun follow in the sky?
4. Which way does the Sun move in the sky compared to the stars, and how many degrees per day? (Give the answer in terms of cardinal directions, as in "north to south".)
5. Which way is the declination of the Sun changing on each of the dates in question 2? (Give the answer as increasing or decreasing, and also "moving north" or "moving south".) What would be the declination δ of a *planet* visible after sunset 30° east of the Sun, would δ be larger or smaller than the declination of the Sun, on each of these three dates? On which of these dates would the planet be easiest to observe, and when would it be hardest?
6. Most of the meridian in to the south. How long is the piece of the meridian that is not, and what cardinal direction is it?
7. A star is located exactly in the vernal equinox in 2000.0. What will its equatorial coordinates be in 6,500 years? (Neglect the star's peculiar motion.) Calculate the rate of change in *as/year*.
8. What constellation is the Galactic North Pole in?
9. Why is it hard to see the Milky Way at 9 pm in April?
10. Why are there few star clusters and nebulae in the sky early at night in spring? What deep-sky objects are abundant instead?

II.6. Motion and phases of the Moon and the planets

The Moon is an exceptional satellite in the Solar System in that it revolves around Earth in the plane of the ecliptic (the orbit of Earth) and not along the equator as most other satellites in the solar system do. It makes a circle around the sky in a month, on average passing a half a constellation every day on the way. As almost all bodies in the Solar System, it moves in the positive direction, west to east. We mention here that the Sun's motion is also west to east (4 min = 1^o per day), and so is normally the motion of all the planets in the sky. The exception is the daily motion of whole the sky with the fixed stars on it, which is opposite (east to west) because it represents the reflection of the actually west-to-east rotation of our planet. The almost even motion of the Moon means that the Moon rises and sets 50 minutes earlier each day.

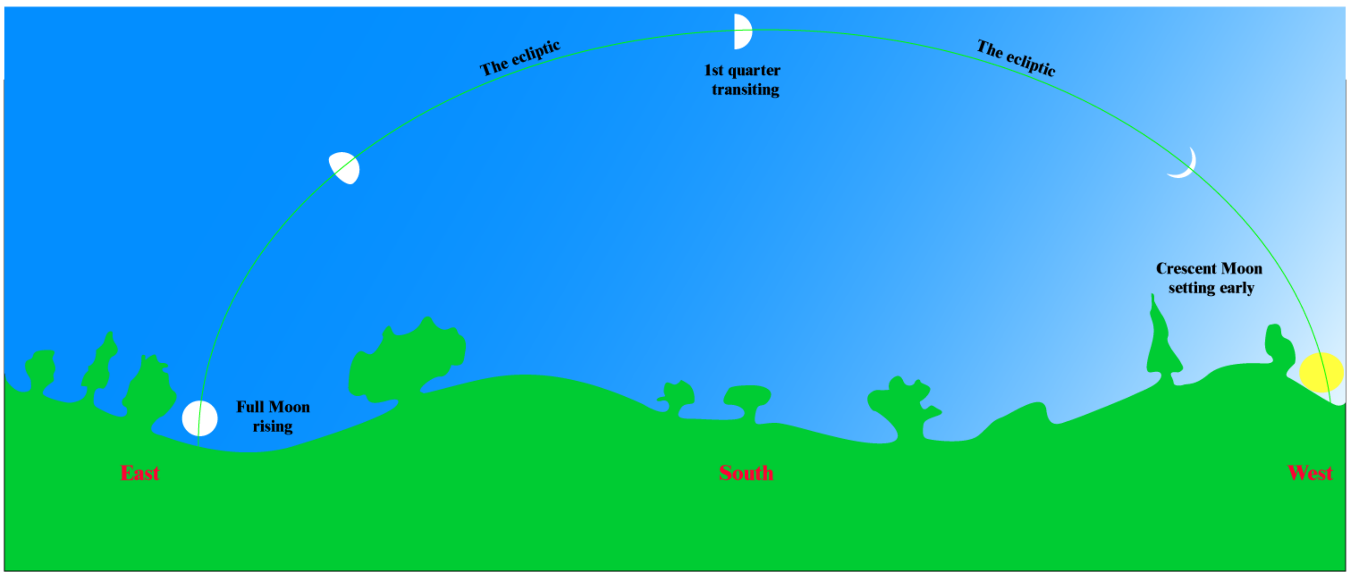


Fig. 5: At sunset, the first quarter is high up but the full moon is only rising.

The phases of the Moon are, by simple geometry, related to the position of the Moon in the sky (see Fig. 5). At new moon the Moon and the Sun are close together in the sky, and the Moon is invisible. In two days it appears as a narrow sickle 24^o to the left of the Sun (i.e. in the southwest right after sunset), and sets a good hour after the Sun. As the days pass, every day the Moon moves another 12^o to the left and on the 7^{th} day the already half Moon is high up in the south at sunset, at 90^0 away from the Sun. It sets at midnight, and is very well suited for observation. The shadows at the terminator (the limiting line between the bright and dark part of the Moon) are long and emphasize the relief. The first quarter Moon is ◗ - shaped (the Sun is to the right of it).

During the following week the Moon keeps waxing, getting brighter and brighter. At sunset, it moves farther and farther towards east, and sets later and later. By the end of the second week the Moon is full, is just rising in the east at sunset, transits high up in the south at midnight, and sets at sunrise. The Moon is so bright around full moon that almost any astronomical observation becomes impossible. The full Moon itself is an absolutely disappointing view: it receives the light from behind us and no shadows are visible on the surface.

To visualize what is involved take a flashlight in a dark room and illuminate the floor from the top. Now keep watching the floor from above but illuminate it with the flashlight from the side at a small angle (see Fig. 6). You'll see all the tiny details of the floor very clearly. Keep this in mind if you ever drop your golden ring!

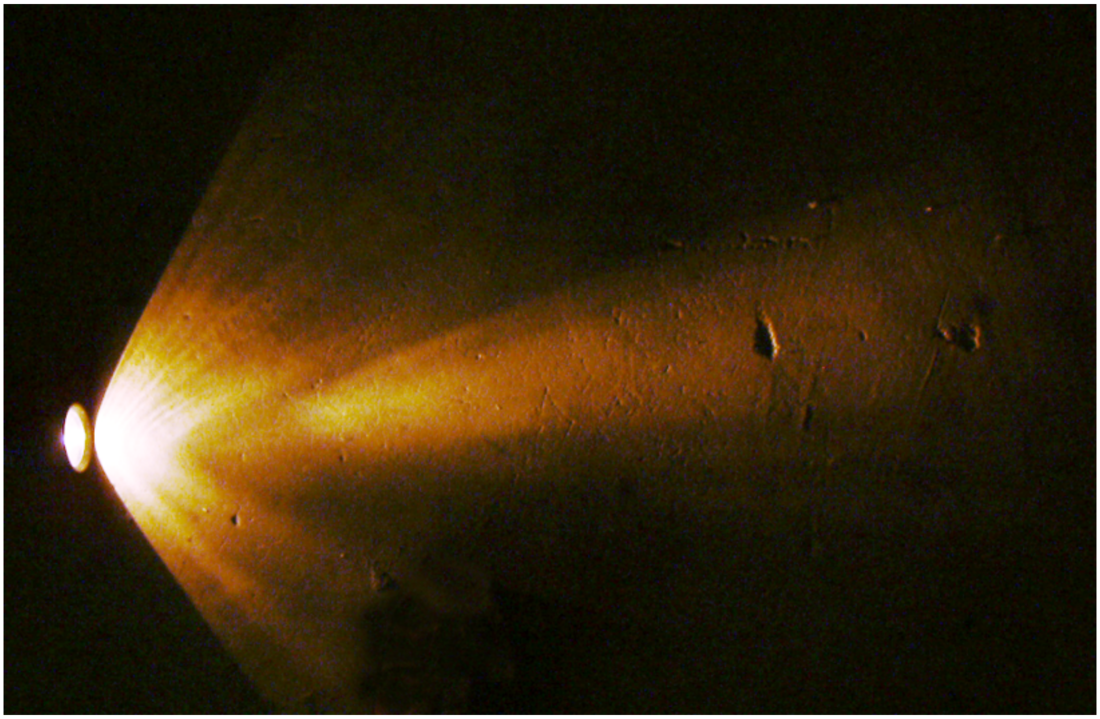


Fig. 6: Grazing light enhances relief – the terminator at the quarter Moon is spectacular, while very little detail is visible on the full Moon. Showing this experiment in classes greatly helps understanding.

The week after full moon sees it waning. It continues rising *50 min* later every day. A few days after full moon there is a gap of an hour or two after dark before the still bright Moon rises and makes observations impossible. These few days after full moon are also reasonably well suited to observe the Moon because the shadows on the surface start reappearing. In a week, at last quarter, the Moon comes up at midnight and does not interfere with early-night observations any more.

The first quarter Moon is ◖ - shaped (the Sun in to the left of it). It is high up in the south at sunrise, and easy to spot while going to work.

During the following week the Moon keeps getting closer to the Sun, and waning. Two days before new moon it vanishes as a narrow (- shaped sickle in the light of the rising Sun.

The Moon, the same way as the Sun, is not equally high up in the sky at all seasons and lunar phases. The full Moon is high up in the winter (and a serious impediment to observation), while in the summer it is low over the horizon. This is simple to understand: the full Moon is located opposite to the Sun in the sky and the Sun is low under the horizon in summer nights and deep under in winter nights.

In fall the Sun is "sinking" down south, and the first quarter Moon is ahead of it: it is very low and sets early. In spring however, the first quarter Moon is very high up and gives an excellent view. Spring is the greatest time to observe the Moon and the planets!

Exercises

1. Imagine you are looking at the Moon at sunset every night. How far in degrees, and in which direction does the Moon move in the sky day by day? How many *cm*'s per day would that correspond to, measured with your outstretched hand?

2. The Moon looks like this: . What is the phase of the Moon, where and when is it visible in the sky? When does it rise and set?
3. The Moon looks like this: . What is the phase of the Moon, where and when is it visible in the sky? When does it rise and set?
4. The Moon looks like this: . What is the phase of the Moon, where and when is it visible in the sky? When does it rise and set?
5. The Moon rises at 7 pm tonight. When will it rise the day after tomorrow, and a week from today?
6. Examining calendars that list the time of moonrise you will find that on some days the Moon does not rise at all. How is this possible, and what is the phase of the Moon at that time?
7. Why is the Moon more often up in the spring semester during lab than in the fall? Explain.
8. Why is the full Moon not good for observation?
9. How old is the narrow sickle of the Moon when it is first visible after new moon, and how old is the first quarter, and how old is the full moon?
10. Why is the first quarter called a *quarter* when what we can see is the *half* of the Moon?
11. Why is it not possible to explain the sickle shape of the Moon by the shadow of Earth? Base your answer on the position of the Sun and the Moon in the sky.

II.7. Timekeeping and celestial coordinates

The various civil and astronomical times are clearly explained in [1]. Be it sufficient here to mention the fact that our Central Time is shifted from Universal Time (UT = GMT) by 5 or 6 hours:

Central Standard Time (winter): $CST = UT - 6^h$,

Central Daylight Savings Time (summer): $CST = UT - 5^h$.

All astronomical objects are so far away that to all intents and purposes they might be considered infinitely far away. We cannot even measure the distance to any celestial object without using sophisticated methods and equipment. For this reason we can pretend with impunity that all objects are "painted" on a sphere of large radius we call "sky". Because the surface of a sphere is two-dimensional, two coordinates characterize the place where a star is located.

All celestial coordinate systems work on the same principle as geographical longitude and latitude, or the familiar-to-physicists spherical coordinates.

The standard coordinate system, basically fixed to the stars, is called "equatorial coordinates" (Fig. 7). The latitudinal coordinate is called declination (δ), ranges $-90^o < \delta < +90^o$. The celestial North Pole is at $\delta = +90^o$, the equator is at $\delta = 0^o$, the celestial South Pole is at $\delta = -90^o$. The longitudinal coordinate is called "right ascension" (α). It is measured from west to east in the sky in hours and minutes. This means that a person facing south will say that α increases from right to left. For a person facing north, α increases in the *clockwise* direction around the North Pole. The origin of α is fixed at the vernal (spring) equinox. Recall that the vernal equinox is the intersection point on the equator and the ecliptic where the Sun is located on March 21, in the constellation of Pisces. This implies that the coordinates of the vernal equinox are $\alpha = 0^h$, $\delta = 0°$.

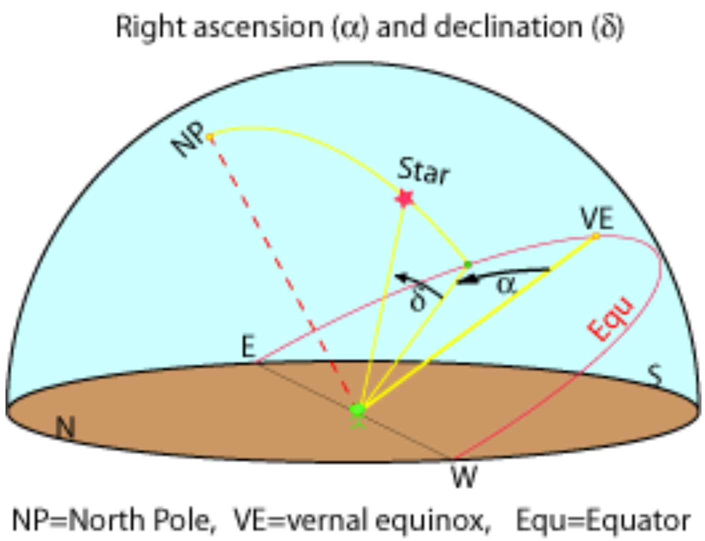


Fig. 7: The most often used coordinate system (called "equatorial") is fixed to the stars. Its starting point is the vernal equinox, which rises, transits, and sets with the rest of the stars in the sky. Right ascension is measured towards the East (positive direction) in hours, and declination is measured from the equator towards North.

Right ascension is measured in hours, minutes and seconds, 24^h corresponding to 360^o. This will be convenient when clock angle and sidereal time are added together in the following paragraphs. The conversion between hours-minutes and degrees representing distances in the sky is not simple though. When distances between objects are small, the difference in right ascension between two objects corresponds to a smaller angular distance than the difference in their right ascensions: $\Delta = 15\,am \times \frac{\alpha_1 - \alpha_2}{\min} \times \cos\delta = 15\,as \times \frac{\alpha_1 - \alpha_2}{\sec} \times \cos\delta$. The $\cos\delta$ factor is analogous to the fact that the geodesic parallels are shorter at higher latitudes.

We should be aware that the vernal equinox is not exactly tied to the stars. The major effect is precession: the vernal equinox slowly moves around along the ecliptic, completing a full circle in 26,000 years. The equatorial coordinates of a distant star change, even if the star is not really moving at all. To clearly specify the coordinates, we must tell what "epoch" it refers to. For example, we often chose to use "equatorial 1950.0" or "equatorial 2000.0" coordinates. The difference is small (about a half a degree at most), but *not* negligible.

The normal equatorial coordinates are fixed to the stars. Because the vernal equinox moves around the sky daily, the zero of right ascension is unnatural for telescope mounts. The natural coordinates that are easy to use with equatorially mounted telescopes are the "clock angle – declination" system. The latitudinal coordinate is still declination, but the longitudinal coordinate is called "clock angle (Θ), and is measured from the meridian towards west (see Fig. 9). This means that hour angle and right ascension are measured in *opposite* directions, and their zeros are not the same! For example, a transiting star has $\Theta = 0^h$, and its hour angle increases in time as it moves toward west. The cardinal west point has $\Theta = 6^h$, the cardinal east point has $\Theta = 18^h$. A star in the north has $\Theta = 0^h$ if it is higher up than the North Pole, and $\Theta = 12^h$ if it is below the North Pole.

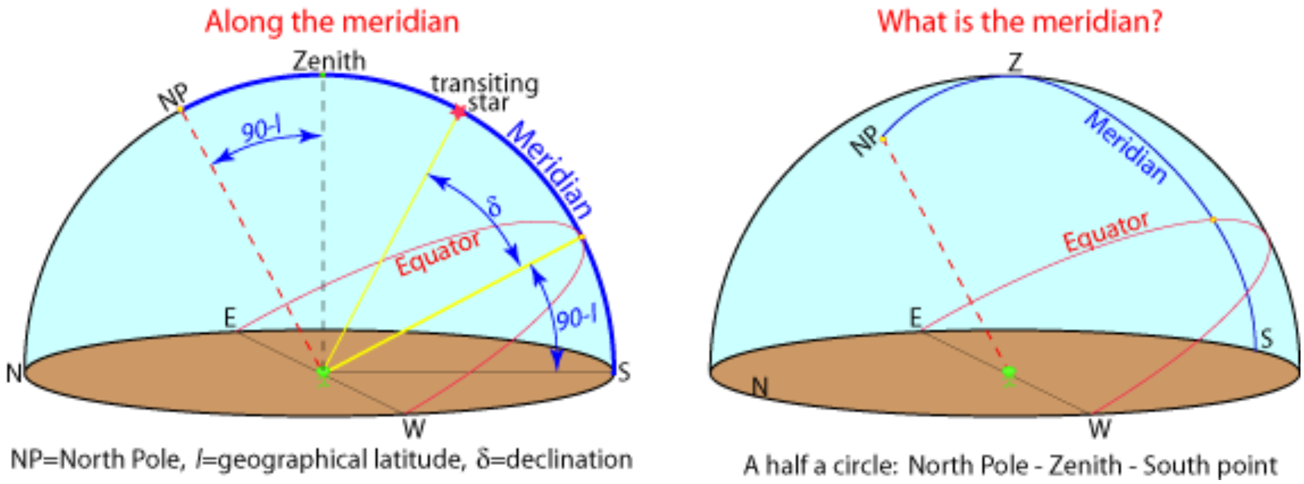


Fig. 8: The meridian is towards South. Stars cross the meridian when they transit – that is when they are highest up in the sky. Notice that the height of the equator, of the north pole, and of a transiting star.

The relationship between the Θ - δ (hour angle and declination) and the standard equatorial (α - δ) coordinates is established by the hour angle of the vernal equinox. This quantity is called the "sidereal time" (t): sidereal time is the hour angle of the vernal equinox. The relationship between the right ascension and the hour angle of any star is $\Theta = t - \alpha$. This relation is useful when we aim a telescope using coordinates (a standard practice on the Grubb 15-in refractor in the big dome). By the way, this relationship also tells us when an object with right ascension α will transit: at sidereal time $t = \alpha$. In other words, sidereal time equals the right ascension of the meridian.

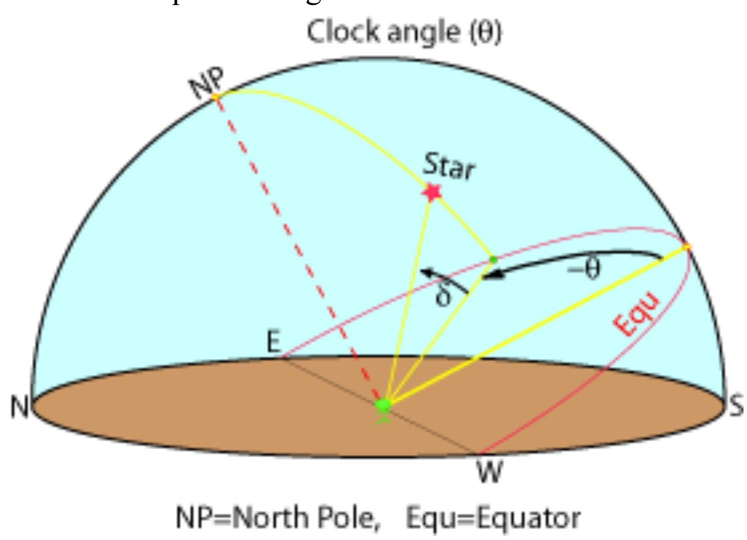


Fig. 9: The clock angle – declination coordinate system is fixed to the observer, not to the stars.

Sidereal time actually represents the true time of the day better than civil time in that it truly corresponds to the rotation of Earth. A sidereal clock goes *4 min* too fast per day, which adds up to a whole day per year. So a sidereal clock will think that a year consist of 366.22 days.

Both of the above coordinate systems are unnatural for the human observer. In order to appreciate where our star is located in the sky, we need to relate its place to terrestrial objects. The so-called "altazimuthal" coordinates do this, accepting the price that the conversion formulas between "altazimuthal" and "equatorial" coordinates are quite complicated. The coordinates are "altitude" (h), measured in degrees over the horizon, and "azimuth" (Az), measured in degrees from south towards west, i.e. to the right (see Fig.). With this definition, the rising Sun on March 21 has $h = 0^o, Az = 270^o$, the west point is $h = 0^o, Az = 90^o$, and a star transiting in the south has $Az = 0^o$. The North Star in Oxford is at $h = 34^o21', Az = 180^0$. Zenith has $h = 90^o$, and Az undefined.

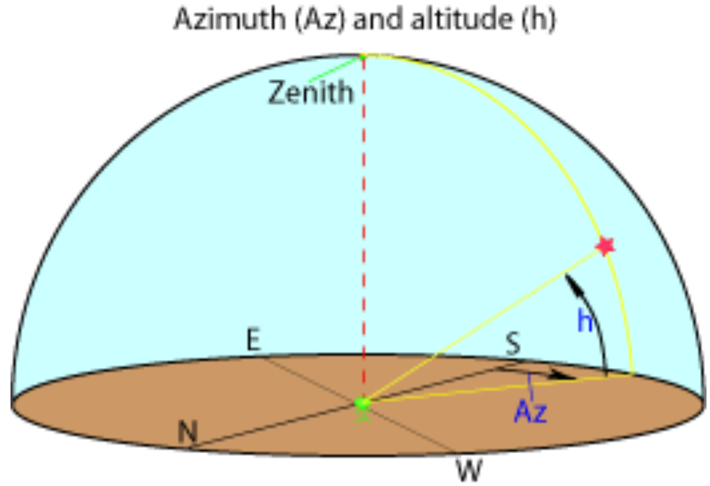


Fig. 10: The horizontal coordinate system, with coordinates called azimuth (Az) and altitude (h) is fixed to the observer. Notice that the daily motion of stars will keep these coordinates continually changing at variable rates.

It should be noted that some authors use a different definition of azimuth. Both the direction of measurement and the starting point can vary, and there are actually four versions in use (south to west, south to east, north to west, north to east). Before using someone else's data, be sure to understand their definition of azimuth!

It is somewhat trivial but we should mention the following usage of cardinal points and directions. The terms east, south, west and north *cardinal points* designate the directions as they are usually applied, or the corresponding points in the sky – that is, for example, all these points have $h = 0$. The terms east, south and north *directions in the sky* refer to a relative direction from one star to the other (e.g. in the field of a telescope). Star B will be to the north of star A if it is located towards the North Pole from A, i.e. $\alpha_A = \alpha_B$ but $\delta_A < \delta_B$; similarly Star B will be to the west of star A if $\alpha_A > \alpha_B$ but $\delta_A = \delta_B$. In everyday terms, facing *exactly* south, you'll find north up, south down, west to the right, east to the left. When you are not *exactly* facing south, these directions will be turned; for example, north will not be exactly up any more. When you turn east or west, or north, it takes some ingenuity to figure out which way these directions are. An equatorially mounted telescope might come in handy in the process.

Exercises

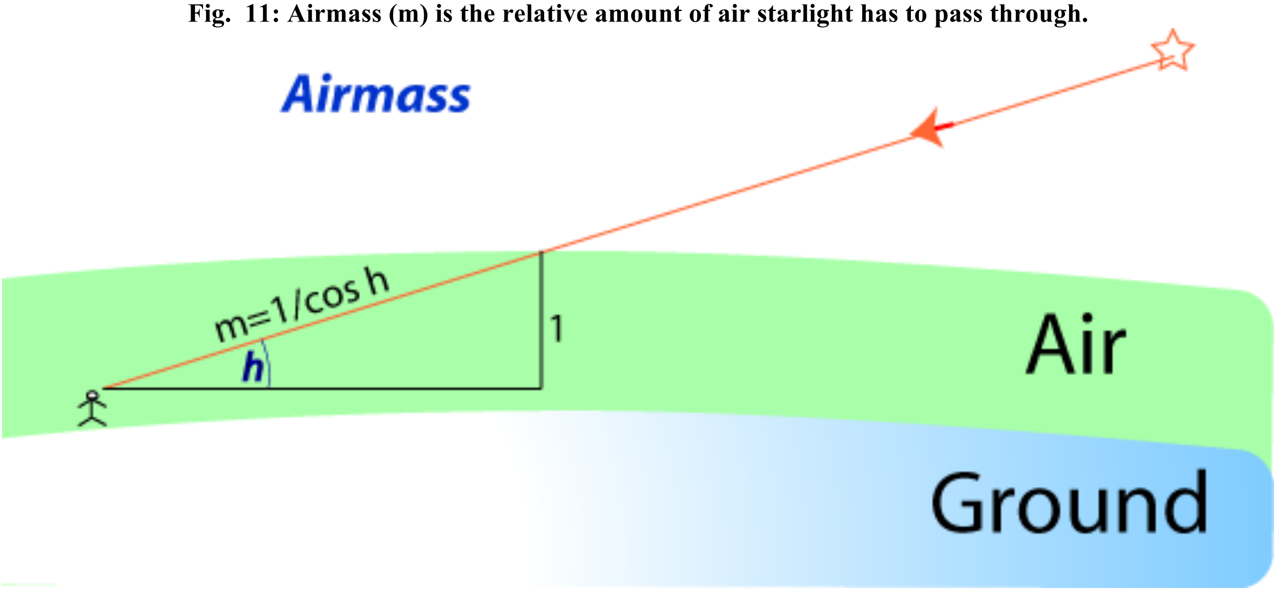
1. It is Dec. 12, 2005, and the clock says 6:15 pm. What is UT? What is your answer at 6:15 pm on July 12, 2006?
2. Imagine moving your telescope S $\rightarrow$ N. Which of the equatorial coordinates increases, decreases, and does not change? What if you move E $\rightarrow$ W?
3. Imagine looking at the sky facing south. Right ascension increases in the sky from your left to right, right to left, towards up, or towards down? What about declination?

4. What is the clock angle of the meridian? What is the clock angle of the east point (the point in the sky, towards east, on the horizon)? What about the west, south, and north points? What is the clock angle of Zenith?
5. A star in Leo has $\alpha = 11^h 51^m$. What is the sidereal time when it transits?
6. Pisces is setting. What is the sidereal time?
7. How many degrees are in an hour?
8. Which of the following is continuously changing? The right ascension, the clock angle, declination, height, azimuth. Give the rate of change (include the sign) for those that change at a constant rate.
9. How fast does the azimuth of a star change if and when it crosses Zenith? What are the practical consequences of this for an altazimuthally mounted telescope?

II.8. The effect of the atmosphere on starlight: seeing, twinkling, extinction and refraction

The atmosphere of Earth affects starlight and causes much trouble for astronomers. In clear weather it absorbs 20-30% of the light in Zenith and 99% of the light near the horizon (this is called *extinction*). The atmosphere makes stars jump around in the sky a few arc seconds even when the atmosphere is calm, and a lot more near the horizon or after a weather front passes (this is called *seeing*). It makes stars *twinkle* in color. It blurs the image of stars in the telescope (another component of *seeing*). It raises the apparent location of stars in the sky (this is called *refraction*). It raises the stars more in blue than in red, so it separates color and paints the top of the objects blue and the bottom red, especially when the object is low over the horizon (this is called *differential refraction*).

Fig. 11: Airmass (m) is the relative amount of air starlight has to pass through.



All these disturbing effects are much worse when the observed object is low over the horizon. The effect is geometrical (see Fig. 11): starlight from an object at low altitude *h* must pass more air by a factor of $m = 1/\sin(h)$ (this factor *m* is called *airmass*). When we observe an object lower than at *h = 30⁰*, right after it rises or before it sets, or a southern object that never rises high up, atmospheric disturbances become severe. As a rule of thumb, never observe anything under 30^0 if you can help it.

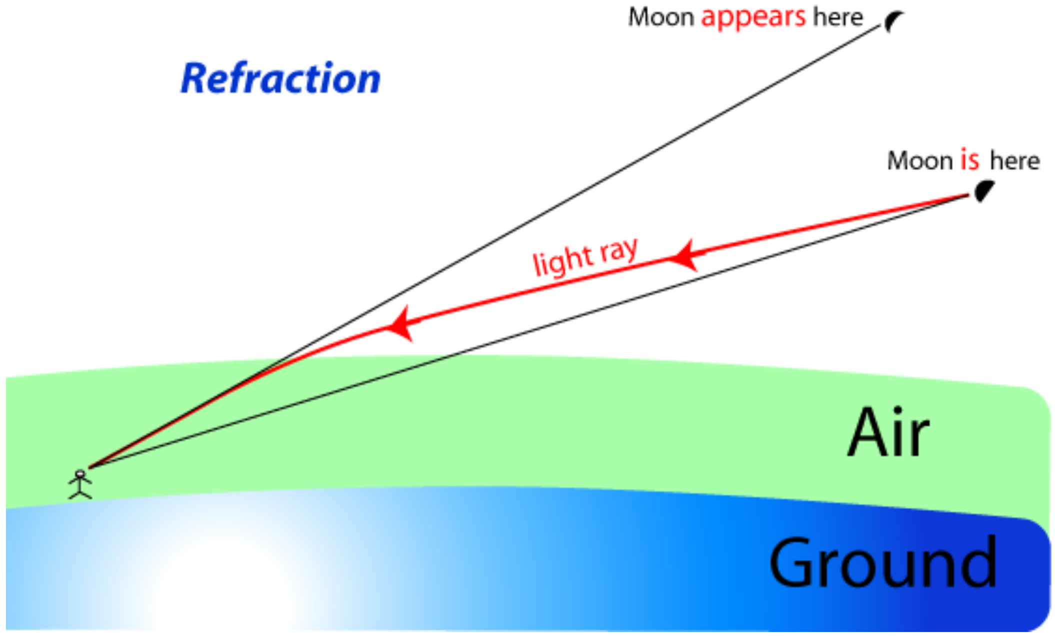


Fig. 12: Atmospheric refraction apparently raises the Moon and stars.

Extinction makes stars appear fainter when they are lower in the sky. Even in Zenith, and in excellent transparency conditions, only about two thirds of the star's original light makes it to sea level. On another day, when transparency is not so good, only a quarter of starlight reaches us. The human eye is not well equipped to measure absolute brightness, and the large changes in atmospheric transparency go usually undetected. However, photography will immediately detect these changes. You will find that some nights are simply no good for picture taking. The culprit is usually moisture in the atmosphere.

The amount of extinction increases when the star is lower in the sky. On average, a star appears *5 mg* (a hundred times) fainter on the horizon than it looks in Zenith. Extinction is even more severe in blue, so the apparent color of objects shifts towards red as they go close to the horizon. This fact must be taken into account in photometry and may play havoc with color photography, especially if different color filters are used at different times. The upshot for visual observation is that, if we have a choice at all, we always choose objects that are at least 30° over the horizon, and preferably close to Zenith at the time.

Another damaging effect of the atmosphere is refraction. The denser lower atmosphere acts as a lens and apparently raises the stars higher (see Fig. 12). The change in the position of stars is minor unless they are close to the horizon. On the horizon refraction grows to over a degree and depends on altitude so much that the shape of the setting Sun or Moon is visibly distorted (see Fig. 13). For stars higher up, refraction is small (parts of an arc minute), but it must be taken into account when precise positions are measured. The approximate amount of refraction is calculated as

$$refraction = \frac{60as}{\tan(h)} \times \left(1 - \frac{T}{273C}\right) \times \left(1 + \frac{1670nm - \lambda}{12000nm}\right)$$

where h is the height of the object over the horizon. The second and third terms are small corrections, and the first term indicates, for example, that at h = 45^0, halfway up in the sky, refraction is still 1 am.

Fig. 13: Refraction distorts the shape of the setting Sun into something like an egg.

The biggest trouble refraction causes is due to the fact that it is color dependent. Air, as a prism, separates light rays of different colors and raises the image of a star more in blue color than in red. This so-called differential refraction is clearly visible in the telescope when the object is lower than 30^{o} over the horizon. As the formula indicates, the amount of differential refraction between blue (λ = *400 nm*) and red (λ = *700 nm*) is $1.5as/\tan(h)$. Venus, always close to the (setting) Sun and low in the West when it is visible at early night, appears as if we watched it through a bad quality telescope with chromatic aberration. The "top" of the image is blue; the "bottom" is red (see Fig. I.12). In color photography, some improvement results if the color components are taken with separate filters and then digitally realigned.

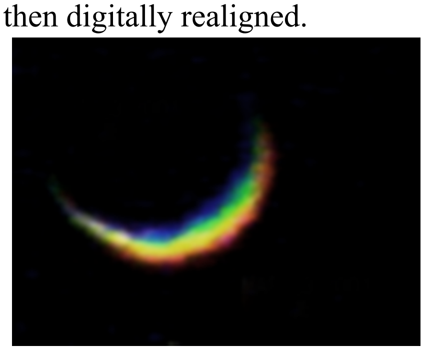


Fig. 14: Differential refraction turns the setting Venus into a rainbow.

The most damaging effect of the atmosphere, even on clear nights, has come to be called "seeing". Variations of air temperature on the distance scale of a few inches cause slight variations in its index of refraction. Bubbles of slightly warmer and colder air refract starlight and cause three distinct but related detrimental effects: jumping, blurring and twinkling. In listing these, we must appreciate the fact that (i) the characteristic size of these air bubbles is on the order of a few inches, and that (ii) the ever-present wind keeps these bubbles in motion all the time. Air bubbles also blur the image of stars. In normal conditions this blurring is much less than the "jumping" component of seeing, on the order of *1/10 as*. However, neither the human eye nor a camera can compensate this blurring.

Starlight is deflected by these bubbles, so stars keep jumping around *0.5 - 2 as* in the sky, several times a second. The human eye can partially follow this jumping in the telescope's field, but a photographic or a CCD camera cannot (unless we use an exposure time shorter than *0.1 sec*). On long exposure images stars are always blurred due to this component of seeing by an amount ranging from ½ to *2 as*.

The numbers indicate that the "jumping" component of seeing dominates in all except the smallest telescopes. The diffraction pattern from a star appears undulating, jumping, but not completely blurred out visually. In long exposure images, however, the diffraction pattern is always blurred out completely by the "jumping".

The most obvious, but least harmful, way the atmosphere affects starlight is that any one observer will see the amount of light from a star to keep changing. This is obvious even without a telescope: stars twinkle. Scintillation (the scientific name for twinkling) is *not* directly related to seeing, because it affects only the intensity of light but does not cause blur or jumping. It is true, however, that on nights when stars twinkle a lot, the other two components of seeing are usually also bad: after all, all three effects are caused by an unsteady atmosphere. It is a pity that on nights after a cold front passes, when the air is usually very transparent and stars look extremely bright, the atmosphere is still unstable and seeing is very bad. Stars twinkle. The next night seeing improves, but dust and moisture accumulates and the transparency declines. One cannot have it all at the same time.

A large fraction of seeing is caused by the air a few miles above the ground. The only way to fight that is to move to a high mountaintop. However, local effects may sometimes cause even more seeing. The amount of angular deflection (the "jump") caused by a warm air bubble is about

$$\delta = 0.2\tfrac{as}{^\circ C}\int dl\, {}^{\partial T(x,l)}\!/_{\partial x},$$

where the integral is along the line of sight, "*x*" is the perpendicular direction, and *T(x,l)* is the temperature of the air. One can estimate this as $\delta \approx 0.2\tfrac{as}{^\circ C}\Delta T$, where ΔT is the temperature difference inside and outside the air bubble. Clearly, the warm concrete of a parking lot or the inside of a dome will cause air bubbles, warmer by a few degrees than the environment, to keep rising, and the result is seeing on the order of a good arc second. The best way to avoid that is to (i) keep the environment in thermal equilibrium up to about one or two degrees, and (ii) use the telescope over a surface, such as grass, which does not absorb much heat during the day. Professional observatories are built in mountaintops over *inversion layers*, places where local atmospheric conditions cause warmer air sit on top of a layer of colder air. That is the best way to make sure no warm air bubbles keep rising, but there are few places on Earth where an inversion layer is formed in a place where the weather is regularly calm and clear. This explains why there are so few places with really good seeing: Mauna Kea in Hawaii, the Canary Islands in the Atlantic, or the area of Cerro Tololo in Chile.

All atmospheric effects increase greatly when a star is low over the horizon, being proportional to ${}^{1}\!/_{\sin(h)}$. Stars twinkle a little when they are high up, but scintillation is most obvious and beautiful when a bright star is low over the horizon. Probably no one has ever seen Sirius in the US, always low and bright, in steady light. It is always spectacularly twinkling in a telescope!

Twinkling is actually due to the fact that starlight hits the surface of the Earth unevenly. The light that is missing in one place goes to another. When we are looking at a planet, however, the different parts of its disk do not scintillate in synch. The human eye cannot resolve the disk, it adds together all the light, and the result is that scintillation is cancelled out. Planets do not twinkle. Lack of scintillation is a quick and easy way to tell a planet from a star. When seeing is so outrageous that even planets scintillate to the naked eye, we know immediately that few details will be visible in the telescope on that night.

The "blur" component of seeing limits magnification even in visual observation. For this reason the maximum magnification is usually determined by this blur (except for very small telescopes, under four inches), and cannot be more than $50\times$ - $300\times$, depending on the state of the atmosphere. It is interesting however, that in the process of a long and careful observation we sometimes catch moments of exceptionally calm air for a tenth of a second when much detail becomes momentarily visible. To wait patiently for these instants of exceptional seeing is the best way to observe the planets.

Exercises

1. How large is extinction in Zenith on a clear night? Give your answer as a percentage and also in magnitudes. Is this significant? Now what is the answer for a star $30°$ over the horizon? And for a star only $5°$ over the horizon?
2. How much is geographical latitude determination, based on the height of Polaris, affected by refraction?
3. How much is differential refraction between red ($\lambda = 700\ nm$) and blue ($\lambda = 400\ nm$) for Mars when it is halfway up in the sky? Does this cause any visible blur in the telescope? What is the answer for Venus when it is only 15 degrees over the horizon?
4. Atmospheric effects make stars jump around, be blurred, and twinkle. Give a ballpark number for how large each of the three effects is. Which one is also called scintillation?
5. Up to a certain diameter, a larger telescope gives a more detailed image by visual observation, but not in long exposure imaging. Explain why.
6. How much (quantify) seeing is caused by 2-3 degrees of temperature difference between the inside of the dome and the outside air?
7. Which one is better for seeing, a telescope set up in a parking lot, or on lawn, and why?
8. On some nights stars look very bright in the sky. Is that good seeing? Explain.
9. Give a ballpark number for extinction (in Zenith) in clear summer nights in Oxford.
10. Explain the pros and cons of observing Venus during the day. Focus on the amount of seeing.
11. What is the largest magnification seeing usually allows in Oxford? How does this number depend on the diameter of the telescope?
12. Why don't planets twinkle?
13. Observe a bright star with a 12-inch Meade telescope at large magnification. (Perhaps ~ 600 times.) Choose a star that is low over the horizon. (For example, good ideas are Sirius, Antares, or the rising or setting Vega, Arcturus, Aldebaran, or Capella would do.) Identify the three components of seeing.
14. The resolution of DSS images is not better than the resolution of the images taken in Kennon Observatory. The plates for the Digitalized Sky Survey were taken with the 5 - m Hale telescope on Mount Palomar, this fact is quite surprising, but true. Why?
15. Derive the formula $\delta = 0.2\frac{as}{°C}\int dl \, \partial T(x,l) / \partial x$ for seeing. *(Hint: the index of refraction of air is proportional to the density of air, which can be found from the ideal gas law. Which one is larger, the effects of temperature or pressure change?)*

III. Telescopes

The easiest way to think of a telescope's workings is to say that the object is located at infinity and the objective lens or mirror forms an image of the object in the focal plane. This image is then viewed through a positive lens serving as a magnifier glass. (Galileo's telescopes with negative eyepieces are not used in astronomy because they have a tiny field of vision at any reasonably high magnification.) This simple explanation is accessible to students without having to grasp the concepts of ray diagrams.

III.1. Image scale and f-stop

Telescopes serve two purposes in astronomy. Weather it is a lens, a lens system or a concave mirror, the objective of a telescope forms an image in the focal plane. The size of this image is determined by the focal length of the objective: $d = f \times \tan\theta \approx f \times \theta$, where θ is the angular size of the object. For example, the Moon is $\theta = ½°$ in diameter, $\tan(½°) \approx 1/100$, so the size of the image of the Moon is 1/100th of the focal length. A 12-in Meade with $f = 3048\ mm$ makes a $30\ mm$ - size image of the Moon.

The easiest way to take a picture of the Moon is to use this 'prime focus' (as it is officially called), simply attaching an SLR camera (with its lens removed) to the telescope. The size of the film is $24\ mm \times 36\ mm$, so the Moon nicely fits in the picture in this example. However, a $1\ as$ - size crater, still resolved by the telescope, will be $f \times \tan(1\ as) = f / 200{,}000 = 1/60\ mm$, so the film has to have a decent fine resolution to bring out all the small detail.

The amount of light per unit area (i.e. the brightness of the image) is determined by the ratio of the focal length to the diameter of the objective, called *f-stop*, f/D. For example, the aforementioned Meade telescope, $f = 3048\ mm$, $D = 12\ in = 304.8\ mm$ is said to be an $f/10$. The illumination (i.e. intensity per unit area) of the image in the focal plane is inversely proportional to the *square* of the f-stop, and is *independent* of the diameter or the focal length separately. An extended object like a galaxy will look equally bright with an $f/10$ Meade and a professional 4-meter, $f = 40\ m$ telescope.

In photography, the exposure time required to show a faint extended object depends only on the f-stop of the lens, and is proportional to $t \sim (\text{f-stop})^{-2}$. For this reason, a lens (or telescope) is called *slow*, when f-stop≥8, *fast*, when 8>f-stop≥4, *very fast*, when f-stop<4. Slow telescopes are great for seeing small detail (like for planets or double stars), fast telescopes are great for seeing faint extended light (like for deep sky objects).

Exercises

1. The Grubb refractor in the big dome has $D = 38\ cm$, $f = 457\ cm$. How large is the image of the Moon in its primary focus? What is the image scale in *as/mm*? Is that a slow or a fast telescope? What is its f-stop?
2. Which one would give a brighter image of a galaxy, the Grubb refractor, or the Pronto with its $D = 70\ mm$, $f = 480\ mm$? Explain the reasoning carefully.
3. Aim a telescope on the Moon. Remove the eyepiece, and hold a sheet of paper in its place. Focus the image of the Moon on the paper. Measure the size of the Moon on the paper. Does your result match with what you would expect from the focal length of the telescope?

III.2. Magnification

Telescopes serve two purposes in astronomy. They can resolve small details through magnification, and they collect more light than the human eye does. The light collection power of a telescope is proportional to the surface area of the objective, so it is determined solely by the diameter of the telescope. The fully dilated human pupil is *5 mm* in diameter. A telescope with diameter ϕ will collect $(\phi/5mm)^2$ times more light than the human eye. The gain in the limiting magnitude of a telescope for stars is then $gain[mg] = 5 \times \log \frac{\phi}{5mm}$. A 12-in ($\phi$ = *300 mm*) telescope, for example, would gain *8.9 mg* and thus have a limiting magnitude of *14 mg* in a dark location.

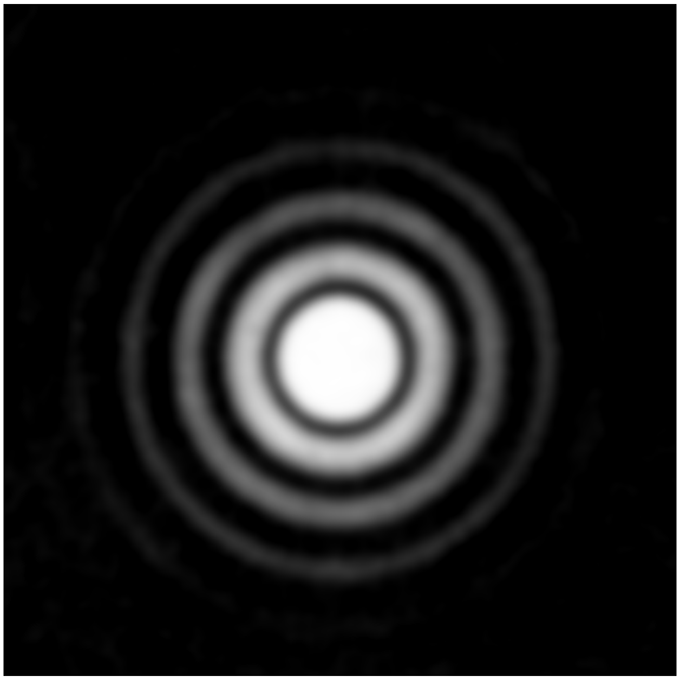


Fig. 15: Diffraction turns a star's image into rings. The central patch of light is the Airy disk.

When we are watching a bright object, the human eye has a resolution of *1 am = 60 as*, mainly due to the fact that the retina rasterizes the image. A telescope with magnification M would be able to resolve as small details as *60 am / M*. Most of the time this calculation is illusory, however. Diffraction of light caused by the finite size of the objective turns the supposedly pointlike image of a star into a diffraction pattern (see Fig. 15). The diameter of the central disk (called Airy disk) is in angular measure $\varphi = {}^{118as}/_{\phi[mm]}$, and this depends only on the diameter of the objective. This is the "resolution power" of the telescope, which cannot be improved upon in any way. For example, a 5-in (ϕ = *125 mm*) telescope has a resolution of *1 as*, while the diffraction limit of resolution of a 12-in (ϕ = *300 mm*) telescope is *0.42 as*.

Both of these two purposes of telescopes depend on the diameter of the telescope, which for this reason came to be its most important characteristic. Telescopes under *8 in* are usually considered "children's toys", and the *8 in - 25 in* region is an amateur-sized telescope.

It stands to reason to use as much magnification as needed to turn the Airy disk into *1 am* in diameter. With this "useful magnification" we can already see all the details the telescope will ever show. The discussion above implies $M_{useful} = {}^{\phi}/_{2mm}$, so a 12-in telescope has $M_{useful} = 150x$. In practice, under excellent atmospheric conditions, it makes sense to use twice as much magnification, $M_{max} = \phi[mm]$ (in the above example, $M_{max} = 300x$), simply to make the small details more comfortable to view. Any larger magnification will not bring out more details but will only blur the image more, and is called "empty magnification". It should be also mentioned that there is a lower limit to magnification. The outgoing pupil (that is, the diameter of the light beam leaving the eyepiece) has a diameter ϕ/M and at the minimum sensible magnification $M_{\min} = \phi/5mm$ it is just as thick as the size of a dilated human pupil. A smaller magnification results in loss of light.

The magnification of an (amateur-sized) telescope is almost always limited more severely by the motion of air than by diffraction. The motion of air blurs the image of a star and causes it jump around with characteristic frequencies between 1-100 Hz. The human eye can follow the jumping star to some extent and can eliminate the 1-10 Hz component of this "seeing" (as it is called). The blur and the high frequency components are, however, usually on the order of *0.3 as to 2 as*, depending on the weather conditions. This lowers the useful magnification to $M_{useful} = 30-200$, and at magnifications beyond $M_{\max} = 60-400$ the image will be blurred and undulate very fast. This "seeing" changes much from one night to the next, and can be assessed only through actually trying to use high magnification. In fact, there is no correlation between moisture in the air, clouds and seeing: the best seeing conditions often arise in hazy and somewhat cloudy skies. However, when stars twinkle strongly (especially at high altitudes in the sky), that is an indicator of bad seeing. Seeing is an especially severe problem for astrophotography, because in long exposure images the 1-10 Hz component of seeing is not compensated as it is by the human eye, and this component is usually large (*2 as* to *8 as* in Mississippi conditions).

The magnification of a telescope

Minimum	$2 \times \phi$ [cm]	$\approx$	$5 \times \phi$ [in]
Useful	$5 \times \phi$ [cm]	$\approx$	$12 \times \phi$ [in]
Maximum	$10 \times \phi$ [cm]	=	$25 \times \phi$ [in]

Another issue relating to magnification is surface brightness. In the case of extended and faint deep sky objects not much of the above applies. At low light the human eye increases its sensitivity at the expense of resolution. A large collection of individual sensors in the retina act together as one and sense faint light, but the resolution decreases from *1 am* to as low as *20 am* to *60 am*. In these conditions there is very little gain from magnification, while the surface brightness of the image decreases as $1/M^2$. We should use the lowest available magnification. A little thought indicates that no telescope can ever increase the surface brightness of an object, and the best you can do is not to decrease it. Using the minimum $M_{\min} = \phi/5mm$ will do exactly that.

The only exception from the practical rule of using M_{min} on all faint extended objects is when the background sky is bright due to light pollution. Using higher magnification will also reduce this unwanted background and allow the observer's eye to adapt to dark. In practice, the optimum must be found by trial and error. One special case is M57 (the Ring Nebula in Lyra), a small planetary nebula, for which a magnification 100 – 200 × works best.

The field of view of a telescope is determined by the magnification and the field of view of the eyepiece. Obviously, *(The field of telescope) = (The field of eyepiece)/(magnification)*. Modern eyepieces usually have *40 deg* to *60 deg* of field, so for example, with $M = 100\times$ you can expect a field of $\approx 0.5\deg$, the size of the Moon. At higher magnification only a small part of the Moon will fit in the field. It is good practice to start viewing any object with small magnification, and then gradually try shorter focal length eyepieces until an optimal view is found.

Exercises

1. If you know the diameter of a telescope in centimeters, how can you tell the (i) minimum magnification, (ii) the useful magnification, (iii) the maximum magnification?
2. A decent finder telescope must have at least *5 cm* diameter to show faint enough stars. What is the minimum magnification of such a finder? Why are 6 × 50 binoculars useless? What happens if you do build one?
3. What is the minimum, the useful, and the maximum magnification of a Celestron or Meade 8-inch telescope, of a 12-inch Meade, and of the Grubb refractor?
4. The 5 m telescope on Mount Palomar used to be the largest telescope in the world for 40 years. What is its minimum magnification? Compare your answer to the upper limit on magnification due to seeing, and conclude why such a large telescope is never used visually?
5. Define the term *useful magnification*. (The question is not *how* you calculate it, but what it means!)
6. What is the resolution of a telescope with diameter *24 cm*?
7. Calculate the apparent size of Betelgeuse in *mas*, which is probably the largest-looking star in the sky. Use data from the textbook. Is it possible to resolve any of the stars' disks with any presently existing telescope?
8. What is the resolution of the human eye?
9. Why is it that a telescope can have better resolution visually than photographically?
10. How fast is seeing? Explain.
11. A standard Ploessl eyepiece has a *44°* field. At what magnification will the Moon exactly fill out the field? Does seeing usually allow as much magnification? How large should the telescope be to keep that magnification useful? What is the size of the smallest detail on the Moon (in *km*'s) that you would still make out with that magnification?
12. Using an 12-inch Meade, look at a bright star with large magnification. Use a *4 mm* eyepiece. Observe the Airy disk and the diffraction rings.
13. Look at a tight binary star, and also at a planet with a set of magnifications. Observe the resolution and the blurring as magnification increases.
14. Look at a deep-sky object with various magnifications, and observe how the surface brightness decreases with increasing magnification.

III.3. Observation basics: how to look into a telescope?

A major issue among beginners is to figure out how to look into a telescope. The following points might be useful in teaching students observational skills.

The outgoing beam that leaves the eyepiece is diverging. It is important for the observer to catch all the light, so it is absolutely required that they place their eye directly on the eyepiece (touching; see Fig. 16). This point must be emphasized repeatedly in classes. For the same reason, glasses must be removed and any near- or farsightedness must be corrected for by refocusing the telescope. Each student must refocus every time s/he looks into the telescope – this is a skill to learn.

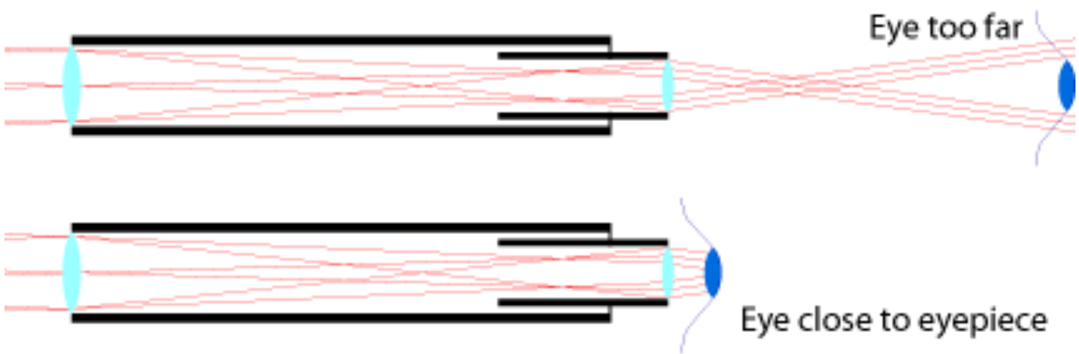


Fig. 16: It is natural to try to look into a telescope while keeping the eye far from the eyepiece. Doing that, however, keeps most of the light out of the observer's eye. Students need to be taught the correct way to observe.

Focusing might be confusing for some students. Quite often they confuse the out-of-focus light disk with an image of a star and will think that they are seeing details of the star's surface. Another reason for confusion is that many will confuse "focusing" with "aiming". They need to understand what focusing means.

Many objects are faint or contain details that are hard to make out. Observing carefully is an art that needs to be learned through training. It is necessary to look at the same object repeatedly, look up existing pictures of the object before observation, and make drawings of what we see. Such training improves our skill to really see and not only to look!

Eyepieces come in various qualities, focal lengths and sizes. The standard has become *1¼ in* and *2 in* diameter, the *2 in* being only used for long focal length. Modern good quality eyepieces are usually heavy, a price paid for the large field of view. It makes sense to use the best quality available. All *1¼ in* eyepieces work with all telescopes, but the *2 in* eyepieces can only be used with the 12-in Meades. Do use them whenever you can!

Many times it is quite inconvenient to look straight into a refractor or a Cassegrain when the object is close to Zenith. A "star diagonal" (a prism with an adapter) can be used to make viewing comfortable. The image will, however, be mirror-flipped. The same happens with Newtonian reflectors. Any star/planet charts need to be printed as mirror images when they are used with such instruments. Students also find it confusing why the object is not seen in the same direction where it is actually located in the sky. An explanation and a demonstration with a mirror might come in handy.

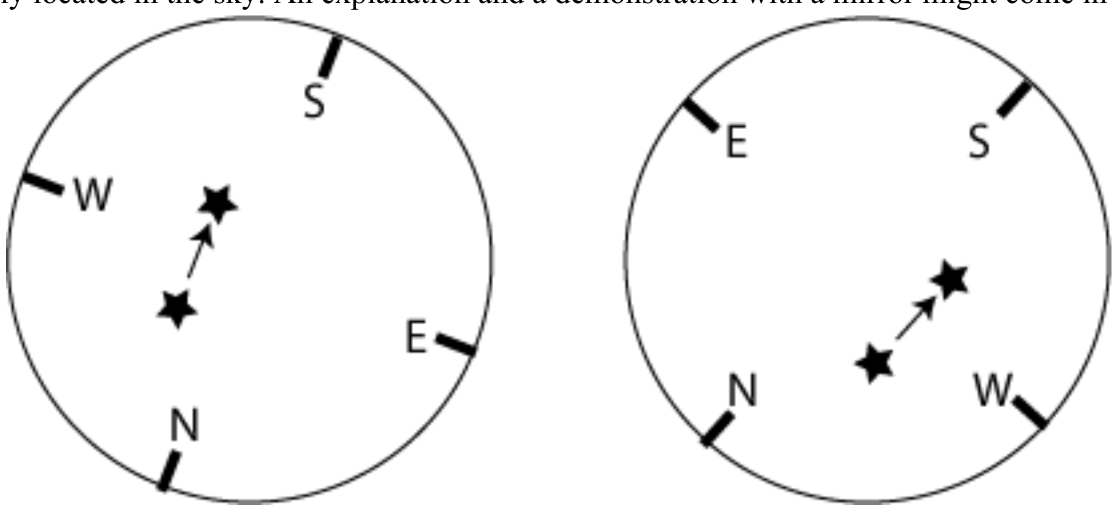


Fig. 17: When the telescope is moved North around the declination axis, a star moves South in the filed, whether the field is simply inverted (left) or mirrored (right). This is the easy way to tell the cardinal directions in a telescope.

The cardinal directions in the sky become confusing. Non-mirror-flipped telescope systems (such as refractors or Cassegrains) give inverted images. In their fields, South is towards Polaris (which may not be in the "up" direction!), and east is 90^o to the right of it. In Newtonians or when star diagonals are used, east is 90^o to the left of South, but it is usually difficult to guess which way South is. The most practical way of telling the cardinal directions is to move the telescope a little towards North (only in declination). The stars will move towards South in the field (see Fig. 17).

Exercises

1. Aim a telescope at a bright star with a Meade telescope or a Dobsonian. Turn the focuser out of focus in both directions, and observe the shape of the "image" of the star. You'll see a dark spot in the middle. Explain in a drawing what is happening.
2. Look at a field of stars with a telescope, with your glasses on, then without them. (If you do not have glasses, use someone else's glasses.) In each case, focus the telescope. Observe that the side of the field is hard or impossible to see with the glasses on, because your eyes are too far from the telescope. This is why the observer's eye should be *touching* the eyepiece.
3. Aim a Meade telescope, with a star diagonal, at Saturn. Use an illuminated reticule eyepiece. Using the keypad, slowly move the telescope towards N, S, W, and E in turn. Align the reticule parallel to the N - S direction. Make a drawing of what you see in the field. Indicate the N, S, W, and E directions in the drawing.
4. Practice how to turn the star diagonal on both the 8-inch and the 12-in Meade telescopes to make viewing most comfortable.

III.4. Telescope mounts

To the layperson, the telescope mount sounds something trivial. Perhaps this is the reason why department stores are so successful in selling junk scopes on rickety mounts by the thousand before Christmas. Actually, in a reasonable telescope of any size, the mount is more expensive and requires more careful craftsmanship than the optics! To see this, imagine a 5-inch mirror, which has a resolution of 1 *as*. The telescope is driven with the sidereal rate with an $r \sim 10\ cm$ gear. Dust grains in the gears, as small as $10\ cm \times tan\ (1\ as) \approx 0.5\ \mu m$, the size of a small bacterium, would make the telescope shake an arc second, and you could never see the diffraction pattern! Clearly, all gears and bearings should be made with extreme mechanical precision, and designed to retain that precision despite wear and dirt. Clearly, only the very best mounts are really made to match the quality of the optics they carry, and they are the bottleneck in telescope performance.

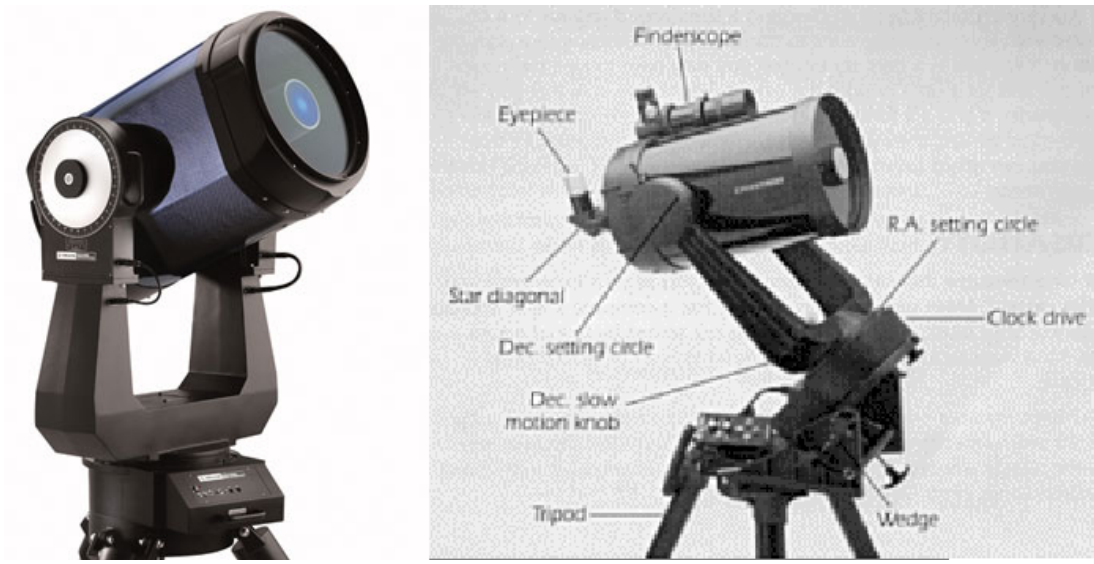


Fig. 18: The right ascension axis of an equatorial mount (right) points at the North Pole. The declination axis is stationary while the telescope is tracking the stars, while the right ascension axis turns by a constant sidereal rate. In an altazymuthal mount, the telescope needs to be turned around both axes at a variable rate to track the stars.

The telescope must be aimed at any object, and that means turning around two axes. In addition, the stars must be tracked with the slow but steady rate of *15 as /sec* around an axis parallel to the axis of Earth. Until the advent of computerized telescope control, the only sensible way to achieve that was to mount the telescope on two axes, and align one (the right ascension axis) parallel to Earth's axis. The alignment should be as precise as $\pm 1^o$ for visual observation and ± 1 *am* for photography (these amounts of misalignment would result in a drift of *1 am / 4 min* and *1 as / 4 min* respectively). Such a mount is called equatorial (see Fig. 18). The two axes correspond to declination and clock angle (or right ascension, if you will). Wherever you look in the sky, the tracking should be the same steady rate around the right ascension axis, which is relatively easy to achieve.

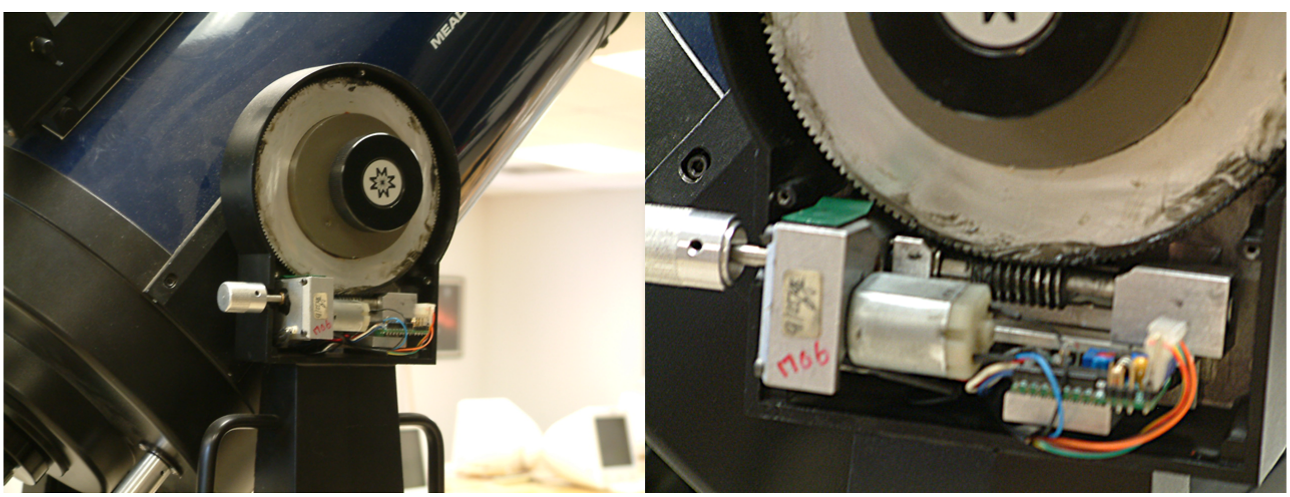


Fig. 19: The wormgears of a 12-inch Meade telescope. Any small damage to the gears will cause jumpy tracking.

The telescope can be moved around both axes. In each direction, cursory aim is achieved with the locks open. When the two locks are shut, the telescope can still be moved slowly using the fine motion knobs in each direction. These knobs turn “worms” that are attached to “wormwheels”, which slowly turn the telescope (see Fig. 19). These wormgears, plus the bearings holding the two axes in place while letting them turn smoothly, are the really sensitive part of the mount. Dirt should be carefully kept away from them, and they should be spared all mechanical strain or shock. For this reason, we should (i) never try to force a telescope to move when the locks are shut, and (ii) never carry a telescope with the locks shut, and obviously, (iii) never drop a telescope to the ground.

Telescopes, instead of an equatorial mount, can be riding a mount with a vertical and a horizontal axis. The vertical axis would move the telescope in azimuth, the other in altitude, hence the name “altazimuthal mount”, ALTAZ for short. You can regard an equatorial mount as an ALTAZ whose vertical axis has been tipped towards the celestial pole. ALTAZ mounts are of course cheaper, but to track a star with them is a nightmare. The telescope must be turned around both axes simultaneously with variable speed. In addition, close to zenith (where observing conditions are always the best) the angular speed of the telescope is large, theoretically infinite when the telescope is pointing straight up. In our computer age, it is possible to drive a telescope with sufficient precision on an ALTAZ mount, but it is an exceedingly challenging engineering problem to do it as precisely as needed to compete with the constant speed tracking of an equatorial mount. For this reason ALTAZ mounts are used only for very small refractors (up to magnification ~30), cheap Dobsonians built for complete beginners, or very sophisticated giant professional telescopes. There are telescope mounts in the middle range, such as the Meade LX200 mounts, carrying 8 to 12 inch telescopes, which can be used as ALTAZ, but it won’t work well: pointing is inaccurate and the starts drift out of the field. You cannot buy a reasonable quality ALTAZ mount for less than a million dollars.

Fig. 20: Dobsonian telescope mounts are cheap but easy to handle. They usually carry Newtonian reflectors.

In addition to that, even if an ALTAZ mount is made to track the stars, there is field rotation. In less than a minute, the field of a photograph turns a few arc seconds and stars become streaks. The camera must be rotated, again with a variable speed, to compensate for this.

There are several designs of telescope mounts used in astronomy. The simplest one is a Dobsonian (see Fig. 20), which can be made from simple ingredients, but of course no precision is expected. The design is sufficient for visual observation by beginners, and is dirt cheap. Of course you can’t use them to take a picture. Aiming and tracking is difficult, but if your aim is the Moon or Saturn, you can do it. Because the purpose is to get away as cheaply as possible, a Newtonian design is used.

Recently, reasonably large optics started to appear mounted on simple Dobsonian mounts, a proof of our previous statement that the optics is *not* the most expensive part of a telescope. (Otherwise, who would put an expensive mirror on a rickety mount?) Computerized drives have been added to assist aiming and some sort of tracking, which is sufficient for visual observation. Now you can buy a computer-controlled 40-inch telescope, mounted on a trailer, for 20 k$. Don’t try photography, but you will see a 17 mg star with it!

The German equatorial mount (Fig. 21) is used on many quality telescopes, including the 15-inch Grubb refractor in Kennon Observatory. This is the mount of choice for large refractors and Newtonians. They cost somewhat more than fork mounts, but the quality you get for the investment is much better. The most important factor is that the center of mass of the telescope is close to the bearings, which do not have to withstand and excessive amount of torque.

Fig. 21: The 15-inch Grubb refractor pointing at the same object in lower and upper views.

There are two drawbacks of German Equatorials though. First, a counterweight should be applied at the end of the declination axis, and this makes the mount heavy and bulky. This is not a problem in an observatory setting, but makes it difficult to carry the telescope around. German equatorials are rarely portable. Second, and more importantly, the bottom end of the telescope can hit the pier when the observed star crosses the meridian. In general, a star can be seen with the telescope from two positions, called "lower view" and "upper view". When the telescope crosses the meridian, you have to switch "views", that is to move the telescope 180^0 around both axes. (In practice there is some overlap, so one has a half an hour to complete a photo before the telescope hits the pier.)

We should mention the historical fact that telescope makers of the 19th - 20th centuries made an exceedingly good job in telescope mechanics. Their mounts carry telescopes in the present-day amateur range in aperture, but the mounts are much better than any one can buy on the market now. However, they utterly failed when it came to the quality of clock drives. The precision required to properly track for photography was simply not attainable with mechanical devices. Whichever old instrument you visit, from Berlin, Germany to England to Lick Observatory, you find that old clock drives are regularly thrown out and replaced by drives controlled by electric motors.

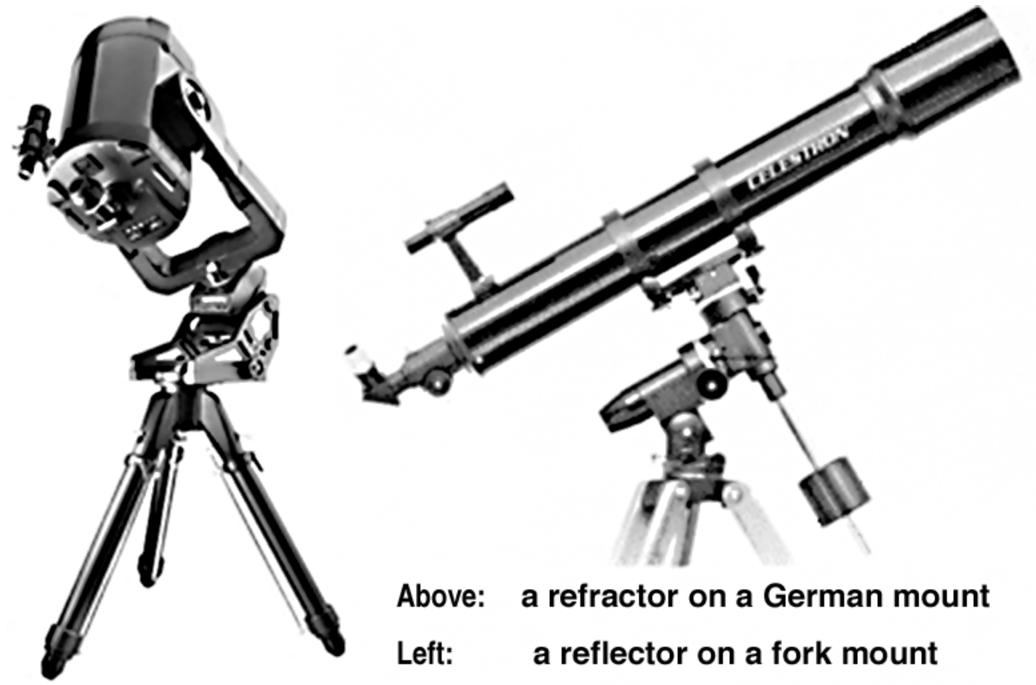


Fig. 22: Fork mounts (left) are easier to make, or carry, but German equatorials (right) are usually more precise.

Another frequently used design is the fork mount (Fig. 22). It is less expensive than the German equatorial, but it is very difficult to achieve a matching quality. The center of mass of the telescope is far from the bearings that hold the right ascension axis, which for this reason must withstand a large torque. It is not easy to avoid wear when extreme precision is required. Another problem is that the bottom of the telescope tube is inside the fork when the telescope is aimed close to the North Pole. Visual observations are difficult there (the observer's head does not fit) and photographic or CCD imaging is also difficult (the camera does not fit). A longer fork is not the answer because it would increase the torque the bearings have to carry.

Some of the largest telescopes are sitting on an "English" mounts (Fig. 23). This mount is essentially a fork mount, with the open end of the fork closed off and held up by another set of bearings.

This design relieves the large torque from the right ascension bearings, but of course the telescope cannot be used at all to observe in the vicinity of the North Pole.

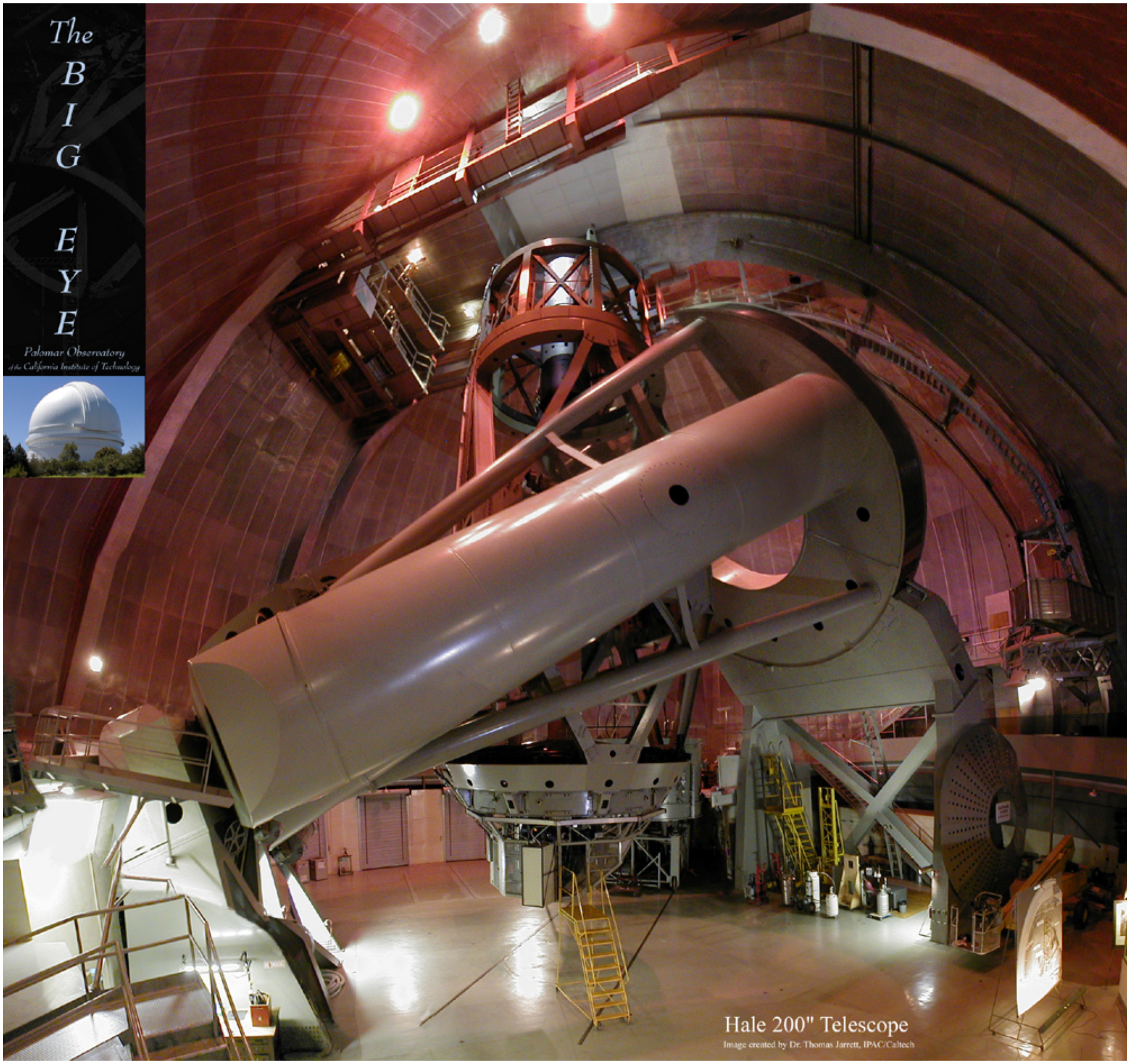


Fig. 23: The 5-meter Hale telescope of Mt. Palomar Observatory in California uses an English mount.

A telescope that is to be turned around two axes with high precision needs to be carefully balanced. The center of mass of the telescope must be located very close to the point where the right ascension and the declination axes intersect. If this condition is met, the telescope is properly balanced, and will not move away from the object, even when the locks are opened up. When a new instrument is fixed on the telescope tube, it needs balancing with the appropriate counterweights until internal friction is sufficient to keep the telescope in place. The consequences of unbalanced mounts are twofold: (i) the tracking motor will work against resistance and the rate of tracking becomes inaccurate,

(ii) the gears carry more torque than were designed for and get damaged. Nevertheless, telescopes used for image taking are usually left *very slightly* unbalanced. The idea is that the resulting torque will keep the wormgears pressed to one side, helping to reduce endplay.

Exercises

1. Formulate the condition that a mount is full equilibrium? How many parameters should be adjusted to achieve that?
2. Why are good mounts usually left slightly out of balance?
3. What is the order of magnitude of the precision (in millimeters) required to drive a telescope?
4. What are the names of the axes of an equatorial mount, and what do each point at?
5. What are the names of the axes of an altazimuthal mount, and what do each point at?
6. Around which axis/axes does the clock drive of an equatorial mount turn the telescope? Is the rate of turning constant? What is this rate (if not constant, what is the maximum rate)?
7. Around which axis/axes does the clock drive of an altazimuthal mount turn the telescope? Is the rate of turning constant? What is this rate (if not constant, what is the maximum rate)?
8. How precise should the polar alignment of an equatorial mount be (i) for visual observation, (ii) for photography?
9. Why can we not put a Schmidt-Cassegrain telescope on a Dobsonian mount?
10. What are the advantages of a German Equatorial mount over a fork mount?
11. Which mount requires a counterbalance?
12. What happens when a star transits while observed in a telescope on a German Equatorial mount?
13. Visit the large dome in Kennon Observatory; put the telescope on the bearings. Move the telescope around and experience the advantages and disadvantages of a German Equatorial.

III.5. Telescope designs

The basic working principle of a telescope is that the objective, be it a lens or a mirror, forms an image of a distant object in the focal plane, and this image is viewed through the eyepiece as through a magnifier glass. Many different realizations of this idea exist.

Eyepieces and the Barlow lens

In astronomy only positive lenses (more precisely, lens systems) are used as eyepieces. In the sky the up and down directions make little sense anyway, so the resulting inversion of the image is not really an issue, confusing as it is for students. A negative eyepiece would secure an erect image; but at high magnification the field of vision of these eyepieces is impractically tiny.

It has become a standard for most eyepieces to slide into a 1.25-inch drawtube. Regular eyepieces have a focal length between *10 mm* and *30 mm*, but for high magnification *4 mm* to *7 mm* eyepieces are also used. The latter are cumbersome and with most telescopes require good seeing, good optics and a good mount for tracking. Some long focal length eyepieces may slide into 2-inch drawtubes; these are used with focal lengths over *40 mm*.

One important measure of the performance of an eyepiece is its field of vision. For example, a standard $f = 26\ mm,\ 52^0$ eyepiece on a Meade *12-in*, $f = 3048\ mm$ telescope would have $M=117\ x$, and a field of $52^0/117 = 27\ am$. The Moon would almost fit in the field.

During the last 30 years eyepiece performance improved spectacularly. Gone are the days of eyepieces with significant chromatic aberration and few people would want to use an eyepiece with a field smaller than 45^0. These Ploessl, Nagler and other type eyepieces are complicated lens systems. Some have as large a field as 80^0. However, these systems may come with a quite heavy price tag.

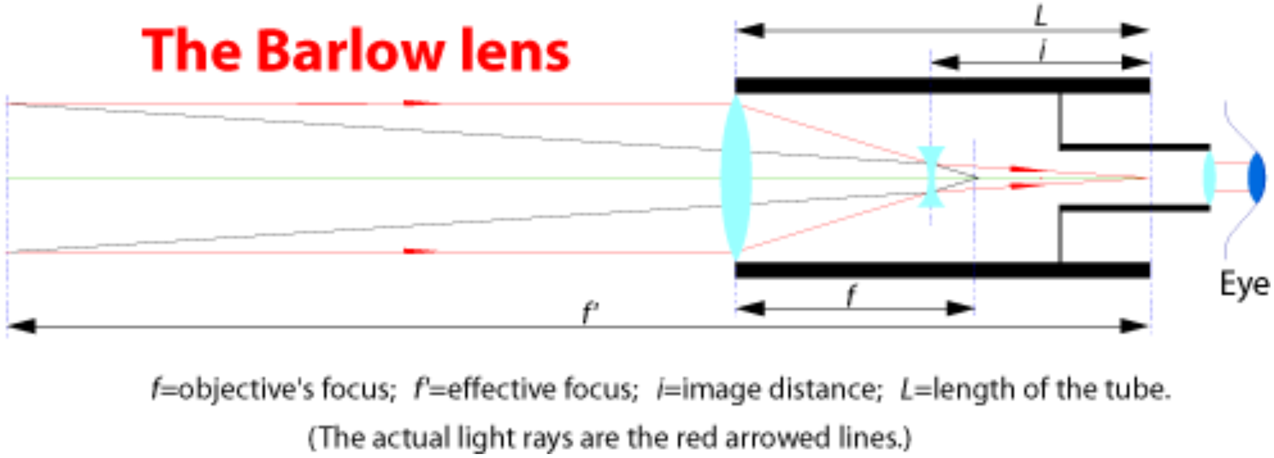


Fig. 24: A Barlow lens extends the focal length of a telescope much longer than the length of the tube.

In special applications very short focal lengths would be required. It is impractical to use such systems because of their inconveniently tiny dimensions. The solution is the Barlow lens. An achromatic negative lens is placed within the focal plane of the objective. The resulting image is formed outside the original focal plane of the objective; and the image is magnified. The mathematics can be read off Fig. 24. The magnification due to the Barlow lens is $M = 1 + i/(-f_B)$, where the focal length of the Barlow lens, f_B , is negative, so M is always larger than 1. A Barlow lens can only be used with one given value of the tube length i, because chromatic aberration is corrected for the factory-given "sweet-spot" value of i. In practice this means that each Barlow lens has a predetermined magnification and tube length. From the point of view of the observer, the objective plus Barlow lens system works as if it were one objective, with a focal length $f' = M f$. This effective focal length can be much longer than the length of the tube!

Barlow lenses effectively lengthen the focus of the objective. They can be used to increase the size of the image in photography. For example, an $f=1m$ objective forms a 0.2 *mm* diameter image of Jupiter, too small for photography. A Barlow lens may be used to achieve a longer focus and a larger planet image.

A Barlow lens can also be used to increase "back focus". A very awkward but frequently arising problem is that the focal plane is some distance D out of the back of the telescope, and we want to use a new device which is larger than this distance D. It won't fit; we say that is lacks back focus. A Barlow lens, even if its magnification is small, will project an image farther out and may help to solve the problem (see Fig. 25).

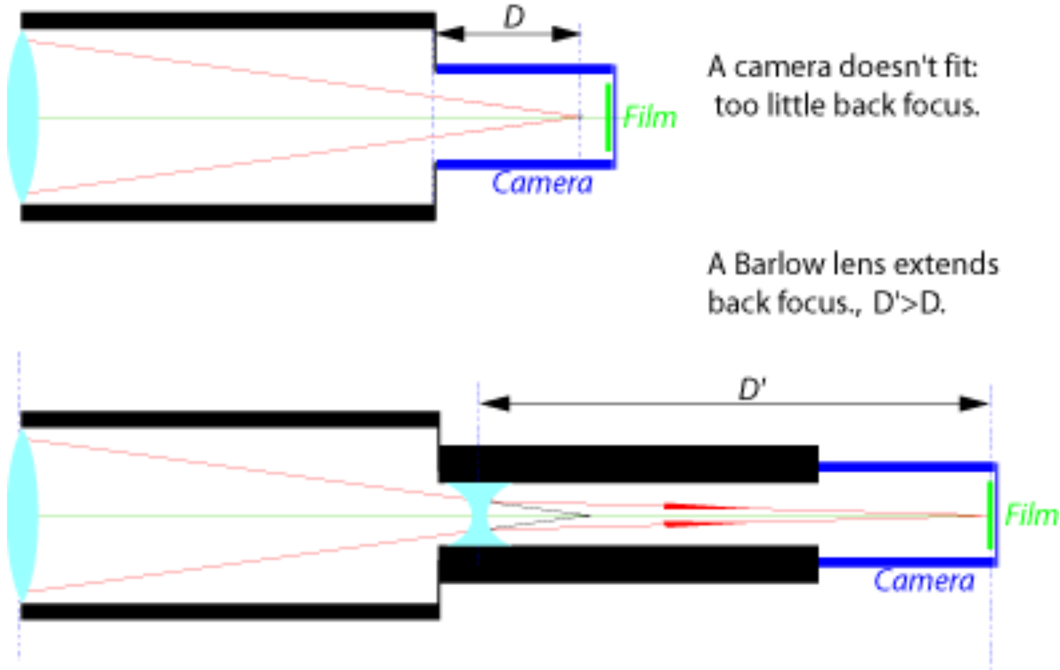
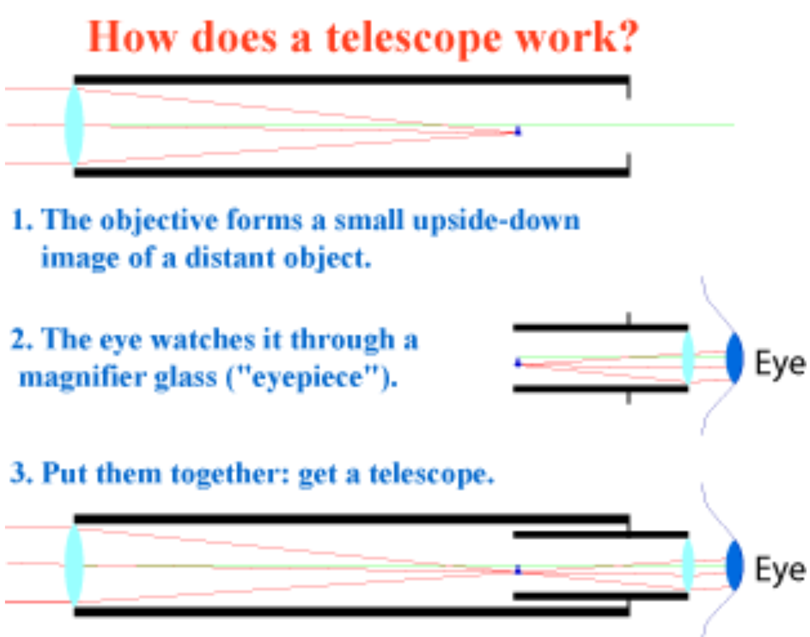


Fig. 25: Gaining back focus with a Barlow lens.

Notice that that the secondary mirrors of Cassegrain telescopes work on the same principle as Barlow lenses, providing a long focal length telescope in a short tube.

Refractors

Fig. 26: A simple explanation how a telescope works. This reasoning is accessible to students who never studied the optics of lenses and have a hard time following ray diagrams.



The objective is a lens (see Fig. 26). In order to lessen chromatic and other aberrations it consists of two lenses made of different glasses (*achromats*). The two lenses may be glued together or a small air-filled gap is maintained between them. The focal length is usually long (f/6 though f/15; it is much easier to fight aberration with a large *f-stop*). In recent years, lens systems of three or four lenses became available. These *apochromats* are quite expensive, presently on the order of $3000 for a 4-inch lens, but provide excellent contrast and lack of aberrations.

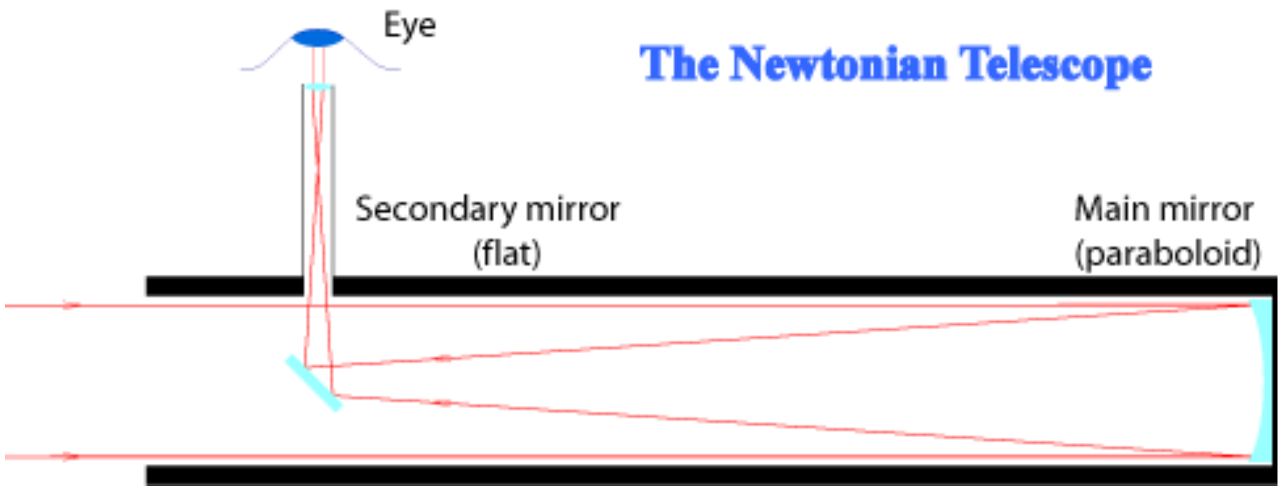


Fig. 27: A Newtonian is the simplest design for a reflector used in astronomy.

There are several advantages of refractors over mirrors, especially when used for planets and the Moon. The telescope tube is closed, which cuts off some of the turbulent motion of air inside the telescope. Once the lens is collimated, it will never again need recollimation. The design is less sensitive to thermal deformations of the optical surfaces than mirrors are. Finally, the eyepiece is located at the end of the telescope, more convenient for observation, and usually ample back focus is available. There is no obstruction due to a secondary mirror, which would superpose a diffraction pattern on the image. For this reason, virtually all telescopes of less than 6 in aperture are refractors.

It is increasingly difficult and costly to build large lenses. The largest in the world is a 40-inch refractor at Yerkes Observatory, now over a century old. Lenses must be held up at the edges, and large slabs of glass sag under their own weight. The thick glass of the lenses absorbs much of the light. A larger lens than that has never been built.

Refractors, as we said, always have a low f-stop, and this fact limits their application. They are less well suited for deep-sky observation than reflectors, but may be excellent for objects of the Solar System or double stars. In addition, any reasonably large size refractor (e.g. the 15-inch Grubb refractor in the large dome of Kennon Observatory) needs a whole observatory to house it and is certainly not portable.

Newtonian reflectors

The simplest telescope design, shown in Fig. 27, uses a paraboloid-shaped mirror. Parallel light rays from a star that is located exactly on the optical axis are accurately collected in the focal point, and there is no chromatic or spherical aberration. (A sphere-shaped mirror would have spherical aberration when light rays from the mirror's edges cross closer to the mirror than light rays reflected by the middle of the mirror.) The light is sent out of the tube by a plane secondary mirror for viewing.

The Newtonian design has several drawbacks.

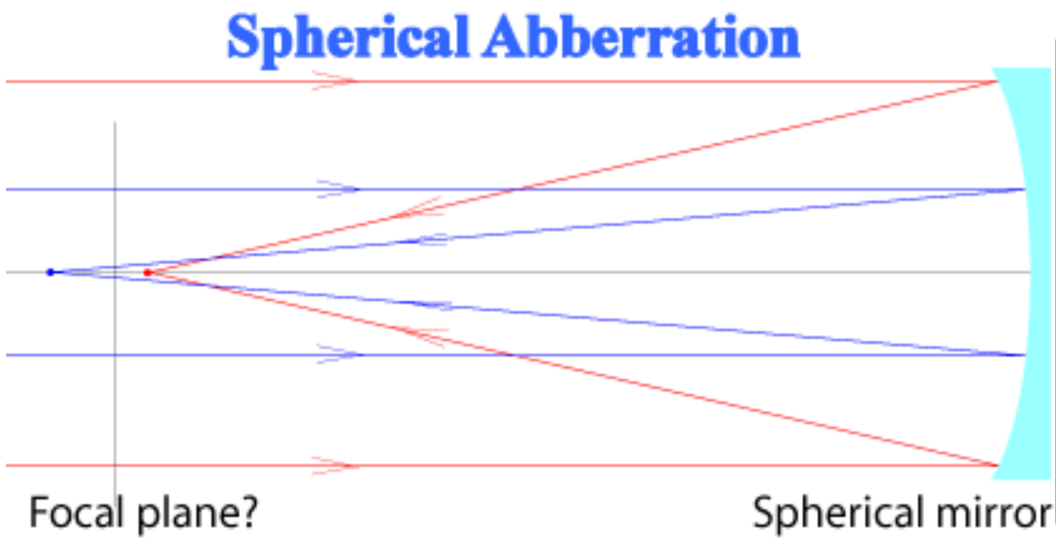


Fig. 28: Spherical aberration in a sphere-shaped mirror. The edge of the mirror has a shorter focal length, and a star's image can never be focused into one point. A paraboloid-shaped mirror avoids this but suffers coma off axis.

(i) The telescope tube is open, and air flows freely in and out of the tube. This makes the telescope very sensitive to thermal balance. Newtonians need a long time (sometimes an hour or two) to "settle down", and until that happens, you'll see a blurred, distorted and constantly undulating image. Condensation may form on the main mirror, and once it is there it is hard to remove it.

(ii) The telescope's tube is as long as the focal length of the mirror. As with lenses, fast f-stops cannot be used (f/6 to f/12 is the usual range) because fast mirrors would require huge secondaries that obstruct most of the light. This fact again makes Newtonians less suited to observe faint objects.

(iii) Coma. A paraboloid-shaped mirror does not form a perfect image of a star that is located away from the optical axis (Fig. I.2.15). This is due to the fact that the shape of the mirror is not a sphere: a spherical mirror, due to its symmetry, would not care whether the star is on the optical axis or not – but of course spherical mirrors have spherical aberration. The effect gets worse quickly with decreasing f-stop, and at f/3 the coma-free field is only a few arc minutes.

(iv) Due to coma, Newtonian mirrors are sensitive to perfect collimation. They get out of collimation when transported, shocked, or simply stored and need frequent recollimation.

Fig. 29. Stars at he edges of the image on the right suffer from coma. The picture on the left shows a fraction of the left edge, magnified.

All these drawbacks notwithstanding, Newtonians are widely used. There is one single reason for this: at a given aperture, they are the cheapest.

The Cassegrain design

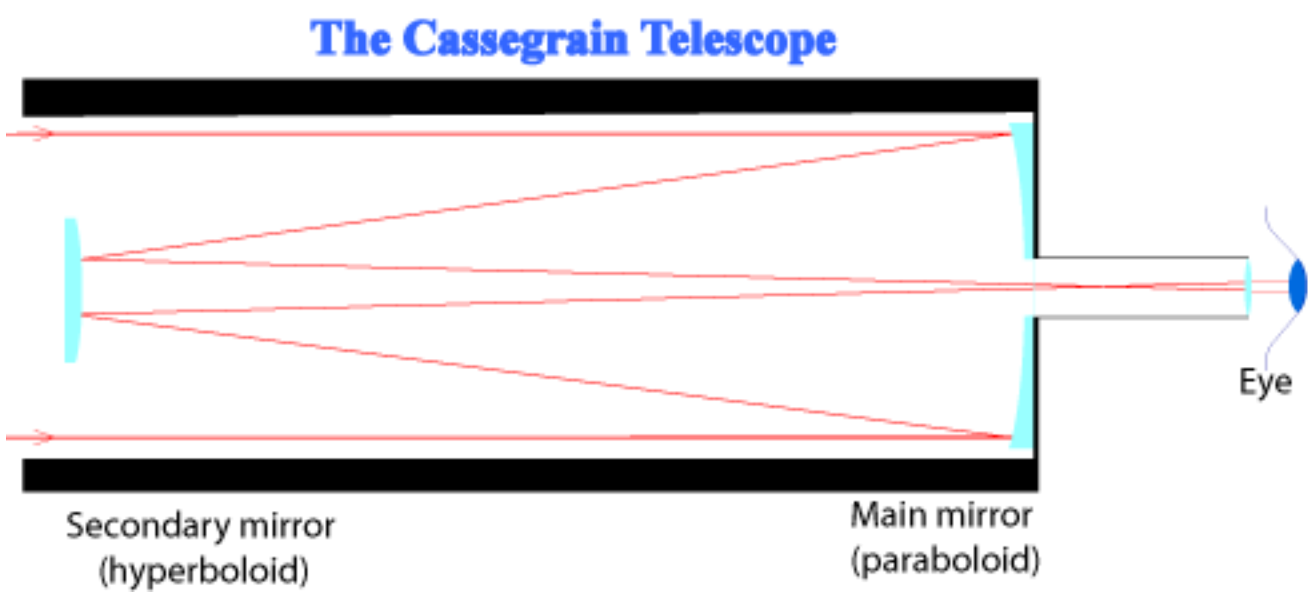


Fig. 30: The Cassegrain telescope results in short tube length, excellent for small details but not very at large fields.

Due to coma, Newtonian reflectors cannot be used for wide-field work. It would make sense to use long focal length mirrors if only small fields are viewed anyway, but then the tube would become exceedingly long. The clever Cassegrain design achieves this by using a convex secondary mirror (see Fig. 30) to lengthen the focus, and sends starlight through a hole born in the primary mirror. The concave mirror, hyperbolic in shape, acts as a Barlow lens, lengthening the effective focus many times. As you can see directly in Fig. 31, the effective focal length is much longer than the telescope tube. Cassegrain designs are very compact.

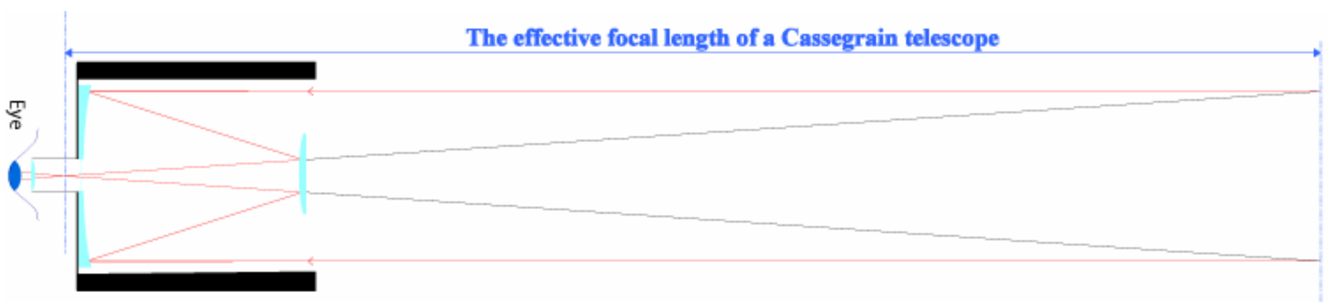


Fig. 31: Lengthening the focus beyond tube length.

Given the discussion of coma and collimation, the astute reader has already guessed that Cassegrains are very delicate devices: they need extreme care to collimate both the primary and the secondary mirrors with great precision (to make the tube short, we use f/3-f/4 primaries!), and they will work only when the effective f-stop is slow (f/10 to f/15).

The Schmidt camera

For wide-field work on faint objects (think of a faint galaxy cluster, spread out over a degree in the sky) we must have a fast f-stop combined with the large field, something a parabolic mirror will never manage to have. The answer is a spherical mirror, which has no coma over any field. A thin lens of a complicated shape (a 4^{th} order polynomial) is placed in front of the telescope to correct spherical aberration (see Fig. 32). Because this corrector plate is thin, it avoids the usual troubles with large lenses (little sagging, little light absorption, little chromatic aberration introduced).

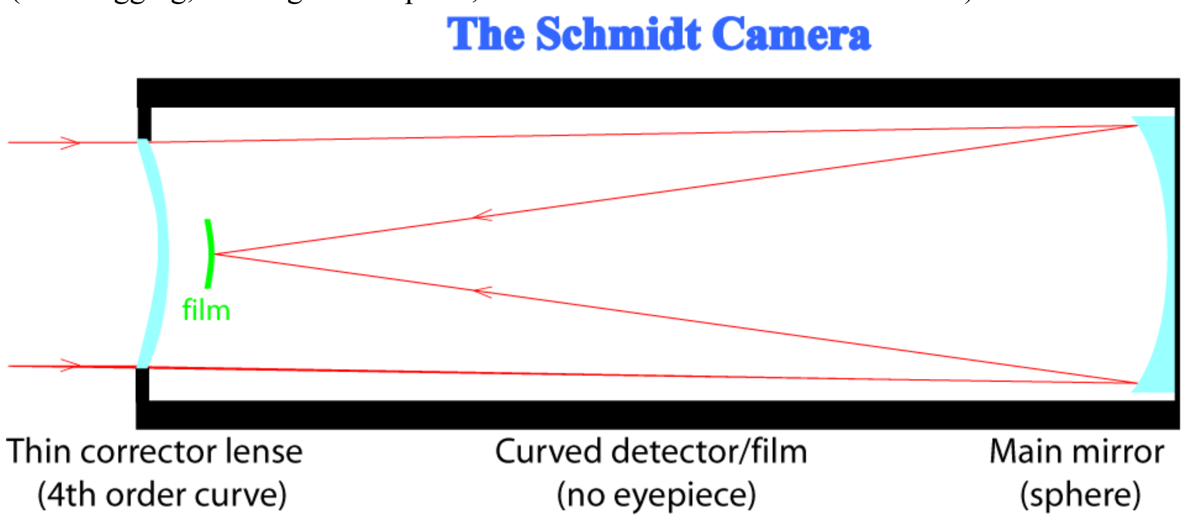


Fig. 32: The design and a picture of a Schmidt camera. Notice that there is no eyepiece; only photography (or CCD work) is possible. The detector is inside the telescope tube.

The largest telescopes of this design are over *1 m* in diameter with f/2.5. At such f-stops it is not possible to send the light out of the tube, so the detector must be placed in the primary focus. Obviously, there is not enough room in the focal plane to fit a person, so a Schmidt telescope can be used only for wide-field photography. For example, the United Kingdom *1.2 m* Schmidt telescope, with a *1.8 m* spherical mirror has $f=3.07\ m$ and can image stars without coma over a $6.5^o \times 6.5^o$ field! The focal plane is curved though, which requires special curved photographic plates.

Variations: Maksutovs, SCT's, Ritchy-Chrétiens

Several attempts exist to fight coma and spherical aberration simultaneously by marrying the Cassegrain design with the Schmidt idea. Professional observatories in fact use individually designed variations of the systems we discuss here that meet their particular needs.

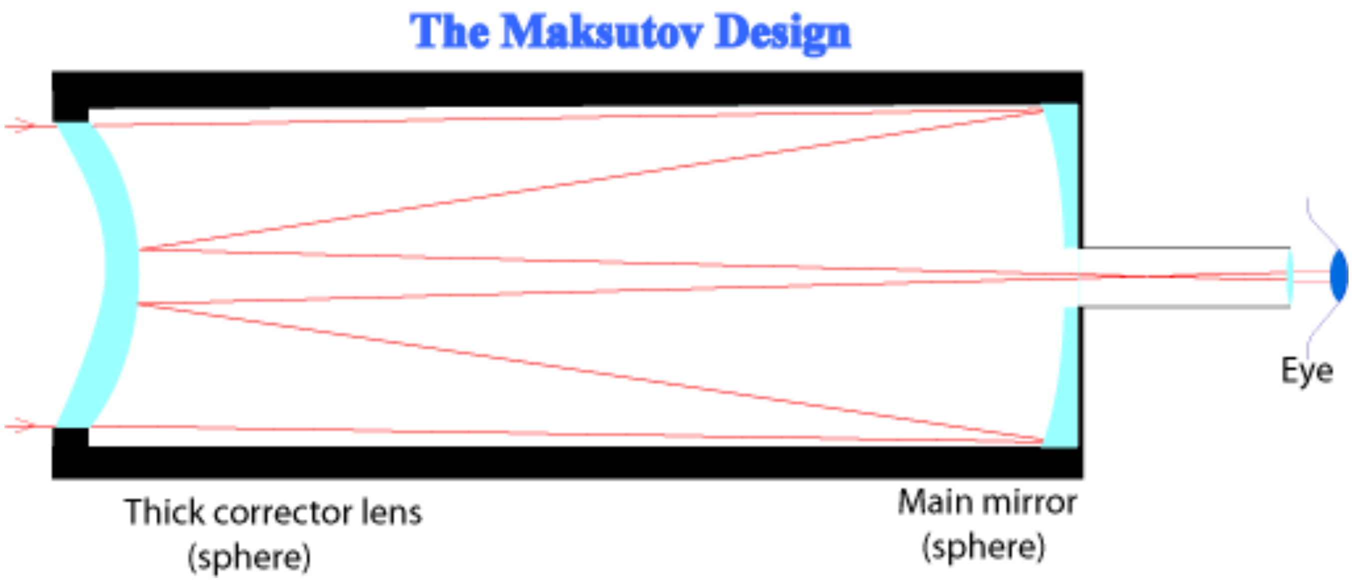


Fig. 33: The Maksutov design is easy to manufacture, but the corrector lens is thick and heavy. It is convenient for everyday photography but not so great in astronomy.

Maksutov telescopes contain a spherical mirror, and spherical aberration is corrected by a thick negative convex-concave "meniscus" lens. The secondary mirror is simply an aluminized portion of the corrector lens (see Fig. 33). Because all the surfaces are spherical, Maksutovs are relatively cheap. However, for the same reasons as with large size refractors, large-size Maksutovs are hard to build. This design is not used for large professional telescopes.

The Schmidt-Cassegrain design (SCT) uses a spherical mirror, a 4^{th} order polynomial surface corrector plate to reduce spherical aberration, and a separate spherical secondary mirror to project the image through a hole in the primary (see Fig. 34). This is a reasonable compromise in image quality while keeping the telescope tube short enough: spherical aberration from the secondary is still present. The secondary mirror is large, which diverts much light into outer diffraction fringes out of the Airy disk, hurting sharpness. The tube is closed, so the telescope is not as sensitive thermally as a Newtonian. Nevertheless, it still takes a good half an hour for a 12-inch Meade SCT to "settle down" after it has been taken outside.

Even though a SCT uses only spherical mirrors, coma creeps back in through the bedroom window. The corrector plate is not sphere-shaped, and causes coma away from the optical axis, in addition to the spherical aberration in the secondary. For this reason, collimation is necessary, although it is much easier than the collimation of a Cassegrain. It involves only tilting the secondary mirror until all coma vanishes in the telescope's field.

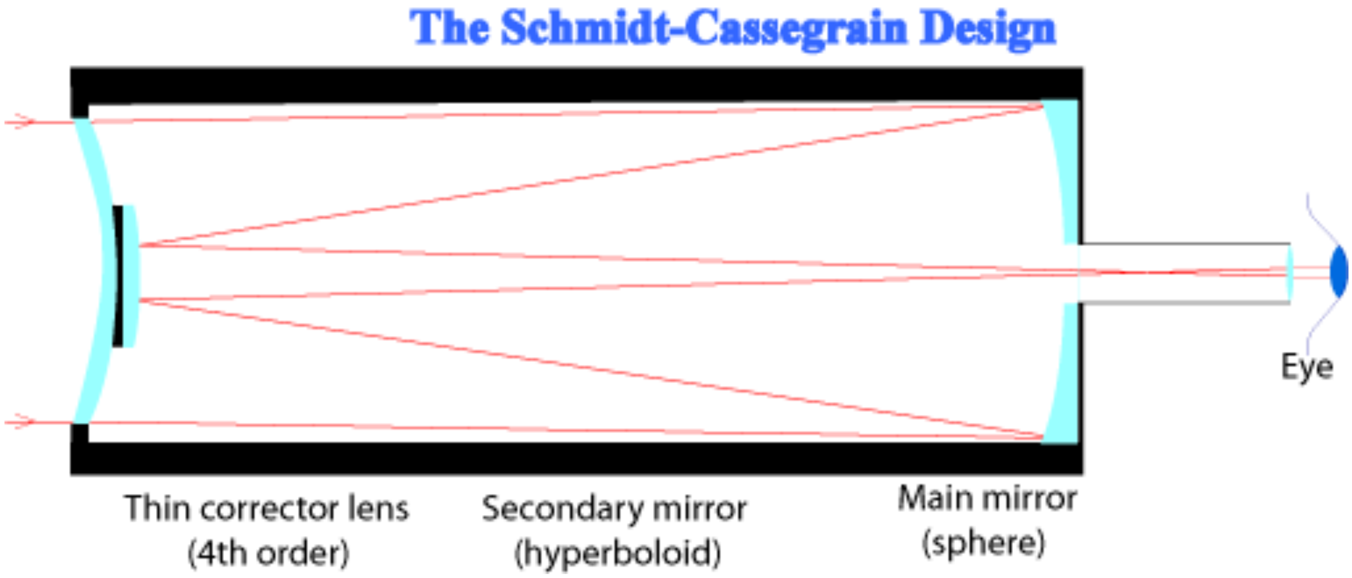


Fig. 34: Many commercial telescopes in the 8 – 16 inch range are of he SCT design. The image quality is acceptable over a reasonably large field, but there is too much coma for professional work.

The most frequently used design of professional general optical telescopes is the Ritchey-Chrétien, including the Hubble Space Telescope (with 2.4 m diameter at f/24). The design looks like a Cassegrain, but the shape of the primary mirror is a hyperboloid and the secondary is an ellipsoid. Maximum correction for both spherical aberration and coma is achieved simultaneously. The resulting system will still suffer from a slight amount of astigmatism and field curvature. On "small" telescopes smaller than 40 inch = 1 m in aperture this remaining aberration is undetectably small, and on larger telescopes it is easily corrected by small corrector lenses placed near the focal plane.

The Ritchey-Chrétien design is superior in image quality, it has a reasonably large field of view without coma, while it avoids the many optical surfaces that cause reflections, absorb light and diminish sharpness. However, the shape of the optical surfaces is nontrivial, and to make them adds to the cost of the telescopes. For example, the best quality 20-inch telescope available on the market at the time of this writing is a Ritchey-Chrétien for around 20 k$.

The Coudé design is mainly used in professional astronomy, especially for spectroscopy. Light from the telescope is reflected into a tube along the declination axis, then into a tube along the right ascension axis. A Barlow lens lengthens the focus to at least f/20 – f/30. Of course, the field of view will be tiny. The advantage is that the detector and the instruments are stationary up to a slow field rotation. Spectrographs, weighing hundreds of pounds, are often too heavy to be installed dangling on the telescope. The design is also useful when images of the Sun can be lead far away from the telescope and projected out in a stationary room or even lecture hall.

Exercises

1. The pixel size in a webcam requires that we use an f/30 system in order to resolve all the small detail on images of planets. The 7-inch Questar is only f/14. We have a Barlow lens with $f = -20\ mm$. Draw a ray diagram indicating the image formation by the Barlow lens, and use the lens equation to

calculate how much back focus is required, and also the required distance of the webcam's CCD from the Barlow lens (i.e. the tube length).

2. What are the magnification and the field of view with a *7-mm* Ploessl eyepiece, used with a 12-inch Meade? What percentage of the Moon's diameter would fit in the field of view?
3. Is the eyepiece of a telescope a positive or a negative lens system?
4. Explain why slow achromatic refractors tend to have less chromatic aberration than fast ones.
5. Fig. I.2.22 shows the path of a light ray reflected from a spherical mirror of radius R. Derive a formula how f changes as a function of d. Expand your result in a power series in d, keeping the first two terms only. Based on this result, (i) what is the focal length of the mirror, and (ii) how much does the focal length differ between light rays hitting the center and the edge of the mirror? How much is the blur caused this way, when converted into arc seconds in the view of the telescopic field? Give numerical results for f/2, f/10 and 1/10 telescopes. How would this blur change if the observed star would not be in the center of the field?
6. Do the same calculation as in the previous problem, for a paraboloid-shaped mirror. Write the equation of the parabola as $y = x^2/F$ prove that $f = F$, independently of d.

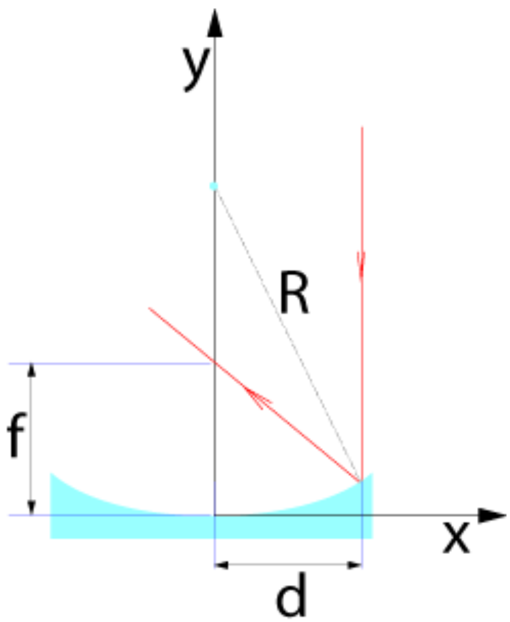


Fig. 35: Calculate the focal length of a spherical mirror for a light ray entering at distance d from the optical axis.

7. The white Dobsonians in the lab have 10-inch mirrors at f/4.5. The focal plane is 7.5 in from the optical axis. The secondary mirror is elliptical in shape. What should be its size to accommodate the light beam from a star in the optical axis? What should be its size to accommodate the light beam from the entire Moon? (*Hint: draw a ray diagram and use similar triangles.*)
8. A Cassegrain telescope has a 14-inch primary mirror at f/2.5. The focal plane is 2.5 inches behind the primary mirror, and arrangement necessary to be able to place a photographic camera in the focal plane. The effective focal length of the system is f = 140 in. What is the radius of curvature of the secondary mirror? (*Hint: draw the ray diagram for a light ray arriving from a star in the optical axis, then use the lens equation for the secondary to find its focal length.*)
9. Which telescope design(s) have much longer focal length than tube length? How do they achieve that? Explain.
10. What limits the field of view of Newtonian reflectors most severely?
11. What design are most telescopes in the *50 cm* to *5 m* range?
12. What design are the Meade 12-inch telescopes? Explain how that design works.
13. What are Coudé telescopes used for? Explain how that design works.
14. What are Schmidt telescopes used for? Explain how that design works.
15. Why do Newtonian telescopes need frequent collimation?

III.6. Telescope care

Optical surfaces

Telescopes are sensitive devices, both optically and mechanically. Optical surfaces have to be of the correct shape up to a fraction of the wavelength of light. Surfaces must be smooth and free of dust and dirt. The precision and smoothness of optical surfaces is usually expressed in fractions of the wavelength of light. This becomes an indicator of optical quality. For example, a $\lambda/2$ optical surface is acceptable but not great; professional astronomical devices are at least $\lambda/16$ quality.

The shape of optical surfaces is as we buy them, we cannot change them. However, any amount of strain deforms an optical surface. It is not advisable to dismantle optical elements, because it will be extremely difficult to assemble them again with the same amount of force holding them down and keeping them in place. In the rare case when an optical device must be taken apart, care should be taken to remember the position of each individual element, including the orientation of lenses in their holders. It is common practice to make pencil marks on the side of lenses so they can be replaced at the correct angles and in the correct order.

Optical elements will change shape under the smallest amount of change in temperature. Glass is a bad conductor of heat. Heat is always gained or lost across the surface, so the inside of a lens or mirror always lags behind as the outside temperature changes. In order to have a reasonable quality image, the temperature in the optics should be even within $\pm 1 - 2\,^oC$. It may take a full hour to achieve such equilibrium after a telescope has been brought out from a building, and until then the image quality will be deteriorated. In addition, temperature gradients inside the telescope tube will generate air currents, which further hurt the image. Seeing does not always originate outside the telescope!

The *shape* of the optical surfaces determines the *quality* of the image. The *smoothness* of the surface determines its *contrast*.

A small amount of dirt and dust will not affect the image, but greasy, overall dusty optics results in decrease of contrast because much light is scattered away from the straight line. The amount of light absorbed by dust or dirt is, however, always insignificant.

As a small amount of dust is not very harmful, it is not necessary to remove it. Cleaning the optics too often does more damage than good. We need to clean the optics only when it is really dirty!

It is, however, very important to keep optical surfaces as clean as possible. We should never touch them, neither by bare hands nor by a cloth or anything else. Grease from human hands quickly accumulates dust. It is also advisable to avoid the condensation of water vapor on the optics, because dirt will accumulate in dew and stay on the optics when the dew is removed. We must always keep all lens caps on. When a telescope has been carried out for observation, the lens cap must stay on for a quarter of an hour, so the optics warms up to the ambient temperature and no more condensation occurs. Also, putting on the lens cap should be the first thing before closing down.

Sometimes it is impossible to avoid that the optics accumulates dew. At night the telescope radiates in the infrared, and cools faster than the ambient air. In muggy Mississippi summers every night is an uphill battle against condensation. You may try to put on a dew shield, an extension to the tube, to keep out most of the dew, but it helps only so much. When all is lost, a strong hair dryer is the only help, although it will upset the telescope's thermal balance. And running a $2\ kW$ hairdryer from a car battery for a half an hour means a long walk home in the dark. But whatever you do, *never try to wipe off the dew with a cloth!* You will permanently damage to the optics.

Cleaning the optical surfaces should be done only when absolutely necessary, and with great care. Only specialized optical cleaner fluids, brushes and wipes should be used. Materials that are too rough, or worse, contain grains of dirt, will damage the optics. Beware of nonprofessional materials, which are oftentimes marketed as “optics cleaners”! Use fluids sparingly: it is extremely difficult to remove cleaner fluid once it got inside an eyepiece. Wipe off dirt without applying pressure. Always clean the entire surface; otherwise you will only smear the grease from one part of the surface to the other.

Cleaning of aluminized reflecting surfaces needs additional care, because the aluminum layer is soft and will be damaged much more easily than any glass surface. The care of these surfaces is beyond the scope of this handbook. Do not try to clean a reflecting surface with regular lens cleaning methods!

Collimation

The optical elements of telescopes must be all parallel to the optical axis, “collimated”. Different designs differ in how sensitive they are to collimation, and which elements need or can be collimated. Newtonian reflectors (Dobsonians included) are most sensitive and require frequent re-collimation. Schmidt-Cassegrains also may get out of collimation after a shaky voyage from the laboratory to the parking lot.

Dobsonian telescopes (which at Ole Miss includes the 24” Obsession) may be successfully collimated using a laser collimator, a simple laser device which is placed in the 1.25-inch eyepiece holder. It emits a red laser beam. The secondary mirror is tilted until the beam hits the exact center of the main mirror (which is marked with a black dot of paint on these telescopes). After this, the main mirror is tilted until the reflected beam bounces back exactly into the center of the collimator device, which is made visible using a flat surface at 45^{o} angle. With small Dobsonians, the whole procedure may be done inside the laboratory.

The procedure with the Meade 12-inch telescopes is more difficult, and it usually requires two people’s cooperation, even though in these scopes only the secondary mirror’s position is adjustable, and the main mirror’s axis is fixed. The idea is to view a bright star in high magnification, slightly defocused. The main mirror needs to be tilted until the shape of the defocused image becomes a perfect circle, evenly illuminated, with the black shadow of the secondary in the middle. The detailed step-by-step procedure is described in the LX200 manual.

Exercises

1. Learn the collimation procedure of the 10-inch Dobsonians with a laser collimator and collimate a telescope. Check the quality of your work by trying to resolve a tight double star.
2. Learn the collimation procedure of the 12-inch Meade telescopes and collimate a telescope. Estimate the resolution of the scope by looking at tight double stars of various separations.

Care of telescope mounts

It will not surprise anyone that telescope optics is extremely sensitive and must be handled with great care. It is less obvious, but equally true, that some parts of telescope mounts are equally sensitive and must be made and kept equally precise. This is true of especially bearings, gears and focusers.

Telescopes should be aimed at the target with a precision of a few arc minutes. The tracking must follow the stars. A mount that causes the target to shake or jump more than a few *as* is unsuitable for visual observation, and for picture taking the image must not be jumping more than a fraction of an arc second. However, *cot (1 as)* $\approx$ *200,000.* A gear with, say, a *100 mm* radius must be much smoother than $\pm 1\ \mu m$. A dust particle or a microbe-sized dent in the gears will cause jerky tracking and the telescope will be useless for picture taking, and very uncomfortable for visual observation.

When a telescope is being carried outside, one should be extremely careful all strain to the gears. It absolutely important not to move any telescope without opening up the right ascension lock first; and whenever practical, the declination should also be kept unlocked. This practice will remove the strain from the gears.

Even with the above caution, telescopes should be transported very carefully. Any sudden jerk will, even with the lock open, cause damage in the bearings. In addition, a heavy telescope with both locks open is hard to control. In practice, contrary to the above, it may be advisable keep the declination locked while carrying the telescope. In that case, it should be moved extremely smoothly to avoid damage to the declination worm gears.

A note is in order about the Meade LX200 mount. When the power is turned on, the fine motion knobs are engaged by the motorized gears. Trying to turn them will cause damage. Again, do not try to use the fine motion knobs on a Meade LX200 while the power is on! Actually, with the declination lock open the *telescope* (but not the *knob!)* can be safely moved north or south. We need to turn the telescope to the south with the declination lock open only in the following one case: when, before aligning the setting circles, the telescope erroneously thinks that it is pointing under the horizon and refuses to move further. The only way to aim it at the alignment star will be to unlock the declination lock and shift down the telescope to the south. Other than this one situation, to be on the safe side, it is best to move the telescope *only using the keypad*!

Exercises

1. How will dusty and greasy optics affect the image of a star, and the image of a planet?
2. In order to get a decent quality image, how close (in ^{o}C) does the telescope mirror have to be in thermal equilibrium?
3. How precisely does the surface of the telescope mirror follow its theoretical shape? Quantify.
4. Collimate the secondary mirror of a Meade SCT telescope, following the instructions in its manual. Examine the way Dobsonians and Celestrons can be collimated.
5. In the beginning of a lab you notice that a Meade 12-in telescope just cannot be focused. Checking it by looking at a star reveals that the shape of the star is irregular, “star shaped”, rays stretching out in a few directions as far as *10 as*. What is happening, and what can be done?
6. What happens if you wipe telescope optics with a soft cloth?
7. What should be done and what should not with a telescope on whose optics dew has condensed?
8. Which part of a telescope mount is the most easily damaged? How do you avoid such damage (i) when carrying the telescope, (ii) during observation?

IV. Observations

In this chapter we will discuss each of the types of objects in turn, indicating what to expect from each, how impressive or unimpressive they look in a telescope, and the particular choices and tricks that make that object look as nice as possible.

Most objects in astronomy are a less than impressive view in the telescope. This is due to the fact that they are very far away, very faint, or both. The great feat of astronomy is that it can extract so much useful information and produce so pretty images when it is so light-starved and sitting under miles of dirty, undulating air that absorbs half of the light and blurs everything smaller than an arc second. *Expectations of our students should be kept low, otherwise disappointment results!*

It takes much learning and practice to acquire the skills to see everything that is possible to see in the telescope. It is quite usual that a not really well motivated student, looking in the telescope for the first time, will only see a "bright dot" of Jupiter. It takes a few repeated trials to realize that this "dot" is actually a disk, that it is actually ellipse-shaped, that there are stripes of clouds and spots on it, that there are satellites around it that look like faint (and then, not so faint) stars. The process of leaning how to perceive details has great educational value: everyone knows countless everyday situations when someone's lack of a skill of perceiving detail leads to frustration. It is part of the mission of a college to teach students such skills.

The human eye can remarkably well adapt to darkness. The pupil of a young person can open up as large as *6 mm* in diameter, while during daylight hours it shrinks to about *1.8 mm*. As the amount of light that enters the eye is proportional to the square of the pupil's diameter, the well adapted eye collects $(6/1.8)^2 = 11.1 \times \approx 2.6$ mg more light. The human eye would have been able to see *2 mg* stars in the daylight sky, had the blue glow of the atmosphere not overwhelmed all starlight.

It takes time, however, for the human pupil to open. As we leave a well-lit room, in the first minute we can see only the very brightest, *1 - 2 mg* stars in the sky. It takes about 5 minutes to start really seeing the stars, but full adaptation is not achieved before 15 - 20 minutes.

The practical lesson from this is that it is absolutely important to wait a good quarter of an hour before any attempt is made to see dim stars in the sky, or watch faint deep-sky objects. It is also very important to shield the observer from all streetlights. A look at distant car's headlights, or into a stray flashlight's beam destroys dark adaptation for another quarter of an hour!

It is an interesting observation that red light does not hurt dark adaptation as much as other colors. For this reason it is a good idea to use a red flashlight while observing in darkness, even though it feels unnatural.

The two main issues in astronomical observation are brightness and resolution. Using a large-diameter telescope increases the brightness of stars. For extended deep-sky objects surface brightness is the relevant quantity, and large-size telescopes are of limited use in increasing that (for details, see Sec. 3.5 below). Objects with a lot of detail need good resolution.

The main impediment to increase resolution is seeing. "Seeing" is a technical term in astronomy designating the apparent size of the image of a star as blurred by the atmosphere, and it is measured in arc seconds. With the exception of small telescopes (less than 5-10 cm in diameter), seeing limits the resolution more than the optical imperfections in the telescope.

The image of a star is supposed to be a dot. However, due to the movement of atmosphere, this dot is jumping around with characteristic frequencies around 1-100 Hz. The human eye can follow the slow component of this "seeing", but the fast component is perceived as blur. On electronic or photographic images with more than seconds of exposures all seeing is perceived as blur.

The amount of seeing depends on the state of the atmosphere. One part originates high in the atmosphere and can be battled only by placing the observatory at high elevations. In stable weather, this part is around *0.2 as* at high mountaintops, and *1-2 as* at sea level. When the atmosphere is turbulent, seeing can be as bad as *5-10 as*.

Local effects cause another part of seeing. Air flowing out of the slit of the dome, or air rising over warm ground can worsen the seeing dramatically. In order to improve this type of seeing the immediate environment of the telescope must be in thermal balance. The inside of the dome must be at the same temperature as outside air. The ground close to the observatory (or next to the telescope when it is used outside) must not be warmer than the air above it. Note that the concrete of a parking lot keeps heat for a long time and causes bad turbulence. Grass or bush is usually planted next to professional observatories due to their good thermal qualities. This sort of local seeing may be quite destructive, as much as *10-1 as* in bad circumstances.

The magnification you want to use on bright objects (such as the Sun, Moon or planets) will be determined by seeing. Recall that the resolution of the human eye is around *1 am = 60 as*. This means that even with a good telescope you will rarely be able to use a larger magnification that 2 - 300 × at any time.

The correct choice of magnification is crucial to bring out all the detail existing in the images. The best strategy is to start with the lowest available magnification, then go up by trying a shorter focal length eyepiece. It is quite usual that observers have three eyepieces at hand, trying each. There is actually no way to precisely predict which will work best, because the optimal magnification depends so much on seeing, atmospheric transparency, and the type of object we are observing.

Exercises

1. An observer has spent 3 minutes watching a cluster in the field of the telescope after leaving a brightly lit room. How many magnitudes fainter objects is an observer able to see after an additional 10 minutes in the dark?
2. Find a part of the sky where you can quickly estimate the limiting magnitude. Open the slit in the large dome, and switch on all the lights. After you turn the light back off again, estimate the limiting magnitude after 0, 1, 2, 3, 5, and 10 minutes. Plot it versus time and conclude.

IV.1. The Moon

The Moon is certainly the most spectacular object in a telescope. At low magnification (20-50 ×) the whole Moon fits in the field, and it clearly gives the impression of a *globe*, while to the naked eye it looks rather like a *disk*. Looking at it in high magnification (200 ×), in reasonably calm weather, we get the unforgettable experience as if we were flying over rugged land. The zillions of craters are a very impressive sight indeed.

At this point the reader should already understand the phases of the Moon, as well as its motion in the sky. We have reviewed it in Sec.~II.6, and the reader is also advised to do the related exercises.

Different parts of the Moon are not equally easy to observe in the telescope. We want to see long shadows to enhance the contrast of the relief. We can get the general idea from the demonstration of the floor illuminated with a flashlight (recall Fig. 6 on p. 4).

Our position relative to the sunlight illuminating the surface is determined by the phase of the Moon. At full Moon, when one would naively think the Moon looks the best, light comes from behind our backs. All shadows are cast *behind* the object that casts them. Even though at the edge of the Moon craters cast long shadows, *we* are so positioned that we do not see the shadows. All we see is completely illuminated land. There is very little contrast, and it is hard to make out even a few of the largest craters (see Fig. 36). The full Moon is *not* a good time to look at the Moon. The general misconception is that this is due to the fact that the Moon is too bright. However, the point is not brightness, but lack of contrast.

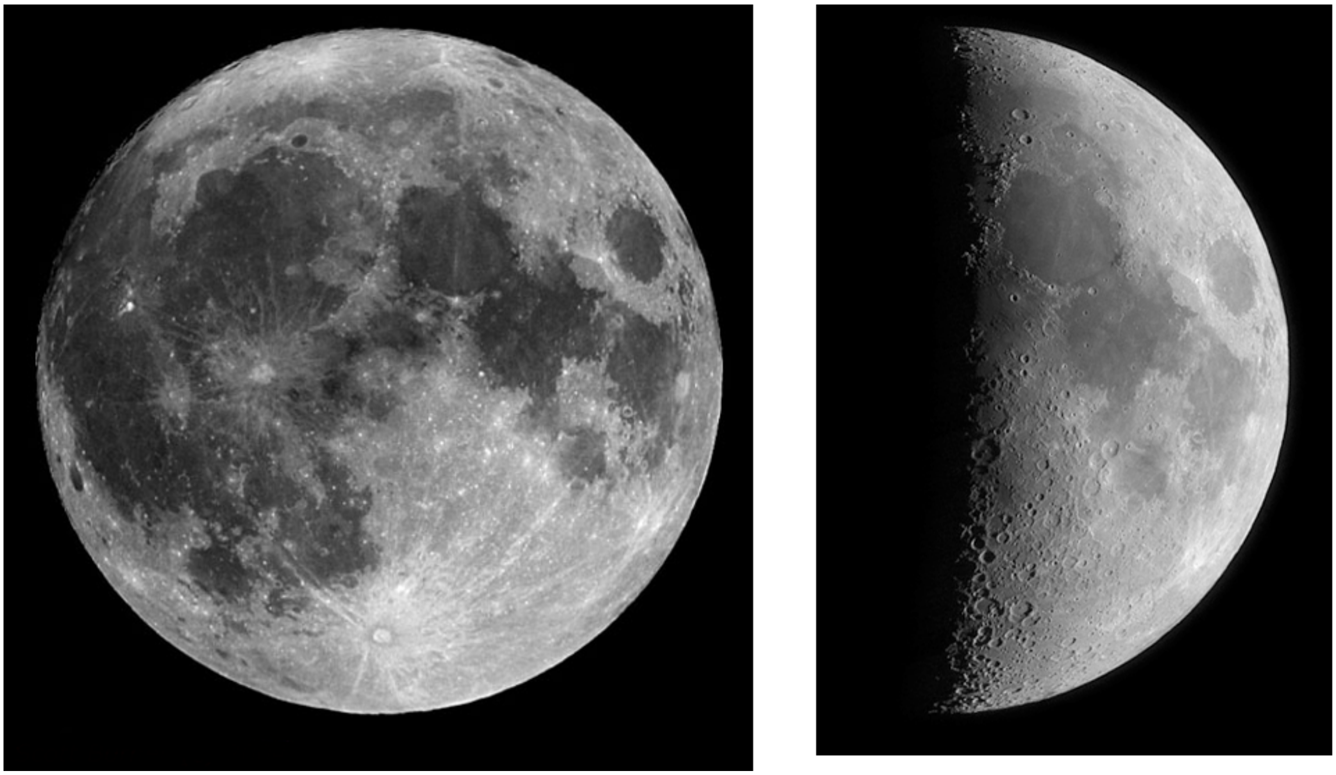


Fig. 36: Lack of contrast makes the full Moon the wrong time for observation. Even on the first quarter Moon contrast is lost away from the terminator.

Around first quarter we are ideally positioned to see all the long shadows that objects cast on the surface of the Moon: sunlight hits the moon from sideways (the Sun is 90^0 away from the Moon in the sky). However, we can only see shadows where there are some. The shape of the Moon is a sphere, not a flat disk. The side of the Moon facing the Sun receives sunlight from above; it is noon for the imaginary astronaut working there. Shadows are short or nonexistent. That part of the Moon in contrast-less and looks "flat" again.

To put all this together, surface relief is enhanced at first quarter Moon, but only along the terminator. The last quarter would be equally good, but it is not up until midnight. The difference is really striking.

It is worth noting the shape of the terminator. It is the sunset-sunrise line on the Moon, a circle shape in actuality, which we are looking at from a perspective. The projection of a circle on the sky is an ellipse, and the shape of the terminator as we see it is a half an ellipse. It is amazing how many people do not realize this and draw both sides of the sickle Moon as circles (see Fig. I.3.3). Yet this is how a lunar eclipse looks different from a sickle Moon.

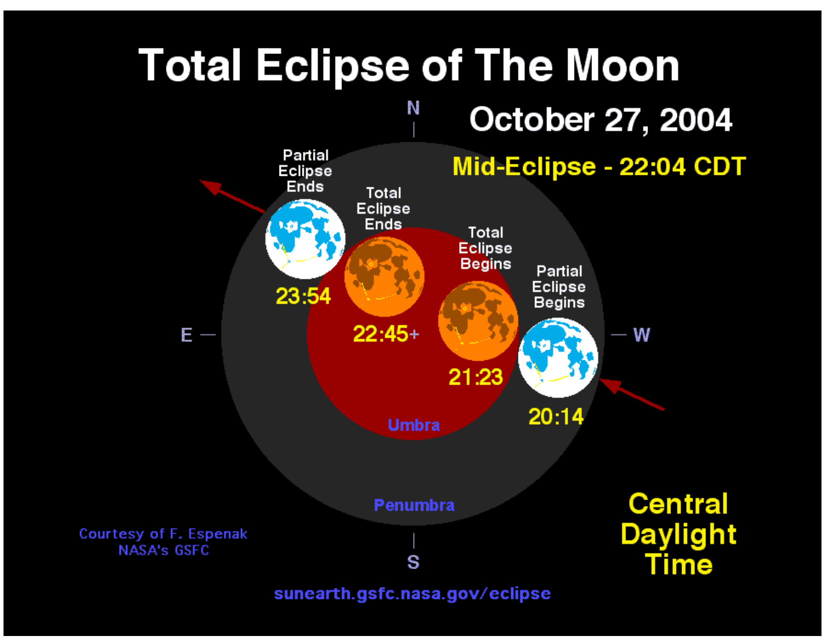
The main features of the Moon include the marea, the craters (with their possible central peaks and sometimes partially missing walls), and bright rays emanating from large craters, a few mountains and rilles. We urge the reader to gain a theoretical understanding of these from a textbook. Also, s/he should memorize the name and location of a few marea and large craters, including the phase of the Moon when they are best visible. A simple map of the Moon will come in handy for this purpose.

Fig. 37: The terminator is a half-an-ellipse shape (right), and not a circle as incorrectly drawn on the left.

We must draw attention to the general confusion in many people's mind between craters and marea. Exercises in identifying craters, central peaks, and marea with a lunar map help to put things in the right place. It is also enlightening to find a feature that is as small as we can still make out, and determine its true size. This will tell whether spacecraft landing on the Moon is large enough to be seen in the telescope*.

IV.2. Lunar Eclipses

Fig. 38: The Moon passes the shadow of the Earth in a few hours during a lunar eclipse.



Lunar eclipses are spectacular events. They happen about once a year on average, rarely enough to be unusual, but often enough for all of us to have a chance to see one.

Earth is about 3.5 times as large as the Moon. By the time the shadow of Earth reaches out to the Moon, it narrows by as much as one lunar diameter. The Moon crosses the remaining 2.5-lunar-diameter-sized shadow, circle in shape, in 3.5 hours (or faster if the Moon does not hit the center of the shadow). An example of the timing is shown in Fig. 38. as it happened on Oct. 27, 2004.

The eclipse starts with the partial shadow, which makes so little difference

* It is certainly *not*.

that it is hard to detect. When the full shadow cuts across the face of the Moon, its edge is a part of a circle, and this fact indicates that Earth is a sphere. (A disk-shaped Earth would cast a shadow whose edge would be a part of an ellipse.) An accurate drawing of the relative radii of the shadow and the Moon allows us to simply measure the ratio of the sizes of Earth and Moon.

During a total eclipse moonlight is dim, and stars are visible for an hour or so as well as they are visible on a moonless night. The Moon does not completely vanish though. It is still visible in some eerie colors, due to scattered light from Earth's atmosphere. It is no coincidence that the colors of the totally eclipsed Moon are so similar to the colors of sunset (Fig. 39).

Dim as the eclipsed Moon is, it is still full Moon. Sunlight still arrives at the Moon from behind our backs, and no shadows are visible on the surface. The Moon is contrastless, and it is as hard to see lunar features as it is at full Moon. In fact, it makes little sense to use large telescopes to watch a lunar eclipse. A pair of binoculars will show as much as we can ever see.

Fig. 39: It is no coincidence that the color of the eclipsed Moon resembles the color of the sunset.

It is tempting to attempt to take pictures of a lunar eclipse. To be successful, we have to consider that usual lenses, telephoto included, make too small an image of the Moon. As the Moon is $½^{o}$ in diameter, the size of the image will be *1/100*th of the focal length of the objective. Even a *200 mm* telephoto lens gives us only a *2 mm* sized image of the Moon. Few digital cameras, and no film cameras will work: there is not enough resolution. With a film camera, we want an image as large as *15-20 mm*, and that translates to a focal length of $f = 1.5 – 2\ m$. Clearly, we need an SLR camera, with the lens removed, the camera attached to a telescope with the above focal length. (With digital cameras, a shorter focal length will suffice because the chip is smaller than regular film size.) Because the eclipsed Moon is faint, we need long exposures on the order of a second. We need to have the telescope on an equatorial mount with tracking.

A good source of information on previous and upcoming eclipses, solar and lunar, is <http://sunearth.gsfc.nasa.gov/eclipse/>.

IV.3. Solar Eclipses

Total solar eclipses are rare events, when the Moon covers Sun. Both the Sun and the Moon look ½ ^{o} in diameter, and a total solar eclipse occurs only when the Moon *exactly* hits the center of the disk of the Sun. This happens about once in 300 years in a particular location.

Partial solar eclipses happen more often. The Moon moves one solar diameter per hour in the sky, so a partial eclipse can take at most two hours. The edge of the Moon is sharp, and it is very difficult to see mountains or craters sticking out of the edge. (A *1 km* tall mountain would stick out about *1 as* only.) A particularly interesting effect is the shape of the shadows of trees during a partial solar eclipse (see Fig. 40). As light seeps through the leaves, each small patch of light becomes the sickle shape of the Sun!

Fig. 40: Gaps between tree leaves act as camerae obscurae in a partial eclipse. Notice the sickle-shaped patches.

Finally, a safety issue should be mentioned. During partial solar eclipses it gets darker than normal daylight, and our eyes partially adapt to the dark. The total amount of light from the Sun is diminished, and we feel that the Sun is not as dangerous to look into as it normally is. In truth, the surface brightness of the uncovered part of the Sun is *not* reduced, and our dilated pupils collect *more* light per squared arc minute! It is dangerous to look into the Sun, even without a telescope, during a solar eclipse! One should wear properly designed “eclipse glasses” to avoid eye damage. Even the darkest sunglasses will not absorb enough light to make is safe to look into the Sun.

Exercises

1. Observe the Moon with various magnifications between 10 × to 400 ×. Find out what magnification gives you an impression of a *globe*, and which gives the impression of *land*. Notice how the length of the shadows depends which part of the Moon you are looking at. Describe your findings.
2. Find at least one instance of the following features on Moon: a mare, a crater with a central peak, a crater with partially flooded wall, a crater whose wall is partially broken by a newer crater, a rille (sinuous, arcuate, and straight rilles are the three different types), a fault line (a lobate scarp), a ray crater. Identify each crater using a map of the Moon. Four resources, use the internet and the Digital Lunar Orbiter Photographic Atlas of the Moon at http://www.lpi.usra.edu/resources/lunar_orbiter/.
3. Using a telescope, find the objects you identified in Exercise 2.
4. Look at the same area of the Moon a few days before and a few days after first quarter. Do you find the two views similar? Why are they different?
5. Learn the name of the major maria and the 10 most conspicuous craters. To check if you remember them, make a drawing of the Moon and place each one on it. Identify these features in the telescope at various lunar phases.
6. Draw the crescent Moon. What curve is the shape of the terminator?
7. How large does the Moon look in the sky? How large do the largest lunar craters look in the sky? What is the resolution of the human eye on the Moon in *km*'s? What is the resolution of a good telescope on the Moon in *km*'s, and what is the main effect that limits it?

IV.4. Planets

While most of anything outside the Solar System looks either faint or tiny in a telescope, some of the planets do look what you would expect in astronomy: disks in the telescope with some detail on them. But even that said, we should recognize the fact that planets are still far away and we are watching them through turbulent air. It takes effort and training to see all the existing detail on the disks of the planets.

All planets follow the ecliptic within a few degrees. When a few planets, possibly also the Moon, are up, it is a rewarding experience to look at the main circle in the sky they follow. We can use our imagination to "see" in the sky how they circle around the Sun. We will mentally image the planets in space and see the Solar System in three dimensions.

The fact that planets follow the ecliptic brings up the same issues about their visibility as with the Moon, with the exception of the phases that do not work the same way. For obvious reasons we concentrate on the early hours of the night. After sunset in September, the southern ecliptic is low over the horizon, and that is not a good time to look at planets (or at the first quarter Moon, for that matter). As the months pass, the part of the ecliptic that is to the south early night becomes higher and higher. By February, the southern ecliptic is very high up, and that is an excellent time to watch the planets.

In the following we will discuss each of the planets in turn, what we can see on their disks in the telescope, when and how they can be observed.

Mercury

Mercury is always close to the Sun in the sky. It is either a morning star, rising in dawn before the Sun, or an evening star, setting right after the Sun in dusk. In maximum elongation, it is 26^0 away and sets a good hour after the Sun. Even though it may become as bright as $-1.8\ mg$, it is hard to find

Mercury in the best of circumstances. In addition, it orbits the Sun fast. Chances are best if we look for it in the one week after maximum eastern elongation in March, when the ecliptic shoots straight up from the setting Sun. It is a good idea to set a GOTO telescope on its coordinates beforehand, and catch a glimpse of it around sunset.

Fig. 41: Mercury is always tiny, and sunlight is always disturbing its observation. Fable has it that even Copernicus never saw Mercury in his life!

Because Mercury is a small planet, it always looks small in the telescope. It shows phases like the Moon, and is "half" at maximum elongation. A week after maximum eastern elongation (the numbers refer to March 14, 2005) it is *8 as* in diameter, *0 mg* in brightness and is at 18^0 altitude at sunset. It is a 30% illuminated sickle shape (see Fig. 41), but within five days it wanes to a very narrow sickle, only *+1 mg* bright. In a few more days and it vanishes in the glare of the Sun.

Mercury is a difficult planet to observe. Small telescopes cannot discern any surface details other than the phases.

Venus

The brightest "star" in the sky, it can reach *–4.4 mg*. Similarly to Mercury, it is either the Morning Star, rising a few hours before the Sun, or the Evening Star, setting a few hours after the Sun. It can never be seen at midnight. Because it is farther from the Sun than Mercury, it is up longer after sunset, and in maximum eastern elongation, 44^0 from the Sun, it can set four hours after the Sun in full dark. Its synodic period is 584 days = 1.6 years. After emerging from the glow of the Sun on the far side of its orbit, it spends a half a year far away from Earth, appearing an unimpressive, not too bright (- *3 mg*), small (*10 as*) slowly waning gibbous shape. When it finally reaches maximum elongation, it is a spectacular - *4 mg* half moon shape of *25 as* size. Then it grows quickly as it approaches us, in six weeks it is *45 as* and a spectacular narrow sickle shape (Fig. 42). This is the best time to look at Venus, even though it is then close to the Sun in the sky. The best way is to find it a few hours before sunset with a GOTO telescope, when Venus is still high enough above the horizon, so that seeing is not extremely bad.

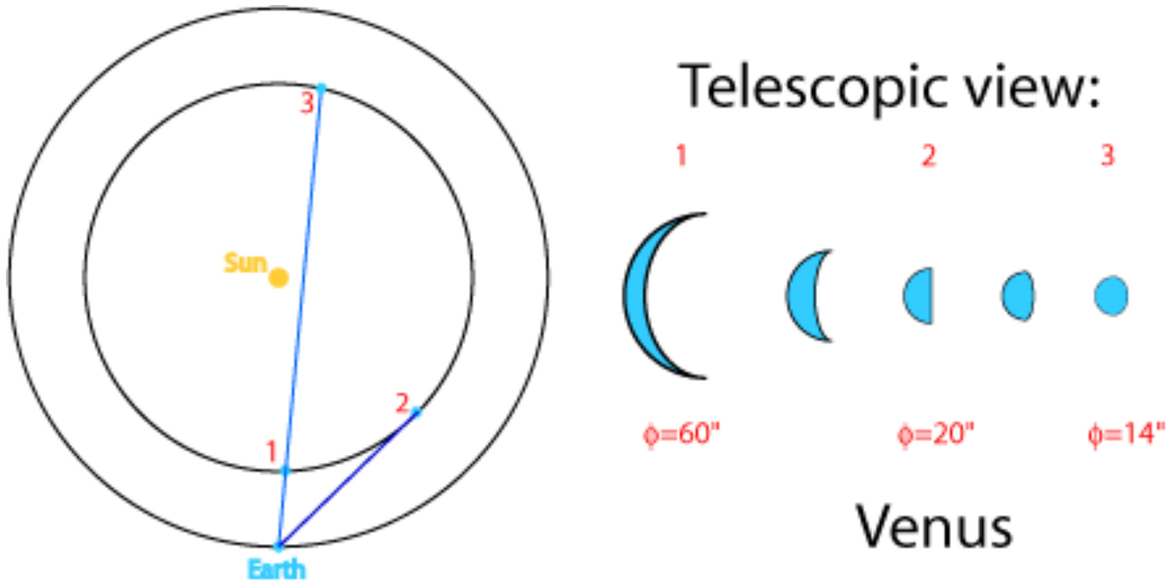


Fig. 42: As Venus wanes, it comes close to Earth, and it grows into a spectacular sickle in the telescope. It spends most of its time, however, on the far side of the Sun looking like an unimpressive tiny gibbous moon shape.

After this Venus quickly vanishes in the glow of the Sun. Although it will grow as large as *60 as*, it is very hard to find it due to the closeness of the Sun. It might be best to look for it during the day at this phase, but it is only visible in very clear skies.

After conjunction with the Sun, the above scenario is played out backwards, this time Venus rising before the Sun. A few weeks after conjunction is the best time to look at Venus in the morning hours. The planet will be again large and sickle shape.

After maximum western elongation comes a full year long period when Venus gets slowly smaller, goes behind the Sun, and slowly emerges again.

Although Venus is a very easy object to observe, the thick cloud layer over its surface does not let us to see any surface detail. However, the phases look really good. People would think they are watching the Moon.

Mars

Mars is farther out from the Sun than Earth and its motion in the sky is quite different. It spends most of its *780 days ≈ 2 years* long synodic period far from the Earth and close in the sky to the Sun. During these times Mars is faint (*+1 mg*) and small (*5-10 as*). After appearing just west of the Sun, rising at dawn, it slowly crawls farther from the Sun, rising earlier and earlier. After a year of this, it speeds up, and in a month it appears opposite to the Sun, bright (*-1 mg*) and large (*20 as*), close to Earth. In opposition it rises at sunset, and is best observed at midnight. In the next month it quickly moves on to the west, rising earlier and earlier, but it also quickly fades and decreases in size. A month after opposition it is insignificant again, and for another year it keeps moving closer to the Sun in the sky. After that it vanishes in the evening dusk.

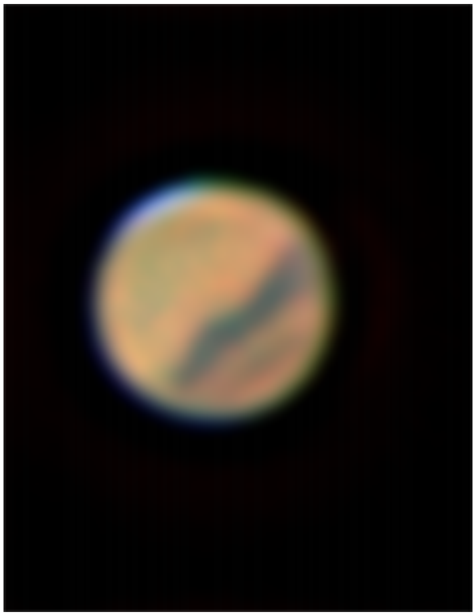


Fig. 43: Mars is a source of disappointment in the telescope. The polar caps are usually visible, but no more than a few dark and bright spots can ever be made out, and these only during opposition.

The short window of a month around opposition is the only time when we can hope to see any detail on Mars. Mars, due to simple geometry, does not show all the phases as Venus or the Moon do. At opposition its disk is full. Three months after opposition, when Mars looks already small, its phase reaches its minimum (a gibbous 90%). A careful look can still detect its phase though. After this the disk starts growing again.

Mars has a more elongated elliptical orbit than any of the other planets. For this reason not all oppositions are equal. When Mars is in perihelion at the time of an opposition, it can get really close to us (these are called "great oppositions") and the planet looks significantly larger. Unfortunately for us, this happens when Mars is in the Sagittarius area (that is the constellation the perihelion of Mars' orbit faces), way down south, so Mars does not come very high over the horizon. When it does come up high in a not-so-great opposition, it is located farther away from us and does not look as large.

Even during a great opposition Mars is a difficult target. There is little contrast on its surface. It is easy to understand this: the situation is analogous to the full Moon. Illumination comes from behind; shadows do not enhance the contrast. There is no such thing as a first quarter Mars. The ice caps on the poles are clearly visible, and good-eyed people in stable weather can detect some dark and bright spots on the red planet (Fig. 43). These spots come back to the same position almost the same hour every night, because the rotational period of Mars is 24^h25^m.

Mars' two moons, Phobos and Deimos, are too faint to be observed visually.

Jupiter

Jupiter, being a giant, has more to offer than the other planets. With its 12 years of orbital period, it moves one constellation to the east every year, and is visible one month later in the year. It first appears rising just before the Sun at dawn, and in a half a year it keeps rising earlier and earlier, finally reaching opposition when it rises at sunset and is best observed at midnight. For the next half a year, it keeps rising (and setting) earlier until it vanishes in the glow of the Sun at sunset.

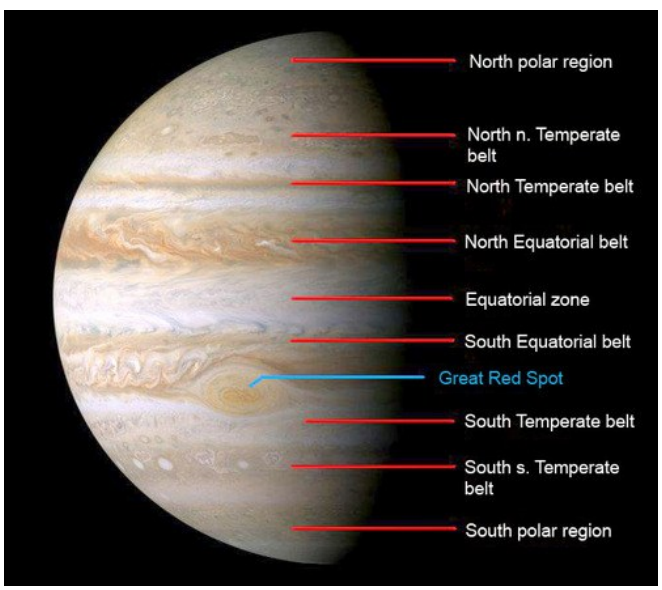
Fig. 44: Careful observation reveals much "surface" detail on Jupiter. Here, Europa is casting its shadow on the planet. This picture was taken with a 10-inch telescope.

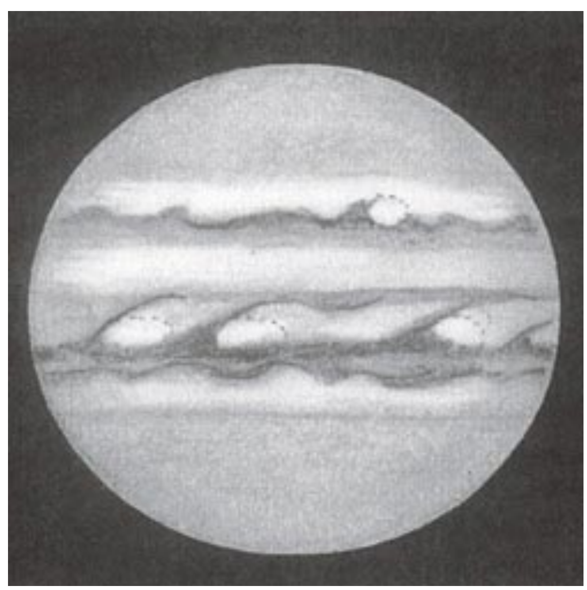
In opposition, and during the months after, it is the second brightest "star" in the sky with its - *2 mg*, and in the telescope it is an impressive disk of *40 as* (see Fig. 44). The shape of the planet is clearly elliptical. Its quick rotation, *10 hours* period, causes the equator to bulge out. Parallel white zones and brown-pink belts cover the planet parallel to the equator. Low-level NH_2HSO_4 clouds are brown. In the zones, rising air produces high level white NH_3 clouds which cover the underlying brown cloud layer from sight. The Great Red Spot, a giant but steady storm, is clearly visible when it faces us. A few minutes of observation are sufficient to see that the Great Red Spot is moving as Jupiter rotates. It is a much harder job, although doable, to measure the differential rotation using less prominent spots.

Fig. 44a: Left, an explanation of Jupiter's zones and belts. North is up. Right, a drawing of Jupiter by Ohio amateur Phil Plante with a 6-inch f/5 Newtonian reflector at 228x. South is up.

As we know, a casual look does not usually allow the observer as much detail on a planet as spending minutes at a time and waiting for the best seeing possible. Observational experience helps much, too. Drawing the planet as we see it in the telescope many times helps us develop a skill to see small detail. Fig. 44b illustrates what an experienced observer can see on Jupiter's disk with a 6-inch telescope in good conditions.

Jupiter has many moons, small and large, but only the four large Galilean moons are visible in a small telescope. All of them move on circular orbits in Jupiter's equatorial plane, so they line up almost in a straight line. They are bright, *4-5 mg*, and only the closeness of the bright Jupiter is the reason why they cannot be detected by the naked eye. Their positions change from day to day, because the orbital periods of Io and Europa are short, *1.8 days* and *3.5 days* respectively. Once every turn they are eclipsed by the shadow of Jupiter, go behind the planet and pass in front of it, and cast a shadow on the planet. These events happen almost daily, and are quite interesting to watch. The timing of these events was used by Olaf Roemer to measure the speed of light for the first time.





Saturn

Saturn is arguably the prettiest sight of all in a telescope. The beauty of the ring will impress any observer.

The planet, being far from the Sun, moves very slowly and takes two years to proceed from one constellation to the next (its orbital period is 30 years). For many years it is in opposition in the same season of the year (presently late December). It appears in the sky the same way as Jupiter: first emerges rising before the Sun at dawn, then in a half a year it gradually rises earlier and finally, in opposition, it rises at sunset and is up all night. After that it gradually moves to the southern, then western sky early night, and in a half a year it vanishes in the glow of the Sun.

Saturn is bright, *+1 mg*; it is easy to find in the sky. The ring is obvious even with small telescopes at moderate magnifications (*15-20* $\times$). However, there is detail that justifies the use of the largest possible telescope and reasonably large magnification (Fig. 45). The ring is divided by the Cassini division, and with a 12-15 inch telescope the Encke division should also be detectable in a stable night. The shadow of the planet, cast on the ring, cuts off a piece, and we can also see the shadow of the ring cast on the planet. The planet is clearly ellipsoidal in shape, due to its quick rotation. In very stable nights Jupiter-like bands may even be discernible on the planet.

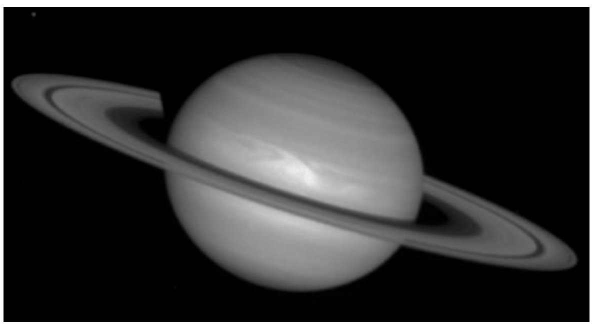


Fig. 45: Saturn impresses everyone viewing it in a telescope. The Cassini division is obvious in small telescopes.

The ring is actually extremely thin, less than a mile. Every 15 years we see it from the edge (as in September 2009), and it all but disappears (Fig. 46). When this happens, Saturn is, by a strange coincidence, in one of the celestial equinoxes because Saturn's and Earth's equators happen to be similarly oriented.

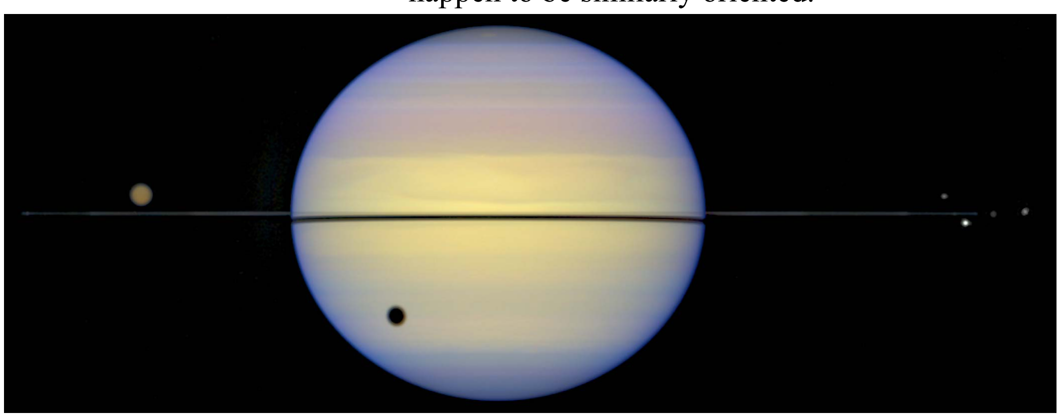


Fig. 46: When the ring is seen from the edge, it almost disappears even in Hubble Space Telescope images.

Saturn has many moons. The brightest is Titan, and is easy to spot as a "star" with its *7 mg* brightness. The rest of the moons are faint, below *13 mg*, however.

Uranus and Neptune

These two planets, giants as they are, are invisible to the naked eye because they are so far away. Both move slowly, and in the foreseeable future they will be crawling in Capricornus and Aquarius, visible in the fall. They are easy targets with telescopes, *6 mg* and *8 mg* in brightness, and look like tiny disks (their diameters are *3.5 as* and *2.2 as* respectively). It makes sense to use a large telescope on them, because when there is enough light, their distinctive colors appear: Uranus is green, Neptune is bluish. We want to use large magnification, weather permitting, to enhance their tiny disks. Needless to say that no surface details are discernible with small telescopes.

Uranus' brightest moon, Titania, and Neptune's Triton are both difficult at *13 mg*. They are an easy target with a CCD camera though.

Pluto

Pluto is not visible in a small telescope. At *14.3 mg*, it will reside in the constellation of southern Ophiuchus for a few decades. It is visible in the summer, a bad time to observe faint objects in the American South's muggy skies. On CCD images, taken on consecutive days, it appears as a slowly moving faint star (see Fig. 47).

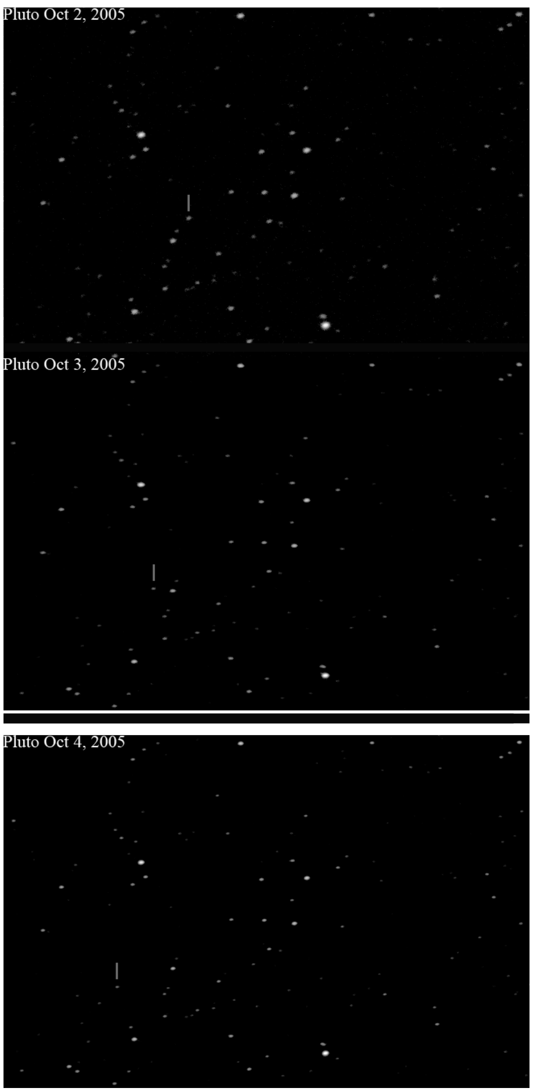


Fig. 47: Pluto appears on this CCD image as a faint 14 mg star, moving from one day to the next.

Exercises

1. Derive the formula that relates the sidereal and synodic periods of a planet. What would be the synodic period of the asteroid Vesta, which is located in the asteroid belt ($a = 2.6\ AU$, use Kepler's 3rd law)?
2. Set SkyGazer to a 1-day step, and trace the motion of Mercury, Venus, Mars, and Jupiter for one synodic period. You will want to change the hour of the day to see the planet. Follow each of the statement in the text about these planets' motion. You will need to set the planets magnified in order to see the change in their sizes and phases.
3. Find a time in March and one in September when Mercury is in largest eastern elongation. Set SkyGazer at sunset, and read off Mercury's altitude over the horizon. Explain the difference and conclude.
4. Which one offers more detail, Mercury through the telescope, or the Moon to the naked eye? Give three reasons for the difference.
5. What surface details are visible on Venus? Explain.
6. The dark spots on Mars appear to the observer on the same spot night by night, and change only in a few weeks. Does this mean that Mars' rotation period is a few weeks? Explain.
7. Why is it that all great oppositions of Mars happen in July?
8. What surface details can you see on Mars? What are the dark and the bright spots? Can you see canals? What else?
9. List all the things that are easy to notice about Jupiter's disk and its moons in the telescope.
10. What happens when Earth crosses the plane of Saturn's ring? How often does that happen?

11. How many moons of each planet are (i) easy to see, (ii) hard to see but still visible in a 12-inch Meade telescope? Estimate the magnitudes.
12. Give an approximate number how bright each planet is.
13. Find a list of the eclipses or passages of Jupiter's moons and time one event though a telescope.
14. Find Uranus and Neptune in the telescope. Use a Meade 12-inch or the Grubb.
15. Draw Jupiter and acquire the skills of seeing full detail and drawing by repeating several times. Identify the stripes and bands on your drawing. You should achieve at least the quality of drawing on the picture above.

IV.5. Constellations

Students take courses in astronomy with the expectation that they will be looking at the night sky and learn about constellations. The stories recounting the mythological events placed in the sky connect well with listeners, and help to demystify and humanize the science of astronomy. In addition, they also help develop respect for the intellectual underpinnings of our culture, so often neglected these days.

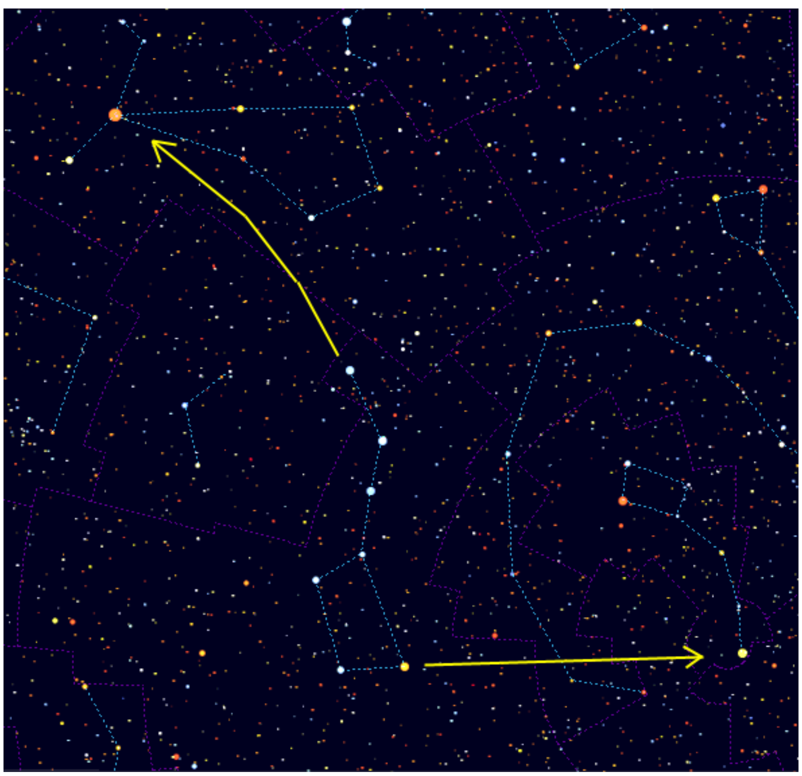


Fig. 48: Starhopping. Use constellations you know to find ones that you don't.

Light pollution on campus makes it virtually impossible to see full constellations or to enjoy recognizing them. It is advisable to teach students as many bright stars as possible though. This needs to be a repeated exercise, done for a few minutes every single clear lab night. Later in the semester a separate constellation lab can be given, taking the students to a reasonably dark location and teach them the full shapes of the constellations. Having learned to recognize a few bright stars will greatly enhance this experience.

The technical skill one needs to find constellations is *starhopping* (see for example, Fig. 48). The broken handle of the Big Dipper, when continued in an arc four times, points out Arcturus (α Bootis). The last two stars of the Big Dipper, continued five times, point out Polaris. This type of skill can also be used to find faint stars in constellations, as well as to find faint objects using telescope viewfinders.

Exercises

1. Use starhopping to find a few deep-sky objects with the 25-inch Dobsonian. The choice of object will depend on the season, but M1, M3, M13, M27, M57 are among those that will help you develop your starhopping skills.

2. Try out the way of finding Polaris explained in the text.
3. In a night when the Milky Way cannot be seen but the sky is clear (i.e. almost any cloudless night in Oxford), follow the constellations that mark the Milky Way. Compare how many stars are visible along it to how many there are in other parts of the sky.

IV.6. Double stars

About half of all stars are actually double or multiple star systems. The collapsing interstellar cloud that gives birth to a star fragments into pieces due to gravitational instabilities. This means that double stars are born together, are of the same age and material, and all the differences between the components are due to differences in their masses.

Both the apparent and the true linear distances between the components vary greatly. Most doubles are so close that no telescope can resolve the pair (spectroscopic doubles), and have orbital periods of a few days to a few years.

More widely separated doubles, with hundreds or thousands of years long orbital periods, might actually be resolved in the telescope. Tens to hundreds of astronomical units separate them, and they normally appear at most a few arc seconds apart in the sky (or much closer in most cases). Their orbital motion is detectable with large telescopes only. The position angle of the two stars changes when we compare observations over a few decades. It is difficult to measure the true distance between these stars because we do not usually know how much farther one star is behind the other. Nice examples of this situation are each of the two pairs of the "Double Double", ε^1 Lyrae and ε^2 Lyrae (the two pairs are too widely separated from each other to form a true double).

The most commonly observed situation is a common proper motion system. These are pairs of stars separated far enough, thousands of AU's or more, so their revolution is undetectably slow (periods of tens of thousands of years or more). In addition, the escape velocity in so widely separated systems is so small that the random speeds the stars usually have are sufficient to break them apart: they do not revolve around each other at all. However, they can be told from random pairing of stars in the sky in three ways: (i) statistically, they tend to be too close in the sky to be the result of a chance alignment (we observe two reasonably bright stars much closer together in the sky than all the other stars of similar brightness are), (ii) their distances from us, however inaccurately measured, are reasonably similar, and (iii) they have the same amount and direction of proper motion in the sky. Many such systems consist of more than two components. They may be separated in the sky typically by a few arc seconds to a few arc minutes, much wider than true binaries. Of course no relative motion is detectable even over a long period of time in a telescope. A bright example of such an easy-to-see triple system is Alcor and Mizar in the Big Dipper.

Some of the brightest double stars are an impressive view in a telescope. Differences in the masses of stars will cause differences in the rate of their evolution, and there are situations when one of the stars has already become a red giant while the other is still on the main sequence. These pairs may show a striking contrast in color. A nice example of a bright colorful double (a common proper motion system) is Albireo (β Cygni).

Double stars are good targets of observation in light-polluted locations and hazy weather. Moisture and some clouds do not necessarily degrade seeing, which is the more important issue here. You want to use the largest telescope available. The human eye will not see the color of faint objects, so in a large telescope the color contrast of pretty doubles is much more spectacular. Of course only the brightest doubles (1^{mg} to 4^{mg}) will show any kind of color in visual observation.

Except for a few, doubles are generally only a few arc seconds or less apart. To resolve them, we need the largest magnification the telescope (and seeing) allows. Observing doubles is a good exercise in training students to see details where a cursory look would only show one single star.

Exercises

1. Learn to find the brightest double stars in the sky: Albireo, Alcor and Mizar, ζ Cancri, Castor, γ Andromedae, ε Lyrae, γ Leonis, Rigel. Which constellation do they belong to, when are they visible? Which category of double stars does each one of these belong?
2. What are the categories of double stars?
3. How long are the shortest periods of those binaries that can still be split by a small telescope? Explain using Kepler's III law.
4. Some stars look colorful in the telescope, others don't. Some others are colorful with the naked eye, others are not. Explain.
5. Use a reticule eyepiece to measure the separation and polar angle of a close binary.

IV.7. Deep sky objects

In the 21st century the much of the study of the Solar System became the realm of space missions, and it employs methods that have little to do with what we call ”astronomy”, the only exceptions being the study of asteroids and comets. True astronomy starts with other stars these days.

The Solar System is but a tiny speck in the whole of the Universe, yet everything else is so light-starved that we must do our utmost to squeeze out information from the little light we see. Stars remain dots in any magnification; star clusters, nebulae and galaxies are invisible without devices and are very faint and unimpressive in a telescope. Beyond individual stars it is these faint "deep sky" objects that most of present-day astronomy is studying.

Books of astronomy are full of astonishing color images. These are acquired by long-exposure photography or CCD imaging, the result of collecting light for many hours. In contrast, the human eye collects light for about *0.1 sec* before it starts to form another "image" again. That is a really short "exposure"! It is enlightening to watch a deep-sky object in a telescope and compare it to an available color picture. One gets the right impression of the power of modern equipment.

Studying deep sky objects teaches us how to discern things that are not obvious for the first sight. It takes effort and practice to teach our eyes and brain to see faint or contrastless detail, yet the general skill of "discerning" is one of the few that sets apart an educated person. In this sense astronomical observation and deep sky objects in particular constitute a useful tool in college education.

Once our eyes are trained to see all there is to see in the telescope, a few objects provide an impressive view. You may enjoy the richness of open star clusters such as the Pleiades, the Double Cluster (χ and h Persei), the Beehive (Praesape in Cancer), or the Wild Duck (M11 in Scutum), the faint but structured nebulous glow of the Orion Nebula, the smoke ring of the Ring Nebula (M57 in Lyra), the half-resolved thousands of stars in bright globular clusters (such as M13 in Hercules or M3 next to Arcturus). There is even a galaxy, the Andromeda Nebula on this list, although it does not exactly live up to the expectations. Little detail can be seen in it, and certainly not the spiral arms. The rest of the deep sky objects are so faint that it is quite an achievement to see them at all.

In the following we will discuss the best ways to observe deep-sky objects, then look at the particular of each of the main types. We will discuss a few of the brightest examples, and outline the physical understanding of each type. The reader is expected, however, to be familiar (or to look up now) the theoretical details in a textbook.

Classification and catalogs

The first detailed catalog of deep-sky objects was due to Charles Messier in the late 1700's. A comet hunter, he compiled a catalog of 109 objects that might have been confused with newly discovered comets. A few proved to be non-existent or doubly counted. The Messier Catalog lumps together such various objects as diffuse and planetary nebulae, open and globular clusters, and galaxies, designated as M1 through M104. More comprehensive catalogs are the NGC (New General Catalog), which contains many galaxies, and the IC. Because galaxies are mostly hard to see by visual observation, few made it too the Messier catalog, but there are many of them in the NGC. We need not say that there is no physical similarity between the various objects in one catalog. Some are individual stars with a gas envelope, others are clusters of thousands of stars a few hundred light years away, others are galaxies millions of light years from us.

Telescope setup

The observation of deep sky objects is a great challenge. It is critical to use the best setup available in order to collect all the light we can and suppress all the disturbing light from other sources.

The way we can quantify the visibility of faint extended objects is through surface brightness. By definition, the surface brightness of an extended object is the brightness you would see if you only looked at a $1as\times 1as$ piece of the object. For example, the full Moon is $-12\ mg$, and its surface area is $(15\times 60\ as)^2\ \pi = 2.54\times 10^6\ as^2 = (-16.0\ mg)\ as^2$, so its surface brightness is $+4\ mg/as^2$, very bright.

Note that surface brightness expressed in mg/as^2 is not a true ratio. For example, if the background sky is $16.0\ mg/as^2$ due to city lights (this is what you normally get on a cloudless but hazy night), in order to calculate how much light comes from an am^2 we need to convert as follows:

$$1\ am^2 = 3600\ as^2 = (-8.9\ mg)\ as^2, \text{ so that } 16.0\ mg/as^2 = 7.1\ mg/am^2 = -1.8\ mg/deg^2$$

The importance of the concept of surface brightness lies in the fact that (for extended objects) it *does not depend* on the distance of the object. Both the total intensity of light and its angular extent decrease as $1/r^2$. In fact, for black body radiation, the surface density depends only on the temperature of the object, $dI/d\Omega = \sigma\ T^4$ (I is the total intensity in $Watt/m^2$, Ω is the angular surface area of the object). This means that the (bolometric) surface brightness of a black body is $-\ 10\times \log\ (T/550K)\ mg/as^2$. Of course, except the Sun, all astronomical objects have much fainter surface brightness than this. Deep sky objects do not radiate as back bodies in visible light, nor do planets. Stars do, but they are not extended objects, so their surface brightnesses are not observable.

Another important point about surface brightness is that *no optical instrument can increase it.*[*] Higher magnification in a telescope will decrease the surface brightness of a nebula. When the magnification is at its smallest (so that the telescope's exit pupil is equal in size to the human eye, $M = \Phi_{tel}[mm]/5$), the surface brightness in the telescope equals the object's original surface brightness. The only gain is from the fact that the surface area (and so the total amount of light) is larger.

The limit of perception of dim light of the human eye is a quite complicated matter. The center of the retina is tightly lined with receptors. When we directly look at an object, the resolution of the

[*] This is a consequence of the second law of thermodymanics.

human eye is as good as *1 am*. When the object is not in the center of the retina (when we are not looking straight at it), receptors are farther apart, and the resolution is lower. However, these out-of-center receptors are more sensitive to light. In order to gain sensitivity, the brain automatically adds together signals from bunches of receptors. The resolution deteriorates to as bad as a half a degree, but we will perceive a whole magnitude fainter object than in the center. A useful technique based on this is called "averted vision". When we want to see a very faint object, we "focus" on a spot away from it. The light of our object will fall on receptors away from the center, and we will see it more easily. It is absolutely important to lean this technique and teach it to students!

So there is a compromise to strike between resolution and light perception. There will be no way to see fine detail in a faint object: we either use averted vision and loose resolution or look directly at the object and loose the faint parts (or the whole object). This determines the general rule of deep sky observing: use the minimum magnification to preserve all the surface brightness, and use as large a diameter of a telescope as you can to gain magnification.

There are exceptions from this rule, however. A few objects (small planetary nebulae) are small in size but have high surface brightness. An example is the Ring Nebula, *1 am* in diameter with surface brightness $17.5\ mg/as^2$. It is bright enough to be seen in somewhat higher magnification (around 100x usually works well), which helps to suppress the surface brightness of the background sky.

Another important point in deep sky observing is to achieve as complete dark adaptation as possible. All stray lights should be covered: someone can stand in the way of a street lamp that would shine into the eye of the observer, or we can use our hands to block out stray light. Observing from a dome is helpful: even if sky glow is not removed, the environment is darker than outside and eyes adapt better to the dark. We usually need five to twenty minutes for full adaptation. We (including students) should be outside for a quarter of an hour before looking into the telescope, and it is advisable to keep the lab lights off, both to avoid strong light blinding observers when the door is open, and to cut the adaptation time for people leaving the lab for the telescope.

When planning deep-sky observation, we need to take into account the weather conditions beyond cloudiness. Moisture in the air may absorb as much as 1-2 mg of light. In the same time, it does not cut off light pollution. On the contrary, it scatters stray light and may increase the skyglow by 1-2 mg. No wonder limiting magnitudes, normally 4-5 mg in Oxford, deteriorate to 2 mg in muggy summer nights.

The detrimental effect of atmospheric extinction steeply increases with zenith distance. Although extinction is proportional to the thickness of layer of air crossed by starlight (called "airmass") $\propto 1/\cos h$ (h is the height over the horizon), skyglow does not decrease and the setting object soon vanishes in the bright background sky. In practice, in downtown conditions, deep sky objects are not normally observable when they are lower than $40\text{-}50^o$ of altitude. And the higher, the better! This is especially unfortunate because the biggest treasure-trove of bright and spectacular deep sky object, the Sagittarius area (which contains the center of the Galaxy) never rises higher than 30^0.

Planetary nebulae

It is believed that the last active "minutes" (lasting a few tens of thousand years only, to be compared to the billions of years of stellar lifetime) of a Sun-like star arrive when the star develops a strong stellar wind and disperses most of its matter into space. Gas leaves the star with speeds around *10,000 km/s*, and the tiny but hot core of the star gets exposed. The hot core ($20\text{-}100{,}000^oK$) radiates mainly in the ultraviolet. Its UV radiation is completely absorbed by the rare gas, which fluoresces in a few very bright emission lines. This unusual spectrum consisting of only a few emission lines make planetary nebulae the most colorful of all objects in the sky. Unfortunately to us, the human eye is unable to see color in faint sources, so the vibrant colors are only visible on pictures (Fig. I.3.16).

These nebulae came to be named "planetaries". They have nothing to do with planets though; they are extremely rare gas shells surrounding dying stars. They (almost all) appear tiny in the telescope; most are only a few *as* in diameter. In fact, it is usually a hard job to tell most planetary nebulae from stars, and it can be done only spectroscopically. Their small-disk appearance accounts for their name.

There are a few planetary nebulae close to us that look large enough in the telescope to be clearly resolved. The largest, the Dumbbell (M27) in Vulpecula is *7 am* in size. At *7.3 mg*, it is huge. Watched from a dark location at small magnification it really resembles a bell that never chimes. The central star, however, is too faint to be seen visually. With its *20.3* mg/as^2 surface brightness, it is a difficult object in light polluted location. Higher magnification does not help, the nebula is already large. A "nebula filter" which transmits only the few nebular emission lines, is a great help if all stray light can be completely blocked from the view of the observer.

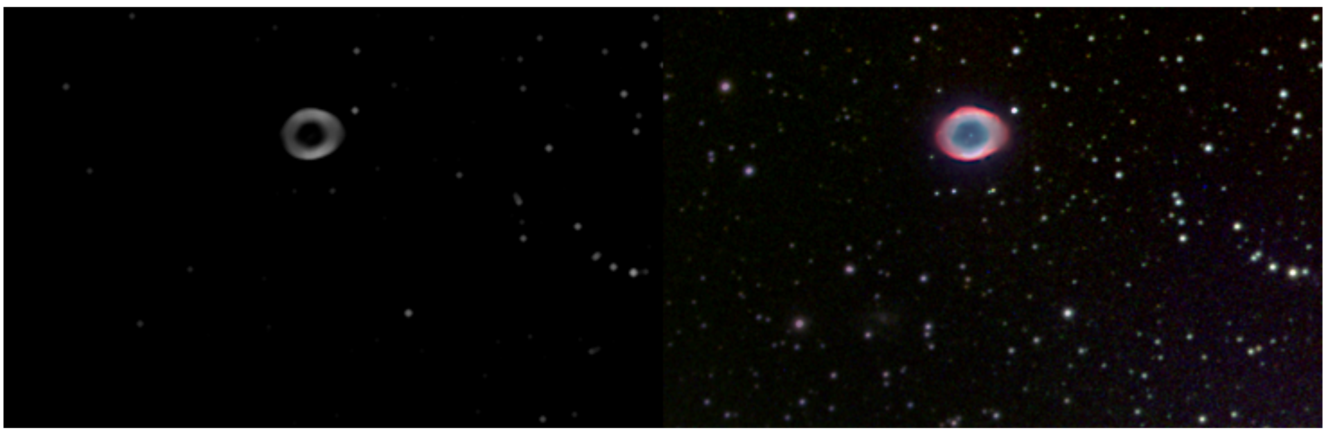


Fig. 49: The Ring Nebula (M57) is easily visible in a 12-inch telescope. It needs well-adapted eyes though, so switch off the lights and give yourself a quarter of an hour to adapt to darkness.

Another famous planetary is the Ring Nebula in Lyra. At *17.7* mg/as^2 it is surprisingly easy to see. As we already mentioned, its relatively large surface brightness and small size (*1 am*) justifies increased magnification. It is essential though that all stray light be blocked. The central star is *14.8 mg* visually, invisible in small telescopes.

All other planetary nebulae are small and faint. It is a challenge to see them even with a nebula filter.

Supernova remnants

Once a century on average, one star in a galaxy blows up in a spectacular event. For a few weeks it outshines its galaxy, then it slowly fades as its material disperses in space. Neither the remaining central object (call it a star?) nor the dispersing gas remain visible from the distance of another galaxy.

Fig. 50: The Crab nebula is impressive on long-exposure images, but it is hardly detectable and completely structureless in visual observation.

It has been three hundred years now without a supernova observed in our Galaxy. If any have blown up, they were well hidden in the dust that blocks the majority of stars in the Galaxy. Our ancestors however did observe supernovae, some of which left behind remnants that still shine.

Most supernova remnants, when they are visible at all, are large and very faint, their matter has become part of interstellar material. A characteristic example is the Veil Nebula in Cygnus, a 2^o-sized arc of ionized hydrogen. Its large size and low surface brightness is prohibitive, the only way to "see" it is on wide-angle photographic images.

There is, however, one bright supernova remnant. The Crab Nebula in Cancer (M 1) contains an active pulsar, whose energy production fuels the nebula (Fig. 50). The probable reason why it is the only bright one is that pulsars exhaust their rotational energy within a few thousands of years, and that not all supernovae actually leave behind a pulsar.

The Crab, with its *9 mg* distributed over *4 am x 6 am*, has low surface brightness, *21.3* mg/as^2. However, as it rises very high in the sky, it is still a reasonable target at low magnification. The filamentary structure, so obvious in pictures, is difficult to see visually however.

Diffuse nebulae

Galaxies are much more than what hits the eye: a significant portion of atomic matter (up to 40%) is in the form of interstellar gas and dust. In our Galaxy, most of the interstellar material is laying in the plane of the disk, along the Milky Way, in the form of rare gas (1-10 atoms of hydrogen per cm^3), and dust (graphite grains covered in ice). Dust blocks the light of anything behind it, stars, bright nebulae, even the very center of the Galaxy (Fig. 51). When a dust cloud is close to a bright star, it reflects starlight. These nebulosities are hard to see in any other way but long exposure photography.

Dust is also prominent in covering dark lanes in the Milky Way, which can be seen easily in a dark location.

Interstellar gas, mostly consisting of hydrogen, can be molecular (H_2), atomic (HI regions) or ionized (HII regions). Molecular clouds are hard to detect directly but are known to be ubiquitous, HI regions can be traced by radio astronomy due to the *21 cm* emission line of hydrogen atoms. HII regions, consisting of ionized hydrogen, glow in visible light. The UV radiation from hot stars, embedded in them, ionizes the hydrogen. Much of the light of HII zones is in the form of a few emission lines, similarly to the spectra to planetary nebulae (although the particular lines may be different). The most prominent of these spectral lines is Hα in red. Images taken with Hα filters are especially full of detail because the filter removes much of the background skyglow.

Fig. 51: The Horsehead (left) is a dust cloud in front of a HII region; the Pleiades (right) is an open cluster embedded in a reflection nebula (i.e. dust).

HII regions arise when a hot star is embedded in an interstellar hydrogen cloud. This situation naturally arises in molecular clouds where stars are presently being formed. Young and heavy stars of spectral types O-B ionize a few light years sized chunk of the cloud and turn it into an HII region. The most spectacular example is the Orion Nebula (M42). In fact there is a giant molecular cloud stretching across much of Orion, and in a few places young stars ionize a small portion and produce HII regions. The four stars of the Orion Trapezoid are located in and are responsible for the existence of the Orion Nebula (Fig. 52). Nebulosity, and a faint glow in Hα marks the entire constellation. We are obviously looking at a close-by stretch of a spiral arm of the Galaxy.

Fig. 52: The Orion Nebula. The image on the right shows the central region (the shock front that is prominent on the right is barely visible close to the center of the left image). Notice the Trapezoid of Orion on the right – the four blue stars in the center of the right image. This image is similar to the impression the nebula makes in a 30-inch telescope (except for the lack of color).

On visual observation, the *5 mg* stars of the trapezoid are obvious. The cloudiness is visible in the smallest of telescopes, but the larger the telescope the better the view. The nebula has large surface brightness (a large part of it is over $16\ mg/as^2$, the brightest parts as bright as $14\ mg/as^2$). It is easy to see even when it is low over the horizon, and it is a great view. However, it is rarely advantageous to use anything but the smallest magnification.

Open Clusters

Open clusters are a collection of physically related, relatively young stars. Because they are young, they are mostly located in the Milky Way in the sky. These systems normally contain a few dozen to a few thousand stars, and are not gravitationally bound. In a few hundred million years they disintegrate. A few open clusters are associated with nebulosity, a relic of the interstellar material of which the stars were formed in the not so remote past. This nebulosity, however, is always faint and not visually observable (see Fig. I.3.21).

Fig. 53: An open cluster with some nebulosity (IC 4954).

The bulk of stars in all stellar systems have low mass. A few luminous stars stand out, but a true essence of the cluster is visible when we reach the many faint solar-mass stars. Oftentimes these stars are not fully resolved in the telescope, and provide a spectacular view for the experienced observer. Rich clusters with thousands of 10-11 mg stars such as the Wild Duck (M11) or χ and h Persei (the Double Cluster) or the Beehive (Praesape) need a dark environment and low magnification. A large aperture telescope helps: the magnitude limit will be deeper.

The Pleiades is a special case. Because it is so close it appears as large as a $\frac{1}{2}^{o} \times 1^{o}$. At this size, a maximum of *50 ×* magnification can be used if we want the entire cluster to fit in the field, but unless we are really fully dark adapted, this is only possible with a 4 – 6 inch or smaller telescope. Large telescopes aren't fit to observe the Seven Sisters!

Globular Clusters

There are only about 120 known globular clusters in the Galaxy. We are sure we did not miss one unless they are hidden behind interstellar dust, because globular clusters are among the brightest compact objects in the Galaxy (M13 has $M_{abs} = -8.4\ mg$, while Betelgeuse is $M_{abs} = -4.6\ mg$). They are huge collections of hundreds of thousands of old stars. In recent years many astronomers came to believe that globular clusters are the remains of galaxies that have collided with our Galaxy and got ripped apart.

Globular clusters look so similar in the telescope that few observers can tell them apart. Except for the brightest few, the stars are not distinguishable visually, and the cluster is a hazy glow. A few of the brightest, such as M13 in Hercules or M3 in Canes Venatici, appear grainy in an 8-inch telescope and a 12-inch already clearly shows individual stars scattered in the face of the general background glow of the many thousand fainter ones (Fig. I.3.22).

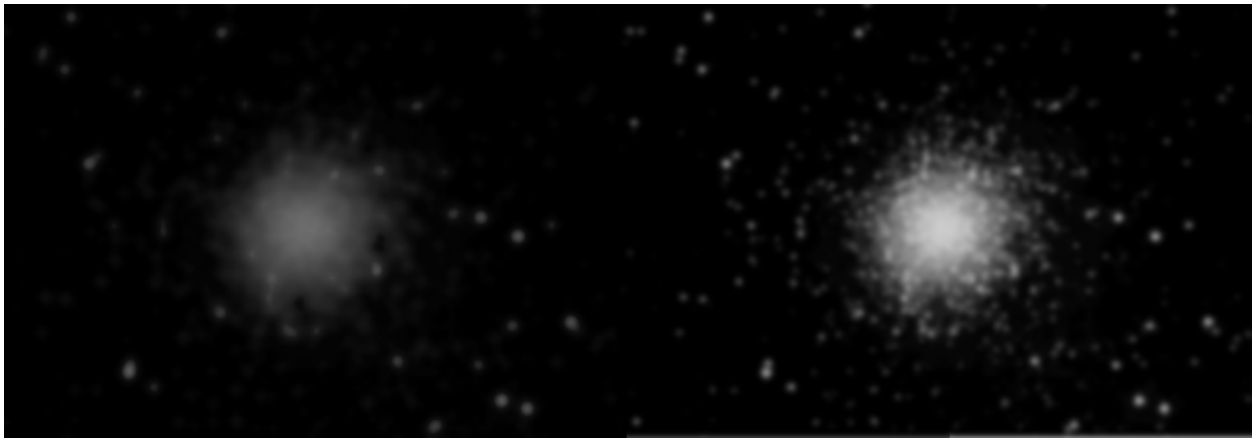


Fig. 54: This is the impression you get when observing M13, the Great Globular Cluster in Hercules, through an 8-inch (left) and a 12-inch (right) telescope.

When we want to see only the general glow of the cluster, background light is not so much of an issue. The surface brightness of globular clusters is reasonably large (for example the central *1 am* of M2 is $16\ mg/as^2$). However, when we try to resolve the graininess or individual stars (and that is what makes them interesting), we need the largest possible telescope, dark adapted eyes, and a magnification somewhat larger than the minimum. With a 12 inch telescope, 100 × will normally do.

Galaxies

All of the above nebulae and clusters were part of our Galaxy. It is pure coincidence that many of them happen to have brightnesses and apparent sizes similar to the bulges of galaxies. This fact made it historically difficult to recognize that galaxies were in fact not part of the Milky Way (Fig. I.3.23).

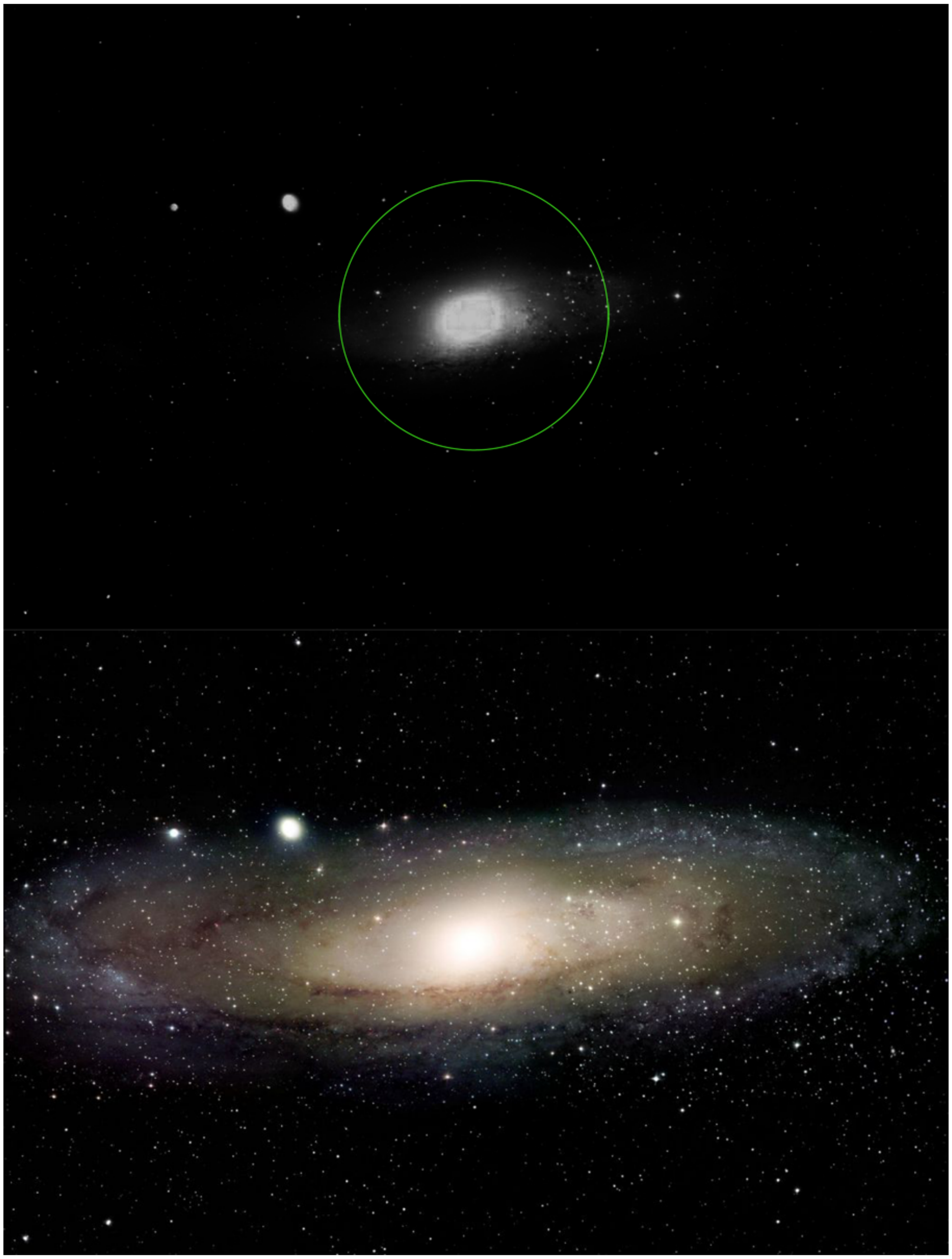


Fig. 55: The Andromeda Galaxy in long exposure photography (bottom; exposure time 28h) and by visual observation (top; with a 12-inch telescope at 100 ×, the green circle the field of the eyepiece). With visual observation only the bulge shows up at all; the spiral arms are not visible. The scale of the two images is the same.

Galaxies are notoriously difficult to observe visually. This is due to their low surface brightness. Elliptical galaxies and the bulges of spirals are reasonably bright, *16 – 18 mg/as*^{2}, but spiral arms or any other structure are at best *21 – 22 mg/as*^{2}. In the best of circumstances, observing from a completely dark location, there may be a hint of the spiral structure of M51 (the Whirlpool Galaxy in Canes Venatici), never visible from light polluted skies. All we can see otherwise is a featureless blob of faint glow, and that is true even of the brightest, the Andromeda Galaxy (M31). The only thing you can see is the bulge, about a quarter of a degree in diameter. Galaxies require the power of CCD cameras for imaging.

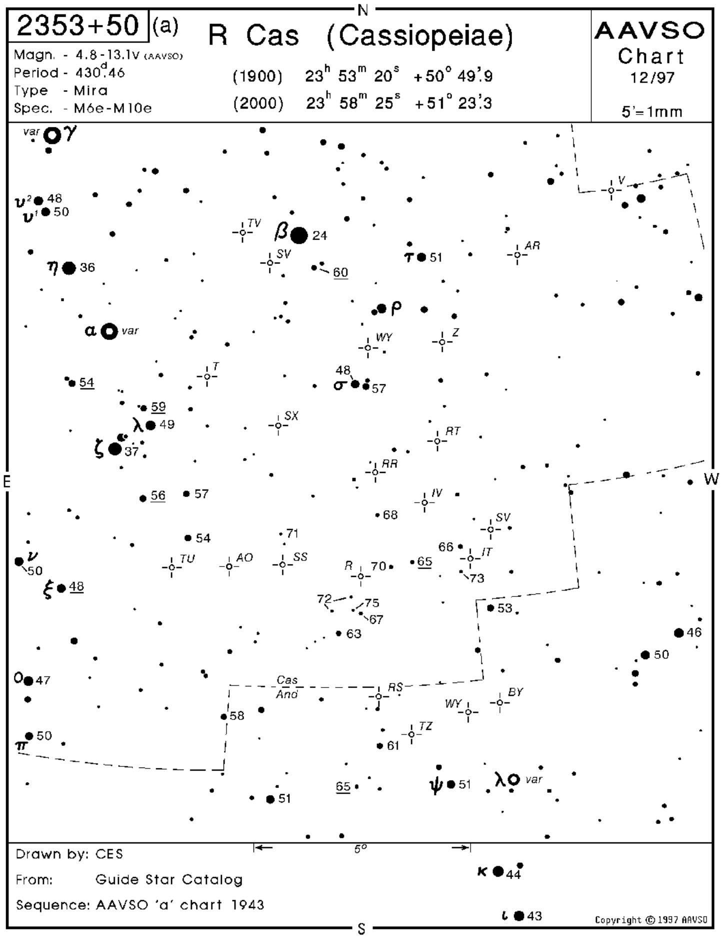
Exercises

1. Why is it much harder to see the spiral arms of galaxies than globular clusters?
2. How many times is more skyglow on campus than in the mountains on a cloudless night?
3. List the six basic types of deep-sky objects.
4. How many Messier objects are there?
5. Explain why does the surface brightness of an extended object not depend on its distance.
6. Give ballpark numbers: what is the surface brightness of the brightest nebulae, of a globular cluster, of the Milky Way, and of the spiral arms of a galaxy?
7. Think of a thought experiment to prove that, as a consequence of the 2nd law of thermodynamics, no optical instrument can increase surface brightness.
8. Show that a telescope with its "minimal" magnification just leaves the surface brightness of extended objects unchanged.
9. What is the resolution of the human eye when a very faint object is observed?
10. Explain what planetary nebulae are, and why they are more colorful than any other object?
11. How many supernova remnants can we see in a telescope (visual observation, not photography)?
12. What is a HII region? Why does it glow and what does its spectrum consist of?
13. Where in the sky are each of the six types of deep-sky objects concentrated?
14. What sort of stars make up an open and a globular cluster? Are they gravitationally bound?
15. List the five open clusters that are visible with the naked eye, at least from a dark location.
16. How large is the Andromeda Galaxy in the sky? How much of it fits in a 12-inch Meade's field of view when a standard *26 mm* eyepiece is used? Explain why the patch of light you see does not fill out the field?
17. What telescope must be used to see the Seven Sisters?
18. Find a globular cluster in an external galaxy. Use TheSky to identify it, then find it with a telescope. You may have to use the 25-inch Dobsonian if the cluster is too faint.
19. Observe a deep-sky object of your choice. Look at it with various magnifications. Observe how the surface brightness of the object seems to depend on the magnification, and observe also how the background skyglow changes. Describe your findings, and conclude on the best choice of magnification.

IV.8. Variable stars

A large percentage of stars change their brightness over time. Most changes are, however, too small to detect with the human eye (we will discuss these observations in Chapter III). A few types of variables, however, have large enough amplitudes that are easily detectable. The first variable ever discovered, o Ceti (the "Mira"), changes its brightness between *2 mg* and *11 mg*, and was discovered by the naked eye.

The changes in brightness may be due to stellar pulsation (such as Mira variables, which have a period of a few months to a few years), or to more or less random changes in the changes in the surface temperature of stars (semi-regular variables such as Betelgeuse), or to eruptions and explosions (novae and the like) or simply due to eclipses caused by a companion star (Algol, β Persei, dims more than a magnitude for a few hours every few days). These changes occur slowly enough so we do not detect



the change during one observation session, but if we compare observations between different days, the change may be obvious. In a laboratory setup, such observations need careful planning if we want them to be instructive to students.

In the past century many amateurs did daily observations of variables all over the world, and they were collected by the AAVSO (American Association of Variable Star Observers, www.aavso.org). The procedure is to compare the brightness of the variable to the brightness of two comparison stars. Appropriate star charts are distributed by the AAVSO (an example of such a star chart is shown in Fig. 56).

Fig. 56: An example of an AAVSO star chart used for variable star observations.

The product of a set of such observation is a light curve, which indicates the change of the brightness of the variable in time. Examples of such light curves are shown in Fig. 57.

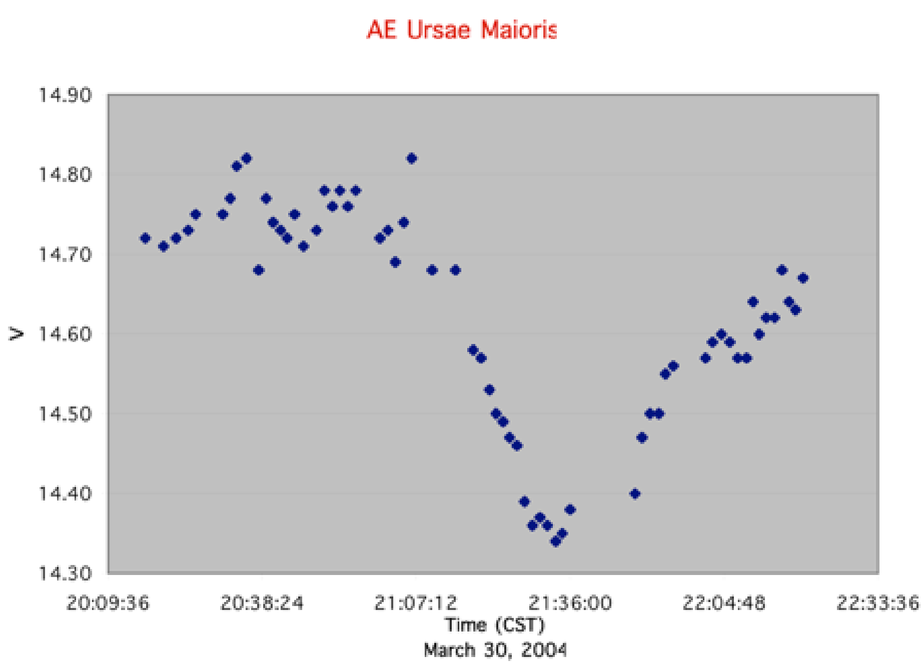


Fig. 57: An example of the light curve of a variable star. This star has a period of 2 hours, amplitude 0.5 mg (δ Scuti type pulsating variable).

Exercises

1. Find a Mira variable star, using an AAVSO chart and estimate its brightness. (Visit aavso.org and download the charts.) Use the appropriate telescope: you'll need a large enough telescope to see a faint star, but small enough magnification to have the comparison stars in the field. Plan accordingly.
2. Look up when Algol is in minimum. Observe it (you'll need to do this at a dark location) and estimate its brightness outside eclipse, then at the time of a minimum. According to your observation, how many magnitudes does is get fainter?

IV.9. Asteroids

The Solar System is full of tiny (and not-so-tiny) space rock that shows up on many astronomical images. A few of the largest asteroids are bright enough to be seen in the telescope: 1 Ceres, 2 Pallas and 3 Juno, 4 Vesta, are 5-7 mg in opposition. They appear as stars in the telescope, but they are usually quite obvious in the field as they are normally brighter than anything else there. In addition, they usually scintillate much less than the other stars in the telescope. (For the same reason why planets do not scintillate; they have a finite size, a few tenths of an arc second.) They do move compared to the background stars, but this motion is too slow and visually undetectable during one night (see Fig. 58).

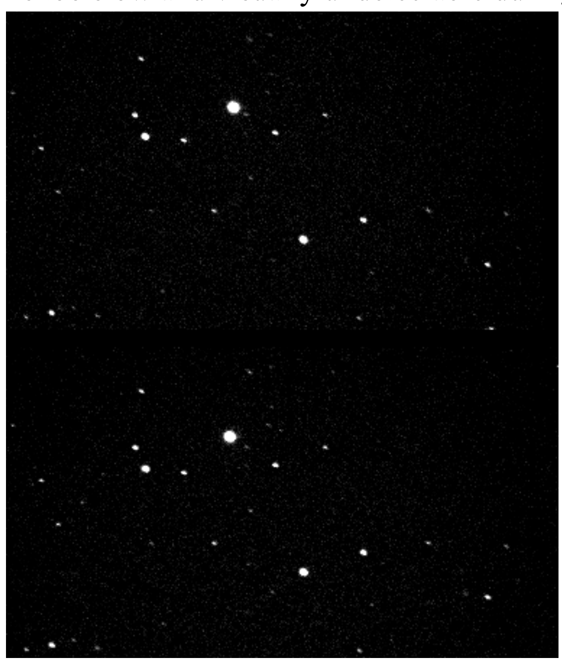


Fig. 58: The motion of 2 Ceres in 20 minutes. The asteroid is the bright star left and up from center. Its motion is hardly detectable in such a short time.

Presently there are about 400,000 catalogued minor planets. New ones are discovered every day. These newly discovered asteroids are usually 17^{mg} - 18^{mg} in brightness, and about *1 km* in size, mostly located in the asteroid belt. As a consequence, they - as the planets - mostly follow the ecliptic in the sky. Their names consist of a number and a given name, such as 18 Melpomene or 532 Herculina. The IAU (International Astronomical union) sanctifies these names on the recommendation of the discoverer.

Most asteroids are too faint to observe visually. Normally there is a dozen visible asteroids at any one time brighter than 12^{mg}, and thousands of faint ones (15^{mg} - 17^{mg}) litter the ecliptic everywhere. None of the minor planets on unusual orbits (Earth-crossing, Trojan, Trans-Neptunian, or KBO's) are bright enough to be seen in an amateur telescope. We will discuss these in the Chapter II on CCD astronomy.

Exercises

1. There are very rarely any asteroids in the Big Dipper. Why?
2. Find one of the four large asteroids, Ceres, Juno, Pallas, or Vesta in the sky. Draw the field and identify the asteroid. Do this again a day or two later, and indicate the motion. You'll need to do this reasonably close (in time) to opposition.
3. Find a 10 - 11^{mg} asteroid in the sky with a 12-inch Meade telescope.

IV.10. Comets

Bright comets, rare as they are, are the most fascinating sight in the sky. Everything else that is bright in the sky (except for the very rare events of a total solar eclipse) follows a well-rehearsed script. But a comet appears from nowhere, follows an unpredictable path, changes its shape, gets brighter and then fainter, and finally fades into the dark sky.

Most comets these days are discovered by amateur astronomers specializing in comet discovery or else by dedicated professional asteroid searches such as LINEAR. A comet approaching the Sun in the night sky rarely avoids detection before it brightens to 11-13 magnitudes, and faint comets are often discovered at *16-18 mg*. These objects usually appear on the discovery images as slightly fuzzy asteroids. They normally take months, sometimes a few years from discovery to reach perihelion when they brighten significantly.

Newly discovered comets are given a name such as, for example, C2000AZ Hyakutake, carrying the name of the discoverer. The very few periodic comets are given a proper name though.

The brightness of a comet changes very fast with decreasing distance from the Sun and from Earth. The brightness of the central part of a comet's head is usually parameterized as

$$m_1 = H + 5 \log d + G \log r$$

where H is the absolute brightness of the comet (how bright it would look from a distance of d = $1\ AU$ from Earth, when it is located r = $1\ AU$ from the Sun). Most comets have an absolute brightness between $H = 2^{mg}$ and $H = 8^{mg}$. The coefficient 5^{mg} simply reflects the inverse square law of brightness versus distance d from Earth. The slope parameter G would also be $G = 5^{mg}$ for a passive object (such as an asteroid), but comets are usually active and have anywhere between $G = 5^{mg}$ and $G = 30^{mg}$ (r is the distance from the Sun). As it can be inferred from the formula, a large G means that the comet brightens fast as it approaches the Sun. In addition, we must understand that the above formula is a parameterization of the brightness which may change irregularly and unpredictably. We may conveniently say that the values of H and G may change as the comet approaches the Sun. These changes occur when the level of activity of the comet suddenly changes (for example, a more volatile region gets freed up in the comet, producing more gas and a larger head.)

An example of a comet light curve is shown in Fig. 59. It is a combination of $H = -2^{mg}$, $G = 10^{mg}$ at $T < -250\ days$ and $H = -0.6^{mg}$, $G = 7.96^{mg}$ at $T > -250\ days$, T is time ($T = 0$ corresponds to the perihelion). We see that this very large comet (see how bright H is!) was brightening slowly as comets go (not too large G's).

When a comet is discovered at a large distance from the Sun, it is hard to predict how bright it will become, or how exactly it will move. As the heat of the Sun starts to free up gases from the body of the comet, the reaction force changes the orbit in an unpredictable way. The change is not large, it is on the order of a few percent only, but it may lead to a significant difference in how bright the comet becomes at perihelion. After all, perihelion brightness is extremely sensitive to the distance to the Sun.

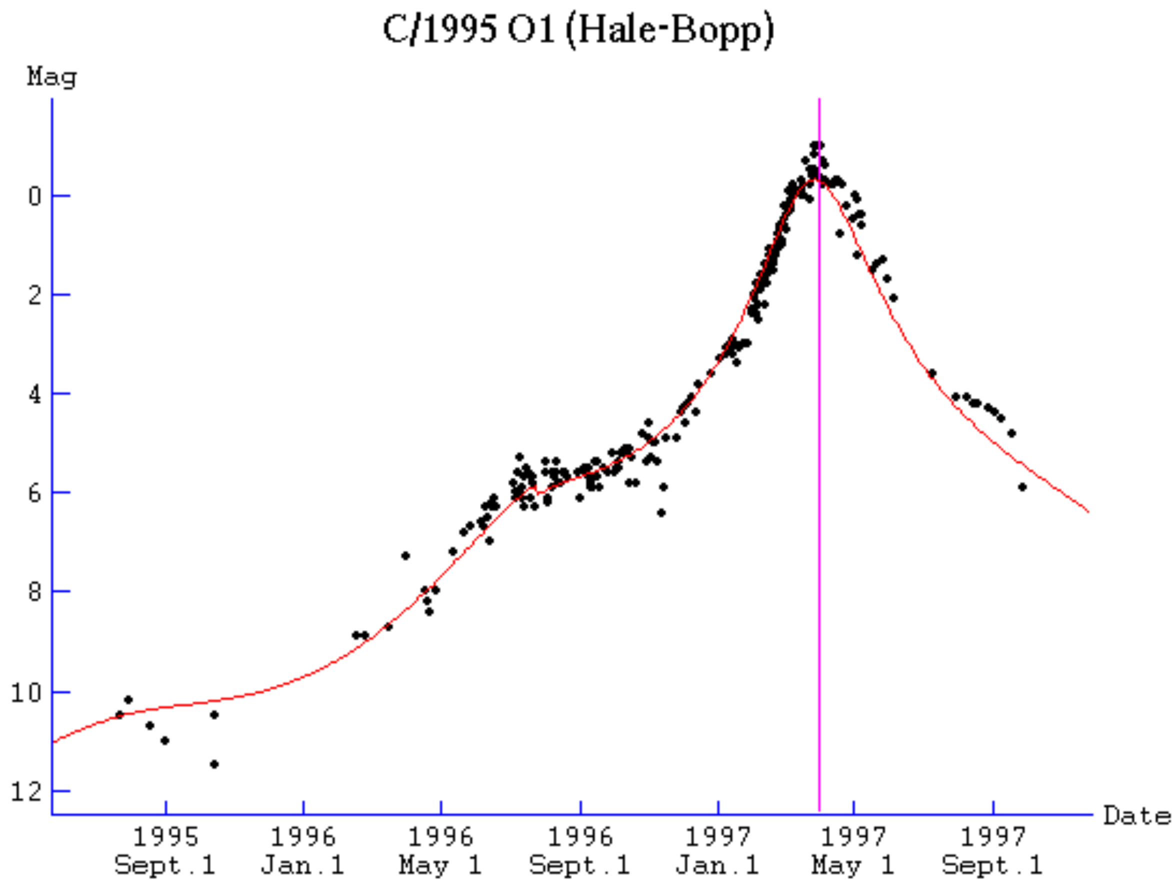


Fig. 59: The light curve of a bright comet.

It is even harder to predict at early stages how bright a comet will be at closest approach to us. A very significant factor is how much matter gets loose with increasing temperatures, and no one can predict that. As a rule of thumb, there is as many magnitudes of inaccuracy in the prediction as the quarter of the number of months till perihelion. For example, we can predict the perihelion brightness of a comet only within $\pm 3^{mg}$ a year in advance, which is not very precise indeed. Closer in time to the perihelion predictions become more reliable.

Every year there are a few comets that become visible to the naked eye for a period of a few days. These comets spend about a year in the night sky, slowly brightening from ten-odd magnitudes. Because the orbital inclination of comets to the ecliptic is not generally small, about half of these faint comets spend most of this time at very southern declination (invisible for us), and after perihelion they go back south. The other half is high up in the sky and is an easy target for CCD imaging (see Chapter

II), but are usually quite impractical for visual observation. (See the website http://www.aerith.net/comet/weekly/current.html for observable comets.)

When these comets approach the Sun, they normally brighten from 7-8 magnitudes to visible in a matter of a few days. At this stage they are located close to the Sun in the sky, and become difficult targets. It is ironic that comets are in the most "ugly" part of the sky when they are brightest and their tails are most spectacular, visible for a short time after sunset or before sunrise, low in the sky. Fig. 60 indicates such a typical situation.

Fig. 60: Comet Hale-Bopp, as most bright comets, sets shortly after the Sun. Notice the glow of the dusk.

Bright comets usually appear large in the sky, their heads extend a few to a few tens of arc minutes, with a very pronounced central concentration. Apart from this very bright nucleus, the head looks very similar to globular cluster. Small magnification and possibly dark environment helps. (As much as it is possible at all in the glow of dusk.) The tail of even a bright comet has low surface brightness, and might be a challenge in light-polluted or hazy conditions. Tails of bright comets may be a few degrees long, so quite often a small refractor is the best instrument to observe them. Such small refractors make aiming a much easier job, too.

A few comets approach the Sun and Earth "by stealth", from behind the Sun. Because it is very hard to discover a 10-magnitude comet when it is not too far in the sky from the Sun, these comets are only discovered when they become very bright in perihelion. We normally are informed first by the media. It is a shame, but Nature conspires against teachers of astronomy to make them look dumb, their students knowing about a very bright comet before they know. But that is how things actually happen.

Exercises

1. Which comet is most easily visible at this time early night in Mississippi? List the top candidates and explain your No. 1 pick.
2. Explain why G = 5^{mg} means an asteroid, not a comet.
3. Why are most bright comets visible right after sunset or right before sunrise only?
4. Using the website http://www.aerith.net/comet/weekly/current.html., find out what comet is easiest to observe early night. Print sky charts with TheSky6 and find the comet at the Dark Site in a telescope.

IV.11. The Milky Way

The one single thing in the sky that moves people the most is the bright silvery band of the summer Milky Way – or so it used to be before electric streetlights were invented. It is a hallmark of how much modern life became remote from Nature how few of us have ever seen the Milky Way, or have even an idea of what it is. In the common mind the Milky Way became confused with telescopic images of spiral galaxies. Most of our students think that they need a telescope to see the Milky Way, a small and distant patch of light deep in the sky. It is very important to provide an opportunity for them to really experience it, and ask them to imagine the disk composed of millions of stars as it is projected in the sky.

Fig. 61: Top: an edge-on galaxy NGC 891, bottom: a whole-sky picture of the Milky Way. Can you see how similar they are? Notice the similar color, the dark dust lanes, the similarity of structure.

Standing under the dark summer sky, we gain a feel of the immense star system we are a part of. The Milky Way goes all the way around the sky, and we see the bright patches of glow in Scutum (the Shield), then in Sagittarius where the center of the Galaxy is located. We cannot see any sign of the center (it is behind so much interstellar dust that its light is darkened by more than 20 magnitudes!), we certainly detect a very large number of clusters and nebulae, concentrated in the Sagittarius – Scorpius (and Centaurus, if you are willing to travel to the South) area.

As we carefully follow the outline of the silver glow of the Milky Way, we detect that it is split in two somewhere just south of the constellation of Cygnus. A large dark dust lane, similar to the dust lanes so obvious on many images of spiral galaxies, covers the Milky Way all the way to Sagittarius. With a little use of imagination we will see, with the mind's eye, how we are inside one of those pretty spirals that are so familiar from pictures (Fig. 61).

A good pair of binoculars (use at least an 8×50) will resolve much of the Milky Way into millions of faint stars. By extension, we can easily imagine that the remaining unresolved clouds are also collections of very many faint stars. The bulk of the diffuse light of the Milky Way comes from *14-17 mg* stars, and binoculars will not be able to resolve those.

The surface brightness of the band of the Milky Way is *19-21* mg/as^2. Even the brightest "clouds" of stars are overwhelmed by light pollution on campus, which is around *18* mg/as^2. Only on exceptionally transparent nights might the experienced observer have a faint inkling of where the brightest patches of the Milky Way should be. Driving a few miles out of town on a side road and letting our eyes dark-adapt for a few minutes will change it all.

The Milky Way is a full circle all the way around the sky. The galactic North Pole (GNP) is located in the constellation of Coma Berenices, just northeast of Leo. At times when the GNP is high up in the sky (it can get almost to Zenith, for example, at 10 pm in mid-May), the Milky Way will basically spread out along the horizon and be invisible. Spring early nights are good for external galaxies but not for galactic deep-sky. When the GNP is setting or rising, the Milky Way comes high up to Zenith and is very nice to observe. In early night hours this happens in February (GNP is rising, Taurus in Zenith), and in September (GNP is setting, Cygnus is in Zenith). It is different early night in November though, when the GNP is under the horizon. Because the Milky Way is deeply inclined to the equator, the GNP does not go very deep under the horizon and the Milky Way does not again follow the horizon. A not-too-bright section of the Milky Way crosses somewhere between Zenith and Polaris in the North (the constellation of Cepheus).

Another aspect of the Milky Way is that the constellations along it contain many bright stars. It is a good idea to learn the names of the large constellations the Milky Way passes through, together with the season of the year when these constellations are highest up at early night:

Summer: Sagittarius, Scutum, and Aquila

Early Fall: Cygnus, Cepheus and Cassiopeia

Late Fall: Perseus, Auriga, and Taurus

Winter: Gemini and Orion.

Exercises

1. Where is the Milky Way early night in late April?
2. Does all the light of the Milky Way come from stars that a good pair of binoculars can resolve? What percentage of the light does not? (*Hint: Use the information given in the text.*)
3. Which are the most conspicuous constellations along the Milky Way? List them by the season.
4. How bright is the Milky Way and how bright is skyglow (i) on campus, (ii) in a dark location?
5. Why is the Milky Way split in two in the summer? Where is the center of the Milky Way located in the sky? What makes up the light of the Milky Way? How far is its center? Explain.

IV.12. Shooting stars

Meteors fall all the time of the year and are quite impressive also for laypeople. Most of the time, however, it takes a trip to a dark location to have a chance to see any.

Many students have no idea of what a shooting star looks like; they may imagine them standing or slowly drifting in the sky. It makes good sense, even if it is not practical to take a laboratory section out to the country, to provide them at least a first-hand account of what a meteor looks like.

Sporadic meteors fall all the time. Any dust particle larger than a few micrometers will burn hot and be visible as a shooting star. At a dark location an observer who is continuously watching the sky will detect a sporadic meteor every 5-10 minutes.

Meteor showers come on certain days of the year, on a regular basis. They are debris left behind by disintegrating periodic comets whose orbit they all follow. Consequently, they appear to radiate from one point in the sky (the "radiant"). Once we have looked up what meteor shower is active on the day of the observation, it is a simple exercise to continue backwards the path of a meteor in the sky. If that line goes anywhere close by the radiant, chances are the meteor did belong to the shower.

A little thought of the geometry of a meteor's path convinces us that few meteors will be visible from a shower while its radiant is under the horizon: they will simply fall down on the other side of Earth. A few meteors make it through to the dark (night) side of Earth when they just "graze" the atmosphere. These are the ones all of us see early night in Mid-August (see Fig. 62). The radiant of the rich Perseid meteor shower is under the horizon, but we still see a few Perseids per hour. Once the radiant rises over the horizon, the number of observed meteors quickly grows. We see the most of them when the radiant is as close to Zenith as it can get.

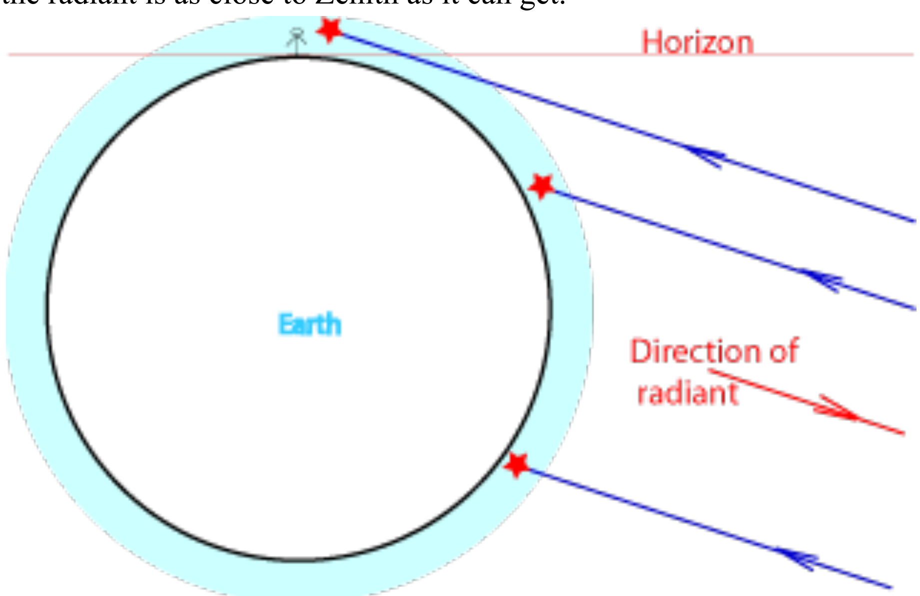


Fig. 62: Due to the motion of Earth around the Sun from the left to the right on the picture, the radiant of most meteor showers are in a direction that rises around midnight. A few meteors fall early night, but the hourly rate increases dramatically after the radiant rises. The best time to see shooting stars is just before dawn.

A practically useful measure of the "activity" of a meteor shower is the *Zenith Hourly Rate* (ZHR), which eliminates these geometrical effects. The ZHR is the number of visible meteors per hour, from a dark location, when the radiant is ideally located in Zenith. Obviously, the actual rate is smaller, and can be simply calculated through knowledge of the altitude of the radiant over the horizon.

A good piece of practical information relies on the fact that Earth is moving around the Sun with a speed of *40 km/s* towards a point *P* that is 90^o to the right of the Sun on the ecliptic. For comparison, this point *P* is where the last quarter Moon would be located, and we all know that the last quarter Moon rises at midnight and is high up in the sky at sunrise. Now the velocity of Earth is vectorially added to the meteor shower's own velocity, so that meteor shower radiants tend to be closer to this point *P* than you would randomly expect. In everyday words: meteor showers have a tendency of coming *opposite* to the direction of motion of Earth, and that is a direction in the sky that usually comes up after midnight. The consequence is that most meteor showers are really active after midnight, with a pronounced peak just before sunrise. You need to be a *night owl* to be an astronomer!

Some meteor showers faithfully return on the same day every year. You see Perseids, with the same ZHR, every August 13. Their meteors are spread out along the orbit of the shower, so whenever Earth crosses the orbit, there is a shower. Other showers are more "lumped", their meteors still retain a memory of where the originator comet used to be on the orbit. These showers of course return on the same day of the year, but only every so many years. For example, the extremely rich Leonid meteor shower shows up on November 17 only every 33 years – that is the period of the orbit of the meteors.

The "shooting stars" we see every day are actually quite tiny dust particles. Rarely and unexpectedly we may spot a larger chunk hitting the atmosphere. A millimeter-sized rock, coming with a speed of a few times *10 km/s*, shows up as a very bright meteor. These bolides leave a visible tail on their paths (a tube of hot ionized gas that lingers for a few seconds), they are visibly colored, might even make objects cast fast-moving shadows, and if they are really large, even produce an audible growling sound. Witnesses of really bright fireballs may help to find any meteorite pieces that survive the fall by accurately recording the path of the fireball among the stars, along with *their* exact location.

Exercises

1. How many shooting stars can you expect to see per hour in a dark location on August 13?
2. At what hour of the day are there most shooting stars?
3. Why are there more fast meteors after midnight than before?
4. Are there any shooting stars during the winter?
5. A bunch of dust particles left behind by a disintegrating comet spreads out mostly along the orbit, but the particles still all follow the original ellipse. Why?
6. How large is, in meters, a 1^{mg} meteor? Give a ballpark number.

IV.13. Spacecraft

Most artificial satellites orbit Earth not far above the atmosphere. Many are a few feet sized metal instruments a few hundred miles above the ground, and as long as the Sun shines upon them they are easily visible in the sky. They normally appear as slowly moving "stars", passing though the sky in a matter of a few minutes. Many times it is hard to tell them from airplanes. Airplanes always have a blinking red light, but quite often this red light is invisible, covered by the body of the airplane, or overwhelmed by the very strong headlights directed towards us.

Spacecraft may produce effects that appear "unusual" and "weird" for the first sight. They may change their brightness in a more or less periodic fashion (due to the rotation of an irregular-shaped body), keep flashing (when a flat metal piece reflects sunlight towards us for a fraction of a second), suddenly appear or vanish (when they enter the shadow of Earth). They appear to follow a somewhat wiggly path, an effect of changing refraction along the path.

A few large satellites appear as impressive bright stars, and they may even show some detail in binoculars. The spectacular passages of the International Space Station are forecast at the websites www.heavens-above.com or <http://liftoff.msfc.nasa.gov/Realtime/JPass/>.

Exercises

1. An about 2^{mg} "star" moves from west to north in the sky in three minutes, and suddenly disappears. It seems to follow a slightly wavy line. Can it be a satellite? Explain.
2. What is the maximum angular size of a *10 m* spaceship in the sky? Can the human eye resolve it?

IV.14. Venus at daylight

Venus, brighter than any other "star" in the sky, can be seen during the day by the naked eye under very special conditions. At its brightest, *-4.4 mg*, it is about 40^o from the Sun. You might be able to spot it if you know exactly where to look (find it with a telescope first, then look next to the telescope). It is always hard, though.

In the telescope Venus is an extended object. Its surface brightness is $+2.2\ mg/as^2$ (independent of the phase), while the blue sky is $+2\ mg/as^2$ to $+6\ mg/as^2$, depending how close the Sun is. Obviously, Venus sticks out. Venus' surface brightness is larger than that of the Moon, so Venus looks actually brighter in the telescope than the Moon does!

It is easy, however, to see Venus with an equatorially mounted telescope such as a Meade LX200. The only complication is that the LX200 does not allow alignment using the Sun.

The procedure is first to read off the coordinates of the Sun from SkyGazer at the hour of the observation. Here is an example:

Date: Oct. 25, 2004, 9 am CDT; Sun: $\alpha=14^h01^m14^s$ $\delta=-12^o21'$

Note the precision needed: use *± 1 sec* in right ascension (which corresponds to *± 0.25 am*), *± 1 am* in declination, *± 1 h* in time. (At fastest, Venus moves at *6 am/h* relative to the Sun.) You want the planet to end up no farther than a few arc minutes from the center of the field, because it is not sure you'll be able to see it in the viewfinder). It is also a good idea to look at SkyGazer's simulated sky and memorize which part of the sky Venus is expected to be. (Perhaps you want to estimate Venus' location in the sky compared to the Sun.)

The LX200 will at this point not be aligned, so that the GOTO feature will not work properly. As a crude first approximation, you can aim the telescope in the location where you estimate Venus would be, and lock the RA and DEC locks. Now, bring up Venus in the catalogue (Star 902) and match the coordinates. Of course, this matching will not be accurate, but at least the telescope will not have to be turned by an extensive amount.

Now move the telescope using only the keypad – do not unlock the RA or DEC locks – to the coordinates of the Sun. Be sure to keep on a solar filter. **Be careful not to look into the telescope or the finder without a proper filter while it is aimed at the Sun**. The scope will point close, but not quite at, the Sun now. Unlock the RA and DEC locks and aim at the Sun.

Looking at the shadow of the telescope on the ground is a good trick, and it helps to aim the telescope at the Sun. Use low magnification (50-60 ×) and a sheet of paper to project the image of the Sun on it. Now center the Sun in the field (still manually; the coordinates on the keypad must not be changed!), and carefully focus the telescope to your eye It is important not to change this focus (do not touch the focuser after this, whatever you do!) because otherwise it will be impossible to see anything in the field of the telescope over the background of the strong skyglow.

The result of these operations is a focused Sun in the middle of the telescope's field, and the Sun's coordinates on the keypad. But this means that the telescope's coordinates have been, in fact, correctly matched, even though you never pressed the 'ENTER' button.

At this point simply slew the telescope to Venus, take off the solar filter carefully and Venus should be in the field of the telescope.

If you have missed it, look in the finder first. Unless Venus is low over the horizon or the sky is too hazy, you should be able to see it. The reasons for complete miss may be: (i) incorrect focusing, (ii) incorrectly read coordinates, (iii) strong haze makes Venus impossible to see. Perhaps repeating the whole procedure more carefully might help.

Once you found Venus, you want to precisely match the coordinates in the usual way (bring up Venus as "STAR 902" and keep "ENTER" down for 3 seconds). If you ever lose it, you can use "GOTO" to go back to it again.

In the telescope Venus will appear as a very bright sickle, or half-moon shape, or disk. Laypeople will often think they are seeing the Moon! It is a nice experience though to see a "star" during the day! There are no details on Venus to see, however. A very thick layer of clouds covers all surface details, weather we look at Venus day or night.

Seeing conditions are usually worse during the day than at night. You'll rarely be able to use a magnification larger than 100-120 ×. There is an added benefit about Venus though: as Venus is always close to the Sun, it is always located low over the horizon early night (or dawn) when it is up at all. During the day, it can be high up, where seeing is better. It makes much sense to check ahead of time, when you are planning your observation session, how high over the horizon Venus will be. The setting or rising Venus is even more disappointing a view during a day than at night!

In the example Venus was $39^0 \approx 2$ hours east of the Sun (see the "elongation" above). The best hour for observation is when Venus is highest up, and that is at its transit: 2 hours before local noon in this example. Local noon is around 1 pm when daylight savings time is in effect, so Venus is best in the example at 11 am. It was at 52^o altitude, just reasonable. It appeared in the telescope as a small disk (it was only 14" in diameter).

The best time to view Venus is when it is large and sickle-shaped, as far from the Sun as can be. This occurs for a period of a few weeks around "dichotomy" (i.e. half-Venus). When Venus is close to Earth and is sickle-shaped, it grows as large as *1 am* and gives a spectacular view (see Fig. 42). Venus as Morning Star is viewed best a few hours before noon (~10 am, Fall 2004, Spring 2006), and Venus the Evening Star viewed best a few hours after noon (~3 pm, Fall 2005). Note that in Spring 2005 Venus will be (almost) behind the Sun, practically unobservable.

Similarly to Venus, one can also spot a few of the brightest objects during the day. Their surface brightness is much lower, so they are usually unimpressive. Mercury, Jupiter, Saturn, Sirius, possibly even Vega and other very bright stars are somehow visible. Mercury especially makes sense to observe during the day, because in Mississippi conditions it is almost hopeless to ever see it after sunset.

Exercises

1. How bright is the sky on a clear day close to the Sun?
2. Calculate the surface brightness of Mercury at maximum elongation. Take the diameter and brightness data from SkyGazer. Compare your result to the surface brightness of the sky. Can Mercury be seen during the day in a telescope?

3. Calculate the surface brightness of a 2^{mg} star, assuming a reasonably good *2 as* daytime seeing. Will this star be visible in a telescope? What do you expect for the magnitude limit to be?
4. Jupiter is also visible in the daytime in a telescope, but it looks much worse than at night. Why?
5. Find Venus and a few bright stars during the day with a 12-inch Meade telescope.

IV.15. The Sun

One would think that the Sun is easy to observe, bright as it is. It turns out, however, that two factors actually make the Sun a hard object: low contrast and bad daylight seeing.

The most obvious things on the Sun are sunspots. Their centers are much colder (around 4500^oC) than the rest of the photosphere (around 6000^oC). According to Stefan-Boltzman law, the surface power density is σT^4, the umbrae of sunspots are about $3 \times (\approx 1.2\ mg)$ darker than the photosphere, while the penumbra is only about a 0.5 mg darker. Compare this to the contrast of ten magnitudes or more between the shadowy and sunny portions of a lunar crater near the terminator! The contrast in sunspots is similar to the contrast on the surface of Jupiter, and small details of sunspots are as difficult to observe as the details of the stripes and bands of Jupiter. Granules and faculae are even less contrasted on the background of the photosphere. Although a factor of 3 in darkness appears a lot, the human eye is not very good at detecting small contrast differences. When there is enough light, small differences in color are much more conspicuous than even large differences in brightness. Witness to this fact is that in visually estimating the brightness of variable stars, we have a hard time telling whether the variable or the comparison star is brighter, even when the difference between them is as large as a quarter of magnitude (≈25%).

Another difficult point is seeing. During the day the heat of the Sun generates streams of warm air moving upwards. These streams are generically small, on the order of *10 cm* in diameter. The moving air in these tubes significantly worsens seeing as compared to seeing at night. The small size of these air tubes means that telescope objectives larger than around *10 cm* will not provide improved resolution. Even in good weather, we can rarely see any detail smaller than 1 arc second (visually, for example with a 12-in telescope, we may observe planetary details as small as *0.4 as* at night). The conventional wisdom also works: we get a much better view when the Sun is high up, that is at noon, than before sunset, when the Sun is low over the horizon.

In observing the Sun we must battle the huge amount of light and heat radiated by the Sun. One simple technique is to project the image of the Sun on a piece of paper. We can simply keep the paper at some distance from the telescope and move the eyepiece out of normal focus, to achieve a sharp image on the paper. (This technique is called "eyepiece projection", see Fig. 63. Sunspots are normally easy to see this way, and an added bonus is that a few people can see the projected image at the same time. We should be careful however with the amount of heat absorbed by the optics. A large telescope collects enough heat to crack the lens of an eyepiece!

Another way of watching the Sun is through a solar filter. We state the obvious: **never look at the Sun** through a telescope without a solar filter, and the not so obvious: even looking at the Sun through the viewfinder gets you a quick trip to and a long stay in the hospital. An even **graver danger is a stray visitor looking through an unattended telescope**! Always cover, or better remove, the viewfinder from the telescope, and keep the solar filter on when you leave it unsupervised for even a minute.

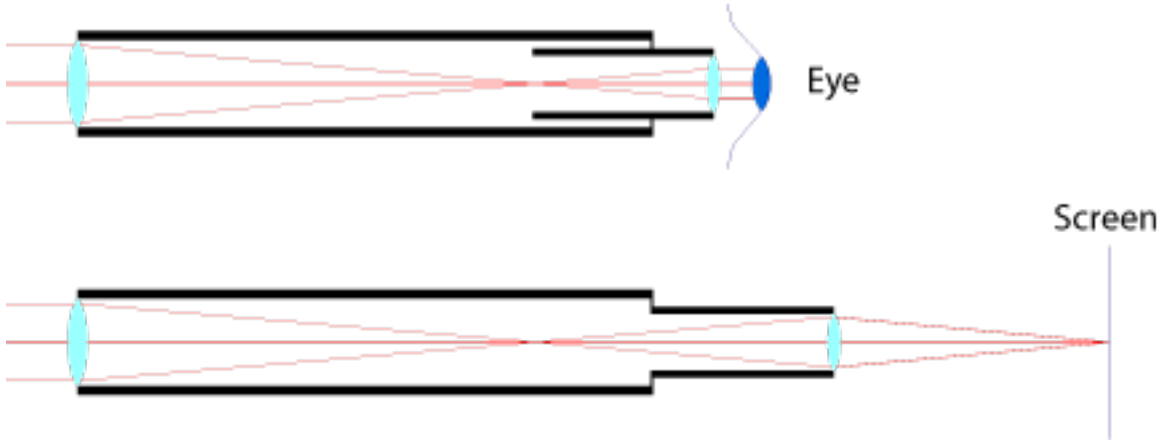


Fig. 63: This is how eyepiece projection works. The eyepiece must be moved farther out and a screen is place behind it. The eyepiece is moved to focus the projected image.

The solar filter must be placed in front of the objective. A dark filter placed next to the eyepiece is tantamount of suicide: the filter quickly heats up and cracks, and the observer's dark-adapted eyes suddenly receive the full blast of the heat of the Sun. After all, a piece of paper would catch fire in a few seconds when you place it behind the eyepiece. A good solar filter filters out 10 to 15 magnitudes (transmits a 10^{-4} to 10^{-6} portion of light).

Fig. 64: The Sun in a telescope offers a view of sunspots, faculae, granulation, and limb darkening. Do not expect to see any solar flares!

Depending on the phase of the solar cycle, one may observe a few to a few tens of sunspots at a time. One can make a drawing of the Sun every day for a few days, using eyepiece projection. The rotation of the Sun quickly becomes obvious. It is worth drawing the Sun at intervals of one month when several large sunspot groups are present, because long-lived sunspots will show the differential rotation of the Sun. Fig. 64 indicates about how much we can see in the Sun in a simple telescope.

After sunspots, solar faculae are the easiest objects to detect. Limb darkening is obvious with any telescope, and the bright white faculae show much better against the darkened background of the solar limb. Granulation can also be seen with a little effort. Because the average size of granules is *1-2 as*, somewhat higher magnification (say, 150 ×) and reasonably stable weather is needed.

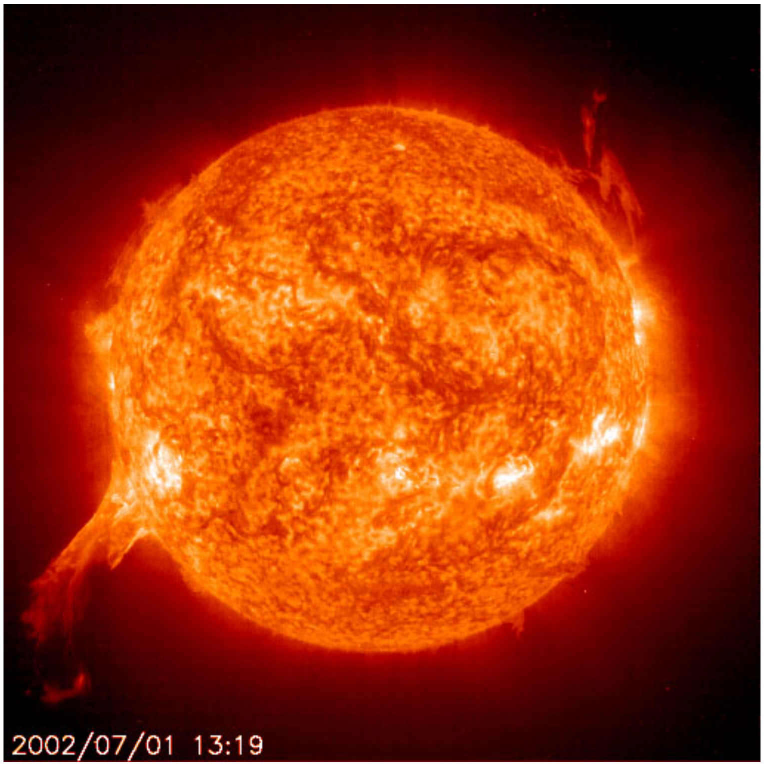


Fig. 65: A solar prominence with a Hα filter.

A narrow-band Hα filter dramatically increases the contrast on the Sun. It is an expensive and sensitive device; it takes some time and practice to align it properly. Once set up however, we very clearly see solar faculae, and it does not take much effort to find a few prominences at the edge of the Sun (Fig. 65). It is an unforgettable experience to see a solar prominence when its motion suddenly accelerates and it changes shape in a matter of a few minutes. Admittedly, we need some luck to catch them at the right time.

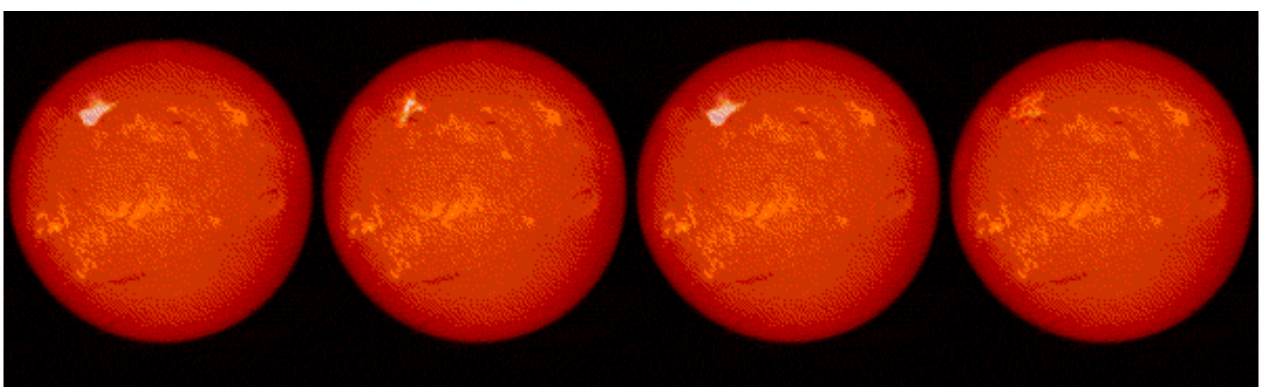


Fig. 66: The development of a solar flare over a half an hour.

A popular misunderstanding is to mix up prominences and solar flares. Solar flares are rare and short-lived events, appearing on the face of the Sun. In a flare, a sunspot-sized area brightens up for a few minutes, and then fades again (see Fig. 66). Prominences are hot gas arcs next to the edge of the Sun, often stationary.* They may last for days without much change. Flares and prominences are sometimes genetically related, but more often they are not. You do *not* need a flare to produce a

---

* Prominences, of course, exist also across the face of the Sun but they are invisible in white light. In Hα they show up as hard-to-see filaments.

prominence. Without very much time spent at the telescope the chances of ever seeing a solar flare are practically zero.

The website www.SolarMonitor.org contains almost real-time information on the visible surface of the Sun - a good place to check out if there are any sunspots before an observation session.

Exercises

1. The surface of the Sun shows much less obvious detail in the telescope than the surface of the Moon. Give two reasons why.
2. How many times is the umbra of a sunspot darker than the photosphere?
3. How come the edge of the Sun is sharp when we know it does not have a solid surface?
4. Is it safe to look at the Sun in a telescope through a dark filter placed behind the eyepiece?
5. What is the biggest danger of leaving a telescope unattended, aimed at the Sun, with a solar filter placed in front of the tube?
6. Is there any advantage in using a 12-inch telescope over an 8-inch to observe the Sun?
7. What is the difference between a solar flare and a prominence? How often can you see one (i) in white light, and (ii) in Hα? How long does each live?
8. Look at the Sun in white light and identify (i) sunspots, (ii) the umbra and penumbra of a sunspot, (iii) a bipolar sunspot group, (iii) granules, (iv) faculae. Calculate the Wolf number.
9. Look at the Sun with the Hα filtered solar telescope. Identify the features mentioned in the previous exercise, and find a filament, and a prominence. Find out its latitude. Using the resources available on the Web, find out over which active zone it hovers, and download a picture of that zone taken previously. (Note that you can do this only when there is a prominence on the edge of the Sun that is turning away from us.)
10. Draw the Sun three times in 4 - 5 day intervals, using eyepiece projection. From the motion of a sunspot, determine the rotational period of the Sun.

IV.16. Stellar spectra

Most of what we know about stars (or anything outside the Solar System at all) comes from the study of spectra. The faint light of stars must be spread out along the spectrum, and that is the reason why spectroscopy is always extremely light-starved. Even a low-resolution stellar spectrum, just detailed enough to identify a few spectral lines, requires almost research-grade equipment. With a visual spectroscope attached to a 12-in telescope, it is possible to see a few spectral lines of bright (*0-1 mg*) late-type stars such as Betelgeuse, but that is about as far as we can go.

A slitless stellar spectroscope may be attached to a small telescope to view the spectra of the brightest stars. A diffraction grating is used to separate the colors, and a cylindrical lens is necessary to stretch out the spectrum sideways, to produce spectral lines (without it the human eye is practically unable to detect the black absorption lines). The cylindrical lens needs to be aligned perpendicular to the spectrum. The whole procedure needs a certain amount of perseverance and dedication; it will not be successful with the bulk of the students at the level of an introductory course.

The spectral types of individual stars can actually be determined without seeing individual spectral lines, through the use of an objective prism paired with long exposure photography. There are also reasonable quality spectrographs in the several-thousand-dollar category. All these devices work best when used in conjunction with CCD cameras, and will be discussed in Chapter II.

Exercises

1. Use a visual spectroscopy to observe the spectral lines of a few bright stars.
2. What is the main factor that makes it all but impossible to see detailed stellar spectra without large professional telescopes?

V. The 12" Meade SCT telescopes

The most versatile instruments in our laboratory use are four 12-inch Meade Schmidt-Cassegrain telescopes; one set on the roof of Kennon observatory, three at the Dark Site, all on permanent equatorial piers. The optical quality of these telescopes is acceptable but not excellent. When laymen (or students) first look into a telescope, or when the observing conditions are less than optimal, these instruments should be used. They can be quickly set up and aimed. There are two limitations, however: (i) Deep sky objects are essentially unobservable with any telescope from campus, even when the lights are switched off, and (ii) for planets, double stars (as well as detailed observations of the Moon) the resolution is only sufficient when a cursory look is attempted.

V.1. The setup procedure

The following items are needed for successful observation:

A power supply or a 12-V electrical cord, a declination cord, a keypad.

A set of eyepieces. A good set is with focal lengths 38 mm, 26 mm, 16 mm, 10 mm, 6 mm.

Two flashlights: one strong for setup, and one weak red one during observation.

A dew removal kit.

The 12-in Meade telescopes come with a built-in microprocessor in the mount called the LX200. It keeps track of the telescope's position and can aim the telescope at any of the hundreds of thousands of objects in its catalog. This telescope is a complicated system, which needs a few alignment steps before it can be used. It is advisable to perform this operation before lab starts because fixing an unforeseen problem with the class watching is a very uncomfortable experience.

During setup and observation the telescopes must be handled carefully to avoid mechanical shocks and excessive force. Keep in mind that a *1 μm* sized dent in the gear, caused by a jolt, would make the telescope jump *2 as*, the size of the planet Neptune!

The electronics runs, nominally, on un-stabilized 18V DC power. However, due to a design problem, the LX200 circuit when regularly run on 18V has a short lifetime. Optimal is, in fact, a regulated 14V power supply. Lacking that, the telescopes run even on 12V taken directly from a well-charged car battery. (The power source at the Dark Site is a good quality car battery, located in the shed, kept charged during the day by solar cells.)

For convenience, setup should preferably be done before dark. Setup starts with unlocking the secure declination lock. (Be sure not to put on the power before this step!) Be sure that the electrical wires are drawn behind the telescope: it becomes very annoying when the wires get entangled in the dark! Then, the three electrical parts must be connected; the N/S must be set to North *before* power-on, otherwise the telescope will track *backwards*.

The next step is power on. The keypad should come to life in less than a minute of initialization. We should mention that (other than forgotten connections) two types of errors are common and the telescope operator should know about these: (i) When the clock battery inside the telescope is low, the saved telescope parameters may become compromised. This results in the LX200's inability of finding objects automatically – the telescope will aim at the wrong spot in the sky. This case can be easily diagnose by looking the RA/DEC reading. The RA reading should be constant over time, but when this error happens, the clock does not 'go' but the RA reading is changing, 'going'. An attempt to re-set the time may fix the problem, but usually a battery replacement is necessary.

Note that we cannot use the GOTO feature correctly at this point because the origin of setting circles has not been aligned yet! Note also that the equatorial piers are already well aligned with Earth's axis, **we do not need to through the polar alignment procedure**! We only need to match the zero-points of the setting circles.

As the next step we must aim the telescope at a known object, a planet, the Moon, or a bright star. Use the N-S-W-E buttons and the speed buttons on the keypad. The speed buttons are "SLEW", "FIND", "CENTER" and the almost useless "GUIDE". **Never try to touch the fine motion knobs on the mount while the power is on** – you will damage the gears!

Telescope users should develop the skills to aim the telescope at a bright star without the use of a finder-telescope or an aiming device (a Telrad). However, in a real observing situation we first try to use the Telrad to get a bright object into the Meade's field – this will almost always work because the Telrad only rarely gets out of alignment. Once we have a bright object in the field though, it is important to **immediately align the Telrad and the finder** with the Meade. (It is tempting to skip this step, but doing so backfires when we later try to aim at a faint object.)

At this stage we also match the coordinates of the aimed-at object with its known coordinates. Once you have the star in the center of the field, bring up its name in the LX200 catalog (use "STAR", "NAME", and then scroll to the star's name, "ENTER"). Then keep "ENTER" down for *3 sec*, until you hear a beep and an answer "COORDINATES MATCHED". At this point the LX200 will know where it is pointing.

Note: It is possible to user the Meade telescopes on a tripod set up as an alt-azymuthal mount. The LX200 software includes a polar alignment procedure for this case. However, in our practice we so rarely use this setup that the details of the setup procedure are not worth spending our time on.

Exercises

1. Set up a 12-ich Meade telescope for observation. Make sure each step is done correctly.
2. Learn how to aim a 12-inch Meade telescope at a bright star **without** the use of a Telrad or a finder-telescope. (This skill is needed when the Telrad and the finder are out of alignment in the first place. Normally, you should be able to use them to find a bright star and then re-align them precisely.)
3. Lean all the functions of the LX200 keypad using the telescope manual. (Except the programing and the star catalogue, which are largely useless.)
4. Use TheSky6 to find an observable minor planet in the 10 - 11^{mg} range. Print out a sky chart of its area. Use a 12-inch Meade telescope to find it. (You'll need to do it at the Dark Site, or wait for a time when the parking lot lights are switched off.)
5. Practice re-aligning the finder telescope and the Telrad.

V.2. Using the telescope

After the finder, the Telrad, and the zero of the coordinates have been aligned, the GOTO feature can be used to aim the telescope at an object. The LX200 includes a named-star catalogue (which unfortunately does not include the Bayer or Flamsted designations of stars), a numbered-star catalogue (which is essentially useless), a large part of the SAO star catalogue (up to about 7 magnitudes), the Messier catalogue, the NGC catalogue, and the GCVS (the General Catalogue of variable stars), and the planets. The planets are coded as numbered stars; 901 is Mercury, 902 is Venus, 903 is the Moon, 904 is Mars, etc. Unfortunately, the Sun is not included (it is not a star?!) but the Moon is (it is a star?!).

Occasionally you notice problems when the GOTO feature is used. It happens that all stars and deep sky objects are correctly found, but solar system objects are not. It also happens that, when slewing to an object that is obviously up in the sky at the time, an 'OBJECT UNDER THE HORIZON' error message is generated. This happens only when the telescope parameters (most often the date and/or time settings) are corrupted. A re-setting of these, and possibly a battery change, fixes the issue.

Sometimes an error occurs in the middle of an observing session, when there is no time to fix the problem. The telescope can still be used for a restricted set of objects. If tracking is still working, everything except the planets or the Moon can be still found using GOTO; the bright planets do not even need the GOTO feature. If tracking is not working (i.e. when there is no power), we can still use the telescope, but have to aim and track manually. Except for faint deep-sky objects as well as Uranus and Neptune, this is only a minor inconvenience though.

The globular cluster ω Centaury – a really spectacular object when it is visible in late Spring - cannot be found using the GOTO feature, because the telescope cannot point under -45° declination. However, one can aim at Spica, and then – unlocking the declination lock – the telescope may be manually moved South. The cluster will cross the field of the finder on the way.

The Meade SCT telescopes have been designed in such a way that there is only one optical element that can be collimated: the tip and tilt of the secondary mirror can be adjusted. The procedure is too complicated to be described here; for details refer to the Meade manual. It is however important to know how to detect when the scope is out of collimation. An obvious symptom is when, even with a good quality 1-inch eyepiece it is impossible to get a sharp image of a planet or the Moon. To be sure, look at a bright star with a 1-inch eyepiece and defocus, so the star's image looks like a donut. Correctly collimated, the donut should look perfectly concentric at all amounts of defocus. If it is not, re-collimation is necessary.

A detailed description of all the functions of the LX200 is beyond the scope of this book. It should be carefully learned directly using the Meade telescope manual.

Exercises

1. How is it possible that the LX200 erroneously declares an object to be under the horizon?
2. You are trying to aim at a faint deep sky object, and the GOTO feature does not put it in the field of view. There are three things you may try. List them.
3. How do you check if the battery is not low in the Meade LX200?

V.3. Dew removal

In hot and muggy nights dew often condensates on the telescope's optics. It first appears on the corrector, but it can also show up on the back surface of the eyepiece.

The reason for dew is that the telescope optics (the optical element facing the sky, which is the corrector lens in the case of an SCT system) radiates infrared into the sky effectively enough to cool off faster than the ambient air does, even at early night. Moisture condensates on the cold glass.

There are several ways to fight dew, but none of these has been installed permanently as of this writing (March 2017). A dew shield may be placed on the front of the telescope; small fans may be installed in front of the corrector; or a dew heater may be installed to keep the corrector lens warm. Obviously, it is impossible to guarantee that the dew heater warms the corrector lens to evenly, and only to ambient temperature, so that the quality of the image is always compromised. However, this is still better than a dewed-up telescope, which is essentially unusable.

It is important not to touch or wipe the optical surface for dew removal. One could cause damage to the optics, and new dew would immediately start forming on the lens anyway. A practically well working solution is to use a hair-dryer to dry off the dew and to warm up the optics sufficiently so as no new dew starts forming again. Of course, this practice will hurt the thermal balance for a few minutes. The power required for a strong enough hair dryer is close to a kW. This works reasonably well on the rooftop of Kennon observatory. At the dark site, where 12 V batteries are used, success is usually limited. In such a case wiping-off with optical tissue is the only solutions, which, as we said, does not work well.

Exercises

1. Why do the optical surfaces of a telescope dew up even when the ground is still completely dry?
2. How do you remove dew from the telescope?
3. What can you do to avoid the formation of dew on the telescope lens?

V.4. Closing down

After each day's observations are finished, the following needs to be done:

(i) Switch off the telescope's power, and replace the lens cap.

(ii) Open the declination lock (and leave it open), aim the telescope at the North Pole, and engage the declination safety lock. Lock the RA gently, but not very tightly.

(iii) Remove the electrical connectors and eyepieces, insert the dust plug.

(iv) Ensure that the Telrad is off, then replace the telescope cover.

Make sure nothing is left out exposed to the elements.

Exercises

1. Write a list of what needs to be done before leaving the lab.

VI. The Lunt solar H_α telescope

We have a 152 mm Lunt solar telescope in the Lewis Hall laboratory. It is equipped with two ("double stacked") narrowband H_α filters, 0.65 Å bandwidth each. The double stack, when the wavelengths are perfectly matched, provides a reduced 0.5 Å bandwidth. With these filters the absorption features originating in the solar chromosphere appear dark, greatly enhancing the contrast of granulation and filaments. The most spectacular things to see though are prominences at the edge of the Sun, which are strong in H_α emission, while the bright background sky's light is greatly reduced.

This telescope is, in fact, is the largest one commercially available off shelf in the market.

Solar telescopes, and particularly the narrowband filters, are expensive and sensitive devices. The telescope's interior and optics must be particularly clean, dust-free and smooth in order to avoid scattered sunlight. Interference filters need great optical precision and are sensitive to shaking and jolts.

The telescope is mounted on a regular Meade LX200 mount, which permanently resides on a dolly with wheels. It may be carefully wheeled out for use. There are, however, a few special points about the setup and use of this telescope.

(i) **Seeing:** As the telescope is used during the day, fighting seeing due to solar heating of the ground is a particularly sensitive issue. The main point where one can make a difference is the positioning of the telescope. For one, it is important to find a place for the telescope where the Sun is not blocked. The best practical way to judge that is it must be set up away from any shadow on the ground; but one should also estimate, ahead of time, which way the Sun is going to move in the sky during the expected duration of the observation. Second, a location must be found where the light ray coming from the Sun into the telescope passes over no rooftops and no concrete of the parking lot. The heat of these generates a strong updraft which makes seeing as bad as *10 as*. Even large sunspots would not be discernible with such bad seeing, making the telescope completely useless. At a proper location, a seeing as good as *1 as* may be achieved.

(ii) **Shade and quiet:** The filtered image in the telescope's eyepiece is quite dim. Strong sunlight badly disturbs the observer, but the telescope cannot be placed in the shade for solar viewing. It is a good idea to place the telescope in a reasonably secluded location, where at least the rest of the sky (i.e. the part away from the Sun) is blocked by trees or bushes. In practice, we found that a place near the South entrance of Kennon observatory is a reasonable compromise. An additional very good idea is to provide shade for the observer's eye by simply covering sunlight by placing an open hand in the way.

(iii) **Explanations:** Laypeople and students usually do not know what the details on the Sun's disk mean. An explanatory picture may be used and details must be explained.

(iv) **Polar alignment and transportation:** The telescope is on three wheels. It must be moved slowly and carefully to avoid jolts; the dolly is not quite stable, so watch out that it does not tip over! The RA axis should be directed toward North; but there is no need for a precise polar alignment. Direct the RA axis, as much as you can guess, within 5-10 degrees of North.

(v) **Pressure tuning:** The solar filters are equipped with pressure tuning. The air pressure on one side of the filter can be changed by turning the large black knob on the side of the filter. This changes the wavelength of the filters, which – for best contrast – must be **both matched** with the wavelength of the H_α absorption line. This is a delicate procedure.

As a practical guide, a properly tuned pair of filters gives as much contrast as possible on the granulation and prominences. The matching of the two filters' wavelengths with each other is correct when the image is the brightest: a small mis-tuning of the second filter darkens the image.

When the filters are properly tuned once, they stay reasonably well-tuned for a few days at least, and only a little fine adjustment is necessary at each observation session. The pressure tuner on each filter slowly loses air pressure however. After a few weeks, it becomes impossible to pressure-tune properly. When that happens, the black adjustment know must be completely removed and re-inserted. The re-threading of the knob must be done **very carefully**: mis-threading followed by using force will permanently damage the filter!

Prominences are visible at the edge of the solar disk at almost all times. Solar flares are rarer; during the years of solar maxima one can expect to see one solar flare every day (but they last for a few minutes only, so they must be 'caught').

Exercises

1. Practice setting up the solar telescope. Be careful to follow all the instructions. Chose the best location, and set the best magnification.
2. What is the appearance of a sunspot in the solar telescope?
3. Explain what happens to the image when one H_α filter is correctly tuned, but the other is not.
4. Explain why prominences are visible with the solar telescope while not in white light.
5. What type of telescope is best for observing sunspots?

VII. The seven-inch Questar

The best-quality commercially available telescope of all in the market is the Questar Schmidt-Caassegrain. We have a 7-inch scope installed on an equatorial tripod with wheels, and it may be taken outside for observation. Despite the small size (diameter) of this telescope, it is the best we have for planetary and lunar observation. It is a very slow telescope, and its mount has no go-to features, so it

is not convenient for objects other than planets, the Moon, and bright double stars. Also, it has no collimation screws – it has been collimated in the factory for good, and designed to be solid enough not to come out of collimation. This fact makes is **sensitive to jolts and shaking** during transportation though!

Special points about the setup and use of this telescope:

(1) **Seeing and telescope settling:** As the telescope is stored in a heated/air conditioned location, it need a long time (at least an hour) to settle in thermal balance with the outside environment. Correct use is to wheel out the telescope an hour before use, but leave on the lens cap while the scope is settling. It is no use to have an expensive telescope of excellent optical quality and destroy the quality by not letting it get into thermal balance.

(2) **Location:** Seeing in the parking lot is usually very bad, particularly compared to the capabilities of this telescope. It is important to choose a location where the light does not pass over concrete. This might require a hard compromise because trees might get in the way of the observation.

(3) **Dew:** On muggy nights dew may form on the corrector lens. The use of the dew shield help somewhat, but the only true help may be the use of a hair dryer. The dew shield should be screwed on the telescope before use. It has a fine thread on its reverse side, so be very careful not to mis-thread it. If you need any force to screw it on, it is not in the thread correctly and **you are damaging the telescope**!

(4) **Electrical connection and polar alignment:** The tracking uses a synchronous motor, and needs electric power. There is a specialized power cord, and a long extension cable will be needed to lead the power from the closest wall plug. The connector on the telescope is weak and polarity-sensitive. It appears to be possible to insert the plug the wrong way, but in fact it is not. **Forcing in the plug in the wrong way brakes it**, requiring repair! As with all visual observation, a crude polar alignment, within 5-10 degrees of North, is necessary but precision is not very important. A good guess of correct North and turning the RA axis that way usually suffices.

The telescope comes with its own built-in eyepiece. Magnification can be changed only by inserting/removing the Barlow lens using the dial at the back of the scope. Another dial can be used to insert the finder-telescope's view in the field. However, the finder is so small that it is practically useless.

The scope comes with good quality RA and DEC fine motion gears and knobs. Use them for precise aiming. However, the large-scale motion of the telescope is done through simply pushing the scope by hand: there are no locks on the RA and DEC axes.

Exercises

1. Practice setting up the Questar. Be careful to follow all the instructions. Chose the best location, and set the best magnification.
2. Observe a tight double star (such as ε Lyrae, ζ Cancri) with both the Questar and with a 12-inch Meade and compare the resolution.
3. Look at the Moon and a planet with high magnification through the Questar and through the Grubb. Compare the sharpness of the images. (This comparison may be most conveniently done during an open house event.)

VIII. The 24-inch Dobsonian: the 'Obsession'.

Our largest telescope, located at the Dark Site, is a 24-inch Newtonian reflector. It has been built as a 'light bucket', to be used for deep-sky objects. Its fast f-stop (1/4.5) allows the use of small magnification, but the price is a bright sky background and extreme sensitivity to light pollution. This is why we use it at the Dark Site.

The large size of the scope means it is stored in a shed and assembled for each use. This set-up takes a few hours of work, and is done only very occasionally.

The scope has been built with savings in mind. The 'mirror cell' is a simple linen tape; there are no gears. The telescope lays and turns on a few Teflon pads. The mount is, of course, alt-azymuthal. The result is savings in the price (it costs about 1/5 of a research quality scope of the same size), but limited use. For example, using it for photography is not really possible. Also, aiming it requires starhopping and a detailed knowledge of the sky's faint constellations.

Despite the cheap design, the main mirror is good enough quality to be used for planets. Jupiter and Saturn look quite spectacular at high magnification.

Exercises

1. Use the 24-inch Dobsonian to look at a few deep-sky objects and planets. Make drawings.

IX. The small Dobsoninans and Orion refractors

We have 12 Orion refractors and 7 ten-inch Dobsonians in the laboratory for student use. These are cheap telescopes that students can use; they can reasonably withstand the inevitable manhandling they receive in everyday use. We only comment on a few issues that may not be immediately obvious:

- The refractors come with (manual) fine motion knobs. Use them!
- The lens caps of both the refractors and the Dobsonians are irreplaceable. Please make sure that they do not get lost. The best practice is to provide a box and ask the students to put the caps in the box before taking out the scopes from the laboratory.
- The Telrads on the Dobsonians do not have an automatic power switch-off. After use, check if they are all off!

- The Dobsonians' mirror cells are attached to the end of the telescopes. If they are placed on the ground with the mirror touching the ground, they get out of collimation. Make sure they are always sit on the rubber legs when taken out of the mount!

The Dobsonians need to be re-collimated every semester anyway.

Exercises

1. Learn how to collimate the Dobsonian telescope using a laser collimator device.
2. By experimentation, find out the easiest way you can lift and carry an Orion telescope.
3. Use both a Dobsonian and an Orion to aim at the Moon and a planet. Try out high magnification.

X. Computer software

At present the 24 computers in the two laboratories are identical Mac's. They have the following software installed for astronomy labs:

- SkyGazer College Edition – planetarium software.
- CLEA astronomy laboratories.
- Safari and Firefox Internet browsers. In the toolbar you'll find a link to the Astronomy 103/104 lab home page, and to a list ("Lab Objects") of the most interesting objects visible in the sky. Pictures, data, and a short explanation accompany each object. Another toolbar link called "Lab Resources" leads to various files used in particular laboratory exercises.

These computers may also run as Windows computers by holding down 'option' at re-start. They have the following software installed for astronomy labs:

- SkyGazer College Edition (mostly useless).
- TheSky6 – sophisticated planetarium software.
- CCDops and CCDsoft – for image processing.
- CLEA astronomy laboratories. (Particularly useful is the Mass of Jupiter lab.)
- Adobe Photoshop and Microsoft Office.

Exercises

1. Go through all the menu items in SkyGazer CE, and understand what each one does.
2. Bring up data of stars in SkyGazer by clicking on them. Understand each item. In what range is the distance to the majority of stars in the sky (obviously, only the stars that are visible to the naked eye). How does this range compare to the size of the Galaxy, or to the distance from the galactic center to the Sun? Make a sketch.
3. Examine the links on the web browser's toolbar. Look up the phase of the Moon, what planets are visible, what bright asteroids are in opposition, and what comets are visible. Look at what double stars and deep-sky objects are in the "LabObjects" link, and which ones are visible now.
4. Start up one of the computers in Windows. Start up TheSky6, go through all the menu items and understand what each one does.
5. (a) Use TheSky6 to find a 10^{mg} asteroid that is high up, close to Zenith at observation time. Print a mirror-reversed star chart in such a size that the Meade field of view covers the central ¼ of the chart. Make sure the field of view of the Meade with a 26-mm eyepiece is indicated. Record also the coordinates.

   (b) Use this chart to find the asteroid in the sky using a 12-inch Meade at the Dark Site.

XI. The 15-inch Grubb

In the late 1850's the University of Mississippi, under the leadership of Chancellor Barnard, decided to build the world's largest telescope. The design of the building to house the telescope followed that of the famous Pulkovo Observatory built in 1839 outside St. Petersburg, Russia. In January 1863, Alvan Clark of Massachusetts, who later made the largest lens in the world (the 40-inch refractor in Yerkes Observatory in Wisconsin), finished grinding and polishing Barnard's 19-inch lens and tested it on Sirius, the brightest star in the sky. During this testing he made one of the most important discoveries in 19th century astronomy: he discovered the white-dwarf companion star of Sirius, now called Sirius B. This star is as heavy as the Sun, but only as large as Earth! Unfortunately, the Civil War broke out and Mississippi could not muster the payment due on the lens that would have made Ole Miss the leading astronomical institution in the country. It ended up at Northwestern University in Illinois.

By the time Barnard Observatory received its telescope in 1893, the 15-inch refractor, built by Sir Howard Grubb of Dublin, Ireland, did not make it among the largest telescopes of the world. Observatories also started to be built in locations with much better seeing, less moisture and fewer clouds on mountaintops. No more cutting-edge observational research was possible in locations like Oxford.

The 15-inch telescope has been relocated to the big dome on top of Kennon Observatory in 1939. Its design bears the hallmarks of professional quality: the usual shortcuts that make off-the-shelf amateur telescopes affordable were avoided. Its mount is quite robust (which, as we know, is usually the number one problem with amateur instruments). However, during the many decades the instrument's condition has gradually deteriorated. Its outdated clock drive has been replaced by an electrical drive in 1953, and after a half a century it has been replaced by an electronically controlled motor. The objective lens surface lost some of its smoothness, which results in a bright halo around bright stars; the sharpness of planetary images is somewhat compromised. There is no automatic slewing in a 113-year old instrument. These issues are presently being addressed and a slow refurbishment is being done. An electrically controlled lenscap has been installed. (No need to climb up to the objective for every opening and closedown.) The declination readout telescope has been given a new, better quality eyepiece. An electronic right ascension readout has been installed, much simplifying the aiming of the telescope. The old focuser unit has been replaced by an electronic one.

As the telescope was designed to do research work, to observe the same object for days at a time, setting it up and aiming it at a new object is a slow process. It requires advance planning, and some familiarity with the technical details of the mount.

The fact that the telescope is located in the big dome offers some advantages over any other instrument at Ole Miss. It is impressive - laypeople appreciate its size, its history. Because it is enclosed in the dome, streetlights do not destroy the dark adaptation of the eye. Deep sky objects, which are hard to see from the parking lot, appear brighter. It is important, however, that all the windows are kept darkened (they cannot be kept closed because that would stop the circulation of air and build a temperature difference between the inside of the dome and the outside air). Of course, the larger aperture of the telescope is also helpful. The robustness of the mount allows excellent tracking and stability. The arrangement of the large dome makes it easier to keep the attention of a class than in the parking lot, where students are distracted by campus life. All this shows that with some work this instrument can be made the best Ole Miss possesses.

XI.1. Controls and properties

The telescope has a 15-inch achromatic lens. Two lenses, made of different types of glass compensate each other's chromatic aberration. They must be kept aligned very precisely so their optical axes coincide with each other and with the main axis of the tube. They are separated by a narrow layer of air and held in place by three tiny metal foil spacers. It is a large job to take these lenses apart (or, rather, to put them back together again). The exact position of the lenses must be marked and precisely restored. One time in the past this job was not done perfectly, which resulted in a small misalignment. The quality of the image suffered accordingly, and it has been rectified only in 2011, when the lens was re-aligned in a Pennsylvania optical shop.

All large refractors are made with very slow f-stops (the Grubb is f/12), and the result is a *4.52 m* focal length. There are targets that "ask for" slow f-stops and reasonably large magnification: planets, the Moon, double stars, even some deep sky objects (planetary nebulae). Parallel to the main telescope a 9-inch astrograph has been installed. It was used for wide-field photography. The main scope with its large magnification could serve as a manual guider. However, in the light polluted sky on campus, the astrograph is now completely useless.

The mount is very robust, the bearings are large and precise. The polar alignment, once precisely performed, should not noticeably deteriorate over time. If appropriate care is taken, the mount is able to aim with arc-minute precision, and track within seeing size for ten-twenty minutes.

With a German equatorial mount, in theory, every object can be seen in two "views". When the telescope is rotated 180° around both the RA and the DEC axes, it ends up pointing at the same object. In practice, the "upper" view must be used most of the time, because in the "lower" view, when the telescope is under the RA axis, the optical tube may hit the pier. An object on the east side of the sky (i.e. clock angle $-12^h < \theta < 0^h$) must be watched with the telescope on the west side, and an object on the west side of the sky (i.e. clock angle $0^h < \theta < +12^h$) must be watched with the telescope on the east side. The "flip" between the two views occurs when the object transits (i.e. crosses the meridian from east to west). To flip the mount is a hard and slow job – it is advisable to avoid watching objects within a half an hour of transit!

Finding objects in the sky is not always easy with this telescope. "Star-hopping" is impractical in light-polluted skies. For anything other than the most obvious objects (the Moon, Jupiter, Saturn, Mars, M42, Castor and not much else) the coordinate readouts must be used.

The most sensitive parts of the mount are the RA bearings. They must turn very smoothly while they carry tremendous weight. In order to preserve their precise surfaces, we lift off the telescope from the bearings when it is not in use, and replace it on the bearings for the observing session.

The tracking motor moves the telescope around the RA axis with the 15°/hour sidereal rate. This is mechanically realized with a rotating "pie", a 2-hour section of a worm-wheel. Observations need to start with rewinding the worm-wheel by moving the telescope in the "reverse" direction with the motor all the way as far as it goes. Fig. 67 indicates the pie when it is completely rewound (notice how it sticks out on the *west* side). This gives us about two hours of observation time before the tracking stops and needs to be rewound again. Note that neither the tracking nor the motorized RA fine motion work when the RA lock is not engaged.

To find an object, the telescope can be moved in RA by hand or by the "captain's wheel" after unlocking the right ascension lock. Once the object is found, the motorized fine adjustment can be used in the east-west direction. There is no knob to turn manually to adjust the telescope east-west.

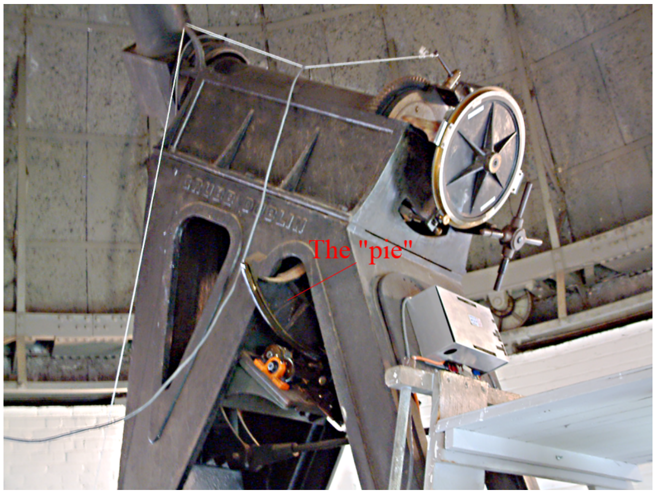


Fig. 67: The "pie" is a sectional worm-wheel. When it is all the way to the west as in the picture, it has been rewound and allows 2.5 hours of uninterrupted observation.

The telescope can be moved in declination by unlocking the declination lock, and manually pulling the telescope (see Fig. 67.). Fine adjustment can be done by turning the DEC fine motion knob. This knob will have no effect when the DEC locked is open, and it has a finite range. At the end of the range it does not move any more in one direction, and needs to be manually rewound to the middle of the range. The declination readout is located far from the observer, and a small telescope has been installed in which the observer can see the actual coordinates.

The dome is turned with a motor, which has directional switches both on the side of the pier and next to the eyepiece. The slit is opened by hand. Care should be taken that the slit is completely closed at shutdown, because otherwise rain may get into the dome. When the slit is opened, usually a large amount of dust and dirt falls. Care should be taken that this dirt does not get into any of the optics. However, if it does, it is an even graver error to wipe it off the lens – cleaning this lens needs professional work to avoid damaging the optics.

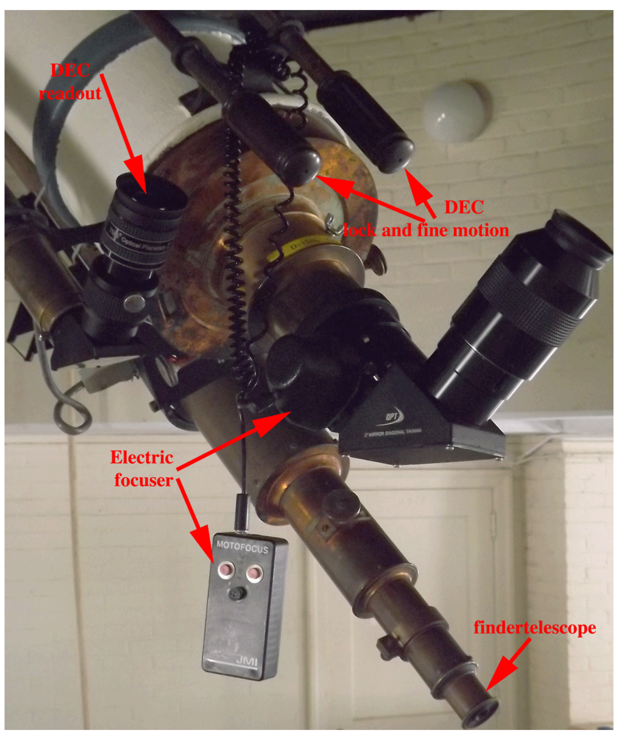


Fig. 68: The eyepiece assembly.

XI.2. The setup procedure

We provide here a step-by-step description of how to set up the telescope for observation.

1. A few hours before observation time start the air conditioning. (You want to cool the inside of the dome even colder than outside air.)
2. An hour ahead of time, open the dome slit and start on the computer. (The computer is intermittently used, and it is very slow in the first hour of its use after startup.) Make sure the date and the clock is correctly set in the computer. Start up TheSky6 and/or SkyGazer. Plan out what objects you will observe, in what order, and whether you'll use east or west side views for each one.
3. In the beginning of the observation, do not do anything (*Do not turn on the power to the tracking!*) before the telescope is placed on the RA bearing. Failing this may cause serious damage to the mount!
4. Open the lens cap. (Make sure you open the lens cap *after* the slit is opened; otherwise dirt will fall directly into the lens!) Switch on the tracking, rewind the RA drive if needed, and move the telescope and the dome slit to the general area of the first object.
5. Aim the telescope at the first object, visually if you can; use the setting circles if you cannot. Section XI. 4 explains how to do this, and how to move to your next object.

Exercises

1. Write down from memory the steps of setting up in proper order. What three steps need to be done long (hours) before the actual observation?

XI.3. Cautions

There are several issues that need to be kept in mind for safe and successful operation of the telescope. This telescope has great historical and monetary value, and its handling needs much more care than any other instrument at Ole Miss that can be replaced when it breaks.

Fig. 69: An object on the right (west) side, i.e. after transit, must be viewed with the telescope on the left as correctly indicated on the picture on the left. An object on the left (east) side, i.e. before transit, must be viewed with the telescope on the left. The telescope in the image on the left is incorrectly used and may hit the pier.

1. As with all German equatorial mounts, the telescope can hit the pier when it is used in lower view. Traces of such accidents are noticeable on the tube; make sure you will not cause such trouble! The general rule is that when you are watching an object before transit (i.e. on the east side), you must have the telescope on the west side of the pier and vice versa (see Fig. 69). When the object transits, you'll need to change views, and it involves turning the telescope 180° around both RA and DEC axes. This flipping is an awkward procedure. Be sure to plan your session properly ahead of time, so you do not have to flip during observation. Notice that there is a ½ hour grace period after an object transits, while the telescope is still avoiding the pier - but you should try to avoid observing *anything around transit*, it is not safe! Of course, SkyGazer/TheSky with the proper setting make it obvious when an object transits; check it out every time!

2. Watch carefully when you move the telescope. Watch out for hitting the pier, the ladders, and for any wires getting stuck. To flip sides, turn the telescope using the captain's wheel (with the RA unlocked, of course), always moving it over the RA axis and *never under it*! (See Fig. 70.)

3. Take care not to move the telescope while it is off the bearings, or when the lock on appropriate axis is locked. Doing so could cause great and unrepairable damage. Make sure, however, that the telescope is locked during observation though. The tracking will not move the telescope unless the RA is locked. **Make sure the tracking power is always off while the telescope is not on the bearings!**

4. The optics need to be protected from dust and dirt. Do not open or close the slit unless the lens cap is on, because a large amount of dirt falls into the lens every time you do this!

5. Make sure the ladder's wheels are locked while people are on it. A ladder that is rolling away while someone is climbing on it can cause a serious accident!

6. You must recognize that working with this instrument is time consuming. Do not rush; plan ahead of time. Trying to do a quick job will end in disappointment, failure, or accident!

Fig. 70: Left: incorrect and dangerous move, the tube is under the RA axis. Right: the correct way to turn the telescope. For complete 180° flipping, it is also advisable to turn the declination to +90°, i.e. parallel to the RA axis, before moving in RA. It will be exceedingly hard to reach the declination controls otherwise.

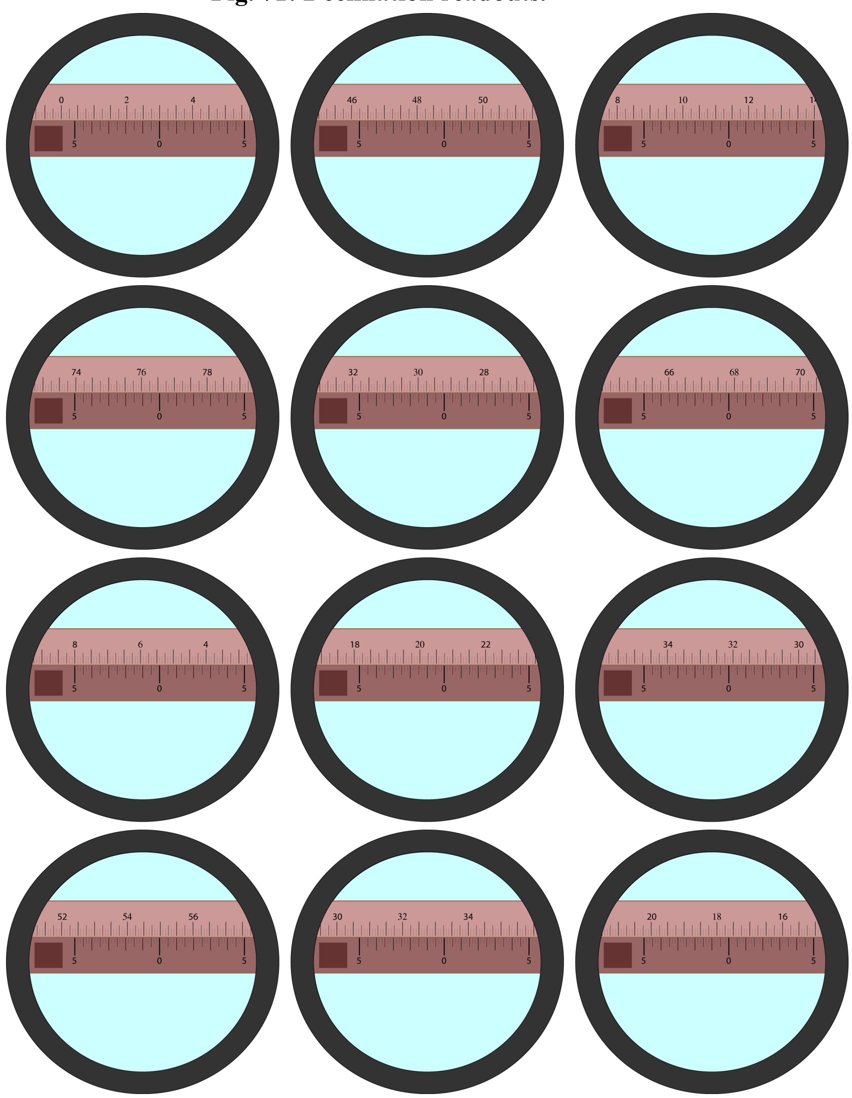
Exercises

1. What direction do you want to move the telescope in RA in order to take off the lens cap?
2. Using SkyGazer, bring up the meridian line on the screen. Record an object that transits during a planned observation session tonight. Write a plan of an observation including that object.

3. The telescope is not tracking, although the clock drive is switched on. Mention two things that can cause this.
4. Write down, from memory, a list of conceivable mistakes a person setting up, using, and closing down the Grubb telescope should carefully avoid. List which ones may damage to the equipment.
5. In what order do you do these steps?
    - Open the slit; remove the lens cap; put the scope on the bearings.
    - Close the slit; replace the lens cap; take the scope off the bearings.

XI.4. Aiming

Fig. 71: Declination readouts.



The telescope mount has no motors to move it in declination, and even in right ascension the motor can move the telescope only a small portion of a full circle. Consequently, aiming must be manual - the telescope will not slew to an object upon pushing a button. Of course, it is always easy to aim at a bright object like Jupiter or the Moon: simply aim the finder-telescope at it, center, and the object will show up in the main scope. One can find some fainter objects by star-hopping, starting with a bright star and following fainter stars on a star chart. In practice however, this proves tricky, because the finder's field is small, and because it is hard to see the stars through the narrow slit of the dome. For faint objects it is almost always necessary to use the coordinate scale.

The size of the field in the main telescope with a 35-mm eyepiece is about 30', so that we need to aim the telescope with a precision of ±15' (i.e. ±1 sec in RA) to surely find it in the field. Much less precision, ±30' (i.e. ±2 min in RA), is sufficient in order to have the object in the finder's 1° field - which will of course do only if the object is bright enough to show up in the finder.

Although the setting circles allow us to go by the coordinates only, it is always advisable to move the telescope to the approximate location of the object in the sky before the setting circles are used for precise aiming. The crude location of the object (if you don't already know from previous practice) may –and should – be read out from the SkyGazer software.

The next thing to do is to set the declination. A small telescope, with its eyepiece next to the main telescope's, is looking at the illuminated declination setting circles (the switch is next to the eyepiece). It has a helical focuser – use it to make the readout sharp. The view in this telescope is something like in Fig. 71. The bottom scale is fixed; the top scale turns as the declination of the telescope is changed. You need to read the top scale at the zero of the bottom scale. With careful reading a ±1' precision aiming is possible without using the bottom (nonius) scale at all, and that is sufficient to have the object in the field with a 35-mm eyepiece. More precise aiming is only necessary in special applications. It is advisable to gain some practice in reading this scale through the exercises below, because at the telescope it is more difficult to see the numbers in the field of the eyepiece. It is especially useful to notice that one (little) tick on the top scale corresponds to 5', so some interpolation is necessary to attain the required precision. A practical problem with the declination readout is that the setting circle does not indicate the ± sign of the declination. You must supply it yourself by looking at the telescope, and decide whether it is pointing North or South of the equator.

Tracking is driven by a stepping motor with an electronic controller that has two speeds: a sidereal rate for tracking, and a much faster rate for precise aiming and rewinding. The motion is normally controlled from the control box located next to the eyepiece, where the direction of the motion may be chosen and fast speed may be switched on with a push-button.

Alternatively, the tracking motor may also be controlled from the computer in the dome through an RS232 serial connection. One way to connect to the tracking controller is to start the *Hyperterm* software by double-clicking on the *GrubbTracking.ht* icon on the desktop. You can find a (short) list of the setting commands if you open the help.txt file on the desktop. These commands check the connection (X), set the correct parameters (see the help file), set sidereal speed (M2000), set lunar speed (M1935) to track the Moon precisely, stop the motor (M0), and rewind the pie (M-64000). Note that each command must be followed by pressing the return key. If no answer text appears on the panel, the communication is broken. (Check the power!)

A more sophisticated piece of software (originally written by this author in Visual Basic 6) provides more extensive control of the telescope. It is under development, and only a few features are working now, so check for the current version. It is called *GrubbControl* and it can be started by double-clicking on the so-named icon on the desktop.

At the time of this writing (March 2017) the only useful part of *GrubbControl* is the RA readout. With the tracking power switched on, after clicking the appropriate CDT/CST radio button, the reader reads off the telescope's RA position and displays it once every 10 seconds. This can be used to move the telescope manually to the required RA coordinate. In practice, the readout is precise enough to aim the telescope so that the object shows up in the field of the 35-mm eyepiece.

A shortcoming (to be fixed soon) of the RA readout is that the hour that it reads may be off by 12 hours. It is easy to notice this and add/subtract the 12 hours to rectify the readings.

Preliminary measurements of the aiming precision indicate that the RA scale is precise to a few seconds, but the declination scale is displaced by 5'-6'. You'll find the object actually this much to the south of its assigned position. Work is in progress to correct this inaccuracy.

Exercises

1. Using Fig. 74, determine each declination reading to a precision of ±1'. Do **not** use the bottom scale at this point. You will need to do this readout with this precision in practice. As an example, the top left reading is +16°22'. Notice that, when the numbers increase to the left, the declination is negative!
2. As a preparation for more detailed work (not very often needed in practice though), decipher the procedure as indicated in the middle and bottom portion of Fig. 74; then read all the declinations to ±1" in Fig. 74. Notice that the right side of the bottom scale must be used for negative declinations, while for positive declinations you will use the left side of the bottom scale.

XI.5. Observing

The focal length of the lens is *180 in = 4572 mm*. For aiming, the 35 mm eyepiece should be used due to its large field of view. (It gives 130 x magnification and a 0.53 degree field.) For most observed objects, higher magnification should be chosen – it reduces skyglow and makes details more apparent. However, experience shows that good resolution can be achieved only when the dome has a few hours of thermal balancing time.

Previous attempts resulted in resolving double stars with 0.6 sec separation in exceptionally good conditions, using the 'lucky observation' technique.

For lunar observation a filter may be screwed on the eyepiece to avoid excessive brightness. This gray lunar filter is kept in the same box where the eyepieces are.

The focuser contains several buttons (see Fig. 68) There is a rack-and-pinion focuser which can be adjusted and it also has a lock. Be sure to examine the focuser, understand what each knob does; than you'll know how to avoid forcing the focuser to turn while it is locked.

The finder-telescope is a large, 100-mm refractor. Many objects, including faint deep-sky, will show up in it. Use it to locate objects as help for aiming!

The focuser and eyepiece are mounted on a rotating platform. This *instrument rotator* is useful for photography.

XI.6. The closing procedure

We provide here a step-by-step description of how to shut down after observation.

1. As a courtesy to the next observer, rewind the RA tracking, then switch it off.

2. Replace the lens caps. Move the telescope to a vertical position and take it off the bearings.

3. Close the dome, and switch off the dome rotator power.

4. Double check all of the following: (i) the lens caps are on; (ii) the RA is off the bearings; (iii) the dome is closed and there is no gap in he slit for rain to get in; (iv) the Telrad, the AC, the

computer, the RA tracking, the dome rotator are all off power; (v) the eyepieces and filters are safe from dust; (vi) all lights are off; (vii) the windows, the doors and the trapdoor to the gallery closed.

Exercises

1. Write down from memory the steps of closing down in proper order. Mention three things that must not be done in the wrong sequence to avoid damage.
2. Practice the skills needed to use the Grubb telescope by repeatedly setting up the telescope and observing various objects. When you have acquired the necessary skills for independent work, demonstrate it by leading an observation session of 3-4 objects in one night. (An open house is a perfect time for such a demonstration.)

XII. Miscellanea

XII.1. Polar alignment

Equatorially mounted telescopes must be polar aligned, in order to match the RA axis with the direction of the North Pole. The required precision is about ±*10°* for casual observation through an eyepiece (a 'guess' of the direction of North is sufficient); about ±*1/4°* for a GoTo telescope on a pier (we want aiming to be precise enough for the object to be in the field); and ±*1am* for precision tracking (such as photography).

There are in general three methods used for polar alignment:

(1) **Two-star alignment.** We measure the amount a GoTo mount mis-aims at a few stars; in principle, two, in practice a half-a-dozen stars are used. This method is described in Appendix IV. This is the easiest method to be used when about ±*1/4°* precision is sufficient.

(2) **Drifting.** Two stars are aimed at, both close to the equator, one close to transit, the other just rising in the East. In case of inaccurate polar alignment, the stars drift in the North-South direction, and the precision of tracking does not affect this drift. If the star in the East drifts, the RA axis must be raised/lowered; if the transiting star drifts, the RA axis must be turned in the horizontal direction. Each degree of polar misalignment causes a drift rate of 1/50 sidereal, i.e. 18 as/min. A crosshair eyepiece and a lot of patience allows even an alignment precision of ±*1am*.

(3) **Telescope mount modeling.** There is a commercially available inexpensive piece of software called *TPoint*, which may be easily integrated with the *TheSky* planetarium software, to facilitate this work. The observer must connect a computer to the mount (through RS232 serial wire in the case of the LX200), and 'map' a large number of stars' positions. This data collection may take a few hours if precision is required. The software quickly calculates the necessary polar adjustment. The ±*1am* precision is quite easily achieved as long as the pier's orientation is adjustable with the required ±*0.05mm* accuracy. For details, consult the *TheSky* software manual.

XII.2. Using the crosshair

We have a number of *f=12.5 mm* eyepieces with a double crosshair. The cross is in the focal plane, so that the *0.28 mm* separation of the parallel lines corresponds to 1.28° in the field; i.e. a separation of $\frac{77\ am}{M}$ in the sky. (*M* is the magnification.) With the 12-inch Meade this translates to *19 as*, and with the Grubb, 12.63 as. A 3x Barlow lens would, of course, reduce this to and *6.33 as* and *4.21 as* respectively. Consequently, the crosshair could be used as a device for crudely estimate the size of the planets Uranus or Neptune, or to guess the separation of tight double stars – but no precision measurement can be done with it.

The crosshair eyepieces come with an illuminator, a laser diode powered with two *1.5 V* watch battery cells. They may be switched on/off by rotating the battery holder. The whole design is very sensitive and the electrical connections are prone to disconnect. In addition, there is no clear indication from the outside when the illumination is on, so that it is easy to make the mistake and leave it on after observation, which results in a dead battery bleeding acid within a few hours. Consequently, the use of the illuminated crosshair is limited. We have found, incidentally, that removing the illuminator and shining a flashlight into the hole made the hairs easily visible.

We may note that the illumination is actually too weak to be seen under the streetlights on campus, and it is of any use only at the Dark Site. The black hairs are clearly visible on campus against the bright sky.

For some uses of the crosshair the lines must be aligned with the E-W direction. Both on the Meade's and the Grubb, this can be achieved by electronically moving a star E-W in the field and turn the eyepiece until the star moves parallel to the crosshair.

Exercises

1. Try out the crosshair on both a Meade and on the Grubb, with and without a 3x Barlow lens.

Appendix I. Data of Objects

1. The Solar system

Name	Synodic period	Diameter (max)	Brightness (max)	Elongation (max)	Note
Sun	365.2422 d	32 am	-26.78 mg		Tropical year
Mercury	116 d	13 as	-1.9 mg	26°	Size & brightness vary
Venus	1 y 7.2 mo	65 as	- 4.4 mg	44°	Size varies
Moon	29.53 d	34 am	-12.5 mg		
Mars	2 y 49 d	26 as	-2.8 mg		Size & brightness vary
Phobos	7 h 40 m		11.6 mg	25”	
Deimos	1 d 5.4 h		12.8 mg	62”	
Ceres	1 y 101 d	0.8 as	7.4 mg		
Jupiter	1 y 33.7 d	50 as	- 2.6 mg		Oblateness: 6.5%
•Io	1 d 18.5 h	1.2 as	5.0 mg	2’18”	
•Europa	3 d 13.3 h	1.0 as	5.3 mg	3’40”	
•Ganymede	7 d 4.0 h	1.7 as	4.6 mg	5’51”	
•Callisto	16 d 18.1 h	1.6 as	5.6 mg	10’18”	
•Amalthea	11 h 57 m		14.1 mg	59”	
Saturn	1 y 12.8 d	20 as	- 0.3 mg		
→Ring		46 as			
•Titan	16.0 d	0.7 as	8.3 mg	3’17”	
•Rhea	4.5 d		9.7 mg	1’25”	
•Thetys	1.9 d		10.2 mg	48”	
•Dione	2.7 d		10.4 mg	61”	
•Iapetus	22.9 d		10.2–11.9 mg	9’35”	
Uranus	1 y 4.4 d	3.7 as	5.6 mg		
Titania	8 d 17 h		13.7 mg	20”	
•Oberon	13 d 11 h		13.9 mg	33”	
Neptune	1 y 2.2 d	2.2 as	7.7 mg		
•Triton	5.9 d		13.6 mg	16”	
Pluto		0.11 as	13.9 mg		In Serpens
•Chiron	6.4 d		16.8 mg	0.68”	
(50000) Quaoar			19.2 mg		In Ophiuchus
(90377) Sedna			21.2 mg		In Cetus
2003 UB_{13}			18.8 mg		In Cetus

2. Surface brightness data

The following is a table of the visual surface brightness (R) of various objects (V-band). Recall that the surface brightness of a resolved object does *not* depend on its distance from us.

Name	**Surface brightness**	**Total brightness**	**Dia-meter**	**Note**
Sun	- 10.6 mg/as^2	- 26.8 mg	32 am	
Moon	+ 3.6 mg/as^2	- 12.5 mg	31 am	At full moon; otherwise fainter.
Venus	+ 2.2 mg/as^2	- 4.4 mg	24 as	At dichotomy (“half Venus”); otherwise R is the same, V and Φ are different
Jupiter	+ 5.4 mg/as^2	- 2.7 mg	47 as	In opposition
Saturn	+ 6.9 mg/as^2	+ 0.7 mg	20 as	V is for the planet; ring and disk have the same R.
Daylight sky	+ 2 to + 6 mg/as^2			Depends on distance from the Sun.
Sky at full Moon	+ 16 to +20 mg/as^2			Depends on distance from the Moon.
Sky at night on campus	+ 17 to +19 mg/as^2			In a reasonably dark spot, with 4 mg stars visible in Zenith.
Natural skyglow	+ 21.5 mg/as^2 + 21.8 mg/as^2			At h=45^0. In Zenith (h=90^0).
Zodiacal light	+ 19.5 mg/as^2 + 22.3 mg/as^2 + 22.0 mg/as^2			30^0 from the Sun 150^0 from the Sun 180^0 from the Sun
Milky Way	+ 21 mg/as^2 + 19 mg/as^2			Average Brightest parts
Globular clusters	+ 15 - 16 mg/as^2			
The Ring Nebula	+ 17.4 mg/as^2	+ 8.8 mg	1.2 am	M 57
The Dumbbell	+ 20.1 mg/as^2	+ 7.3 mg	7 am	M 27
The Orion Nebula (M42)	+ 12.8 mg/as^2 + 10-11 mg/as^2	+ 4.0 mg	66 am	Average Brightest parts
The bulge of a galaxy	+ 19 - 20 mg/as^2			
Spiral arms of a galaxy	+ 22 - 24 mg/as^2			

The surface brightness of the Moon changes dramatically with the phases. The following table gives the brightness of the Moon, and the difference between its changing brightness and the full Moon.

Age	Elongation	$V-V_0$	V	$R-R_0$	R
2.3 days	30°	5.86 mg	- 6.88 mg	2.94 mg/as^2	+6.28 mg/as^2
3.1 days	40°	5.10 mg	- 7.64 mg	2.33 mg/as^2	+6.13 mg/as^2
3.9 days	50°	4.52 mg	- 8.22 mg	1.87 mg/as^2	+6.01 mg/as^2
4.7 days	60°	3.98 mg	- 8.76 mg	1.51 mg/as^2	+5.83 mg/as^2
5.5 days	70°	3.52 mg	- 9.22 mg	1.21 mg/as^2	+5.67 mg/as^2
6.2 days	80°	3.11 mg	- 9.63 mg	0.96 mg/as^2	+5.51 mg/as^2
7.0 days	90°	2.74 mg	- 9.00 mg	0.75 mg/as^2	+5.35 mg/as^2
7.8 days	100°	2.34 mg	- 10.40 mg	0.58 mg/as^2	+5.12 mg/as^2
8.6 days	110°	2.00 mg	- 10.74 mg	0.43 mg/as^2	+4.93 mg/as^2
9.3 days	120°	1.69 mg	- 11.05 mg	0.31 mg/as^2	+4.74 mg/as^2
10.1 days	130°	1.40 mg	- 11.34mg	0.21 mg/as^2	+4.55 mg/as^2
10.9 days	140°	1.13 mg	- 11.61 mg	0.14 mg/as^2	+4.35 mg/as^2
11.7 days	150°	0.84 mg	- 11.90 mg	0.08 mg/as^2	+4.12 mg/as^2
12.5 days	160°	0.56 mg	- 12.18 mg	0.03 mg/as^2	+3.89 mg/as^2
13.2 days	170°	0.28 mg	- 12.46 mg	0.01 mg/as^2	+3.63 mg/as^2
14 days	180°	0.00 mg	-12.74 mg	0.00 mg/as^2	+3.36 mg/as^2

3. Often used numbers

The coordinates of Kennon Observatory: 89°32’12” W, 34°21’52” N, +152 m.

Time difference: UT = CST + 6 h, UT = CDT + 5 h.

Length of the year, tropical (equinox to equinox) 365.2421897 days = 31, 556, 925.19 sec

Length of the year, sidereal (star to star): 365.25636 days = 31, 558, 150 sec

Rotational period of Earth: 23 h 56 m 4.090549 s

The astronomical unit: 1 AU = 149, 597, 870.66 km

A light year: 9.46×10^{12} km = 63, 070 AU

A parsec: 3.262 light years = 9.461×10^{12} km = 206 265 AU

Diameter of Earth (equatorial): 12, 756.272 km

The distance to the Moon: 384, 400 km ± 25, 150 km (± due to eccentricity of orbit).

The diameter of the Moon: 3476 km

The whole sky is 41, 253 deg^2 = 5.35×10^{11} as^2

The number of stars brighter than 12 mg is ~ 4 million stars ~ 100 stars / deg^2

A 1 W white light bulb at 1 mile shines as a 0 mg star.

The Hubble constant: (100 x h) km s^{-1} Mpc^{-1}, where $0.5 < h < 0.85$

The distance to the center of the Galaxy: 27, 000 light years = 8.3 kpc

Julian dates:

$$JD = (1461 \times (Y + 4800 + (M - 14) / 12)) / 4 + (367 \times (M - 2 - 12 \times ((M - 14) / 12))) / 12 - 3 \times ((Y + 4900 + (M - 14) / 12) / 100)) / 4 + D - 32075,$$

where Y is the calendar year, M = month, D = day; JD = Julian date at noon UT.

At 12:00 UT (noon) on	*Julian Date (JD)*
Jan 1, 4713 B.C.	0.0
Jan 1, 2000	245 1546.0
Jan 1, 2005	245 3373.0
Feb 1, 2005	245 3404.0
March 1, 2005	245 3432.0
April 1, 2005	245 3463.0
May 1, 2005	245 3493.0
June 1, 2005	245 3524.0
July 1, 2005	245 3554.0
August 1, 2005	245 3585.0
Sept 1, 2005	245 3616.0
Oct 1, 2005	245 3646.0
Nov 1, 2005	245 3677.0
Dec 1, 2005	245 3707.0
Jan 1, 2006	245 3738.0

4. The human eye

On the retina, there are 2.7 rods/am^2, and 0.1 cones/am^2.

The cones are more sensitive to light, but the rods provide better resolution.

On the fovea (the central part of the retina), which is 100 am in diameter, there are 4.5 rods/am^2, and no cones. The resolution of the human eye on the fovea is 1 am.

The detection threshold for faint, large and steady objects is 27.2 mg/ as^2 with a resolution of ~ 3^o (!!) in complete darkness, possible only outside the fovea (averted vision).

6. The Greek alphabet

Lowercase	Capital	Variant	Name
α	Α		Alpha
γ	Γ		Gamma
σ	Σ	ς	Sigma
θ	Θ	ϑ	Theta
ν	Ν		Nu
υ	Υ		Yplison
ο	Ο		Omicron
ω	Ω		Omega
φ	Φ		Phi
ψ	Ψ		Psi
ζ	Ζ		Zeta
ξ	Ξ		Ksi
β	Β		Beta
ι	Ι		Iota
η	Η		Eta
π	Π		Pi
κ	Κ		Kappa
λ	Λ		Lambda
μ	Μ		Mu
ρ	Ρ		Rho
δ	Δ		Delta
ε	Ε		Epsilon
τ	Τ		Tau
χ	Χ		Chi

Appendix II. Objects for observation

This appendix exists in the form of a PowerPoint presentations, called LabObjects.ppt.

Appendix III. Data of our telescopes

(1) The **Grubb refractor** is located in the large dome of Kennon Observatory. A 2-piece achromatic refractor, Φ = 15 in = 38 cm, f/12, f = 15 feet = 4.572 m. German equatorial mount of professional quality, but designed 130 years ago. Precise setting circles are manually read out. Aiming at a new object is slow, requires a careful half-an-hour long procedure. Less obvious objects need to be found by manually setting the coordinates. Tracking stops after a good hour, the gear needs to be rewound. The right ascension fine motion and the tracking is motorized but in need of complete replacement. The optics is incorrectly aligned, needs realignment. The thermal balance inside the dome is hard to achieve, needs improvement. As it is, the telescope forms a less sharp image than a 12-inch Meade in the parking lot.

However, it is superior for visually observing faint objects because the dome covers much of the streetlight and allows for a better dark adaptation of the eyes. Upon fixing the problems it may become a superior instrument for planetary and lunar observation.

(2) There are five **12-in Meade telescopes**, one permanently installed in the gallery of Kennon Observatory, three set up at the Dark Site, and one (in the laboratory) may be put on an alt-azymuthal mount. The design is Schmidt-Cassegrain, Φ = 12 in = 3048 mm, f/10, f = 120 in = 3.048 m. Magnification with a standard 26 mm, 44^{o} Plössl eyepiece is 120 x, field = 22 am, somewhat less than the disk of the Moon. A computerized modern GOTO fork mount (LX200). The quality of the mount is adequate for visual observation, but marginally inadequate for photography or CCD imaging. The most damage-prone part is the declination gears. The optical quality is reasonable but not superb: the diffraction pattern of a star is visible but there is much scattered light, which damages the sharpness of the view. These telescopes are the best we have for everyday work.

(3) There is one **8-in Meade telescope**, which can be installed on the equatorial piers or on altazimuthal tripods. Data: Φ = 8 in = 203 mm, f/6.3, f = 50.4 in = 1.280 m, Schmidt-Cassegrain design. Magnification with a standard 26 mm, 44^{o} Plössl eyepiece is 49 x, field = 54 am, almost twice the size of the Moon. A computerized modern GOTO fork mount (LX200). The quality of the mount is adequate for visual observation, but marginally inadequate for photography or CCD imaging. The most damage-prone part is the declination gears. The optical quality is reasonable but not superb: the diffraction pattern of a star is visible but there is much scattered light, which damages the sharpness of the view. These telescopes are easy to set up and handle, but for clusters, galaxies and nebulae they are much inferior to the 12-in, due to the smaller amount of light they collect.

(4) There are two **8-inch Celestrons**, which can be set up on the rooftop of Kennon Observatory or on tripods. Data: Φ = 8 in = 203 mm, f/10, f = 80 in = 2.03 m, Schmidt-Cassegrain design. Magnification with a standard 26 mm, 44^{o} Plössl eyepiece is 78 x, field = 34 am, equals the size of the Moon. A rickety fork mount with electric tracking. Inadequate for photography or CCD imaging, but reasonable for visual observation of the moon, planets, and double stars. No computerized mount, and inadequate finder. It is very hard to aim at faint objects in a light polluted environment.

(5) The **Questar**. Data: Φ = 7 in = 178 mm, f/14, f = 100 in = 2.54 m, Schmidt-Cassegrain design. Magnification with the built-in 24 mm eyepiece (without the Barlow lens): 100 ×, field of view: 26 am. Mounted on a heavy tripod or on an equatorial pier. Superior optical quality and superior mount. The image is sharper at the same magnification than with any of our larger telescopes. The best telescope to use for planets and the Moon. For faint objects inferior to the 12-in Meade due to smaller aperture. No GOTO mount, but there is electric tracking on the equatorial pier. Faint objects are hard to find.

(6) The **Pronto**. A superior quality small refractor. Data: Φ = 2.75 in = 70 mm, f/6.8, f = 18.9 in = 480 mm. Mounted on an altazimuthal tripod. Inadequate for photography. The best instrument for the Pleiades.

(7) The **large Dobsonian**., brand name *Discovery*. Data: Φ = 25 in = 635 mm, f/5, f = 125 in = 3.175 m, Newtonian design. Magnifications with a 50 mm eyepiece: 62 ×. The image quality is reasonable, the mount is rudimentary, alt-azimuthal. Aiming at faint objects is difficult. Due to the telescope's large size, it is the best telescope for faint but easy-to-find deep-sky objects such as the Orion Nebula. It is located, dis-assembled, at the Dark Site.

(8) Two small **black Dobsonians**. Data: Φ = 10 in = 254 mm, f/5.6, f = 56 in = 1.42 m, Newtonian design. Magnification with a standard 26 mm, 44^o Plössl eyepiece is 56 ×, field = 47 am, the disk of the Moon fits comfortably. The optical quality is acceptable, the mount is rudimentary. Fit for beginner students' use.

(9) Many small **white Dobsonians**. Data: Φ = 10 in = 254 mm, f/4.5, f = 45 in = 1.14 m; Newtonian design. Magnification with a standard 26 mm, 44^o Plössl eyepiece is 44 ×, field = 1^o, twice the size of the Moon. The optical quality is acceptable, the mount is rudimentary. Fit for beginner students' use.

(10) A 152-mm **Lunt solar telescope**. This is the largest off-the-shelf H_α telescope in the market. It is installed on an LX-200 mount on a tripod, and may be wheeled out of the laboratory for observation. It has an adjustable (zoom) eyepiece. The double-stack H_α filters need careful adjustment for observation, but they are capable of cutting the bandwidth together down to 0.5 μm.

(11) Twelve 5-inch achromatic **Orion refractors** on tripods. These should be used for the bulk of student laboratories. They come with a 26-mm and a 9-mm eyepiece, and an erect-field finder-telescope. The mount is alt-azymuthal, which makes aiming difficult near Zenith, but otherwise easy. The mount comes with handy fine motion in both direction, so precise aiming and tracking is greatly simplified.

Appendix IV. Two-star polar alignment

The following procedure is turns out to be the least time consuming method to polar align a permanently mounted GoTo telescope (such as the Meade LX200). We found that its precision, in practice, is about 10 am, which is sufficient for putting objects directly in the field of the main telescope (a Meade 12-inch SCT) for visual observation. Photography, CCD imaging or spectroscopy would require a more sophisticated method though. The procedure steps are as follows:

(i) We pick a star to match the coordinates on (in the example it was Diphda) and record the time

(ii) We pick another star (Fomalhaut this time), slew to it, then move the telescope to it with keypad. Record the true coordinates and the coordinates at which the star has been found.

(iii) Do this with a total of six stars. Do not match the coordinates in the process.

(iv) Go back to the first star (Diphda) and record at what coordinates it has been found.

The data collection should not make more than about 30 minutes. Note, however, that the precision of the polar alignment will be severely compromised unless each star satisfies the following two conditions: $\alpha_i \neq \alpha_0$ and $\delta_i \neq -\delta_0$, where *i* refers to each observed star and *0* refers to the alignment star (Diphda in our case).

Tel	Star	True coords	Found at	
S	Diphda	$00^{h}44^{m}16^{s}$-17°54’00”	*14Dec2016, 6:23 pm CST*	
	Fomalhaut	$22^{h}58^{m}34^{s}$-29°32’00”	$23^{h}00^{m}05^{s}$-30°25’00”	
	Markab	$23^{h}05^{m}29^{s}$+15°17’00”	$23^{h}01^{m}31^{s}$+14°22’33”	
	Deneb	$20^{h}41^{m}57^{s}$+45°19’59”	$20^{h}36^{m}07^{s}$+43°28’21”	
	Aldebaran	$04^{h}36^{m}46^{s}$+16°32’00”	$04^{h}33^{m}25^{s}$+17°51’28”	
	Capella	$05^{h}17^{m}49^{s}$+46°01’00”	$05^{h}13^{m}12^{s}$+47°25’59”	
	Diphda	*14Dec2016, 6:39 pm CST*	$00^{h}44^{m}20^{s}$-18°02’56”	

The data are now manually inserted into the Mathematica program TwoStarAlignment**.nb, a copy of which form part of this manual. The working of this code is obvious. A scatter plot will be drawn, whose scale might have to be changed. The final result comes in the form of two lines:

-0.300555 deg raised up

2.2175 deg toward West

This means that the polar axis should be lowered by 0.300555° and turned towards West by 2.2175° around the vertical.

We found it practical to do the turning/raising during the day. The pier must be turned, and the best way to do it is to precisely calculate (this is simple trigonometry) the amount of turning needed in millimeter units, then draw a pencil mark on the pier. For the vertical adjustment, we calculate the thickness of shims needed to be inserted/removed. The required precision of the turning is about ± 0.2mm. After the turning is done, the procedure is repeated one more time to ensure correctness.

The calculation in TwoStarAlignment**.nb is explained in the TwoStarAlignment.pdf write-up. The correctness of the formulas is checked with the program TwoStarAlignmentDerivations.nb.

Appendix V. A list of observational exercises

For ease of reference, here is a list of all exercises in this manual that involve observations. Some of these are simple exercises, others are quite complex:

Chapter/Section	Numbers	Chapter/Section	Numbers	Chapter/Section	Numbers
II.1	13	IV.4	14,15	VI.	1,2
II.3	17,18	IV.5	1,2,3	VII.	1,2,3
III.1	3	IV.6	1,5	VIII.	1
III.2	12,13,14	IV.7	18,19	IX.	1,2,3
III.3	1,2,3,4	IV.8	1,2	X.	5
III.4	13	IV.9	2,3	XI. 2	1
III.6	4	IV.10	4	XI. 6	2
IV.1-2-3	1,3,4,5,6	V.1	1,2,3,4,5	XII.2	1

This is a total of 50 exercises.