Physics 10293 - Exam 3 Notes, Part 2

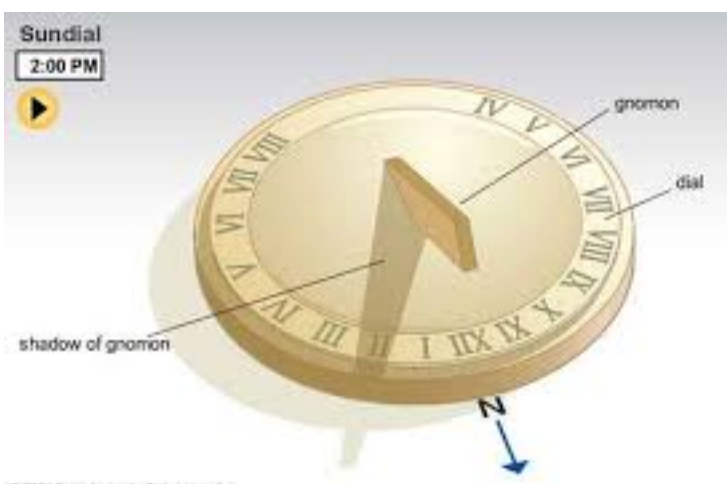
For the second half of the course lecture notes, we will start by discussing timekeeping and calendars. We will then finish with a more thorough discussion of planetary motion (which is related to timekeeping) and how it spurred a revolution in science that bridged the gap between ancient and modern ways of viewing the cosmos.

Using the Sky to Tell Time

Timekeeping on an hourly or daily basis can be accomplished with careful observations and a basic knowledge about how objects in the sky move. During the day, a **gnomon** (or sundial) can help you tell time. A gnomon is usually a simple vertical stick or column that casts a shadow during the day. Sometimes it is angled or shaped like a triangle as in a sundial.

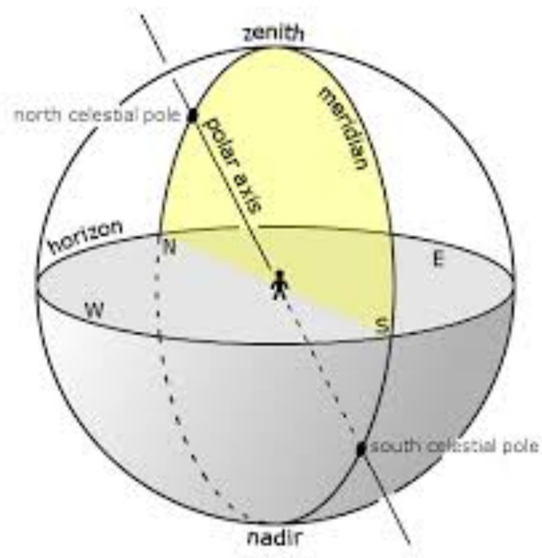
When the Sun rises, it has a low altitude in the sky, and so the gnomon casts a long shadow toward the West or Southwest during the summer. As the Sun rises higher and higher in the sky, the shadow gets shorter and shorter. By noon (when the Sun reaches its highest altitude in the sky and is directly south of us), the gnomon's shadow is the shortest length of the day, and it points directly north.

If you mark this pattern throughout the day, you can use the shadow like the hour hand of a clock, and then you have a sundial.

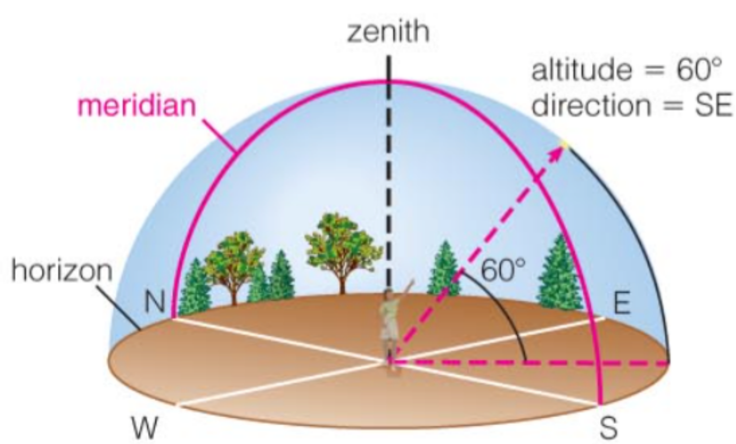


In order to accurately map out what time each shadow position corresponds to, you need an accurate timekeeping device. We will talk about clocks later. For now, let's focus on the easiest time to measure, which is local noon, when the Sun reaches its highest altitude in the sky and the shadow of the gnomon is shortest.

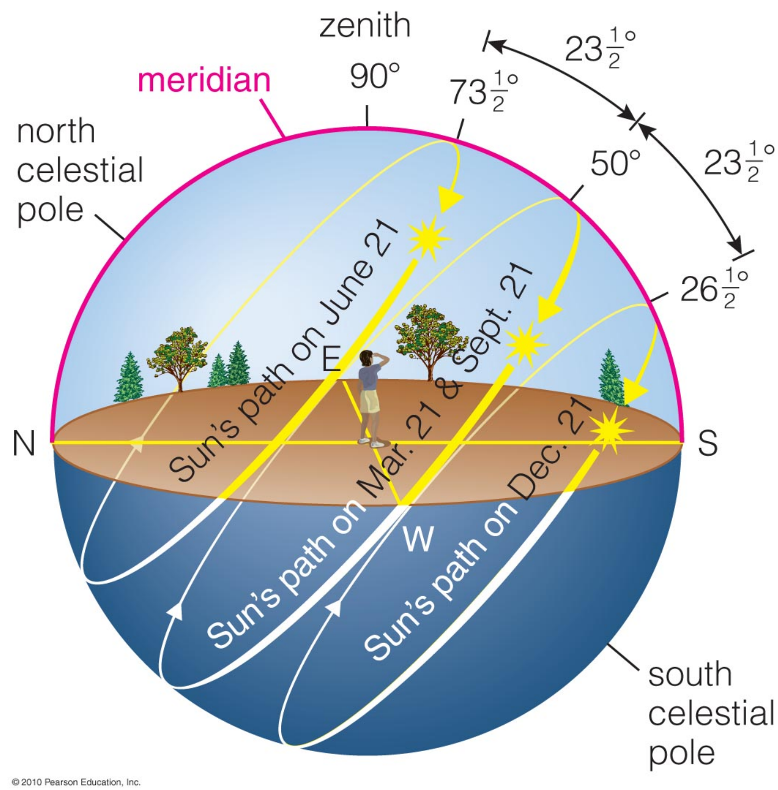
At this time, we say the Sun is crossing the **meridian**. The meridian is an imaginary arc that connects three points on the sky: the northernmost point on your horizon, the zenith, and the southernmost point on your horizon, as shown below.



We have seen the meridian before in our horizon diagrams! This is a piece of Figure A1, showing you the meridian on a horizon diagram.



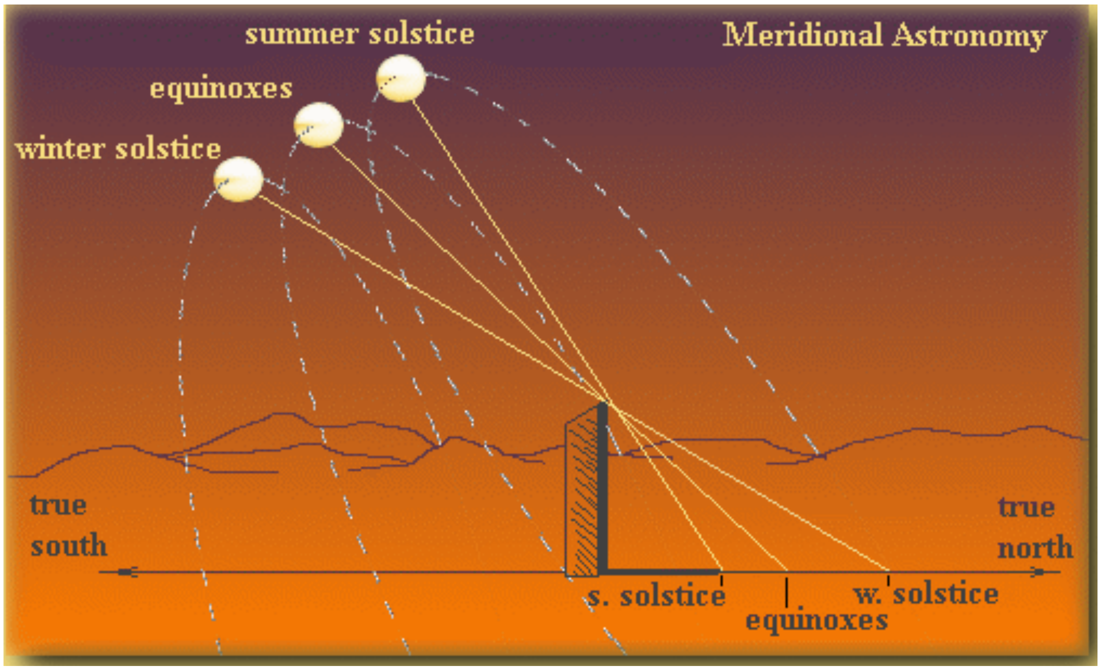
And this is our horizon diagram (Figure C1) showing the motion of the Sun as seen from a latitude of 40° North at different times of the year. Note the meridian marked in pink.



You can see that as the Sun arcs across the southern sky from our perspective, it reaches its highest altitude of the day (we also call this culmination) when it crosses the meridian. We call this time of day local noon (not necessary 12:00 on your watch or clock because of our use of time zones and daylight savings time). Another word we use for meridian crossing is transit. So we can say that when the Sun transits or culminates, the time is local noon.

Not only can the shadows cast by a gnomon indicate the time of day, but they can also be used as a rudimentary calendar, showing you what time of year it is.

In the diagram below, you can see that when the Sun transits on different dates during the year, the length of its shadow varies. The gnomon casts its shortest shadow of the year at local noon on the day of the summer solstice. By measuring the length of the shadow precisely on each day, you can mark the passing of the days of the year just like you can mark the hours of the day with a sundial.



This is exactly what the Chinese accomplished at the sky measuring station of Yang-Chheng, which we first read about in Chapter 2 of "Echoes" (see study guide question #25).

Let's look at the motion of the Sun and the solar day a little more closely. As you can see from the above diagram, the Sun's position at local noon shifts north and south over the course of a year. This seasonal shift is due to the Earth's tilt as Earth orbits the Sun as we have seen.

However, there is another more subtle effect at work here with the Sun's motion, and it results in a pattern we call the **analemma**. An analemma is a special kind of picture you get when you take a photograph of the Sun in the sky at the exact same time about once a week over the course of a year.

On the left is an analemma photograph taken while the camera is pointing due south, so each photograph is taken at exactly 12:00, and the meridian perfectly bisects the figure 8.

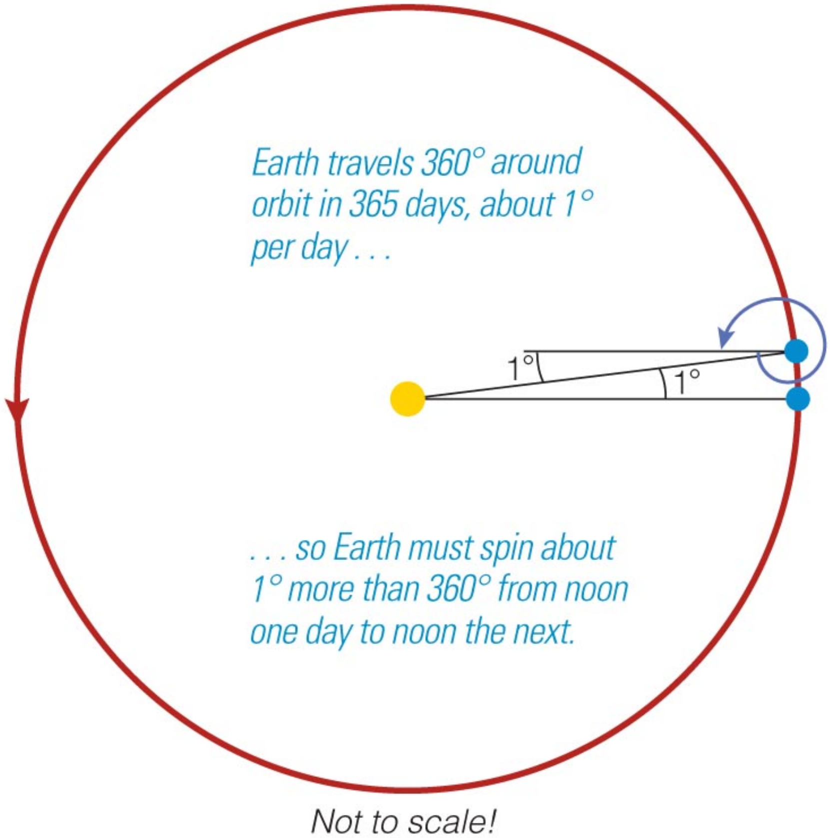
On the right is an analemma photograph taken while the camera is facing due West, and each photograph is taken at exactly 5:00pm. The north-south shifting position of the Sun in each photograph is reflected in Figure C1 from your diagrams file, which I showed you a couple of pages ago.

I want to focus on the left diagram since that one is a little easier to understand, and I want to talk about what is causing the east-west motion of the Sun: it is the Earth's elliptical orbit!

If the Earth's orbit were perfectly circular, the photograph on the left would just be a dotted vertical line, showing the Sun's north-south position gradually changing over the course of a year. But instead, we get a narrow figure-8.

That's because on some days, the Sun crosses the meridian a little earlier than usual (the solar day is a few seconds shorter than 24 hours). On other days, the Sun crosses the meridian a little later than usual. So that makes the Sun's position in this photograph (taken at exactly noon on each) day to shift a little bit to the left and right (east and west).

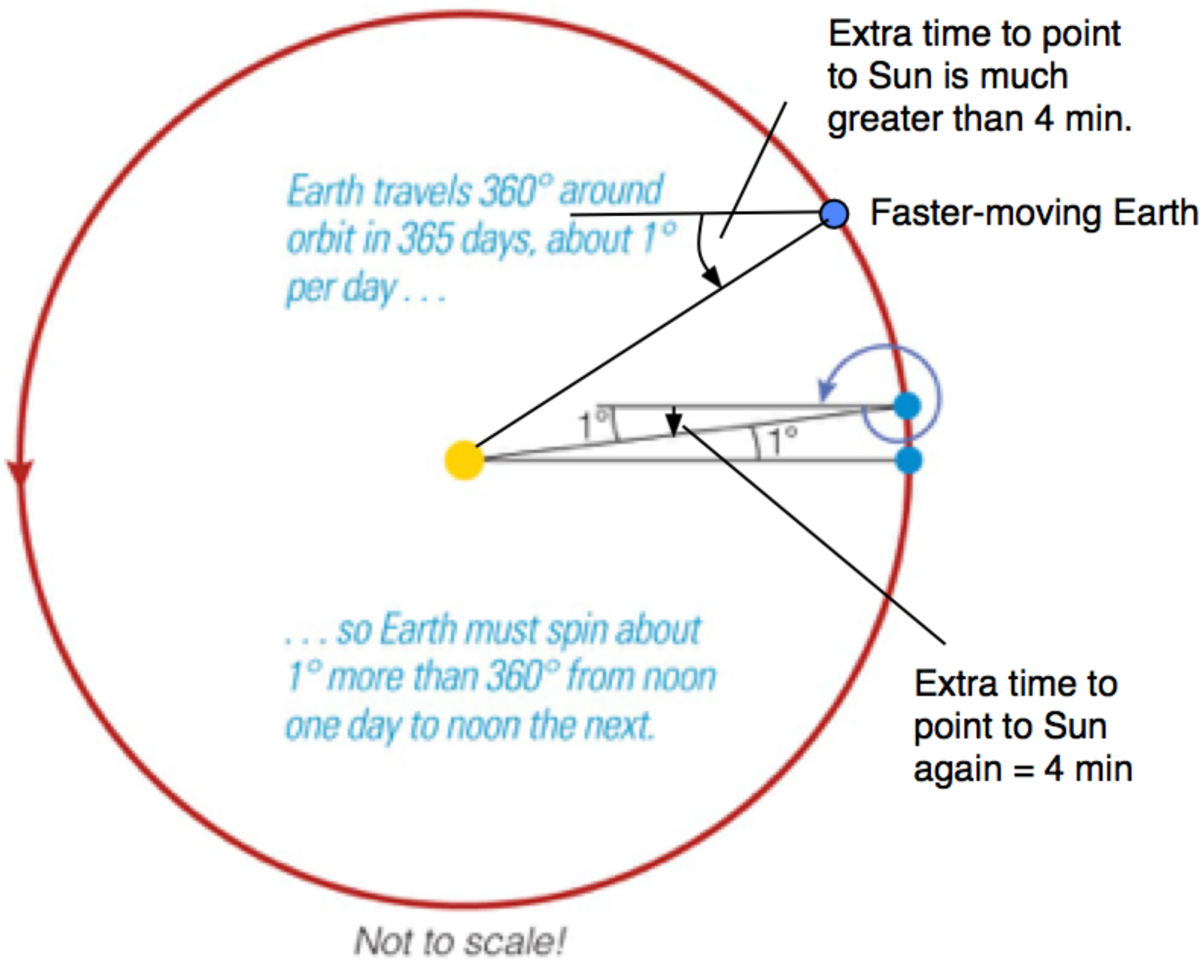
To understand what is causing this, let's go back and take a look at the difference between the sidereal and solar days in Figure B2 from your 10293 Diagrams file.



c Earth travels about 1° per day around its orbit, so a solar day requires about 361° of rotation.

We covered this back in study guide question 31, so you may want to look again at your answer to that. The Earth takes 23 hours and 56 minutes to spin once. But in that time, the Earth also moves a little bit (about 1°) in its orbital path around the Sun. As a result, after 23 hours and 56 minutes (a sidereal day), the Sun is not quite lined up compared to where it was on the previous day. The Earth has to spin an extra 4 minutes for the Sun to return to its same location on the sky (24 hours, the solar day).

What if the Earth were moving a little faster? I'm going to take that same diagram (Figure B2) from the previous page and modify it a bit below.



Now I have added a small arrow to the original diagram showing the extra 4 minutes of time that elapses between the end of a sidereal day and the end of a solar day.

In addition, I have added a faster-moving Earth to the diagram, which is moved MUCH further in its orbit while still spinning at the same rate. The result is that the spin still takes 23 hours and 56 minutes, so the sidereal day is the same, but the solar day is now MUCH longer. The time needed for the Earth to spin past its sidereal reference line (the horizontal line) and point toward the Sun again is MUCH greater than 4 minutes.

In our analemma, this means the Sun will cross the meridian late and in our photograph taken at exactly noon, the Sun will still be approaching the meridian from the East.

What would cause the Earth to move faster in its orbit? Kepler's Laws! We will learn these in more detail later, but for now, suffice to say that the Earth has an elliptical orbit around the Sun. When the Earth is closer to the Sun, it moves a bit faster in its orbit. When the Earth is further from the Sun, it moves a bit slower in its orbit.

Since the Earth's orbit is only about 1-2% away from a perfect circle, these changes in speeds are not very great. But they are enough to cause a few seconds of delay in the completion of the solar day when the Earth is moving faster than usual.

By the same process, when the Earth is moving slower than usual, the delay between the end of the sidereal day and the end of the solar day is LESS than 4 minutes, which causes the Sun to appear a little bit West of its position on the previous photograph. These changes can add up so that the Sun can be as much as 15 minutes early or late crossing the meridian on a given day.

As I said before, if the Earth's orbital speed did not vary, then we wouldn't have this East-West motion of the Sun in the analemma. Every solar day would be exactly 24 hours, and the analemma pattern instead of being a figure-8 would just be a straight line north-south along the meridian showing the seasonal motion of the Sun.

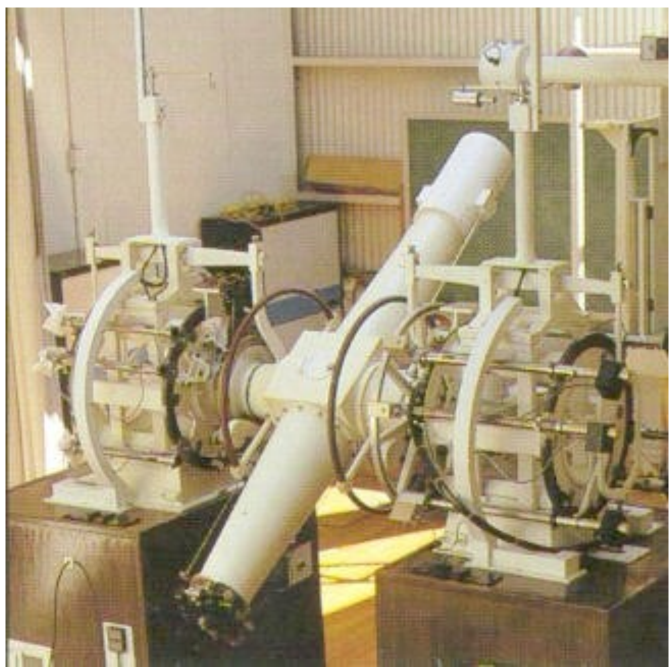
If you want to keep accurate time using the Sun, you have to take into account this effect. And accurate time is important, as we will see, for the purposes of navigation, most of which is done during daytime hours.

Now we have discussed in some detail about how to keep time (or least know when it is local noon) during the day. What about at night when the Sun isn't up?

The timekeepers at night are the stars, and if you can tell when the stars transit (cross the meridian), then you have a way of marking time intervals during the night. The Egyptians had a series of (almost) equally spaced stars spanning the night sky that they tracked for this purpose. They called these stars the "**decans**."

In practice, the decans were about 10 degrees apart, and their heliacal risings (remember from study guide question 15) occurred about 10 days apart, hence the name decan, which contains the root dec- (like decimal or decimate) which refers to the number 10. Stars in the sky move about 360 degrees in 24 hours, which is 15 degrees per hour. So decans, being 10 degrees apart, cross the meridian about every 40 minutes, enabling fairly accurate timekeeping at night.

In more modern times (17th-18th century), as a way of using the sky to calibrate newly invented timepieces, astronomers used transit telescopes like the one shown below to precisely track when stars cross the meridian. That way, they can tell if the clock is showing an accurate time.



Notice the transit telescope here is pointing due South. It is not designed to look East or West. It is designed only to look at things that are transiting (or crossing the meridian). The telescope looks out through a narrow slit in the roof of the building in which it is housed.

One other point about transit timing: If you are trying to use the sky to tell time accurately (or check the performance of a clock), transit timing is actually the best way to do it. You might think that it would be easier to mark the time of day by the moment when the sun first rises above the horizon or the moment when the very last bit of the sun sets.

Actually, though, there are several problems with measuring precise rise/set times (some of which are alluded to in your answer to study guide question 23). First is the weather. Think about the sky on a partly cloudy day.

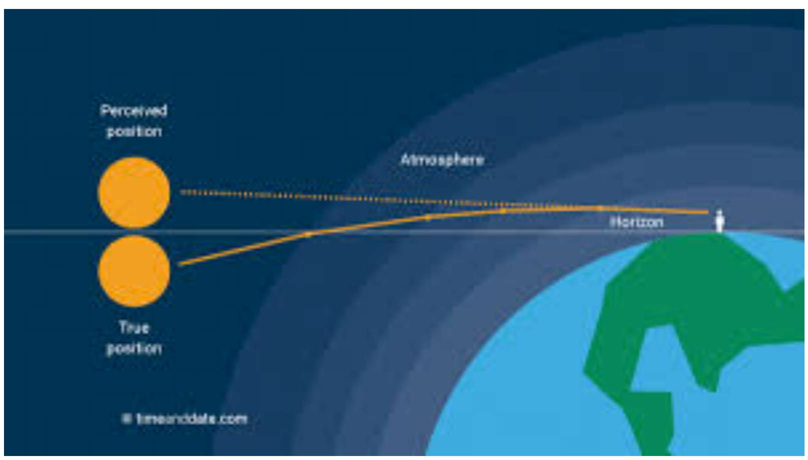
Notice these clouds are scattered and more or less evenly spaced all over the sky. But close to us, if you look up at a high angle, there is a lot more blue sky. The angular size of the spaces between clouds is much greater when you look up because the clouds are closer. However, on the distant horizon, the clouds all seem bunched together, and you can't see much blue sky.

For this reason, clouds are more likely to obscure the sunset or sunrise compared to a solar transit, which occurs at the sun's highest altitude in the sky.

You might think that measuring transit would be more difficult because there is no obvious marker in the sky like the horizon, which clearly marks sunrise and sunset. But once you have determined the direction of true south by watching the shadow of a gnomon, you can just set up a vertical pole or wall and watch a star or the Sun being obscured by a distant building directly to the South.

Another difficulty you would have with using rise and set times as references would be the variation in day length. We already learned in part 1 of the course that the sunrise time is earlier or later depending on your latitude and the time of year. During Spring, for example, sunrise at TCU is earlier by about 1 minute per day, so having the Sun rise at a different time each day will certainly complicate your measurements.

Finally, there is the issue of refraction. When the Sun appears on the horizon, it is not ACTUALLY on the horizon! Refraction of light by the Earth's atmosphere causes the Sun to appear even when it is a little bit below the horizon.



Which would be fine if this effect were always the same, but it isn't. The amount of refraction the Sun undergoes depends on the temperature and humidity of the air through which the sunlight is passing, and that changes day by day, even minute by minute! So this also makes precise timing very difficult. It's not a problem with transits, though, because with transits we are measuring the east-west position (which is not affected like the north-south position) of the Sun.

Timekeeping and Navigation

If you want to know where you are on the surface of the Earth (for the purposes of making an accurate map), you need to be able to use the sky. We use latitude and longitude to specify an exact location on the Earth's surface.

Latitude is a north-south measure, telling you how many degrees north or south of the equator you are. The latitude at the equator is zero. The latitude at the North Pole is 90°. You may recall from our horizon diagrams (e.g. study guide question 30) that the altitude of the North Celestial Pole above your northern horizon is equal to your northern latitude.

Since the North Celestial Pole is fairly close to the bright star Polaris, finding your latitude at night is easy. You just need a tool that measures the altitude (or elevation angle) of Polaris above your horizon.

What about during the day, when Polaris is not visible? Then we have to use the Sun. Recall that the Celestial Equator makes an angle of 90° with the direction of the North Celestial Pole. Since the Sun moves along a path parallel to the Celestial Equator (a bit north or south depending on the time of year), careful observations of the Sun over an hour or so should reveal the angle the Celestial Sphere makes with the horizon and, thus, the direction of the North Celestial Pole.

A useful instrument for modeling the Sun's behavior during the day is the armillary sphere, a version of the Celestial Sphere we used way back in lab week #1. I encourage you to watch this short (3.5 minute) YouTube video so that you can see a model of this device and how it represents the sky:

https://www.youtube.com/watch?v=AaWuJHQL-bQ

We now know understand how to use the Sun or Polaris to find our latitude. What about longitude?

That's MUCH trickier! Because for a given latitude, the sky at local noon (or local midnight or any local time you choose) will be identical. What you need, then, to determine longitude is to know what time it is in two places at once.

Before I get into my explanation for longitude, it would be very helpful for you to first watch a YouTube video about this topic. This video covers time and longitude but also talks about other concepts we have covered, such as latitude, local noon and solar transits. It is about 11 minutes long.

https://www.youtube.com/watch?v=b7yoXhbOQ3Y

As the Earth rotates, you are standing on the surface while it moves East. On the equator, the Earth will carry you around its circumference of about 24,000 miles in about 24 hours. So you will move with a speed of roughly 1,000 miles/hour.

At our latitude, we move in a slightly smaller circle than we would at the equator, so our speed is about 840 miles/hour. Let’s look at an example of how to use time to find our latitude.

Suppose on a given day, we measure the exact time of the sun’s transit here in Fort Worth. On April 13, I find it to be 12:28pm. I don’t want to travel to Lubbock (who does?) so I call my friend who lives there and ask her to measure the time of the sun’s transit. She finds it to be 12:49pm, which is 21 minutes later than the Sun transits in Fort Worth.

That’s because the Earth has rotated beneath the Sun in the sky at a speed of 840 miles/hour. If we use distance = speed * time, then a quick calculation will tell us:

(840 miles/hour)*(21 minutes)*(1 hour/60 minutes) = 294 miles.

So by using an accurate clock, we know that Lubbock is about 294 miles West from TCU. The key to knowing your east-west distance from a given place on Earth (your longitude) is knowing the time in two places at once (for example, the time when the sun transits at each place).

And accuracy is important! 840 miles/hour translates to about 1 mile of motion every 4 seconds. So if our clock is off by just 12 seconds, then our estimated position on Earth’s surface will be off by 3 miles.

Imagine an early European navigator trying to find his way to the rocky coast of New England. An error of just a few seconds on his timepiece could make the difference between finding a safe harbor or getting smashed on the rocks.

Calendars

Since ancient times, calendars have served multiple purposes, some more obvious than others:

1) Agricultural

Initially the most important function of a calendar was helping determine when it was appropriate to plant and harvest crops, especially in regions of the world (high northern and southern latitudes) where growing seasons are very short.

2) Government functions

If a government official (elected or appointed) is only supposed to serve temporarily, a calendar is needed to know when that person should be replaced. When are taxes due? When are courts in session? How does a person know when a prison sentence is over? When are inspectors due to visit? Even very rudimentary governments function much more efficiently and keep their people more satisfied when standards are set and kept.

3) Commerce

On what days will markets be open so that everyone knows when to meet and bring their goods for sale? When are loan payments due? When is an employment contract finished? When are employees paid? When is rent due? These all sound like questions more relevant for our modern economy, but they have been around in some form for thousands of years.

4) Religion

The religious calendar always has a number of "holy days" (the source of the word "holidays") throughout the year. Calendars are needed to we know the proper time to observe these holy days. We also need to know how often regular worship services are held.

5) Society

A less obvious function of calendars is that they provide a common basis for life, making societies function more reliably and peacefully. To understand this better in the ancient world, a recent modern observation may be helpful.

Although this is not true now due to ongoing wars with Russia and some of its former member states like the Ukraine, prior to 2010, it was generally true that of all the wars that had taken place within the previous century, no two countries fought when both countries had at least one McDonald's restaurant.

That's not to say a Big Mac is some kind of magical peacekeeping sandwich. The point is that when two societies have enough freedom of commerce and enough cultural similarities that McDonald's would open a franchise in both, those two societies have enough in common that conflict becomes much less likely.

Think about what leads up to wars today. Why do countries fight? War is a horrible business, so how is it that the people in a country can be convinced to fight a war against the people of another country? If you live in a country which has leaders who want to fight a war against an adversary country (for whatever reason, legitimate or not), the first step is for the leaders of your country to convince you that the people in the adversary country have nothing in common with you.

Certain kinds of language are used when talking about the adversary or its people, degrading them, making them seem less than human. The adversary country's people are uncivilized, they have different religious practices than us, they hate us because of our differences, they are irredeemable, there is no way to reason with them, they are animals, they torture and kill women and children, etc.

Watch for these kinds of quotes in the media that next time one country tries to provoke a war with another. Basically, the greater the differences between two peoples (whether real or perceived), the more likely conflict is to arise. The more likely that conflict will be supported by its people.

Imagine you are the leader of a large empire in the ancient world, composed of several different regions where the people of each region don't have much in common with people from another region. Yet you do not want wars between different parts of your empire, so you need to find a way to give these diverse people some common bonds. A common calendar is a very basic way to do that.

When one group of people observes that others are observing the same holidays they do, meeting at the marketplace on the same days they do, planting and harvesting their crops at the same times they do, it becomes more readily apparent how much these two people have in common. It is then easier to think of similarities than differences, and it is easier to sympathize with the others rather than dehumanize and hate the others.

Now that we have covered some of the reasons why calendars exist, let's look more closely at the history of our calendar. Our calendar was derived from rules originally established by the Greeks and the Egyptians, who themselves no doubt built on more ancient practices that are lost to history in most cases.

The original calendars of the Greeks, Sumerians, Chinese and Ancestral Pueblo were lunar calendars. The solar month, the time between new moons, is 29.5 days. Lunar calendars, therefore, typically have months with alternating numbers of days: 29, 30, 29, 30, 29, 30, … You can see already the seeds of our current calendar system, which has months with day lengths of 30, 31, 30, 31, …

The problem with the lunar calendar, as we have seen before (see study guide question 15) is that when you try to match it up with the solar year for agricultural purposes, 12 months of 29, 30, 29, 30, … days adds up to 354, which is 11 short of a typical solar year. To account for this discrepancy, cultures like the Greeks that used a lunar calendar would insert an extra month into the calendar every 2-3 years in an irregular pattern.

It is possible to keep a stable calendar in this way, as the pattern of extra months will result in the lunar and solar calendars getting perfectly in synch about every 18 years. But is is complicated in the meantime to keep track of, and not every culture consistently inserted months in the same place in the calendar.

The modern Muslim calendar is a lunar calendar, with the first day of each lunar month beginning on the earliest date the newly waxing crescent moon can be seen in the sky after sunset. This calendar "loses" 11 days each year, and so Muslim holy days and celebrations like Ramadan are celebrated 11 days earlier each year by our solar calendar.

The Egyptians were the first civilization to use a solar calendar, by around 4000 B. C. This difference may be due to the extreme importance of consistent agricultural practices in the Nile river valley in the middle of the desert. The Nile river floods pretty reliably every 365 days or so, and that may have been the origin of their calendar rather than an astronomical origin.

The original Egyptian calendar had 12 months, each with 30 days, and then they added an additional 5 days to celebrate holy days in honor of five different gods. Over the centuries, the Egyptian calendar was refined because they came to realize that a 365-day year wasn't quite right. If the Nile would flood on, say, July 1 of a given year, historians noted 100 years later than the annual flood was occurring nearly a month earlier, on June 5.

To maintain a consistent calendar, therefore, Egyptians adopted the practice of noting the date of the heliacal rising of the bright star Sirius (see study guide question 17). On this unique date each year when Sirius is newly visible prior to sunrise, the Egyptians would begin their calendar year. As a result, the average number of days in an Egyptian year became 365.25 days, which is very close to the true number of days it takes the Earth to orbit the Sun.

Our modern calendar was derived from the Roman calendar. The original Roman calendar was a mix of lunar and solar practices. It had 10 lunar months with a total of 304 days. The first day of the calendar was the date of Vernal Equinox (when many cultures at this latitude would plant their crops) and end on the date of the Winter Solstice. The time in between these dates (what we now call January and February) was not systematically kept.

The first four months of the Roman calendar were named after Roman gods: Martius (Mars, god of war), Aprilis (Aphrodite, goddess of love), Maius (Maia, goddess of earth) and Junius (Juno, ruler of the gods). The next six months were enumerated (note the prefixes, which coordinate with the month numbers): Quintilis (5th month), Sextilis (6th month), September (7th month), October (8th month), November (9th month) and December (10th month).

Shortly after this calendar originated, two months were added to the end of the year. Januarius (named after Janus, the two-faced god of doorways and portals) and Februarius (after Februun, a ritual of cleansing, akin to spring cleaning).

This calendar persisted in this form for several hundred years before the year 48 B. C. and is represented in the left two columns of the table below.

In 48 B. C., Julius Caesar implemented some reforms to the calendar. First, he moved the months of January and February to the beginning of the year. Next, he added days to each month so that the total number of days would add up to 365, but February (originally being the last month on the calendar) was left unchanged. He also added the Egyptian concept of the leap year, adding 1 day to February every 4th year. This calendar is represented by the middle two columns in the table.

After some time, more reforms were implemented to get to the final calendar we have today. Months 5 and 6 were renamed in honor of Julius and his son, Augustus, and both were assigned to have the largest number of days (31) to signify their importance. Another day was removed from February to compensate for this, and the alternating pattern of month length was adjusted for the months following August.

Eventually, further reforms were needed due to the fact that the leap year wasn't exactly right (the year length is 365.242 days instead of 365.25 days), so the Roman calendar was destined to lose 1 day every 128 years. An error that became more and more noticeable as the centuries crept forward. This was eventually corrected by Pope Gregory III to result in the Gregorian calendar we adopted (through England since we were still a colony) in 1752 and use today.

Some of these changes are summarized in the table on the following page.

Original Roman			**First reform**			**Final calendar**	
Month	# of days		Month	# of days		Month	# of days
			January	31		January	31
			February	29		February	28
Martius	30		March	31		March	31
Aprilis	29		April	30		April	30
Maius	30		May	31		May	31
Junius	29		June	30		June	30
Quintilis	30		Quintilis	31		July (Julius)	31
Sextilis	29		Sextilis	30		August (Augustus)	31
September	30		September	31		September	30
October	29		October	30		October	31
November	30		November	31		November	30
December	29		December	30		December	31
Januarius	30						
Februarius	29						

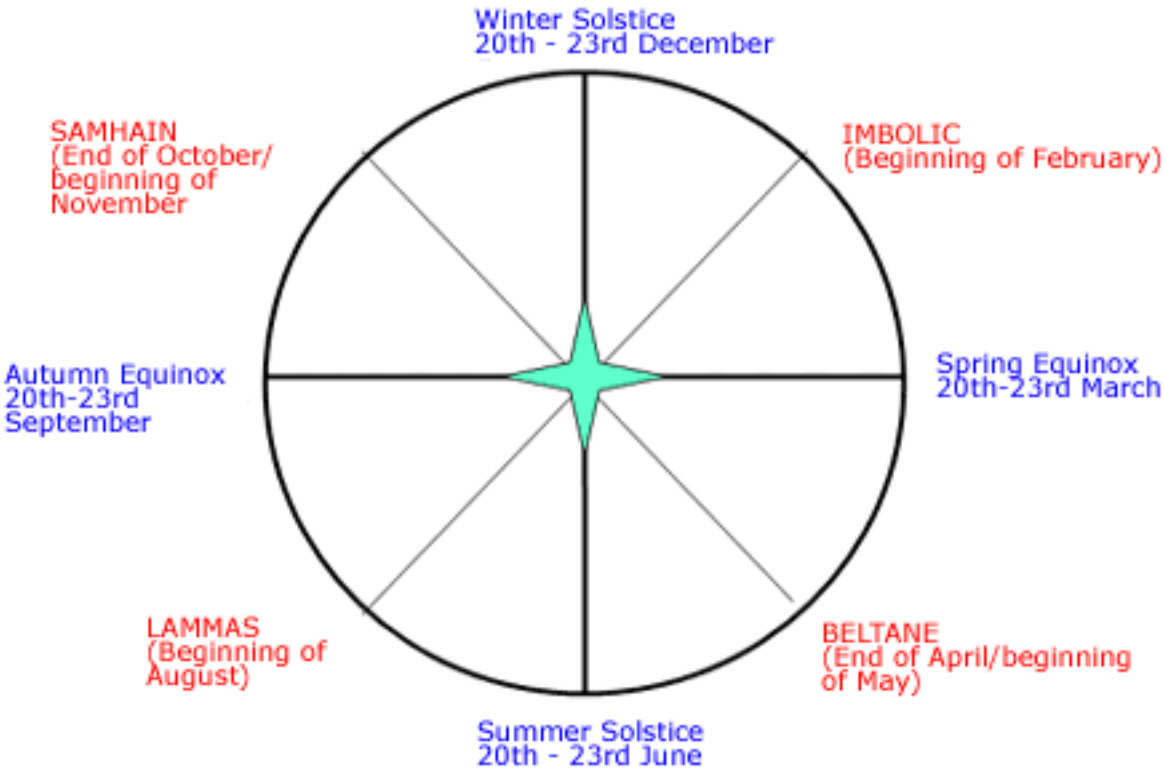
The days of the week are named from a mix of Roman and Teutonic (or Norse) mythology (see study guide question 41).

Sunday named after the Sun (Domingo in Spanish)
Monday named after the Moon (Lunes in Spanish)
Tuesday named after Mars or Norse Tiw (Martes in Spanish)
Wednesday named after Mercury or Norse Woden (Miercoles/Spanish)
Thursday named after Jupiter or Norse Thor (Jueves/Spanish)
Friday named after Venus or Norse Fria (Viernes/Spanish)
Saturday named after Saturn (Sabado/Spanish)

The origin of some of our holidays is based largely on astronomical events linked with certain times of the year. For example, Easter was a holiday meant to symbolize a new beginning or rebirth, and so it was scheduled to occur at the traditional beginning of the ancient year (beginning of the agricultural year) to coincide with the Vernal (Spring) Equinox. More precisely, Easter is scheduled to occur on the first Sunday after the first full moon following the Vernal Equinox.

Another holiday directly associated with a major solar event is the Winter Solstice holiday, at which time we celebrate Christmas (see study guide question 45).

Some other holidays we observe are associated with the Celtic calendar. The Celtic calendar observed four major seasons, with the solstices and equinoxes being the boundaries between those seasons (just like our modern seasons). Then each of these seasons was divided in half:



Two modern holidays that have survived since these ancient practices were established. The first is our holiday that coincides with Imbolc, at the beginning of Feburary. This holiday was originally created in conjunction with the legend of Cailleach, a deity who in some cultures was the personification of winter. As the story goes, on this day of the calendar, Cailleach would determine how much longer winter would last.

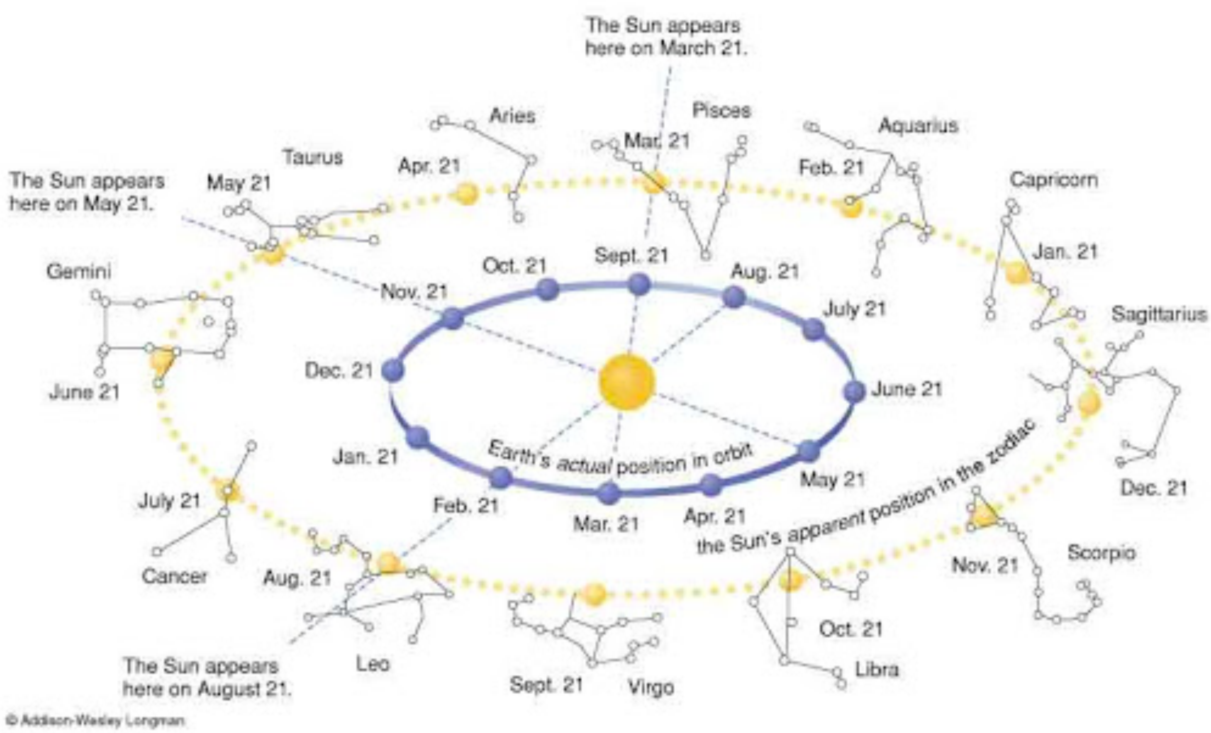
If Cailleach knew that winter would last for at least another six weeks, she would make sure this day was bright and sunny so she could collect firewood. If she knew winter was ending soon, she would let clouds and storms rule the day. Thus our Groundhog Day tradition was born (if it is sunny and the groundhog sees his shadow, that’s six more weeks of winter).

The second holiday associated with the Celtic cross-quarter day calendar is All Hallows' Day, a Christian feast meant to remembering and honoring those who died during the previous year. This time of year was also associated with Samhain, a harvest festival among pagans.

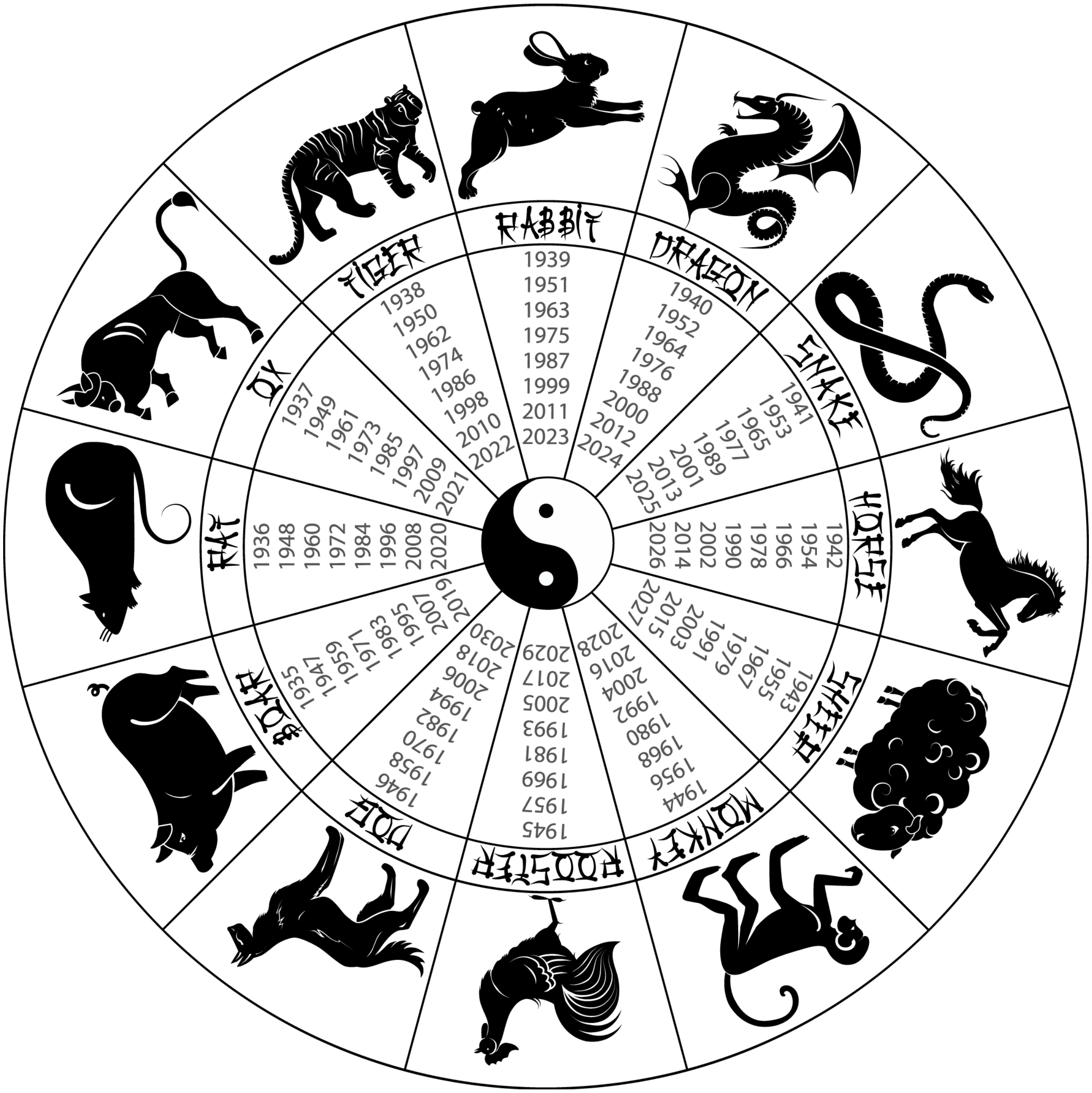
Some believe that, like Christmas, All Hallows' Day was a Christian holiday deliberately placed on the calendar at a time of a pagan celebration in order to make Christianity more attractive to pagans, to give Christians and pagans something in common.

The day before this festival is All Hallows' Eve, which we have shortened to become Halloween.

A couple of other calendars of note: The Chinese calendar, like our modern calendar is a mix of lunar and solar cycles. You are probably familiar with our own zodiac. The 12 constellations that lie in the plane of the ecliptic (the Sun's apparent annual path across our sky) are the signs of the zodiac, shown below.



In Chinese tradition, there is also a zodiac, but it is not based on what month you are born. Rather what year:

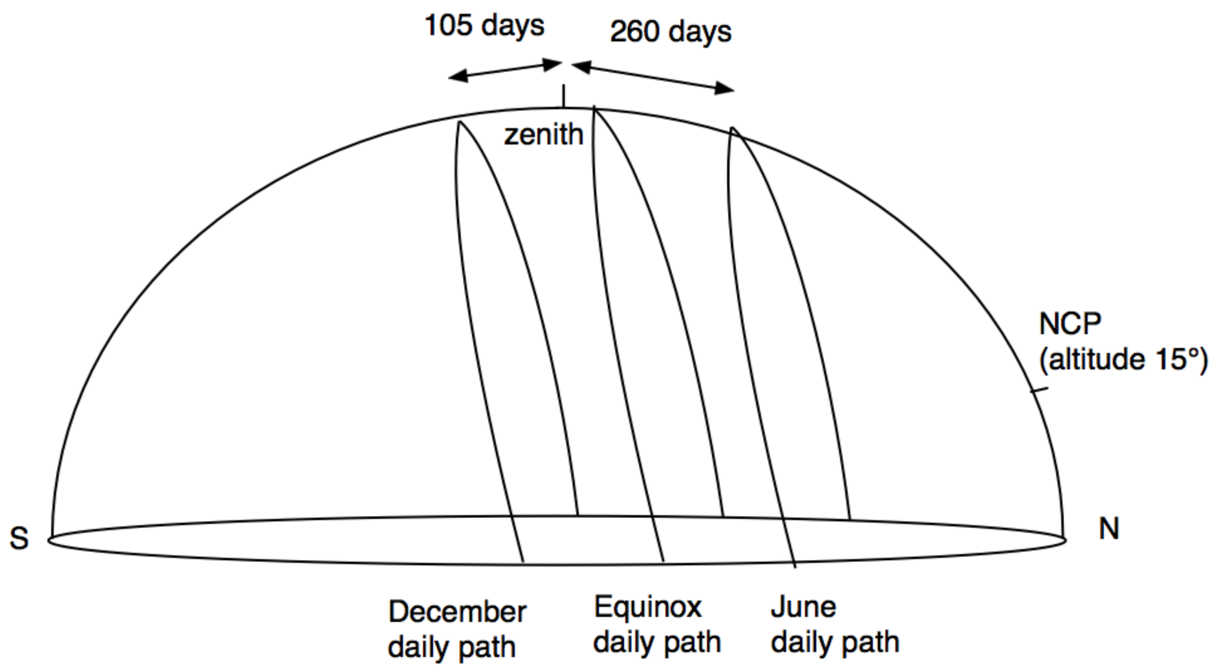


The 12-year cycle of the Chinese zodiac is dictated by the planet Jupiter, which was a 12-year orbit around the Sun. So your astrological sign in the Chinese zodiac depends upon which constellation the planet Jupiter is in during the year of your birth.

Another calendar of note from a culture we have studied is the Mayan calendar, which we learned a little bit about in the film “Tools of the Maya” from the second part of the course (see study guide question 68).

A fundamental piece of the Mayan calendar is the 260-day period known as the Tzolkin. Astronomers have theorized this has to do with the timing of zenith passages of the Sun at some of the earliest Mayan sites, such as Copan, located at a latitude of 15° North, in the lower right part of this map.

At this latitude, if we analyze the horizon diagram of the Sun’s motion, we find that the Sun appears at the zenith twice during the year. When the Sun passes through the zenith heading toward the North (in late Febraury), it will be 260 days before it returns to the zenith heading South (in late October). It will spend 105 days South of the zenith and 260 days North of the zenith during a calendar year.



Here is a horizon diagram drawn to show the solar daily paths from a latitude of Copan, 15° North. The time interval of 260 days between solar zenith passages is also the agricultural season in this part of the world (the other 105 days is the rainy season), so this astronomical cycle (observed via zenith tubes in underground chambers commonly at this latitude) was perhaps the origin of the Mayan calendrical Tzolkin.

Other Mayan calendrical units were more easily seen as solar or lunar. The Mayan calendar had within it the following cycles, arranged in order by increasing length.

uinal = 20 days
tzolkin = 13 x 20 days = 260 days
18 uinal = 1 tun = 360 days
haab = 1 tun + 5 holy days = 365 days (solar year)
Calendar Round = 52 years (time for haab and tzolkin to synch)
20 tuns = 1 katun = 7200 days
20 katuns = 1 bak tun = 144,000 days (395 years)
13 baktuns = Great Cycle = 5125 years (also called Long Count)

A similar calendar system was seen through Mesoamerica during this time, another occurrence of a common calendrical system spanning a very large and diverse group of people.

Planetary Motion

If you have already done online lab #2, then you will already be way ahead on this part. Much of what I will ask about in the study guide from the lecture notes and associated Scientific American article homework questions has already been asked in online lab #2.

The ancient view of the cosmos is very much centered on us. In most ancient cosmologies, the Earth is at the center of everything. We are unmoving, and the Sun, the Moon, the planets and the stars all move around us in a complicated, eternal dance. It is no surprise that this sort of belief was common, based on the evidence available at the time.

Imagine you could go back in time, tasked with a mission to convince some ancient philosopher like Socrates that the Earth spins on its axis once per day and orbits the Sun like the rest of the planets, thereby explaining the motions in the sky. Socrates was not an idiot. He didn't believe in an Earth-centered (**geocentric**) cosmos because he was stupid. He just followed the evidence.

Socrates might reply to you, "Ok, time-traveller, if what you say is true, then the Earth must be spinning so quickly that we are moving almost 1000 miles per hour. When I move more than a few miles per hour on a horse or in a cart, I feel wind on my face, and the motion causes a lot of shaking. Yet I look around me and see no evidence of motion.

"Calm weather, no shaking, no apparent motion. And then you say the Earth orbits the Sun? That would mean we are hurtling through space at a speed of around 65,000 miles per hour, and we feel no effect of that? Why don't you return to the future and return when you can tell me a more convincing fairy tale, ok? Now, run along!"

And that's just the visible evidence around us. Socrates might also point out that the Earth is made of rock and dirt, and it is very heavy. What kind of force could be massive enough to set it in motion, again with no visible effect on our surroundings?

And yet there *were* problems with the geocentric cosmology, they were just subtle and only apparent to careful observers of the sky.

The purpose of a scientific model is an attempt to use our observations of the world as it is and try to extrapolate into the future to predict what will happen. If your model is successful, then such predictions can be very useful. One of the first people (for which there is a written record that survives) who attempted to model the motion of the planets was a Greek mathematician named Claudius Ptolemy.

In his model, the Earth was stationary at the center of all creation, and the Sun, Moon and planets are orbited around the Earth in perfect circular motion against the distant background of fixed, unmoving stars known as the Celestial Sphere. In Ptolemy's model, the Celestial Sphere was a physical thing, an actual boundary at the edge of the known universe. We find it useful to recreate this idea of the heavens because it is easier to understand motions in the sky this was, even though it is not an accurate model.

The main reason Ptolemy went to the trouble of publishing his model of the cosmos was that he was trying to model the motions of the planets for the purposes of predicting their future motions. In Ptolemy's time, the function of Astronomers in a society was to interpret and predict the motions of the heavens, to use this information to predict the future for people on the Earth (casting horoscopes, for example).

To accurately predict a person's fate, it was thought, one needed to be able to relate the motions of the planets to that person's life. And so accurate future predictions of where the planets would be in the sky was of critical importance. And that's where models like Ptolemy's completely failed. No matter how elegant and reasonable it seemed for the planets to move in perfect circles around the Earth, the sky simply didn't behave that way.

In the centuries following Ptolemy's work, other Astronomers attempted to adjust his model so that it would make accurate predictions. They added complex extra circles to the motions of the planets, wheels within wheels, and then they restarted from newly observed positions. And within a few months to a year, the planets would prove their models wrong.

And so there was always a pressure felt by Astronomers to find a simple and accurate model of the heavens. Ptolemy's model was mathematically cumbersome, difficult to understand conceptually (why would planets move on a path described by a bunch of nested circles?) and, worst of all, inaccurate.

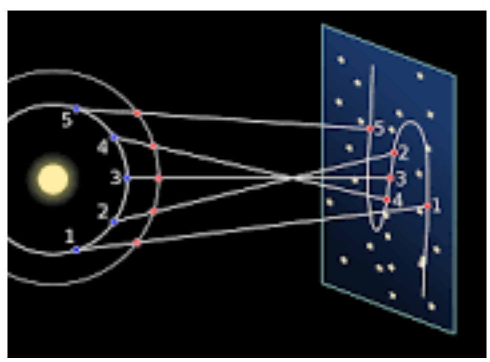
The transition from the ancient thinking about the sky into a more modern view is called the Copernican Revolution, named for the Polish Astronomers Nicolas Copernicus. Copernicus was not the first to hold the view of a Sun-centered (**heliocentric**) cosmos, but he was the first to fully develop the model and publish his findings in 1543 AD.

To help you understand how much simpler the Copernican heliocentric model was compared to the geocentric model, take a look at the following simulation of both types of motion.

http://www.malinc.se/math/trigonometry/geocentrismen.php

Simplicity was the main selling point of the heliocentric model. Not only did it make the motions of planets seem simpler, it also explained the tricky problem of retrograde motion.

If you watch a planet's position night after night relative to the background stars, you will usually notice the planet moves just a little bit to the East each night. We call this prograde motion. If planets only moved in this way, it would be pretty easy to predict their position in the future. The problem is, every so often, a planet's eastward motion slows down and reverses toward the west for a few months (retrograde motion) before resuming its normal prograde motion.



In the left image above is a time lapse photo showing the prograde and retrograde motion of Mars. In the right image is the heliocentric explanation for it, which is fairly simple.

In the geocentric model, retrograde motion is caused by a planet moving on a smaller circle while also moving on a larger circle that orbits the Sun. There was no real reason for this, so the Copernican argument seemed to fit better.

I encourage you at this point to check out a helpful video about what retrograde motion is and how the heliocentric model explains it:

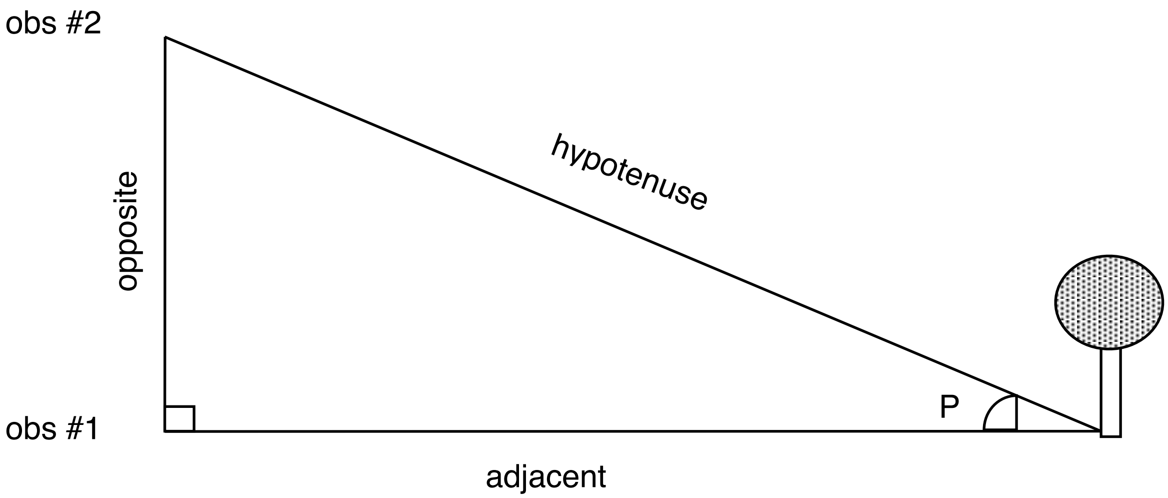
https://www.youtube.com/watch?v=1nVSzzYCAYk

Despite the model's success with retrograde motion, Copernicus' model was not acceptable to most of his contemporaries. The first and largest problem was one of accuracy. Although his model is much closer to the correct model for planetary motion, it still had flaws that made it just as inaccurate as the classical geocentric models. For example, in Copernicus' model, planets orbited in perfect circles around the Sun (which is wrong) instead of elliptical orbits around the Sun with varying speeds (which is right).

In addition, there was a problem with parallax, which many of you studied (or will study) in online lab #3.

Parallax is a distance determination technique that uses geometry to measure the distance to some object when other means (such as a ruler or tape measure) won't suffice. On Earth, surveyors call this technique triangulation.

In the diagram below, we want to measure the distance to a tree that we cannot walk to (perhaps a river is in the way). So we measure its position from two different observation points, drawing a line from each point to the tree and a line connecting our two observation points as shown below.



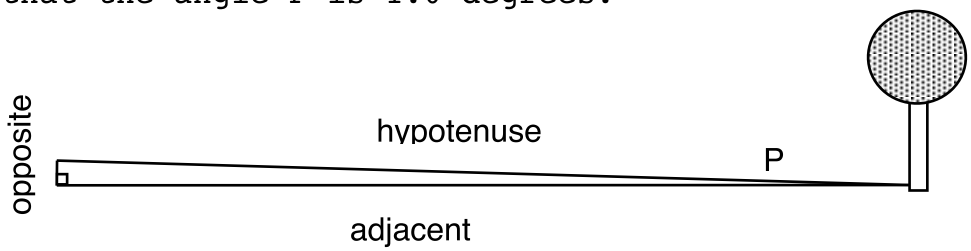
If we physically walk from observation point #1 to observation point #2, then we know that distance. Let's assume it is 25 meters. Using a protractor or other angular measuring device, we can also determine angle P. Let's assume that angle P is 27 degrees.

Basic geometry tells us that for angle P,

sin (P) = opposite / hypotenuse
cos (P) = adjacent / hypotenuse
tan (P) = opposite / adjacent

I won't ask you to do any math on the exam, but a little math here lets us solve for the values of the adjacent side (49) and the hypotenuse (55).

In Astronomy, the angles we measure are much smaller. On the diagram below, assume the opposite side is 25 meters and that the angle P is 1.0 degrees.



Notice that in the second case, the values for the adjacent side (1432.2) and the hypotenuse (1432.5) are nearly identical. For very small angles, this will always be the case, so it doesn't really matter in our triangle which of the two sides we calculate.

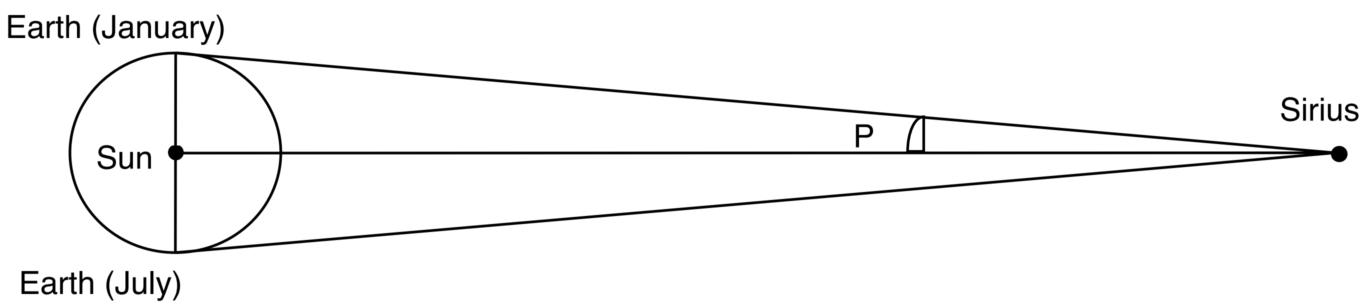
So Astronomers are always looking for ways to measure distances to stars without actually traveling to the stars. Parallax seems perfect! So let's try it on one of the closest and brightest stars: Sirius.

If we try to measure the position of Sirius against the background of more distant stars from two different places on Earth separated by thousands of miles, then in theory, the apparent position of Sirius should shift a tiny bit. There should be a parallax angle, P, that we can measure.

However, if you try it, you will find that Sirius does not seem to shift at all. The angle P is not measurable. It appears to be zero. Sirius really DOES shift a little bit, but if an angle is too small, it is not possible for us to measure it. For example, suppose I were standing on the surface of the Moon holding a grain of sand in the palm of my spacesuit glove. You couldn't possibly see it from way back here on Earth, even though it is there, and the angular shift of Sirius is very much like that.

In fact, Astronomers tried in vain to measure parallax angles for many stars and were completely unsuccessful at this time. We know today that the reason for this lack of success is due to the great distances to stars (hence, extremely small parallax angles).

According to the ideas promoted by Galileo, Copernicus and Kepler, the Earth orbits around the Sun. Astronomers realized that we could use this to our advantage in measuring parallax angles.



Instead of using 3000 miles on the Earth as a baseline, we can use the radius of Earth's orbit (93 million miles). If our baseline is tens of thousands of times larger, then the parallax angle P would also be tens of thousands of times larger and maybe measurable!

But if we look at Sirius apparent position when Earth is at two different places in its orbit, Astronomers prior to the 18th century could not measure a parallax angle.

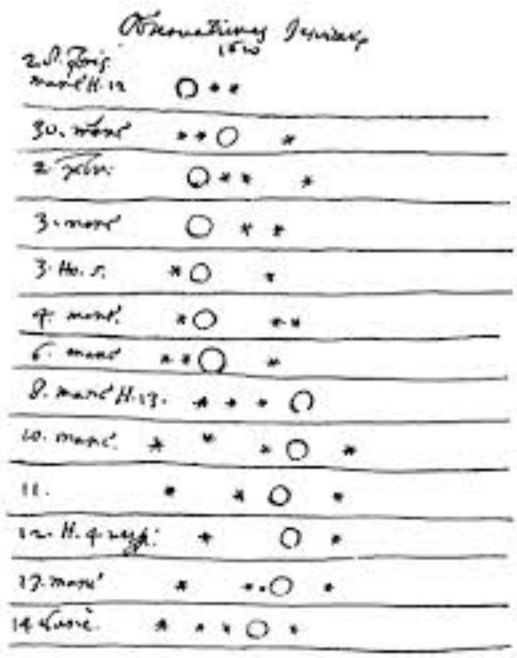
At the time, however, many Astronomers were unwilling to accept the idea that stars were so far away. In order for the parallax angle of Sirius to be too small to measure, they calculated that it would have to be at least 5000 times further away than the most distant planet known at the time (Saturn). From a philosophical standpoint, they thought it was absurd that God would waste so much space. They felt it reasonable to assume that the stars are much closer.

The lack of an observed parallax angle, then, would be explained by the fact that <u>Earth doesn't really orbit the Sun</u>. After all, there are two reasons a parallax angle might be small: Either the distance to the object (the hypotenuse) is really big or the baseline (the opposite side) is really small. So lack of parallax angles seemed to support the geocentric model.

Nevertheless, the debate continued in the scientific community, spurred on later by Italian astronomer and mathematician Galileo Galilei. Galileo famously made two important observations of the sky that seemed to support the heliocentric model of the cosmos.

If you have ever looked at the planet Jupiter through a small telescope, you have no doubt seen the famous Galilean satellites, the four major moons of Jupiter (Io, Europa, Ganymede and Callisto). Here are a few photos taken by amateur astronomers observing Jupiter and its moons:

Galileo was one of the first Astronomers to make systematic use of the newly invented telescope to explore the heavens and publish the results of his observations. He made sketches of the moons of Jupiter and how they changed positions night after night, some of which are shown below.

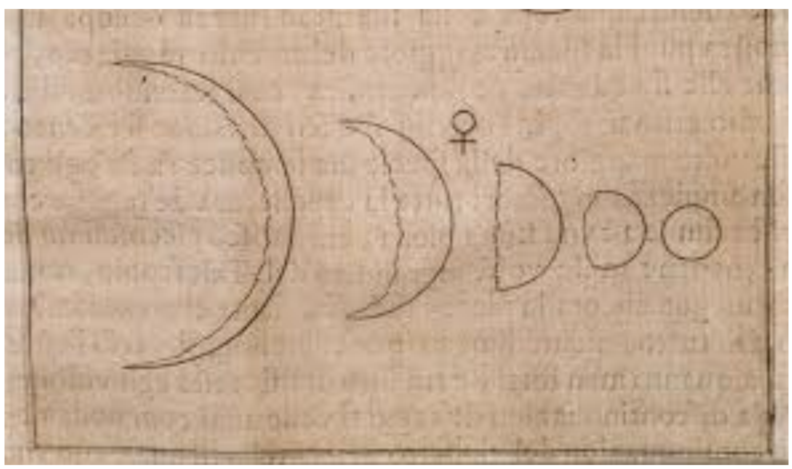


What Galileo eventually came to realize is that these four moons are actually in orbit around Jupiter itself. While that may not seem like a big deal, it was an important point because it conflicted with the geocentric model.

Recall that the geocentric model assumes Earth is at the center and everything revolves around the Earth. But why is that so? Well, you might say because the Earth is very heavy and everything in the sky is very light and ethereal and moves more easily. Or that it just natural that everything moves about the center of the Universe.

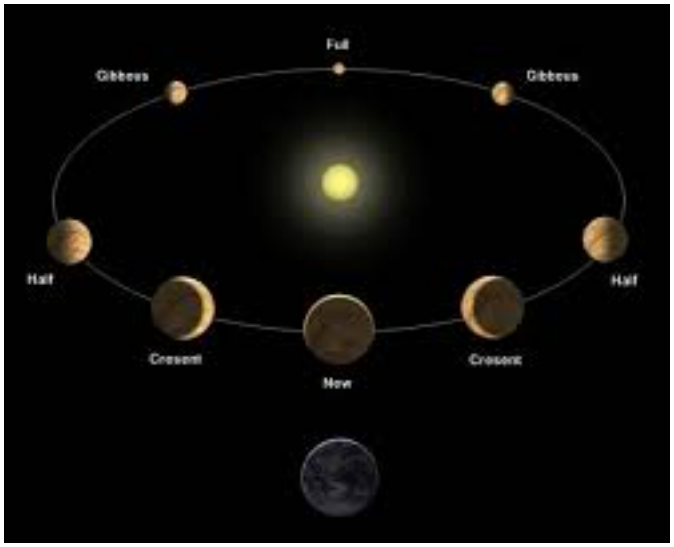
But not the moons of Jupiter! Here was the first definitive example that not EVERYTHING moves around the Earth. And so that starts the cascade of logic: if the Jupiter can be a center of motion, why can't the Sun be a center of motion? The geocentric model had no good answer for why there were objects that didn't have their motion centered on the Earth.

The other major observation Galileo made that was related to this debate was the phases of Venus. Below is a sketch from Galileo's notebook of what he saw as he observed Venus through his telescope over many months:



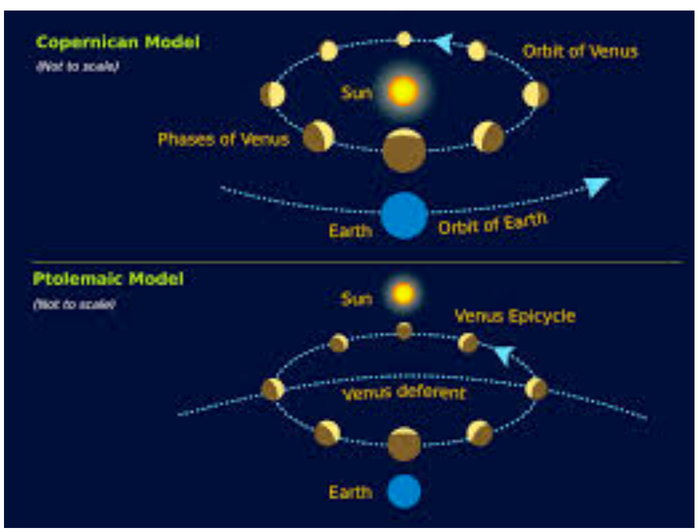
He noticed that Venus shows a complete set of phases, just like our own Moon. Moreover, when Venus is in crescent phase, it has a larger angular size as though closer to us. When gibbous or full, Venus is apparently much further away.

This is very naturally explained in the heliocentric model.



As Venus orbits the Sun, you can see in the diagram above that Venus will show itself as a thin crescent when closer to the Earth and then gibbous or full when far away on the other side of the Sun in its orbit.

By contrast, if you compare the heliocentric model for Venus with the geocentric model for the motion of Venus, it looks something like this:



Notice in the lower diagram, the geocentric model, Venus should never show a gibbous or full phase. This is directly contradicted by Galileo’s observations.

So the evidence in favor of the Copernican model was mixed. There were some apparent problems (like the lack of stellar parallax and the inaccuracy), but there were big problems with the geocentric model as well.

The next major player in this debate was the Danish Astronomer Tycho Brahe, who lived during the late 1500's. Tycho was able to construct a massive observatory, from which he made very careful observations of the motions of the planets over many decades. This database of planetary positions was of enormous importance to those who were trying to construct new and better models of planetary motion.

Prior to Tycho, observations of planetary positions were unreliable. Looking back at the historical record, it was often difficult to tell exactly where a planet was in the sky or how accurate the reported position was. If you want to create a model for how planets move, it is important to have an accurate record to start with.

If you are trying to build a model based on inaccurate observations and your predictions are wrong, you have no way if knowing if the model is wrong or the past observations are wrong. So astronomers who developed new models would have to spend many years testing them with new planetary observations, and these would often go unpublished if the model was a failure.

Tycho was, in fact, interested in developing his own model for the motions of the planets (which you will read about in one of the Scientific American article I am assigning as homework), but his model was ultimately not correct. Tycho's data, however, was the starting point for the work of Johannes Kepler, a German mathematician with an interest in planetary motion.

Kepler was able to use Tycho's data as a starting point and develop a simple model of planetary motion that relied on three basic rules that we now call Kepler's Laws, which I will state in a broad way without all of the mathematical details:

1) Planets move in elliptical orbits around the Sun.
2) Planets closer to the Sun move faster
3) Planets further from the Sun take longer to orbit the Sun.

With these three rules, Kepler revealed that the Copernican model of heliocentric planetary motion was basically correct, but Kepler added details that made the model totally accurate. For decades after Kepler’s model was published, Astronomers would observe planets and check the observed positions against Kepler’s prediction, and Kepler was always right on the money.

And so finally with the motion of planets being well understood, we moved from an ancient view of the cosmos to our more modern view of things. Ultimately, the parallax question was solved as telescopes got better at resolving very small angles, but this didn’t happen until the late 1800’s. Yes, it turns out, stars really ARE that far away.

The other philosophical problem with heliocentric models was the question of what made the heavy earth move? How could the Earth spin so quickly and move so quickly around the Sun in its orbit? Eventually, Isaac Newton solved this issue with his discovery of the laws of gravity and how it relates to orbits, which is a topic for another time and another course.

And now that we have arrived at more or less a modern view of the cosmos after a thorough exploration of the ancients and the remnants they have left behind, it seems appropriate to end the lecture notes here.

I hope you have enjoyed learning about the sky and the history of astronomy as much as I have enjoyed lecturing and writing about it. There will be no further lecture notes this semester. Your third exam will cover material from the two sets of posted lecture notes, which are covered in study guide #3.

As always, if you have questions about the notes or the questions in the study guide, you know you can email me or check in on the discussion board on D2L.tcu.edu.