Chap 2: 
Motions of Earth and the Moon -
a. Celestial Sphere & Coordinates 
b. Time, Calendar, & Navigation 
c. Longterm Climate Change
Chapter 2a: The Celestial Sphere

- The English word **astronomy** originated from Greek ἀστρονομία, where ἄστρον means **astron**, "star" and -νομία means -**nomia** "law".

- "Star arrangements" on the sky changes as geological location and time changes
  - **Constellations** - the arrangement of stars
  - **Celestial Sphere**: (Alt-Az) & (RA, Dec) coordinates

- **Diurnal motion** caused by the spin of the Earth

- **Seasons** caused by the orbit and tilt of the Earth

- **Moon phases and eclipses** caused by relative angles between the Moon and the Sun, as Aristotle realized around 350 BC

- **Fine motion of the Earth** - Precession of the Earth’s spin axis
  - Causes of Ice Ages (Could it also cause the climate change?)
Time Keeping, Celestial Navigation, and Astro Observations

- **RA & Dec of an object:** predefined on sky charts

- **Calendar & Time**
  Geological location + Sky Position ⇒ Date & Time

- **Celestial navigation:**
  Time + Sky Position ⇒ Geological location

- **Astronomical Observations**
  Time + Geological location ⇒ Sky Position
Chapter 2b: Time & Calendar

- How do we keep time?
  through astronomical observations

- What do A.M. & P.M. mean?
  Latin: ante/post meridiem (of Sol)

- How do we make calendar?
  Originally for the purposes of agriculture and religious rituals

- How do we predict the position of objects on the sky?
  Based on date, time, geological location, and celestial coordinates

- How do we navigate through the sea?
  With astronomical observations and marine chronometer
The calendar we use today originated from this ancient city, what is it?

Roman Kingdom (753–509 BC), Roman Republic (509–27 BC), and Roman Empire (27 BC–476 AD)

1. March - Mars, the god of war
2. April - Latin aperio “to open”
3. May - Goddess Maia
4. June - Goddess Juno
5. July - Julius Caesar, Roman Emperor (renamed in 44 BC)
6. August - Augustus, Roman Emperor (renamed in 8 BC)
7. September - Latin 7th
8. October - Latin 8th
9. November - Latin 9th
10. December - Latin 10th
11. January - Janus, the Roman god of beginnings and transition
12. February - Februa, a festival for springtime cleaning and washing
# The Days of a Week (invented by Babylonians of Akkadian Empire 2300 BC, renamed by Romans)

<table>
<thead>
<tr>
<th>Day</th>
<th>Original Latin</th>
<th>Modern Italian</th>
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<tbody>
<tr>
<td>Monday</td>
<td><em>dies Lunae</em> (Luna)</td>
<td>lunedì, martedì, mercoledì, giovedì, venerdì, sabato, domenica</td>
</tr>
<tr>
<td>Tuesday</td>
<td><em>dies Martis</em> (Mars)</td>
<td></td>
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<tr>
<td>Wednesday</td>
<td><em>dies Mercurili</em> (Mercury)</td>
<td></td>
</tr>
<tr>
<td>Thursday</td>
<td><em>dies Jovis</em> (Jupiter)</td>
<td></td>
</tr>
<tr>
<td>Friday</td>
<td><em>dies Veneris</em> (Venus)</td>
<td></td>
</tr>
<tr>
<td>Saturday</td>
<td><em>dies Saturni</em> (Saturn)</td>
<td></td>
</tr>
<tr>
<td>Sunday</td>
<td><em>dies Solis</em> (Sol)</td>
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</table>
Angular Coordinate Systems
Constellations on the celestial sphere
Constellations based on Greece-Roman Mythology

- The entire sky is broken up into 88 regions (48 original): constellations
- Stars within each region create arbitrary patterns
- Resulting myths from human imagination
The division of the celestial sphere is arbitrary: e.g., Lunar Mansions (East Asia) vs. Zodiac Constellations (Europe)

- The stars along the path of the Moon are divided into four quadrants
  - Azure Dragon of the East
  - Black Tortoise of the North
  - White Tiger of the West
  - Vermilion Bird of the South
- Each quadrant has seven lunar mansions
- These 28 lunar mansions correspond to the 12 Zodiac constellations
Stars in the Same Constellation are not at the same distances to us. And brighter stars are not necessarily closer than fainter stars.
Stars in a constellation are not related. e.g., see the Orion Constellation in 3D
Stars in the Same Constellation are not at the same distances to us. And brighter stars are not necessarily closer than fainter stars.
Brighter stars are not necessarily closer than fainter stars, because they could have very different luminosities.
Where is Mt. Everest?
So what is a constellation?

A region of the sky with bright stars forming a \textbf{projected pattern} that evokes \textit{imagination}s.

These projected patterns change over time because stars move \textit{(proper motion)}.

These projected patterns are arbitrary \textit{(meaningless)}. 
Angular Coordinates on the Celestial Sphere

Right Ascension and Declination (RA, Dec) are defined using an intuitive coordinate system.

They do not change over decades for objects outside off the Solar system.
Stars appear fixed on the imaginary celestial sphere, while the Sun, the Moon, and other Solar system objects move across the celestial sphere.
RA & Dec are similar to Longitude and Latitude
HW Q2: Predict the time difference between the local noon at Iowa City and the local noon at Des Moines. Local noon is defined as the time when the Sun transits the local meridian. You are given the following information: (1) the radius of the Earth is measured to be 6350 km, (2) the distance between Iowa City and Des Moines is 115 miles according to Google Map, and (3) both Iowa City and Des Moines are at a latitude of +42 degrees. Choose a sensible unit for your result.

Hint: If you didn’t use the latitude, your solution is incorrect.
RA & Dec are similar to Longitude and Latitude
Because stars, galaxies, and quasars appear to be fixed on the celestial sphere, it makes sense to give them fixed coordinates. We use two angles: right ascension (alpha) and declination (delta).
The Sun and other solar system objects have time-varying coordinates, which are provided as tables called ephemeris.

Still with two angles: right ascension (RA) declination (Dec)

but as functions of time
Ephemeris of Mars

https://ssd.jpl.nasa.gov/horizons/app.html#

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<th>HR:MN</th>
<th>R.A. (ICRF)</th>
<th>DEC</th>
<th>APmag</th>
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### A simplified ephemeris of the Sun

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The ecliptic: the path of the Sun on the celestial sphere

- The ecliptic is tilted 23.5 degrees from the celestial equator, because Earth’s spin axis is tilted 23.5 degrees from the plane of its orbit around the Sun.
At the **autumnal equinox** (September 22), the Sun is on the celestial equator.

At the **summer solstice** (June 20), the Sun is north of the celestial equator.

At the **winter solstice** (December 21), the Sun is south of the celestial equator.

At the **vernal equinox** (March 20), the Sun is on the celestial equator.
Work out (RA, Dec) coordinates of the Sun on the four special dates

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Angular coordinates measured by an observer

Altitude and Azimuth (Alt, Az) are what we measure on the ground

They change all the time: Alt(t), Az(t)
From the perspective of an observer on the ground, each object’s direction can be described by another two angles (Alt & Az).
Measuring azimuth with a compass
Measuring **altitude** with your hand (this week’s lab)
Measuring **altitude** with a sextant
Illustration: How to use sextant to measure the altitude of the Sun
Illustration: How to use sextant to measure the altitude of the Sun
From the perspective of an observer on the ground, each object’s direction can be described by another two angles (Alt & Az)
Diurnal (Daily) motion of objects on the sky
The diurnal motion of objects on the sky is caused by Earth’s daily spin around its poles.
Evidence of Earth’s Spin: Foucault’s Pendulum

On the pole, Foucault pendulum completes one cycle in 23h56m.

Why not 24h?

Foucault's pendulum in the Panthéon, Paris (200 ft, 60 lb)

(not the Pantheon in Rome built in 126 CE)
Sidereal Day vs. Solar Day

From A to A is a Sidereal day 23 hr 56 min

From A to B is a Solar day 24 hr

One sidereal day’s motion on the Earth
Directions of the diurnal motion of objects on the sky

- As the Earth rotates, the sky appears to us to rotate in the opposite direction.

- Imagine you are at the North pole, which direction do stars rotate? CW or CCW? What about the South pole?
Views of the night sky vs. Latitude
Can you tell which place is at a higher latitude?
The altitude of stars depend on its coordinates on the celestial sphere (RA & Dec), the latitude, and the local time of the observer.

From the diagram below, you can see that the altitude of the NCP (close to Polaris) equals the latitude and stars within 30 deg of the NCP never set.
- At Earth’s pole, no stars rise and set.
- The celestial pole is at the zenith.
- Observers can see half of the celestial sphere as it rotates.
- All visible stars are circumpolar stars.
- At Earth’s equator, all stars rise and set.
- The celestial poles are on the northern and southern horizons.
- Observers can see the whole celestial sphere as it rotates.
- All stars rise and set, no circumpolar stars
- At intermediate latitudes,
- Some stars are circumpolar (never sets); What’s their Declination range?
- Some stars rise and set. What’s their Declination range?
- Some stars are never visible. What’s the Declination range?
In Iowa City (42° N), which stars are circumpolar? Give their range in Declination.
If you’re at the south pole, which stars are circumpolar? Give the ranges of RA & Dec.
Recap:

- NCP, SCP, Equator, Ecliptic $\rightarrow$ (RA, Dec)
- Horizon, Zenith, Meridian $\rightarrow$ (Alt, Az)
Every distant object on the celestial sphere has a fixed “longitude & latitude” called RA and Dec.

The celestial sphere of (RA & Dec) is aligned with Earth’s (Lon, Lat).

The two spheres rotate relative to each other because of Earth’s spin, on a period called a sidereal day (shorter than a solar day by ~4 minutes)

RA & Dec of a distant object does change significantly over centuries
# A simplified ephemeris of the Sun

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Separately from (RA, Dec), each object’s direction from the perspective of an observer on the ground are described with another two angles (Alt & Az).
A diagram visualizing the relationship between celestial coordinates (RA, Dec) and ground-observer coordinates (Alt, Az). It helps solve the following problems:

- What's the altitude of NCP?
- What's the Decl. of the zenith?
- What's the Zenith Angle of the Sun at noon?
- What's the Decl. range of circumpolar stars?
- What's the Decl. range of unobservable stars?

The angle between the horizon and the NCP is the same as the observer’s north latitude.
Simple Coordinate Conversion for special locations or sources
How do we put the two sets of coordinates together? (RA, Dec) vs. [Alt(t), Az(t)]
Simple Coordinates Conversion: 
(Alt, Az) of NCP and SCP
- The altitude and azimuth of stars depend on its coordinates on the celestial sphere (RA & Dec), your latitude, and the local *sidereal* time.
- For example, from the diagram below, you can see that the altitude of the NCP (close to Polaris) equals the latitude and its Azimuth is always 0 deg.
Perth is at a latitude of 32° S. (RA, Dec) of SCP = (Undefined, -90d)
What is the altitude and azimuth of the **south** celestial pole (SCP)?
Perth is at a latitude of 32° S.
What is the altitude and azimuth of the NCP?
Simple Coordinates Conversion: (RA, Dec) of Zenith
- (Alt, Az) of local Zenith = (90 deg, 0 deg)
- What is the Declination of a star at Zenith?
- What is the Right Ascension of a star at Zenith?
Iowa City is at a latitude of 41.7° N. What is the Declination of the Zenith?
Iowa City is at a latitude of 41.7° N. What is the Declination of the Zenith?
Vega = alpha Lyra
RA: 18h36m
Dec: +38d47’
Constellation:
Lyra
Practice: Estimate the altitude of Pleiades

- Pleiades cluster (M45) RA 3h47m, Dec +24.1°
- Iowa City coordinates Long = 91.5° W, Lat = 41.6° N
- At LST = 03:47, estimate the Altitude of Pleiades
Coordinate Systems: Summary
This diagram helped derive the equations:

- Altitude of NCP = Latitude
- Declination of zenith = Latitude
- For objects with Declination < Latitude
  - Altitude at transit = $90^\circ - \text{Latitude} + \text{Declination}$
- For objects with Declination > Latitude
  - Altitude at transit = $180^\circ - (90^\circ - \text{Latitude} + \text{Declination})$
Full Coordinate Transformation Formulae: From (RA, Dec) to (Alt, Az)

- RA, Dec, Alt, Az, LST, HA, Latitude = \( \alpha, \delta, a, A_z, t, h, \phi \)
- \((a, A_z)\) varies with time, so we first convert the object’s RA (\(\alpha\)) to HA (\(h\)) at LST (\(t\)):
  \[ h = (t - \alpha) \times 15^\circ/hr = (t - \alpha)/12 \text{ hr} \times \pi \text{ rad} \]
- Next, with spherical trigonometry, we can derive:
  \[ \sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \]
  \[ \tan A_z = \sin h/(\cos h \sin \phi - \tan \delta \cos \phi) \]
- Sanity check:
  calculate \((a, A_z)\) for \(h = 0\), i.e., transit the meridian
Self-test Questions for Coordinate Systems

• Definitions & Diagrams:
  • NP+SP, Equator, Prime Meridian — (Longitude, Latitude)
  • NCP+SCP, Equator, Ecliptic — (RA, Dec)
  • Horizon, Zenith, Meridian — (Alt, Az)

• Simple Coordinate Transformation (at a given location):
  • Calculate the altitude of the Sun at noon on a given date (e.g., June 20).
  • Calculate the altitude of a star (e.g., Rigel) when it transits the meridian.
  • Calculate the declination of a star for which you have measured the altitude when it transits the meridian.

• Navigation Part I: Latitude measurements
  • Describe at least two astronomical methods; List the tools needed

• Calendar and Date
  • How would you determine the length of a year?
  • How would you determine the length of a day?
SOLAR DAY VS. SIDEREAL DAY

Why are there two different days?
Solar Day vs. Sidereal Day

- A (Mean) Solar Day = the time interval between two consecutive noons *(averaged over a year)*
- A Sidereal Day = the time interval between two consecutive transits of a distant star
Sidereal Day vs. Solar Day

From A to A is a Sidereal day 23 hr 56 min

From A to B is a Solar day 24 hr

One sidereal day’s motion on the Earth
Solar Day vs. Sidereal Day

12:00:00

11:56:04  12:00:00

23h 56′ 04″

a sidereal day

3′ 56″

24h

a mean solar day
Motions of the Earth and Obliquity:
The Causes of Earth’s Seasons
Daily Rotation: The Earth spins around its poles every sidereal day (23h56m), causing diurnal motions of objects in the sky.

Spin of the Earth, animated for Summer Solstice (around June 20)
Yearly Revolution: Earth orbits around the Sun every year (365.2422 days), causing the 4-minute longer solar day (24h) and the annual motion of the Sun along the ecliptic.
Obliquity: Earth’s spin axis is tilted from the pole of the ecliptic by 23.5 degrees, causing Earth’s seasons
The combination of Earth’s orbit and its obliquity results in the ephemeris of the Sun below:

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How will the ephemeris change if the obliquity changes from 23.5 degrees to 5 degrees?
Season Factor I: 
The length of daytime increases with the Sun’s declination
The Sun stays above the horizon longer as its declination increases.
Season Factor II: The altitude of the Sun at noon increases with the Sun’s Declination
The Solar Analemma
over
Edmonton, AB

June 21, 2013 - June 2, 2014
09:45 MT
Solar analemma from Sulmona, Italy

A compilation of images of the Sun taken at the same time (12pm) every ten days and at the same place

altitude of Sun at noon = (90 deg - latitude) + declination of Sun
Chichen Itza - Temple of Kukulcan (800-1200 AD)
side slope = 47 deg ~ altitude of the Sun at Winter Solstice

What's the latitude of Chichen Itza?

altitude of Sun at noon = (90 deg - latitude) + declination of Sun
The Slight Elliptical Orbit of the Earth

Earth's orbit around the Sun

- March equinox: March 20 or 21
- June solstice: June 21 or 22
- Aphelion: July 4
- September equinox: September 22 or 23
- December solstice: December 21 or 22
- Perihelion: January 3

- Distance from Sun: 152,100,000 km (Aphelion) to 147,300,000 km (Perihelion)
Ellipticity cannot explain why the Northern & the Southern hemisphere have opposite seasons
Solar Constant

All the energy per unit time that comes out of the Sun, must also come out of the sphere at 1 AU. This is required by conservation of energy.

Sun
$L = 3.86 \times 10^{26}$ Watts

1 AU
$\approx 1.5 \times 10^{11}$ m

Area of a sphere $= 4\pi r^2$

The power per unit area at 1 AU is

$$\frac{L}{4 \pi r^2}$$

$= 1366$ W/m$^2$

and this is the Solar Constant.

DJ Jeffery
UNLV 2003
Altitudes of the Sun in the morning vs. noon cause ground temperature to change.

The key is to understand that how energy is distributed on the ground. At lower altitude, the solar energy is more spread out; at higher altitude, it is more concentrated.
Check out solar energy production
Daily Energy Production of My 4 kW Array

Production: 24.1 kWh

Solar Production
Monthly Production of My Solar Array

<table>
<thead>
<tr>
<th>Month</th>
<th>Quarter</th>
<th>Year</th>
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<td>Jan</td>
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kWh

2019 2020 2021 2022

Estimated
How does the altitude of the Sun affect ground temperature?

The key is to understand that how energy is distributed on the ground. At lower altitude, the solar energy is more spread out; at higher altitude, it is more concentrated.

Noon on Summer Solstice

Noon on Winter Solstice

Sunlight striking the ground nearly face-on is more concentrated.

The same amount of sunlight strikes the ground at a shallower angle and so is spread out over a larger area.
Obliquity & Seasons

Summer

Winter

https://www.youtube.com/watch?v=WLRA87TKXLM
Zenith Angle of the Sun in Summer vs. Winter

1. From the Arctic Circle to the North Pole, there are 24 hours of daylight.
2. At the Tropic of Cancer, the Sun is directly overhead at noon.
3. More than half of the Northern Hemisphere is in daylight.
4. Less than half of the Southern Hemisphere is in daylight.
5. From the Antarctic Circle to the South Pole, there are 24 hours of night.
6. The first day of northern winter is the first day of southern summer.
The Northern Arctic Circle

- Seeing the midnight sun in the arctic circle on summer solstice
- **Magenta lines**: direction towards the Sun at noon and midnight
- arctic circle: latitude > +66.5d
The Southern Arctic Circle

- Seeing the midnight sun in the Antarctic circle on winter solstice
- Antarctic circle: latitude < -66.5°
The axis of rotation of the Earth is not perpendicular to the plain of revolution around the Sun but is tilted 23.5°.
Summary: Obliquity & Seasons

- The 23.5-deg obliquity has the following effects on Earth:
  - The angle of sunlight is more direct in summer, thus the received solar energy is higher per unit surface area.
  - The sun stays above the horizon longer in the summer, shorter in the winter, so the ground receives more energy on a summer day.
  - The ellipticity of the Earth’s orbit has negligible effect on the seasons we experience.
  - Southern Hemisphere experiences the opposite situation of the Northern Hemisphere.
To navigate through the sea, we need to know both our **latitude** and our **longitude**.

- To measure **latitude**, we can use the **altitude** of Polaris, the **altitude** of the Sun at noon given the date, or the **declination** of a star near zenith.

- To measure **longitude**, we need a clock that measures the precise **local time** at a known geological location (home port). That local time could be either **sidereal time** (for nighttime navigation) or **solar time** (for daytime navigation).

---

**CHRISTOPHER COLUMBUS’ FOUR VOYAGES TO THE NEW WORLD**

- **FIRST VOYAGE**: 1492 – 1493 CE
- **SECOND VOYAGE**: 1494 – 1496 CE
- **THIRD VOYAGE**: 1498 – 1500 CE
- **FOURTH VOYAGE**: 1502 – 1504 CE

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© historycrunch.com
LATITUDE:
ALTITUDE OF NCP
DECLINATION OF ZENITH
ALTITUDE OF SUN
This diagram helped derive the equations:

- Altitude of NCP = Latitude
- Declination of zenith = Latitude
- For objects with Declination < Latitude
  - Altitude at transit = 90° - Latitude + Declination
- For objects with Declination > Latitude
  - Altitude at transit = 180° - (90° - Latitude + Declination)
THE ASTRONOMICAL DEFINITION OF TIME

Time is the Hour Angle of Celestial Objects
To keep time, we use **Hour Angle**

- **hour angle** \((h)\) is measured **to the west** from the **local meridian** to the **hour circle** passing through the object (Unit: hr or deg)
- **hour circle**: the great circle through a given object and the two celestial poles
**Hour Angle** is the angle measured to **clockwise** from the **local meridian** to the **hour circle** passing through the object. The diagram below shows that $HA_{\text{Obj}} = RA_{\text{Meridian}} - RA_{\text{Obj}}$, since both HA and RA are measured along the equator but measured in opposite directions.
Practice: Hour Angle Calculation

• Quasar 3C 273 is at RA = 12h29m, Dec = +02d

• Your Zenith is at RA = 7h40m Dec = +42d

• What is the hour angle of 3C 273?

• HA(Obj) = RA(Meridian) - RA(Obj)
**Time** is the **Hour Angle** of a reference celestial object:

- If the object is the Sun, we have the **Apparent Solar Time**;
- If the object is the Vernal Equinox, we have **Local Sidereal Time**.
Longitude difference is time difference:

make sure to compare the same kind of time

\[ \lambda_A - \lambda_B = (LST_A - LST_B) \cdot 15^\circ/\text{hr} \]

\[ \lambda_A - \lambda_B = (MST_A - MST_B) \cdot 15^\circ/\text{hr} \]

\[ \lambda_A - \lambda_B = (AST_A - AST_B) \cdot 15^\circ/\text{hr} \]

Longitudes to the **East** of Greenwich are **positive**; to the **West** of Greenwich are **negative**.
ΔLONGITUDE FROM ΔSIDEREAL TIME
Local Sidereal Time (LST)

• Definition:

LST := Hour Angle of the Vernal Equinox

= RA_{Meridian} - RA_{Ver. Eq.}

⇒

LST = RA_{Meridian}

• As shown on the Time Diagram, we can calculate the HA of any object using a local sidereal clock:

HA_{Obj} = RA_{Meridian} - RA_{Obj} = LST - RA_{Obj}

• Rearranging the above relation, we realize that we can also measure the LST using any objects, not necessarily on the meridian:

LST = RA_{Obj} + HA_{Obj}
Celestial Coordinates of the Local Zenith

Local Sidereal Time
7:17:09

UTC
14:16:43

Longitude: -91.5323

What is Sidereal Time?

RA_{Zenith} = LST
The LST tells us the RA of the Zenith because the Zenith is on the Meridian

Dec_{Zenith} = Latitude
The Latitude tells us the Declination of the Zenith
Difference in Longitude = 
Difference in Sidereal Time \times 15^\circ/hr

\lambda_A - \lambda_B = (LST_A - LST_B) \cdot 15^\circ/hr

Longitudes to the **East** of Greenwich are **positive**; to the **West** of Greenwich are **negative**.
Celestial Navigation with Star at Zenith

• The simplest way is to find the (RA, Dec) of a star closest to the Zenith using a star chart

• You also need a sidereal clock that keeps the LST of a place A at a known longitude, often the GMST (Greenwich Mean Sidereal Time; $\lambda_A = 0^\circ$).

• Your current location B’s longitude ($\lambda$) and latitude ($\phi$) can then be calculated as:
  • $\lambda(B) - \lambda(A) = [\text{LST}(B) - \text{LST}(A)] \times 15^\circ/\text{hr}$
    $\quad = [\text{RA}(\text{Zenith}) - \text{LST}(A)] \times 15^\circ/\text{hr}$
  • $\phi(B) = \text{Dec}(\text{Zenith}) = \text{Alt}(\text{NCP})$

• Positive $\Delta \lambda$ means B is to the East of A.
Practice: Celestial Navigation with Objects near Zenith

• At an unknown location, you saw Pleiades directly overhead. You then looked up its coordinates with a star chart you carried:
  • Pleiades cluster (M45)
    RA 3h47m, Dec +24.1°

• You also carried a sidereal clock calibrated to the LST of Iowa City at Longitude = 91.5° W and Latitude = 41.6° N. The sidereal clock reads
  • LST of Iowa City = 23:17

• What are your geological coordinates?
  • Latitude = ?
  • Longitude = ?

• Equation:
  • \( \lambda(B) - \lambda(A) = [\text{LST}(B) - \text{LST}(A)] \times 15 \text{deg/hr} \), where Positive \( \Delta \lambda \) means B is to the East of A.
Celestial Navigation with Stars not on Zenith

• The more practical way is to measure the **zenith angle of a bright star** \((ZA = 90°-\text{Alt})\), for which you know its \((RA, \text{Dec})\) from a chart.

• You also need a **sidereal clock** that keeps the **LST** of a place A with a known longitude, often the **GMST** \((\lambda_A = 0°)\).

• The \((RA, \text{Dec})\) of the star and GMST tell us the geological location of the place on Earth where the star is at its zenith:
  - \(\lambda = (RA - \text{GMST}) \cdot 15°/\text{hr}\)
  - \(\phi = \text{Dec}\)

• Your location must be along the circle centered on \((\lambda, \phi)\) with a radius of the Zenith Angle you measured.
Celestial Navigation with Two Stars

• The more practical way is to measure the zenith angles of two bright stars (ZA = 90°-Alt), for which you know their (RA, Dec) from a star chart.
• You also need a sidereal clock that keeps the LST of a place A with a known longitude, often the GMST (λ_A = 0°).
• The (RA, Dec) of the stars and GMST tell us the geological locations of the two places on Earth where the two stars are at their zenith:
  • \( \lambda_A = (RA_A - \text{GMST}) \times 15^\circ/\text{hr}, \)
  \( \lambda_B = (RA_B - \text{GMST}) \times 15^\circ/\text{hr} \)
  • \( \phi_A = \text{Dec}_A, \phi_B = \text{Dec}_B \)
• You then draw two circles on the globe, each with a radius equal to the zenith angle you measured. The two circles intersect at two points, and you must be at one of the two positions.
• To break the ambiguity, you can observe the zenith angle of the third star, and draw the third circle.
ΔLONGITUDE FROM ΔSOLAR TIME
Apparent Solar Time vs. Local Sidereal Time

• Apparent Solar Time (AST):
  • \[ \text{AST} := 12h + \text{Hour Angle of the Sun} = 12h + (\text{RA}_{\text{Meridian}} - \text{RA}_{\text{Sun}}) \]

• Local Sidereal Time (LST):
  • \[ \text{LST} := \text{HA}_{\text{Ver.Eq.}} = \text{RA}_{\text{Meridian}} \]

• Given the above two equations, we obtain:
  • \[ \text{AST} = \text{LST} - \text{RA}_{\text{Sun}} + 12h \]

• Homework Question:
  on which day, AST equals LST?
Apparent Solar Time vs. Local Sidereal Time

DATE: FEBRUARY 6th

Use the relation, $\text{AST} = \text{LST} - \text{RA}_{\text{Sun}} + 12h$, to check if the illustration is correct. Or given the illustration, estimate the date.
The Length of a Solar Day varies because of the elliptical orbit of the Earth.
The Two Types of Local Solar Time

• Apparent Solar Time (AST)
  • AST = 12 hrs + (HA of the Sun / 15 deg/hr)
  • Length varies because of the elliptical orbit

• Mean Solar Time (MST)
  • Duration defined as the average length of a solar day (*this is the 24 hours we use daily*)
  • Tracks a theoretical mean Sun with a uniform motion along the celestial equator
Equation of Time: a diagram giving the difference between AST and MST as a function of date in a year
Solar analemma:

A compilation of pictures of the Sun taken at 12PM every ~10 days at the same location on Earth

Technical definition:

A diagram showing the position of the Sun in the sky as seen from a fixed location on Earth at the same mean solar time, over the course of a year.

Solar analemma from Sulmona, Italy
Analemma at **mean solar time** noon from Greenwich Royal Observatory
Simple Celestial Navigation with the Sun

• Measure the Sun’s **altitude** when it transits the meridian. At that moment, the **apparent solar time** is 12:00PM.

• At that moment, use the chronometer onboard to look up the **mean solar time** at a known longitude (A): e.g., Greenwich

• Given the **date**:  
  • Correct the 12:00PM Apparent Solar to Mean Solar Time with the **Equation of Time**  
  • Look up the **Declination** of the Sun from the **ephemeris**

• We can now calculate our current location (B):
  • $\lambda(B) - \lambda(A) = [\text{MST}(B) - \text{MST}(A)] \times 15\text{deg/hr}$
  • $\varphi(B) = [90 - \text{Altitude}(\text{Sun})] + \text{Dec}(\text{Sun})$
What time do we use everyday? Standard Mean Solar Time at a Time Zone

- **Mean solar time** has a precise dependency on longitude, making it difficult to use (e.g., *Des Moines is 8 min [2 deg] behind IC*). So we all use **Standard Time**

- **UTC/UT** = mean solar time at Greenwich (0 deg longitude)
  EST, CST, MST, PST keeps the **mean solar time** at \( \lambda = 75, 90, 105, 120 \) deg W

- **CT = CST + 1 hr (Daylight Saving)**, between March 12 and November 5.
Summary of Time Conversions

- **LST := HA_{Ver.Eq.} = RA_{Meridian}**
- **AST := HA_{Sun} = LST - RA_{Sun} + 12h**
- **MST = AST - (AST-MST)_{Date}**
  
  [need to look up the Eq. of Time diagram]

- **MST - ST = (\lambda_{MST} - \lambda_{ST})/(15°/hr)**
  
  [Western longitudes are negative]

- **UTC, EST, CST, MST, PST, HST** keeps the MST at
  
  \(\lambda = 0°, 75°W, 90°W, 105°W, 120°W, 150°W\)

- **e.g., CST = UTC - 6hr,**
  
  because 90°W means 6 hrs behind
Motions of the Moon
Teotihuacán - Pyramid of the Moon, near Mexico City, built around 100 AD
Phases of the Moon due to its orbit around Earth
The monthly orbit of the moon causes a monthly cycle of moon phases.
Moon Phases fast-forwarded
Moon Phase Diagram
This diagram sets the observer above the ecliptic north pole, ignoring the 23.5° obliquity. From this angle, everything moves counterclockwise:

- Earth spins on its axis counterclockwise
- The orbit of the Earth around the Sun goes counterclockwise
- The orbit of the Moon around the Earth goes counterclockwise

When viewed from Earth’s North Pole, planetary orbits—as well as the rotation of most planets and the orbits of most moons—are counterclockwise.
Part 1: Earth’s Spin and Apparent Solar Time

Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM
Part 2: The orbit of the Moon and moon phases

Chose eight representative positions along a orbit of the Moon.

These 8 positions represent 8 different moon phases because their Sun-Moon-Earth angles are different.

Note that the moon moves just slightly in an Earth day.
Part 3: The appearance of the Moon from Earth at each moon phase

- **About New**
- **Waxing Crescent**
- **1st Quarter**
- **Waxing Gibbous**
- **Full**
- **Waning Gibbous**
- **3rd Quarter**
- **Waning Crescent**
- **About New**

**Left side**
**East**
(facing South)

**Right side**
**West**
(facing South)
Phases: the appearances of the Moon at the eight phases
When the Moon is here in its orbit...

...it looks like this.
Moon Phase Diagram

- Apparent Solar Time
- Orbit of the Moon
- Appearance of the moon at 8 equally spaced positions in the orbit
- Names of the moon phases
Which phase is the Moon in?

A. First quarter
B. Waxing gibbous
C. Waning gibbous
D. Third quarter
E. Waxing crescent
How to estimate apparent solar time from Moon phases?
Suppose today’s moon phase is full, when’ll it rise from the horizon?
How to estimate the apparent solar time when a given-phase moon rises, transits, and sets? For example, the full moon.

Note 1: Everywhere in the world sees the same moon phase, so for simplicity, just imagine yourself on the equator.

Note 2: This diagram is not to scale, and the moon is very far away than it appears on this diagram (no significant parallax)

Direction to the Sun

Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

Draw green arrows that indicate the horizon at each time and use its direction to point at the east
When will a full moon rise?
When will the full moon rise?

Direction to the Sun

Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

Draw green arrows that indicate the horizon at each time and use its direction to point at the east.
You saw a full moon directly to the South, what time is it?
When will the full moon transit?

Sunrise ~ 6AM | Noon ~ 12PM | Sunset ~ 6PM | Midnight ~ 12AM

Draw green arrows that indicate the horizon at each time and use its direction to point at the east
When will a third quarter moon rise (from the horizon)?
You see a third quarter moon directly to the South, what time is it?
Earth’s Fine Motions & Climate Change
(a quick 15 min intro)
The Last Ice Age: 115-12 kyrs ago
Maximum Ice Coverage: 26-20 kyrs ago
Ice covered all of Canada, down to Missouri
The Spread of *Homo Sapiens* across the Continents

- The Last Glacial Period: 115 - 12 kyrs ago
- North America: 12 kyrs ago
- Europe & Asia: 70 - 40 kyrs ago
- Australia: 50 kyrs ago
- Hawaii: 1 kyr ago
Short-term Cycles of Earth’s Motions
daily rotation & yearly revolution

- Vernal equinox
- Summer solstice
- Autumnal equinox
- Winter solstice

Earth’s orbit
Seasons caused by changes in solar isolation

1. From the Arctic Circle to the North Pole, there are 24 hours of daylight.
2. At the Tropic of Cancer, the Sun is directly overhead at noon.
3. More than half of the Northern Hemisphere is in daylight.
4. Less than half of the Southern Hemisphere is in daylight.
5. From the Antarctic Circle to the South Pole, there are 24 hours of night.
6. The first day of northern winter is the first day of southern summer.
Solar Insolation on Summer Solstice at 65°N

Long-term Cycles of Earth's Motions

eccentricity, obliquity, precession
Axial Precession (Wobble)
26,000-year cycles

climate.nasa.gov
Because of the Earth’s precession, the location of the Vernal Equinox moves along the ecliptic, changing the celestial coordinates (R.A. & Dec) and messing up the zodiac of each month.

- Tropic of Cancer has now become Tropic of Taurus (the Sun’s constellation on Summer Solstice),
- Tropic of Capricorn has now become Tropic of Sagittarius (the Sun’s constellation on Winter Solstice)
- Currently the north celestial pole is near the bright star Polaris.

- In 10000 years, it will be close to Vega.
Changes in Obliquity (Tilt)
41,000-year cycles

Relative to orbital plane
22.1-24.5°

climate.nasa.gov
Changes in Eccentricity (Orbit Shape)
100,000-year cycles

*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).*

climate.nasa.gov
Obliquity and eccentricity changes due to gravitational perturbations from other planets.
Milankovitch Cycles & Ice Ages

eccentricity, obliquity, precession
Milankovitch used changes in Earth’s motion to explain its long-term climate changes

- **Eccentricity**
  - 100,000 yr cycles
  - range: 0.0034-0.058
  - present val.: 0.017

- **Obliquity**
  - 41,000 yr cycles
  - range: 22.1-24.5 deg
  - present val.: 23.4 deg

- **Precession**
  - 26,000 yr cycles

Milutin Milanković 1879-1958
Serbian astronomer
Predicting Solar Insolation on Summer Solstice at 65° N

Milankovitch Cycles

Obliquity $\epsilon$ (deg)

Eccentricity $e$

Precession $\sin(\omega)$

kiloyears A.D.
Obliquity
\( \varepsilon \) (deg)
Eccentricity
Precession \( \sin(\varpi) \)
Eccentricity \times Precession
Summer Insolation at 65 deg N
\( \bar{Q}^{\text{day}} \) 65 N (W m\(^{-2}\))
kiloyears A.D.
Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle.

**Green**: obliquity-caused variations

**Red**: total variations (obliquity+eccentricity+precession)

Average solar irradiance (insolation) at latitude of 65 deg N on summer solstice over the past million years
Where are we now in the Cycle?

Obliquity: Intermediate and decreasing, Northern Summer at Aphelion
-> Lower Insolation in N hemisphere -> Less snow melt in N. summer -> Colder climate
How does the solar insolation curve compare with the temperature rise in the past century?
Longterm Climate Change & Earth's Fine Motions
Short-term Cycles of Earth’s Motions

daily rotation & yearly revolution

Vernal equinox

Winter solstice

Earth’s orbit

Sun

Autumnal equinox

Summer solstice
- **Obliquity and Seasons**

(a) **First day of northern summer**
**June 21**

1. From the Arctic Circle to the North Pole, there are 24 hours of daylight.

2. At the Tropic of Cancer, the Sun is directly overhead at noon.

3. More than half of the Northern Hemisphere is in daylight.

4. Less than half of the Southern Hemisphere is in daylight.

5. From the Antarctic Circle to the South Pole, there are 24 hours of night.

(b) **First day of northern winter**
**December 22**

6. The first day of northern winter is the first day of southern summer.
The Last Ice Age: 115-12 kyrs ago
Maximum Ice Coverage: 26-20 kyrs ago
Ice covered all of Canada, down to Missouri
The Spread of *Homo Sapiens* across the Continents

- **Europe & Asia**: 70 - 40 kyrs ago
- **North America**: 12 kyrs ago
- **Australia**: 50 kyrs ago
- **Hawaii**: 1 kyr ago

The Last Glacial Period: 115 - 12 kyrs ago
Long-term Cycles of Earth’s Motions

eccentricity, obliquity, precession
Axial Precession (Wobble)
26,000-year cycles
Tidal forces on Earth’s Equatorial Bulge caused most of the precession.
Earth’s precession changes the celestial coordinates of distant objects.
Precession: The Drift of Vernal Equinox & the NCP
▪ Currently the north celestial pole is near the bright star Polaris.

▪ In 10000 years, it will be close to Vega.
Because of the Earth's precession, the location of the Vernal Equinox moves along the ecliptic, changing the celestial coordinates (R.A. & Dec) and messing up the zodiac of each month.

- Tropic of Cancer has now become Tropic of Taurus (the Sun's constellation on Summer Solstice),
- Tropic of Capricorn has now become Tropic of Sagittarius (the Sun's constellation on Winter Solstice)

On September 1 the Sun is seen in the direction of Leo as viewed from Earth.

The apparent path that the Sun follows against the background of the stars is called the ecliptic.

By December 1 Earth has traveled far enough in its orbit that the Sun is seen in the direction of Scorpius.
Changes in Obliquity (Tilt)
41,000-year cycles

Relative to orbital plane
22.1-24.5°

climate.nasa.gov
Changes in Eccentricity (Orbit Shape)

100,000-year cycles

*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).*
Gravitational perturbations from other planets

- Neptune
  - Triton
  - Miranda
  - Ariel
  - Umbriel
  - Titania
  - Oberon (and more...)

- Uranus
  - Miranda
  - Ariel
  - Umbriel
  - Titania
  - Oberon (and more...)

- Saturn
  - Mimas
  - Enceladus
  - Tethys
  - Dione
  - Rhea
  - Titan
  - Hyperion that should be Iapetus (and more...)

- Jupiter
  - Io
  - Europa
  - Ganymede
  - Callisto (and more...)

- Mars
  - Phobos
  - Deimos
  - A number of small moons (not shown)

- Earth
  - Moon

- Venus

- Mercury
Milankovitch Cycles & Ice Ages

eccentricity, obliquity, precession
How to make an ice age?

- The key is to reduce the amount of ice melting in the northern summer
- Northern Hemisphere: 40% land, 60% ocean
- Southern Hemisphere: 20% land, 80% ocean
- milder summer in northern hemisphere -> less ice melt during the summer -> more reflection of sunlight -> colder average temperature
Solar Insolation on Summer Solstice at 65° N

Milankovitch use changes in Earth’s motion to explain its long-term climate changes

- **Eccentricity**
  - 100,000 yr cycles
  - range: 0.0034-0.058
  - present val.: 0.017

- **Obliquity**
  - 41,000 yr cycles
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  - present val.: 23.4 deg

- **Precession**
  - 26,000 yr cycles

---

Milutin Milanković 1879-1958
Serbian astronomer
Milankovitch Cycles

Obliquity

\[ \epsilon \text{ (deg)} \]

Eccentricity

\[ e \]

Precession

\[ \sin(\varpi) \]

kiloyears A.D.
Recipe to make an Ice Age

- High **eccentricity**, while **precession** shifts Northern Summer to **Aphelion**
- Low **obliquity**: less solar radiation in the summer at high northern latitudes
- These cause **milder summer** in northern hemisphere -> **less ice melt** during the summer -> **more reflection of sunlight** -> **colder** global temperature
Predicted Solar Insolation

Milankovitch Cycles

- **Obliquity**
  \[ \epsilon \text{ (deg)} \]

- **Eccentricity**
  \[ e \]

- **Precession**
  \[ \sin(\varpi) \]

- **Eccentricity x Precession**
  \[ e \sin(\varpi) \]

- **Summer Insolation at 65 deg N**
  \[ \overline{Q}^{\text{day}}_{65 \text{ N}} \text{ (W m}^{-2}) \]

kiloyears A.D.
Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle.

- **Green**: obliquity-caused variations
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Average solar irradiance (insolation) at latitude of 65 deg N on summer solstice over the past million years.
Obliquity $\epsilon$ (deg)

Eccentricity $e$

Precession $\sin(\varpi)$

Eccentricity x Precession $e \sin(\varpi)$

Summer Insolation at 65 deg N $\overline{Q}^{\text{day}}$ (W m$^{-2}$)

Temperature Anomaly from benthic forams $\delta^{18}O$ (%)

Temperature Anomaly from Antarctica Ice Core $\Delta T_s$ (K)

kiloyears A.D.
Where are we now in the Cycle?

Obliquity: Intermediate and decreasing, Northern Summer at Aphelion

-> Lower Insolation in N hemisphere -> Less snow melt in N summer -> Colder climate
Milankovitch calculated that Ice Ages occur either every 41 kyrs or 100 kyrs, following the obliquity cycle or the eccentricity cycle, and we are currently on a **cooling trend** that started 6000 years ago.

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**Ice Age & Glacial**

50,000 years later

**Ice Age & Interglacial**

Present

**No Ice Age or Glacial**

9000 years ago
Milankovitch Cycles & Recent Global Warning
Glaciers on Tian Shan Mountains
'Impossible To Save': Scientists Are Watching China's Glaciers Disappear

October 21, 2017 6:39 AM ET
Weather stations across the world record temperatures of air, land, and ocean
Weather station data since 1880 CE
Where are we now in the Cycle?

Obliquity: Intermediate and decreasing, Northern Summer at Aphelion
-> Lower Insolation in N hemisphere -> Less snow melt in N summer -> Colder climate
If we zoom in onto the past 100 years of the Milankovitch insolation curve, no significant change in insolation is predicted.
Greenhouse Effect

Sun

reflected light

visible light

atmosphere

IR absorbed and re-radiated

infrared (IR) radiation

absorbed by surface

Earth

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GLOBAL TEMPERATURE & CO₂

°C
+1.1° (1.98°F)
+0.9°
+0.7°
+0.5°
+0.3°
+0.1°
-0.1°
-0.3°

1880

PPM
410
390
370
350
330
310
290
270

2020

TEMPERATURE

CARBON DIOXIDE

Global temperature anomalies averaged and adjusted to early industrial baseline (1881-1910)
Global annual average carbon dioxide
Source: NASA GISS, NOAA NCEI, ESRL

1 deg C = 1.8 deg F

PPM: parts per million

CLIMATE CENTRAL
CO2 Level in the past 800 kyrs

For millennia, atmospheric carbon dioxide had never been above this line.

1950 level

Current level