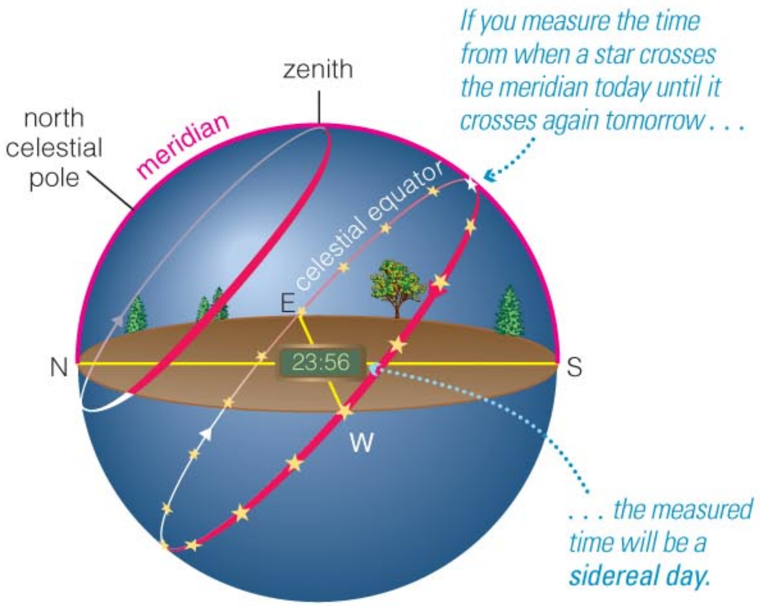
Chapter S1: Celestial Timekeeping and Navigation

Celestial Timekeeping and Navigation

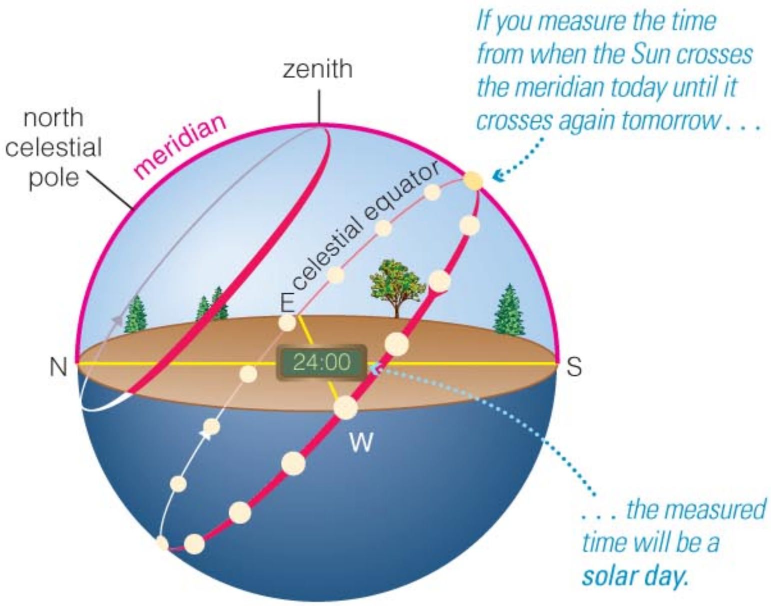
S1.1 Astronomical Time Periods

- Our goals for learning:
  - **How do we define the day, month, year, and planetary periods?**
  - **How do we tell the time of day?**
  - **When and why do we have leap years?**

Sidereal and Solar Days Observed from Earth



a A sidereal day is the time it takes any star to make a circuit of the local sky. It is about 23 hours 56 minutes.

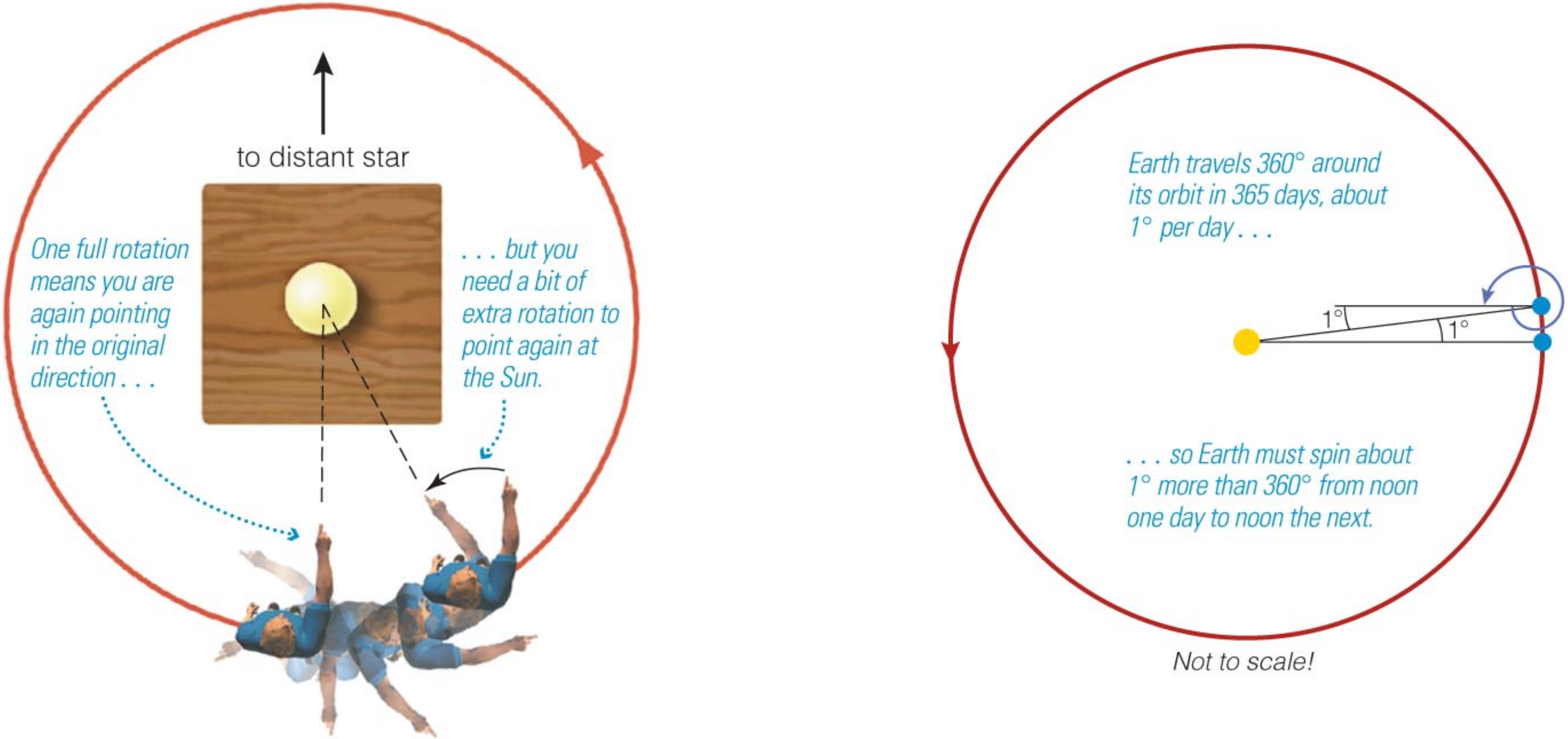


b A solar day is the time it takes the Sun to make a circuit of the local sky. Its precise length varies slightly over the course of the year, but the average is 24 hours.

The Length of the Day

- **Sidereal day**
  - The amount of time it takes the Earth to spin once with respect to the distant stars.
  - 23 hours 56 minutes
- **Solar day**
  - The amount of time time takes the Earth to spin once with respect to the Sun.
  - 24 hours

Why are sidereal and solar days different?



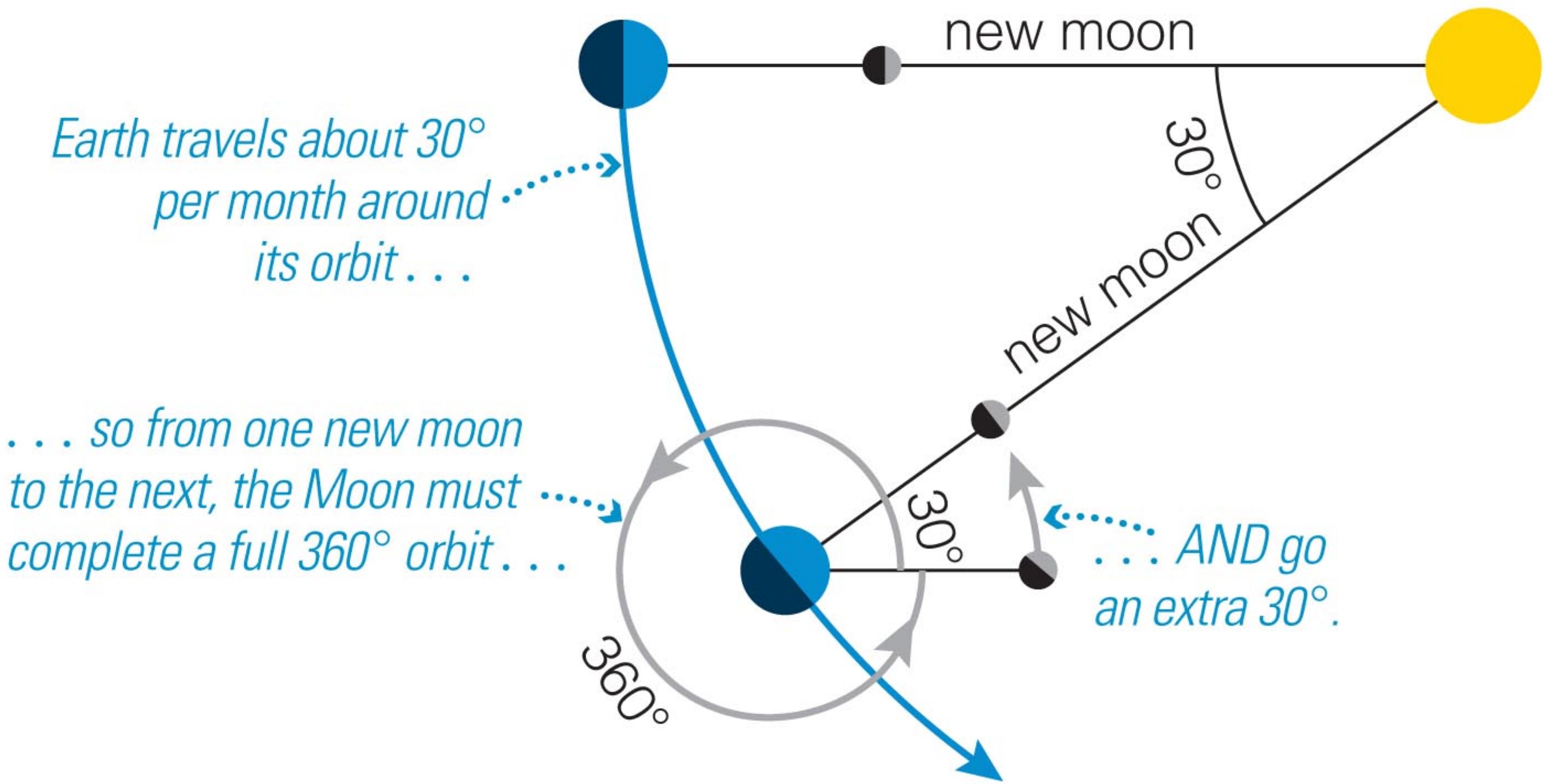
a One full rotation represents a sidereal day and returns you to pointing in your original direction, but you need to rotate a little extra to return to pointing at the Sun.

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

The Length of the Month

- **Synodic month**
  - The amount of time it takes the Moon to repeat its phase (i.e., new to the next new).
  - 29.5 days
- **Sidereal month**
  - The amount of time time takes the Moon to complete one orbit with respect to the background stars.
  - 27.3 days

The Length of the Month



The Length of the Year

- **Sidereal year**
  - The amount of time it takes the Earth to orbit the Sun once with respect to the background stars.
- **Tropical year**
  - The amount of time time takes the Earth to go from the March equinox one year to the March equinox the next year.

Planetary Periods

- **Sidereal period**
  - The amount of time it takes a planet to orbit the Sun, measured with respect to the background stars.
- **Synodic period**
  - The time from when a planet is aligned with the Sun in our sky until it is again aligned similarly.

Planetary Periods (approximate)

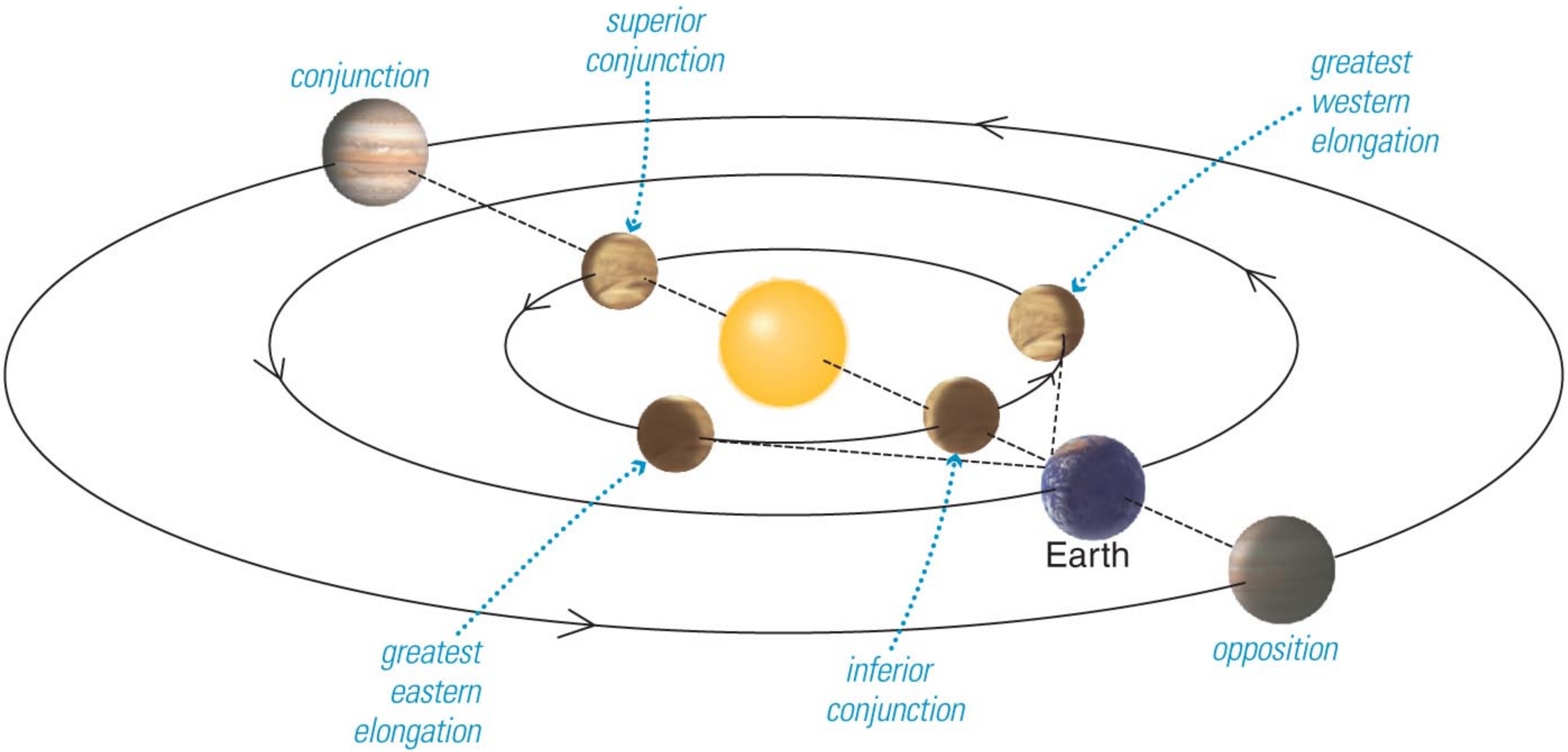
Planet	Distance from Sun (AU)	Synodic Period		Sidereal period	
		Days*	Years**	Days*	Years**
Mercury	0.39	116	0.32	88	0.241
Venus	0.723	584	1.60	225	0.616
Earth	1.0	--	--	365	1.0
Mars	1.524	780	2.14	687	1.881
Jupiter	5.203	399	1.09	4,332	11.86
Saturn	9.539	378	1.04	10,760	29.46
Uranus	19.18	370	1.013	30,685	84.01
Neptune	30.06	368	1.008	60,193	164.8

* Meaning Earth days

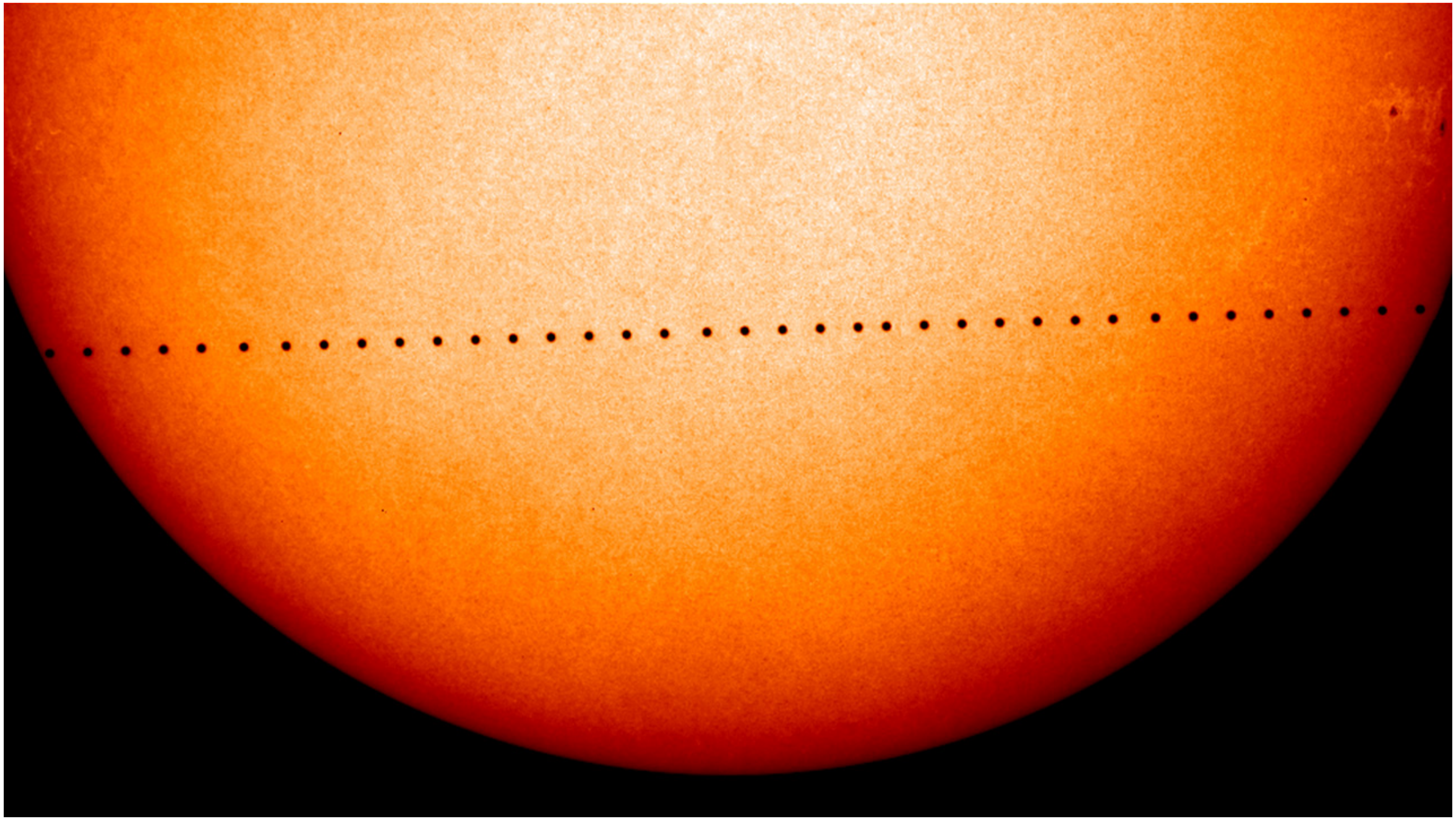
**1 Year = 365.25 Earth days

Notice that the actual (sidereal) periods of planets are longer, the further planets are from the Sun!

Planetary Alignments & Conjunctions



Transit



- When Mercury or Venus are at inferior conjunction, while also being in the Earth-Sun line, a transit is seen.

How do we tell the time of day?

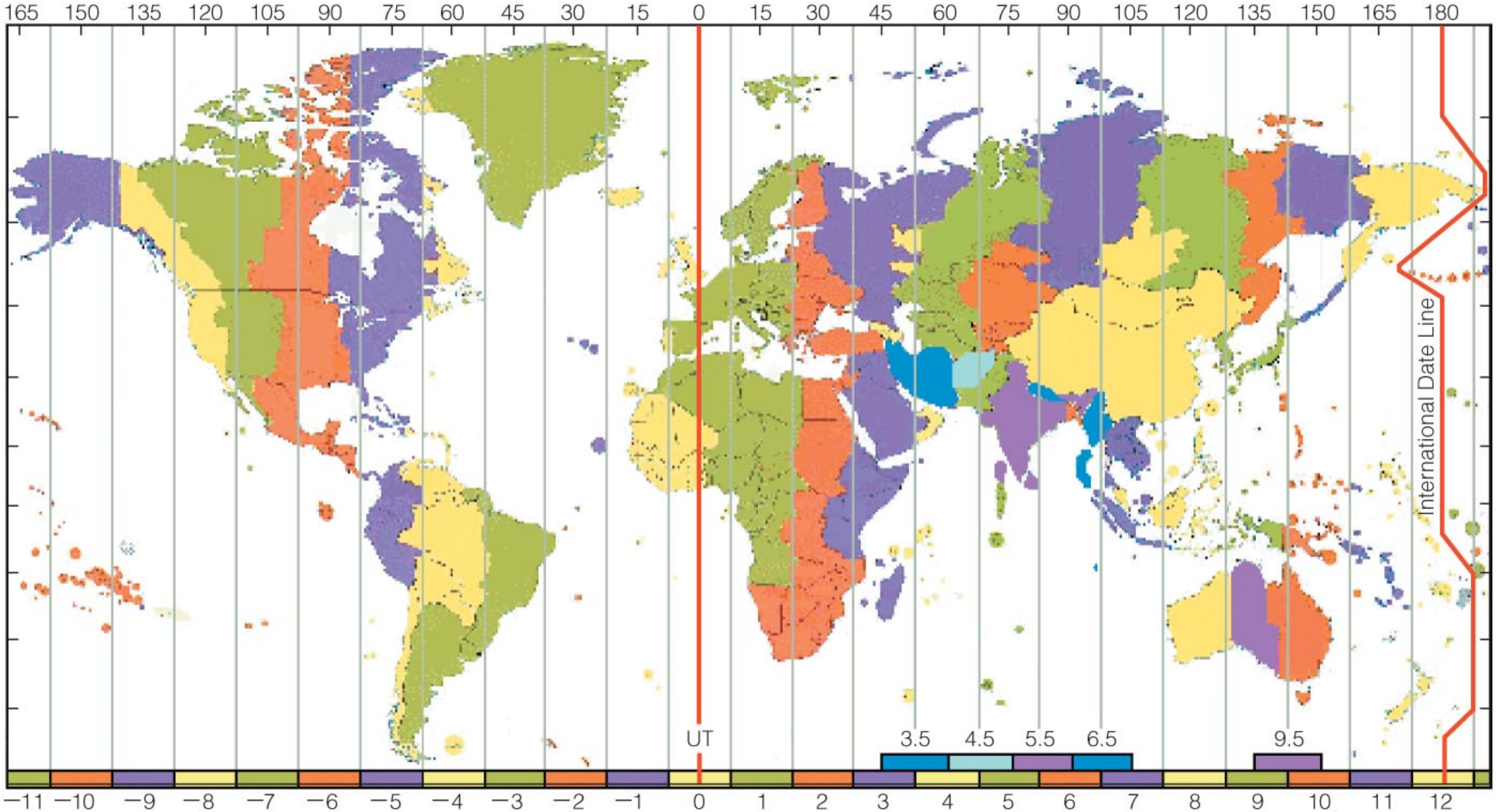
How do we tell the time of day?

- **Apparent solar time**
  - Noon is the time when the shadow on a sundial is shortest.
- **Mean solar time**
  - Noon is set to the *average* time when the shadow on a sundial is shortest. (Accounts for subtle differences in day lengths.)

How do we tell the time of day?

- **Standard time**
  - Mean solar time in the center of your *time zone*.
- **Universal time**
  - Mean solar time at 0 degrees longitude (Greenwich, England)
  - Useful standard for navigation and astronomy.

Time Zones



165 150 135 120 105 90 75 60 45 30 15 0 15 30 45 60 75 90 105 120 135 150 165 180
International Date Line
UT
3.5 4.5 5.5 6.5
9.5
−11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9 10 11 12

When and why do we have leap years?

When and why do we have leap years?

- Because there are ~365.25 days in a year, a calendar based based on 365 days will get out of synch with the seasons
- **Solution:** Add one day every four years!
  - These are *leap years* and are part of the *Julian calendar*.
  - The *Gregorian calendar* adds even more subtle corrections to stop the equinoxes from drifting.

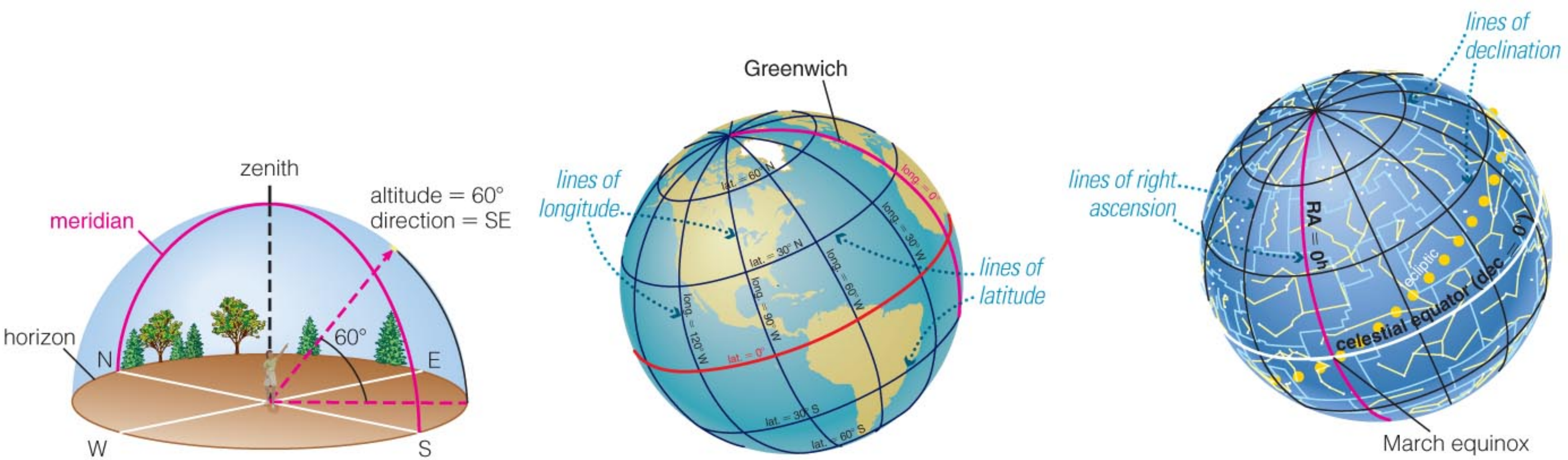
What have we learned?

- **How do we define the day, month, year, and planetary periods?**
  - We define periods of time based on orbits or rotation relative to either the Sun or the distant stars.
- **How do we tell the time of day?**
  - We use a standardized version of timekeeping based on the position of the Sun in the local sky.
- **When and why do we have leap years?**
  - Roughly every four years, as an even number of days do not fit into a year.

S1.2 Celestial Coordinates and Motion in the Sky

- Our goals for learning:
  - **How do we locate objects on the celestial sphere?**
  - **How do stars move through the local sky?**
  - **How does the Sun move through the local sky?**

How do we locate objects on the celestial sphere?



a We use altitude and direction to pinpoint locations in the local sky.

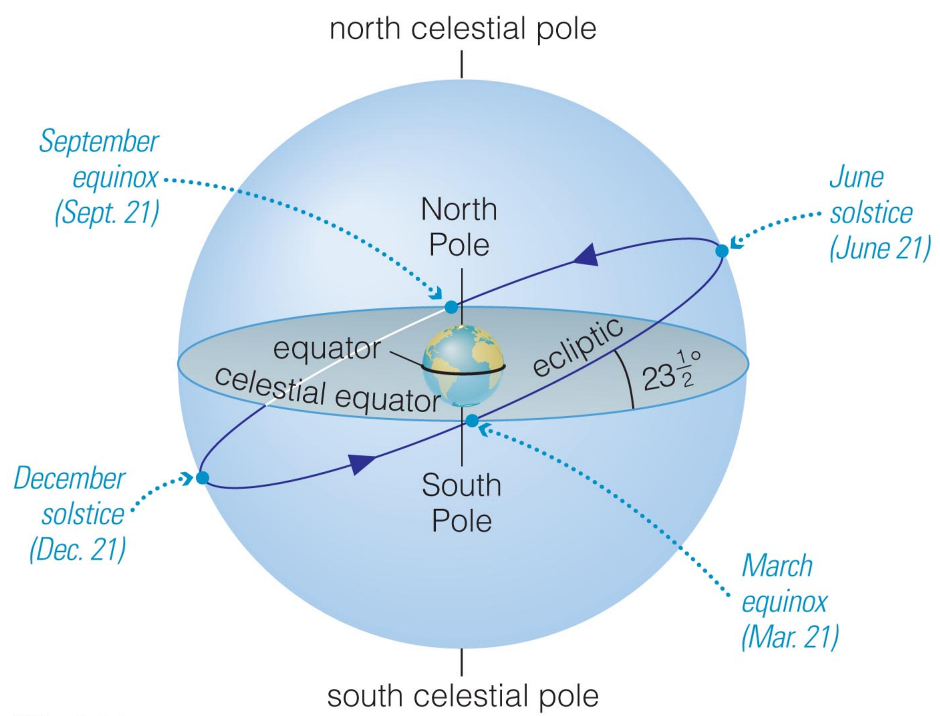
b We use latitude and longitude to pinpoint locations on Earth.

c We use declination and right ascension to pinpoint locations on the celestial sphere.

- Earth's surface: **latitude** & **longitude**
- Celestial sphere: **declination** & **right ascension**

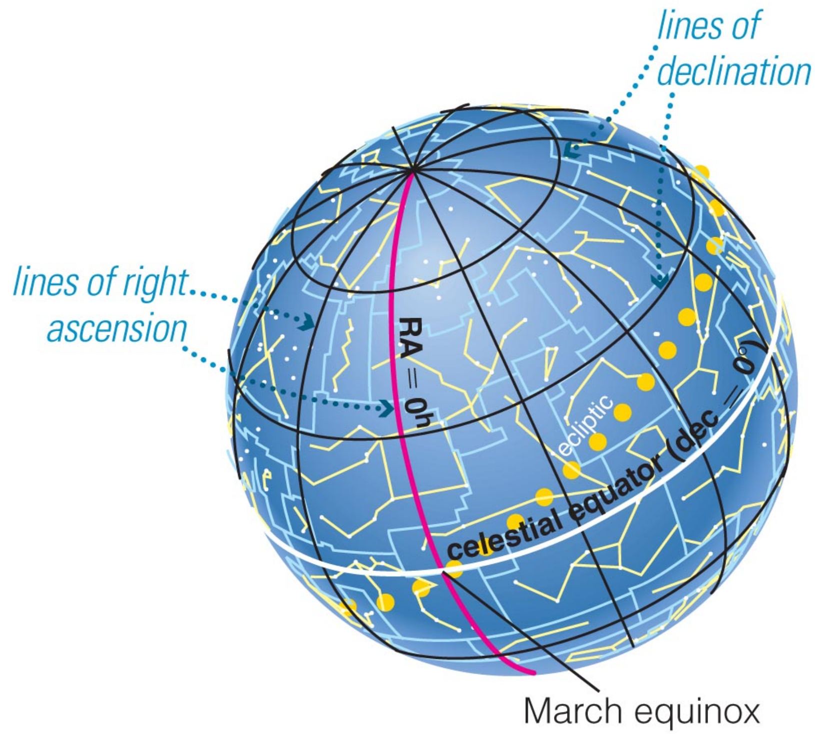
The Celestial Sphere

- Celestial poles
  - Positions correspond with Earth's poles.
- Celestial equator
  - Position corresponds with Earth's equator.
- Equinoxes and solstices
  - Special points on the ecliptic.



Celestial Coordinates

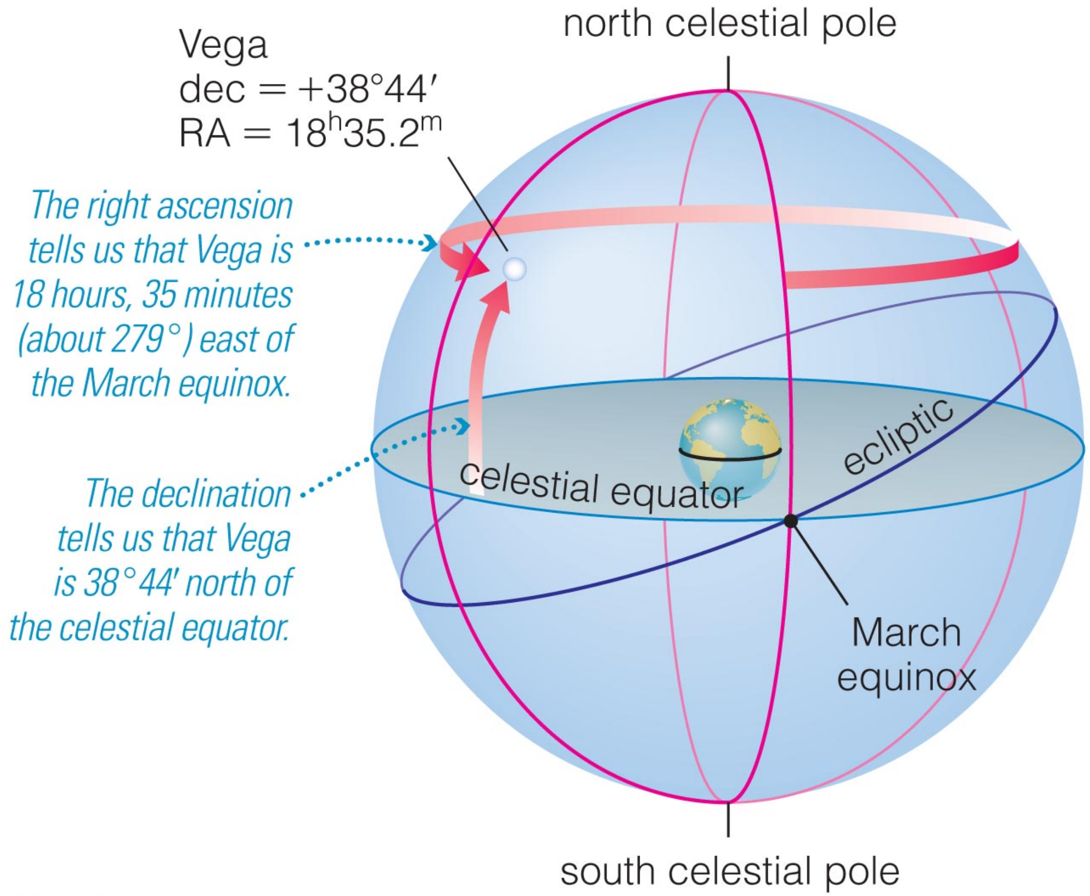
- Declination
  - "Latitude" on the celestial sphere.
  - 0º at celestial equator, +/- rather than north/south.
- Right ascension
  - "Longitude" on the celestial sphere.
  - 0^h at March equinox, measured in hours east.



c We use declination and right ascension to pinpoint locations on the celestial sphere.

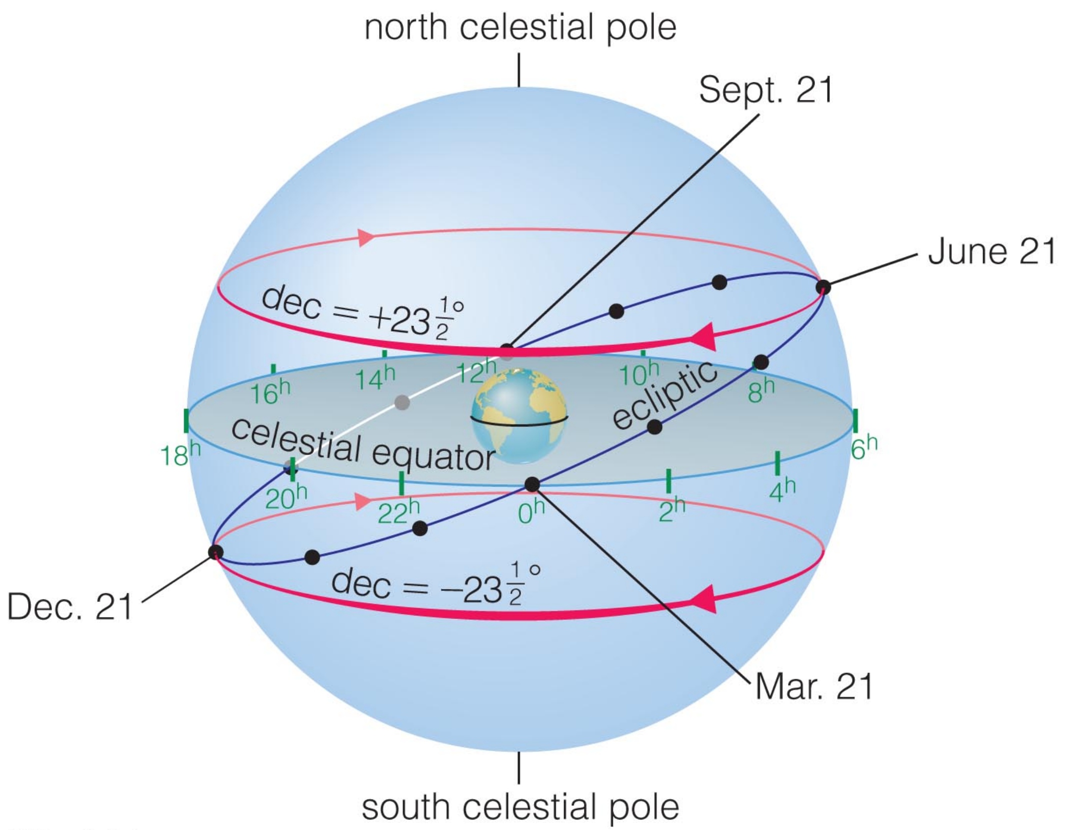
Celestial Coordinates

- Example: Vega
  - Remains at a fixed dec, RA.



Celestial Coordinates

- Example: Sun
  - Moves around the celestial sphere, thus has changing dec, RA.



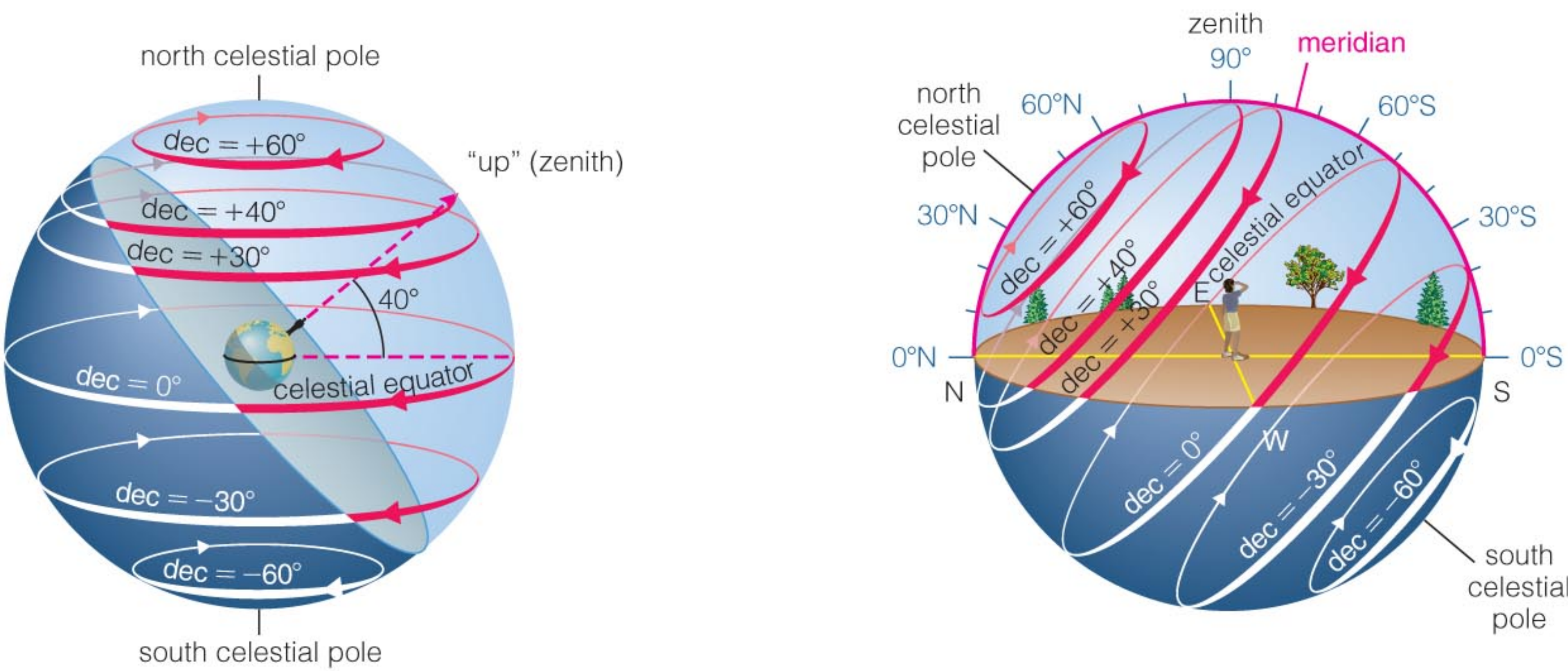
Celestial Coordinates

- Example: Sun
  - Moves around the celestial sphere, thus has changing dec, RA.

TABLE S1.1 The Sun's Approximate Celestial Coordinates at 1-Month Intervals

Approximate Date	RA	Dec
Mar. 21 (March equinox)	0^h	$0°$
Apr. 21	2^h	$+12°$
May 21	4^h	$+20°$
June 21 (June solstice)	6^h	$+23\frac{1}{2}°$
July 21	8^h	$+20°$
Aug. 21	10^h	$+12°$
Sept. 21 (September equinox)	12^h	$0°$
Oct. 21	14^h	$-12°$
Nov. 21	16^h	$-20°$
Dec. 21 (December solstice)	18^h	$-23\frac{1}{2}°$
Jan. 21	20^h	$-20°$
Feb. 21	22^h	$-12°$

How do stars move through the local sky?

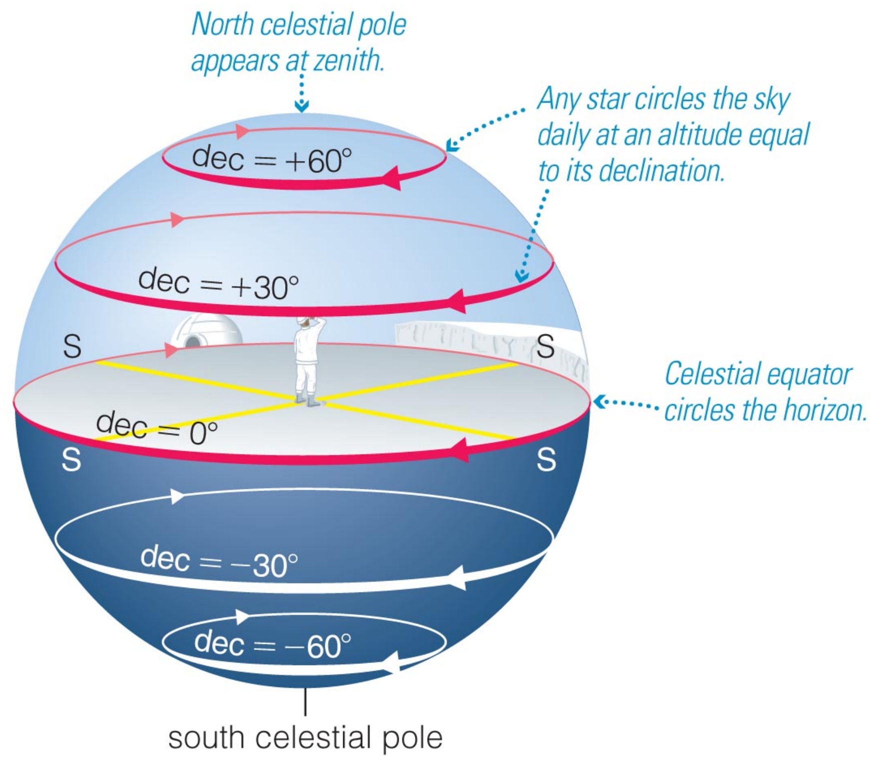


a The orientation of the local sky, relative to the celestial sphere, for an observer at latitude 40°N. Because latitude is the angle to Earth's equator, "up" points to the circle on the celestial sphere with declination +40°.

b Extending the horizon and rotating the diagram so that the zenith is up make the local sky easier to visualize. The meridian is marked with altitudes and directions.

The Sky at the North Pole

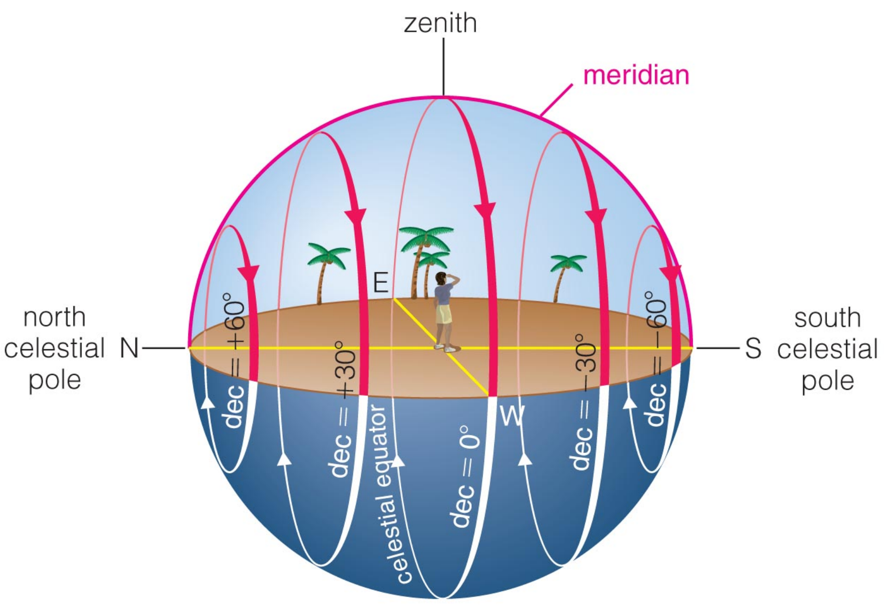
- Stars move parallel to your horizon.
- A star's declination is equal to its altitude.



b Extending the horizon to the celestial sphere makes it easier to visualize the local sky at the North Pole.

The Sky at the Equator

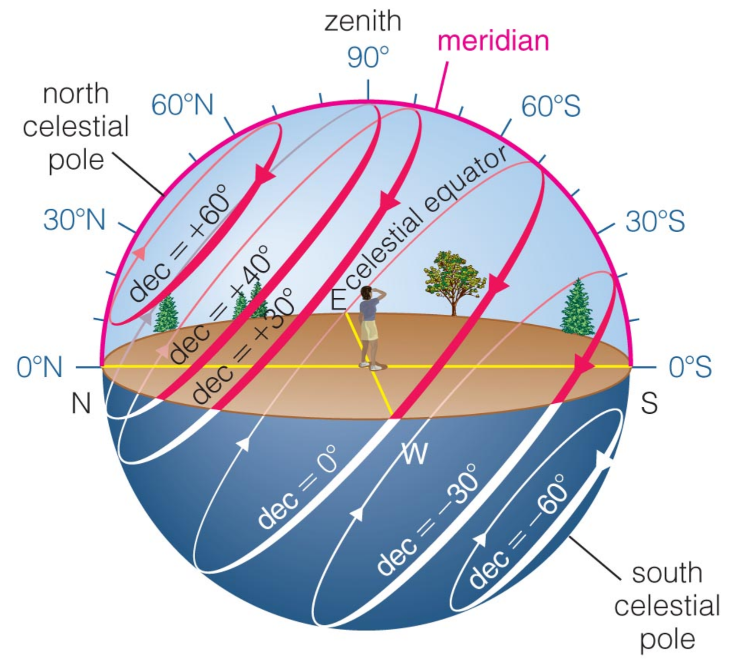
- Stars move perpendicular to your horizon.
- Stars with dec = 0º rise due east, cross the meridian at the zenith, and set due west.
- Stars with dec > 0º rise north of due east and set north of due west.



b Extending the horizon and rotating the diagram make it easier to visualize the local sky at the equator.

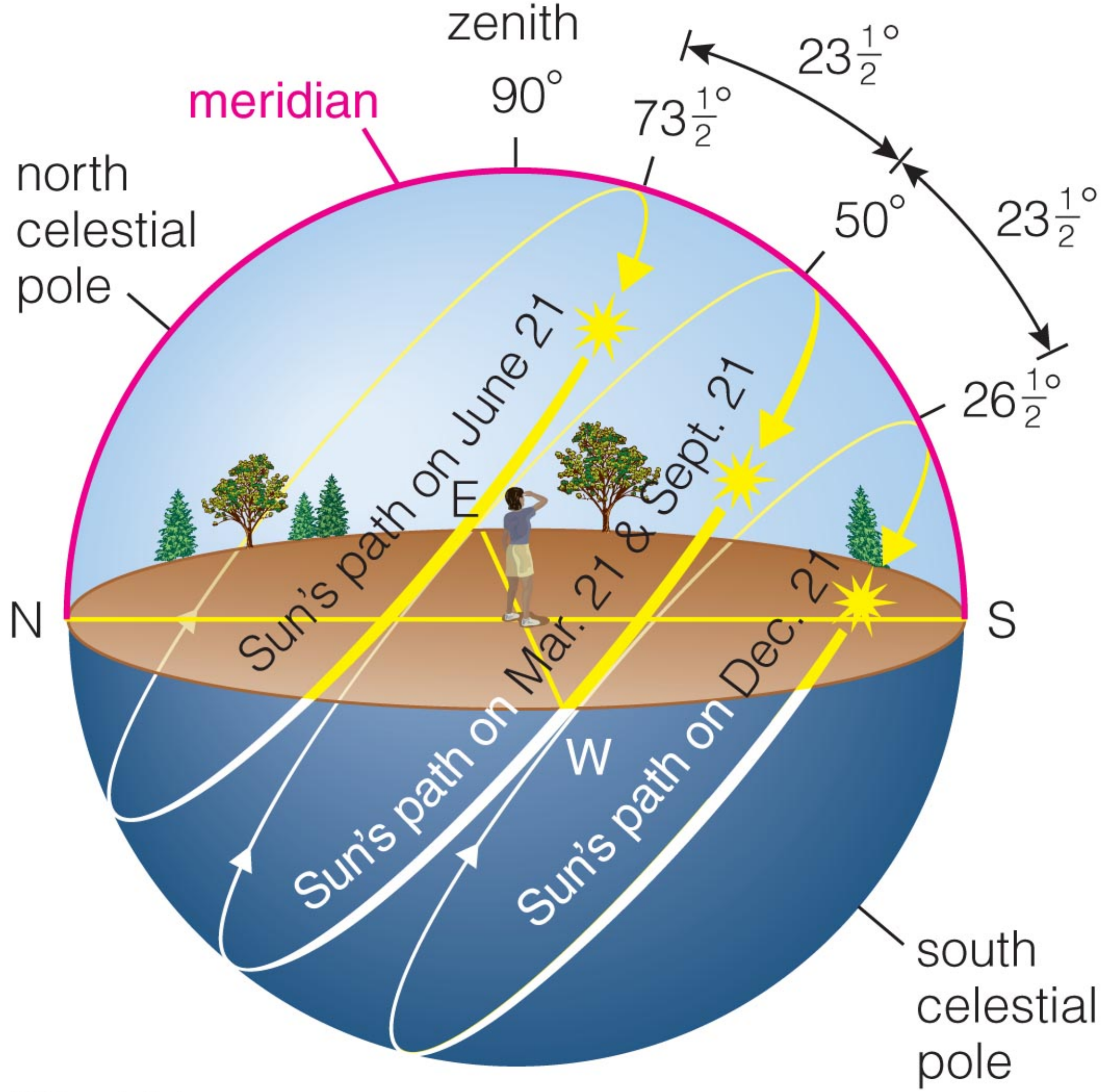
Skies at Other Latitudes

- More complicated—but not too hard to understand by studying the figure!
- Stars at high dec will be circumpolar, never setting below your horizon.
- Stars at low dec will rise and set at an angle to your horizon.



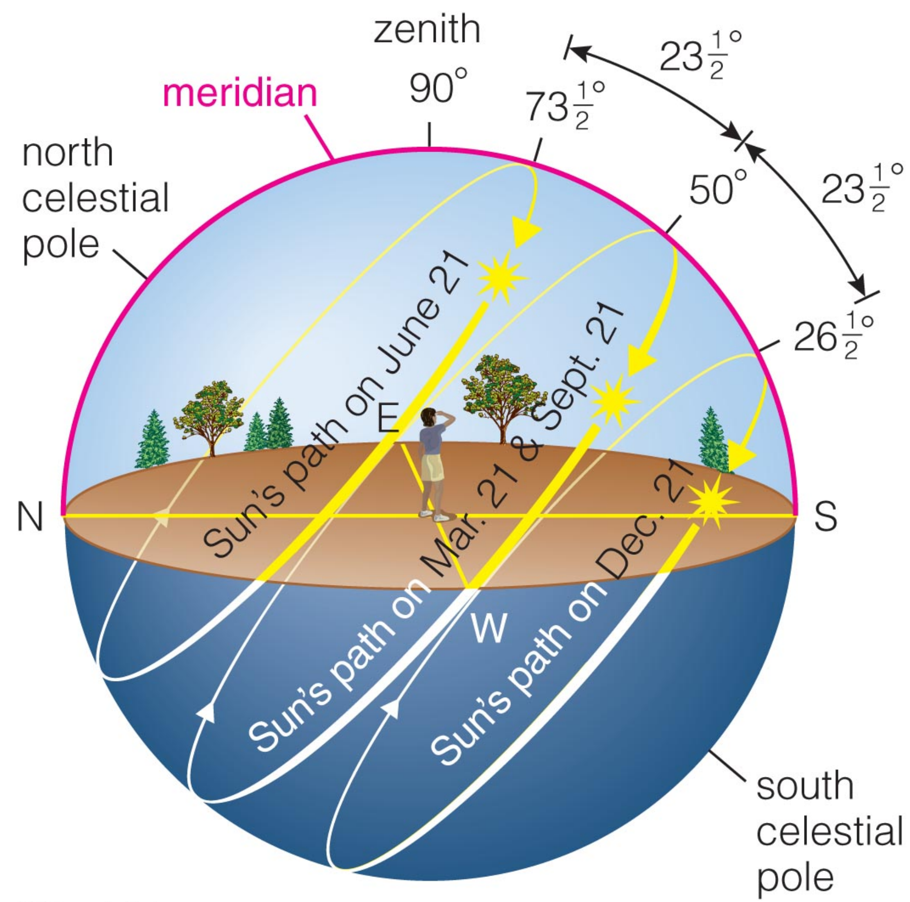
b Extending the horizon and rotating the diagram so that the zenith is up make the local sky easier to visualize. The meridian is marked with altitudes and directions.

How does the Sun move through the local sky?



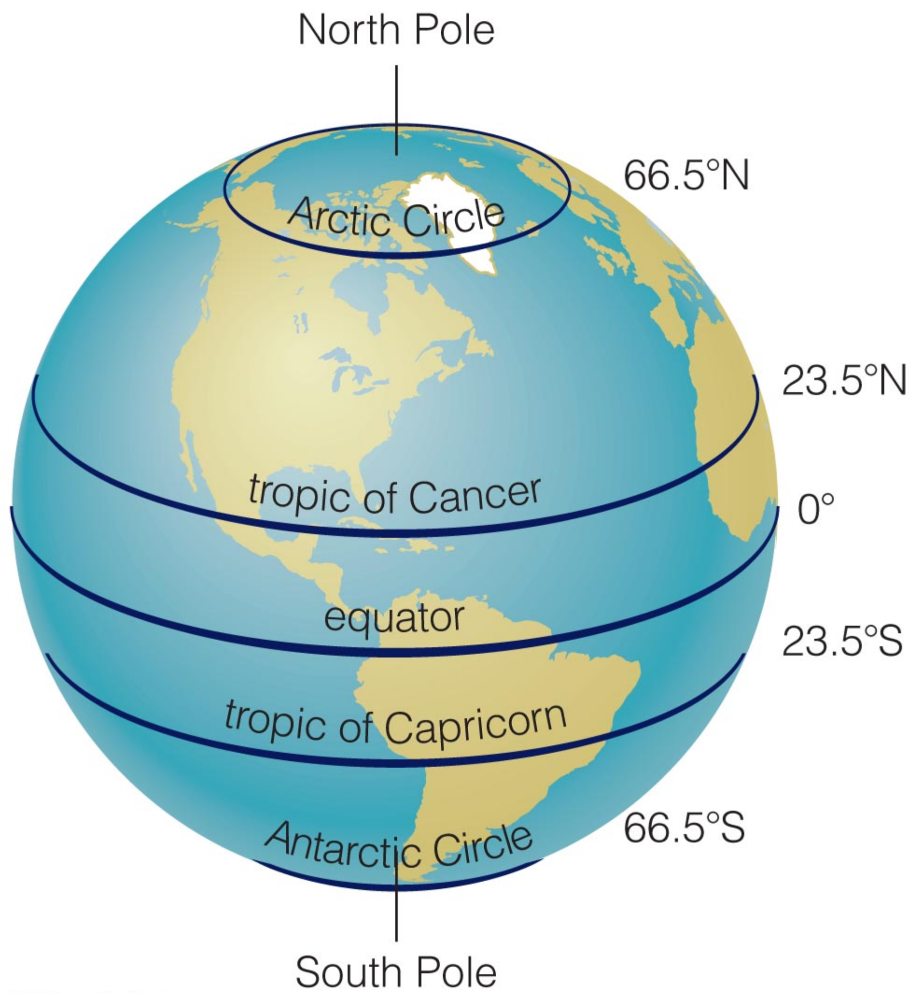
How does the Sun move through the local sky?

- The daily motion of the Sun is the same as any other object at the same declination.
- However, over the course of the year, the Sun's declination changes.



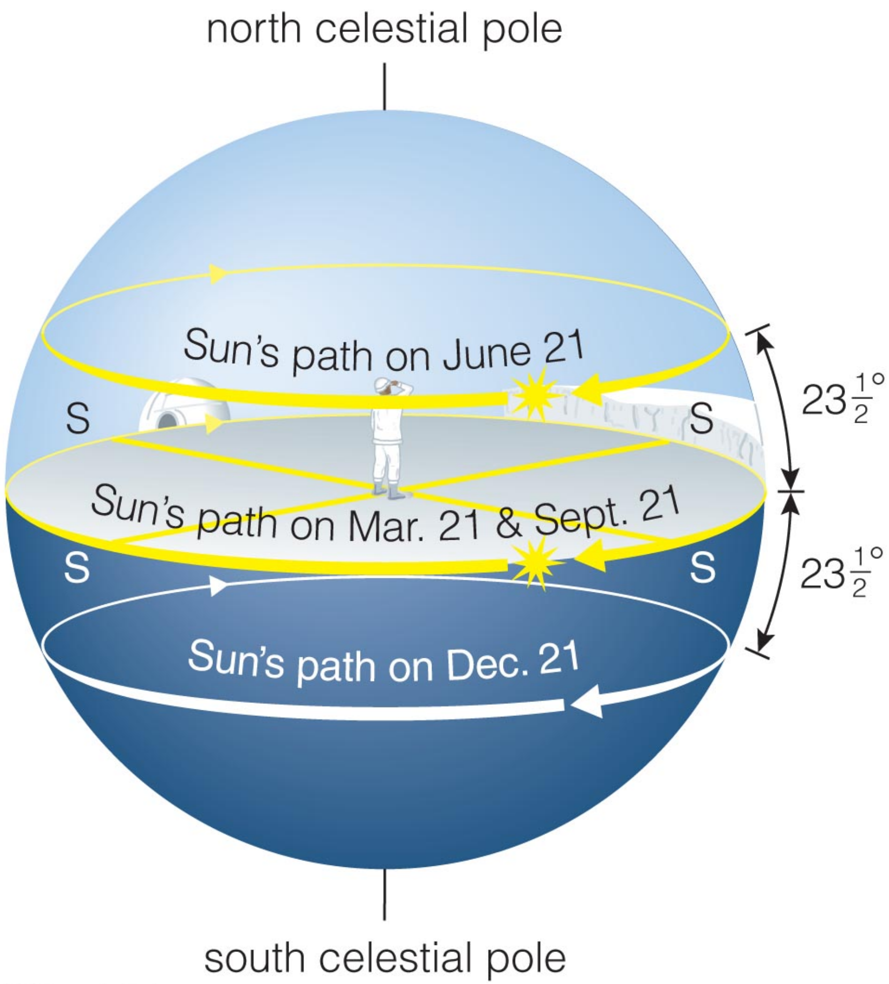
Special Latitudes

- Because the Earth's axis tilt is roughly 23.5º, there are several "special" latitudes.



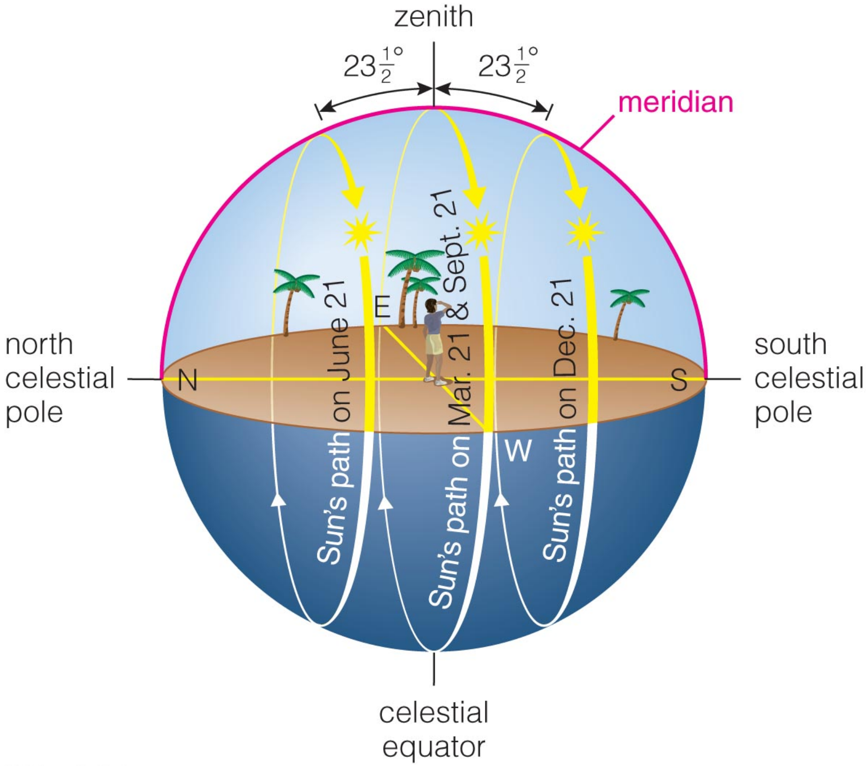
The Sun at the North and South Poles

- The Sun circles the horizon on the equinoxes.
- The Sun circles the sky at an altitude of 23.5º on the summer solstice.
- The Sun circles 23.5º below the horizon on the winter solstice.



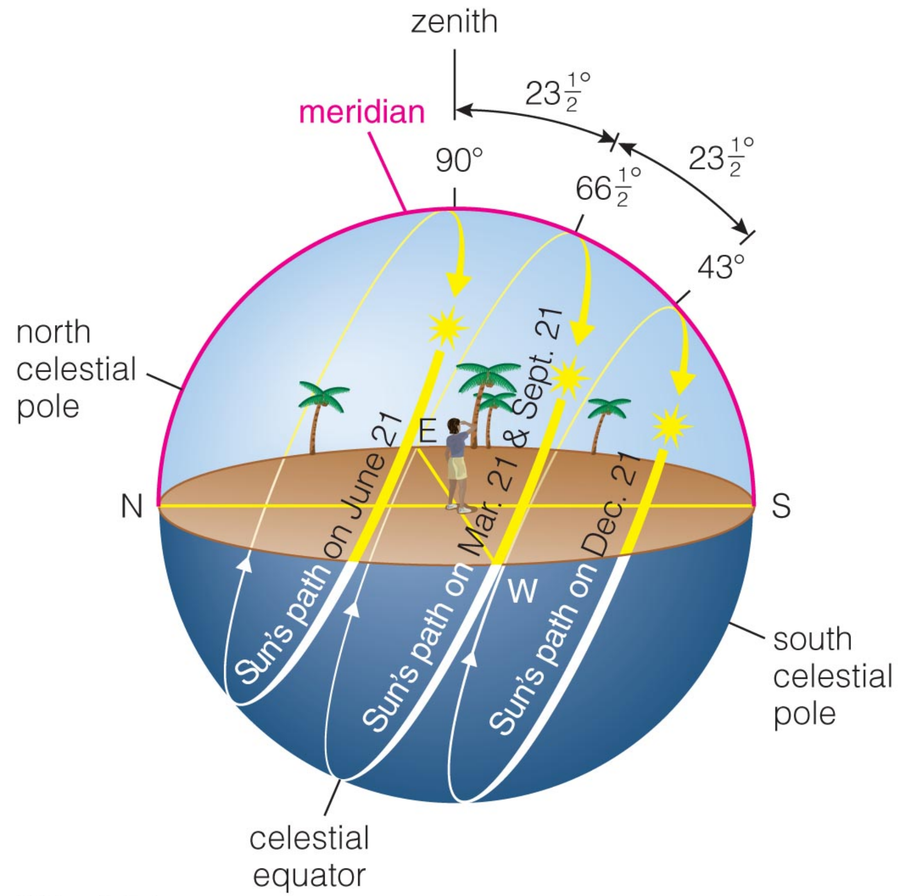
The Sun at the Equator

- The Sun passes through the zenith on noon of the equinoxes.
- The Sun's path takes it furthest from the zenith on the solstices.



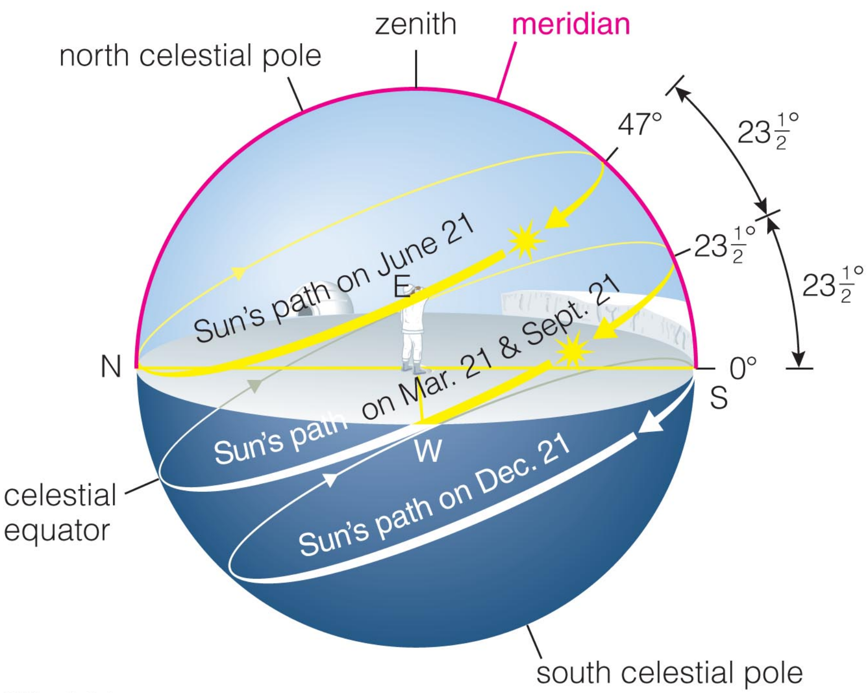
The Sun at the Tropics

- The tropic of Cancer and the tropic of Capricorn represent the northernmost and southernmost latitudes where the Sun will pass directly overhead (zenith) during solstices – June 21 (Cancer); December 21 (Capricorn)



The Sun at the Arctic and Antarctic Circles

- The Arctic and Antarctic circles represent the latitudes above (Arctic) or below (Antarctic) which there will be more than 24 hours of consecutive sunlight during the summer and darkness during the winter.

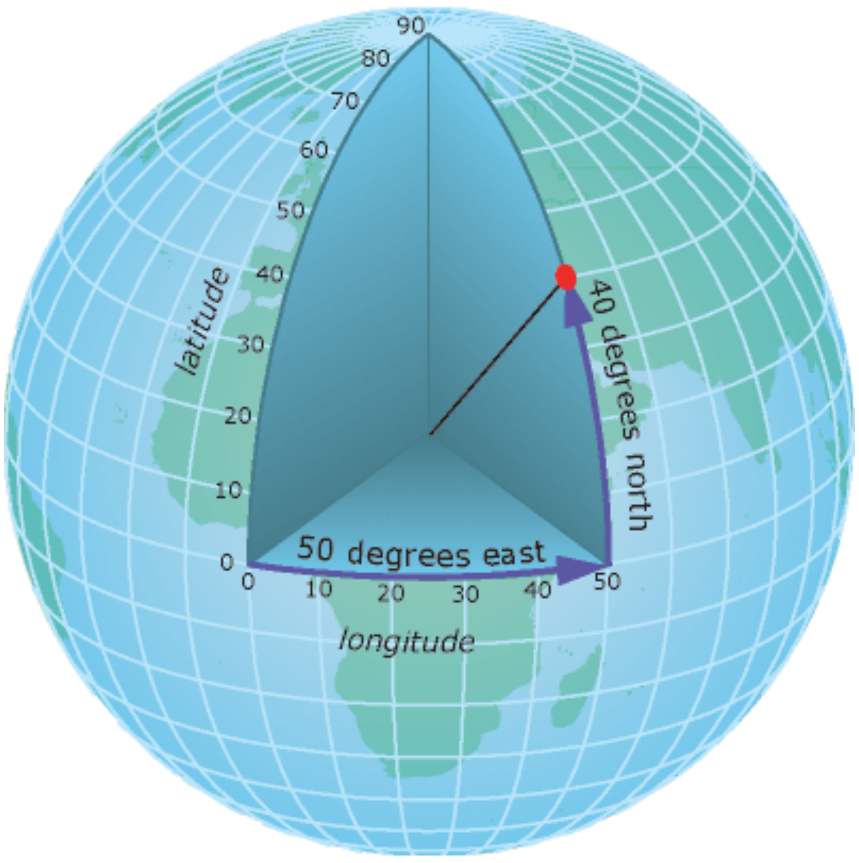


What have we learned?

- **How do we locate objects on the celestial sphere?**
  - We define the coordinates declination and right ascension, analogous to latitude and longitude on Earth.
- **How do stars move through the local sky?**
  - Stars move on paths dependent on their declination and the latitude of the observer.
- **How does the Sun move through the local sky?**
  - Just as stars do, though with a declination that changes throughout the year.

S1.3 Principles of Celestial Navigation

- Our goals for learning:
  - **How can you determine your latitude?**
  - **How can you determine your longitude?**



How can you determine your latitude?

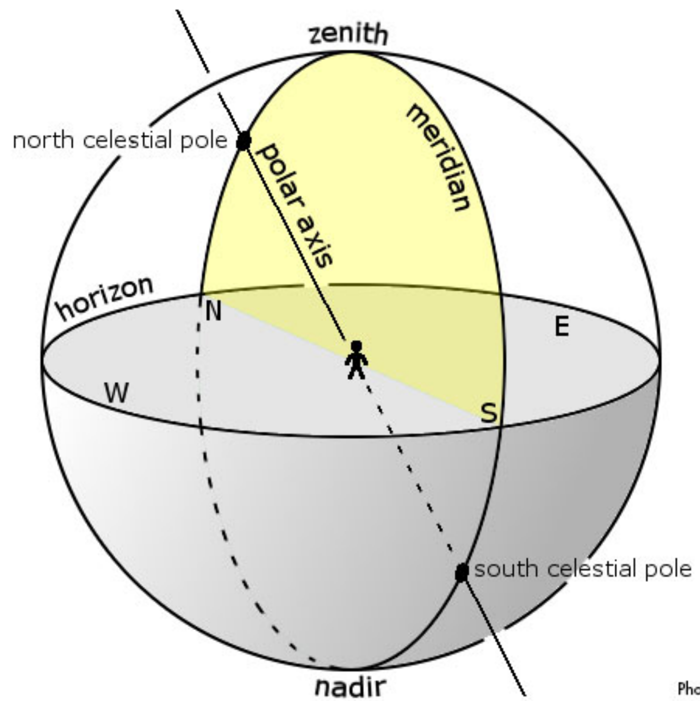
b A copper engraving of Italian explorer Amerigo Vespucci (for whom America was named) using an astrolabe to sight the Southern Cross. The engraving by Philip Galle, from the book *Nova Reperta*, was based on an original by Joannes Stradanus in the early 1580s.

Determining your latitude

- **Rule 1:** the celestial equator (CE) will cross your local meridian at altitude

altitude = 90^{o} – latitude

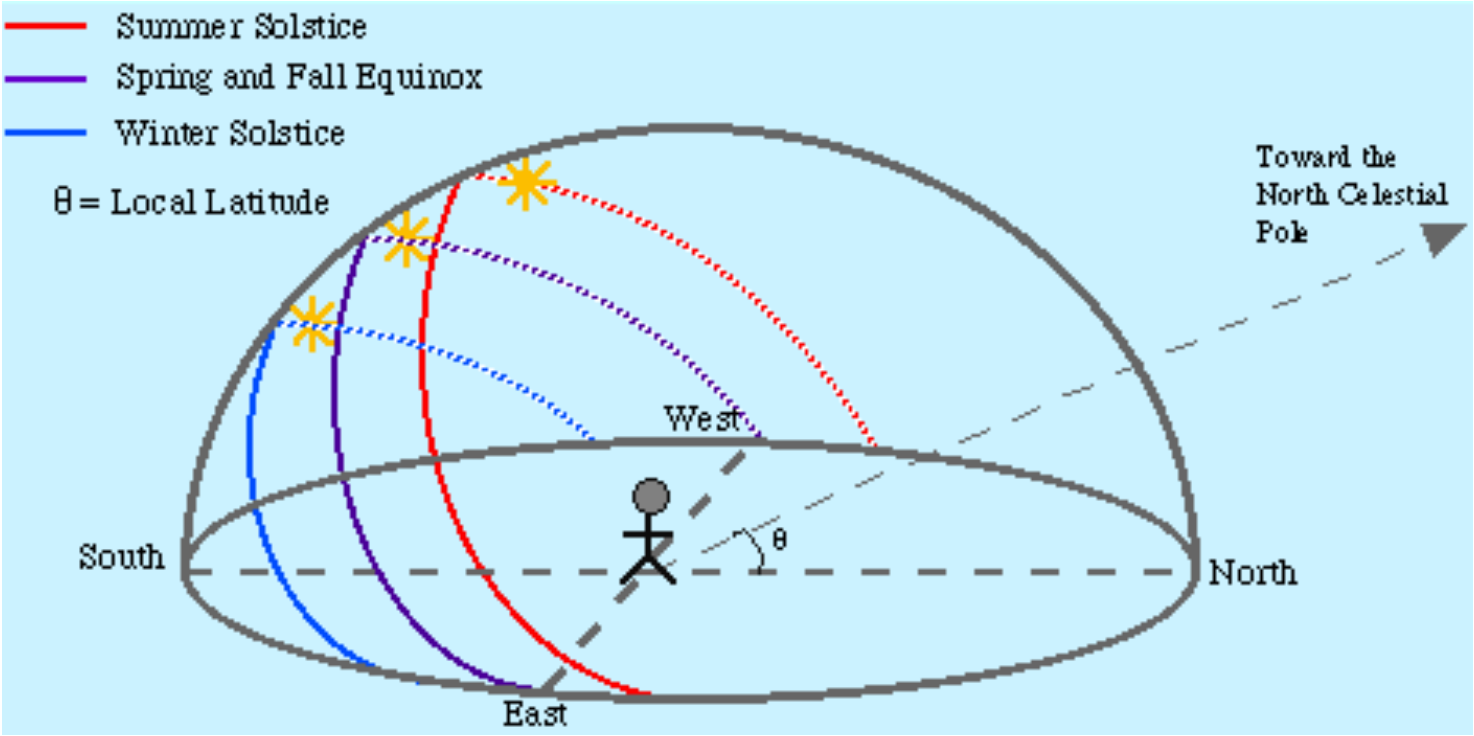
- **Your local meridian:** an imaginary North – South line passing from the zenith



Determining your latitude

- **Rule 2:** if you can find the north celestial pole (polar star; Polaris) or the south celestial pole (Southern Cross), then

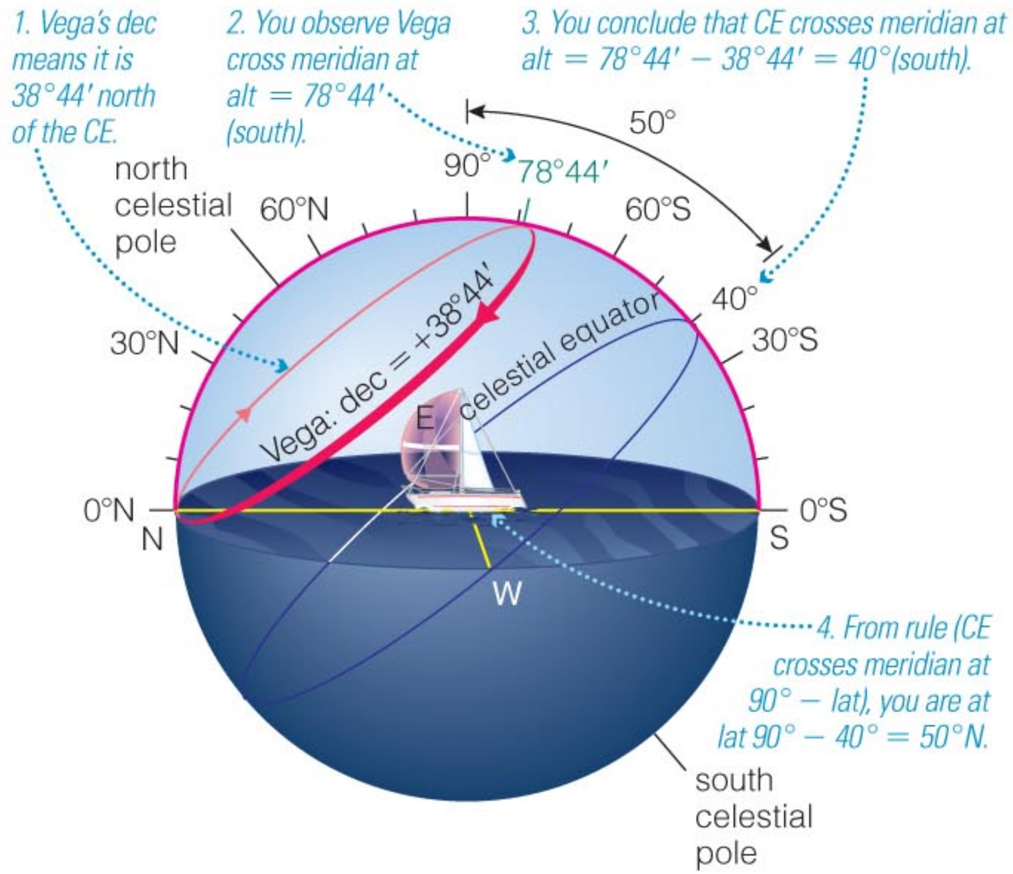
its altitude = your latitude



Application: using stars to determine latitude

Process:

- Use a star with a known declination
- Measure the star's altitude when it crosses the local meridian
- Subtract declination from star's altitude to find altitude of celestial equator (CE)
- Use Rule 1 for CE: altitude = 90^{o} - latitude

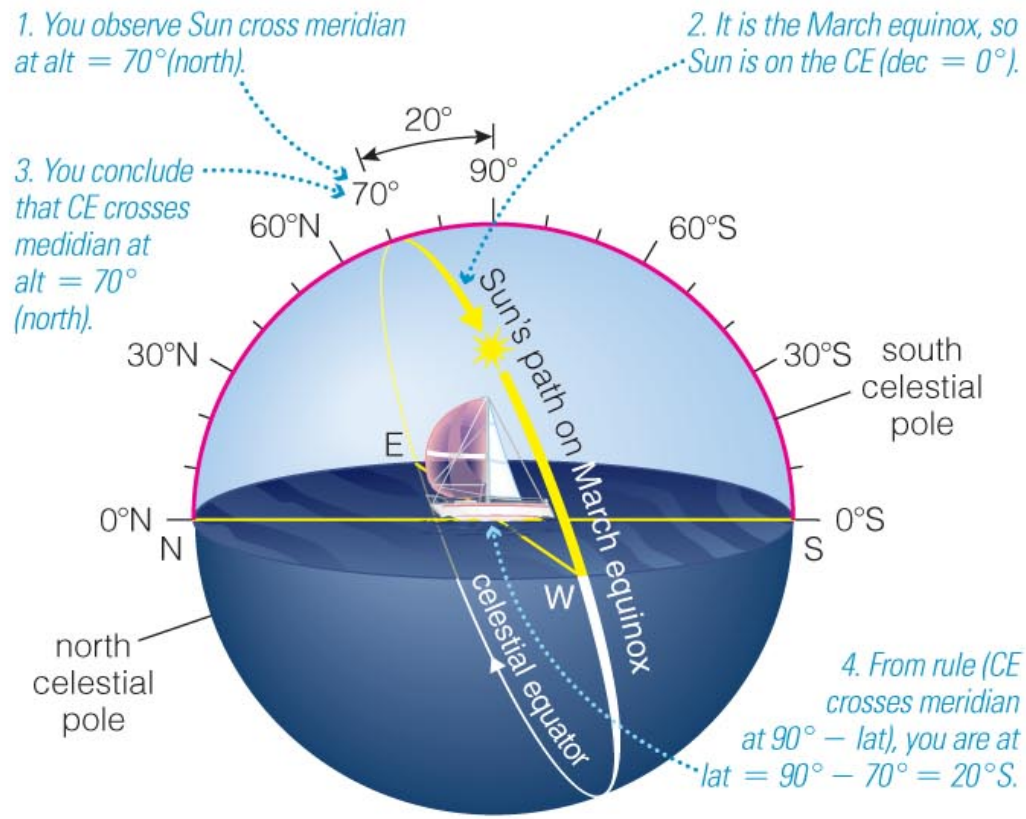


a Diagram showing how you can find your latitude by measuring Vega's altitude when it crosses the meridian. You know that you are in the Northern Hemisphere because the CE crosses the meridian in the south.

Application: using Sun to determine latitude

Process:

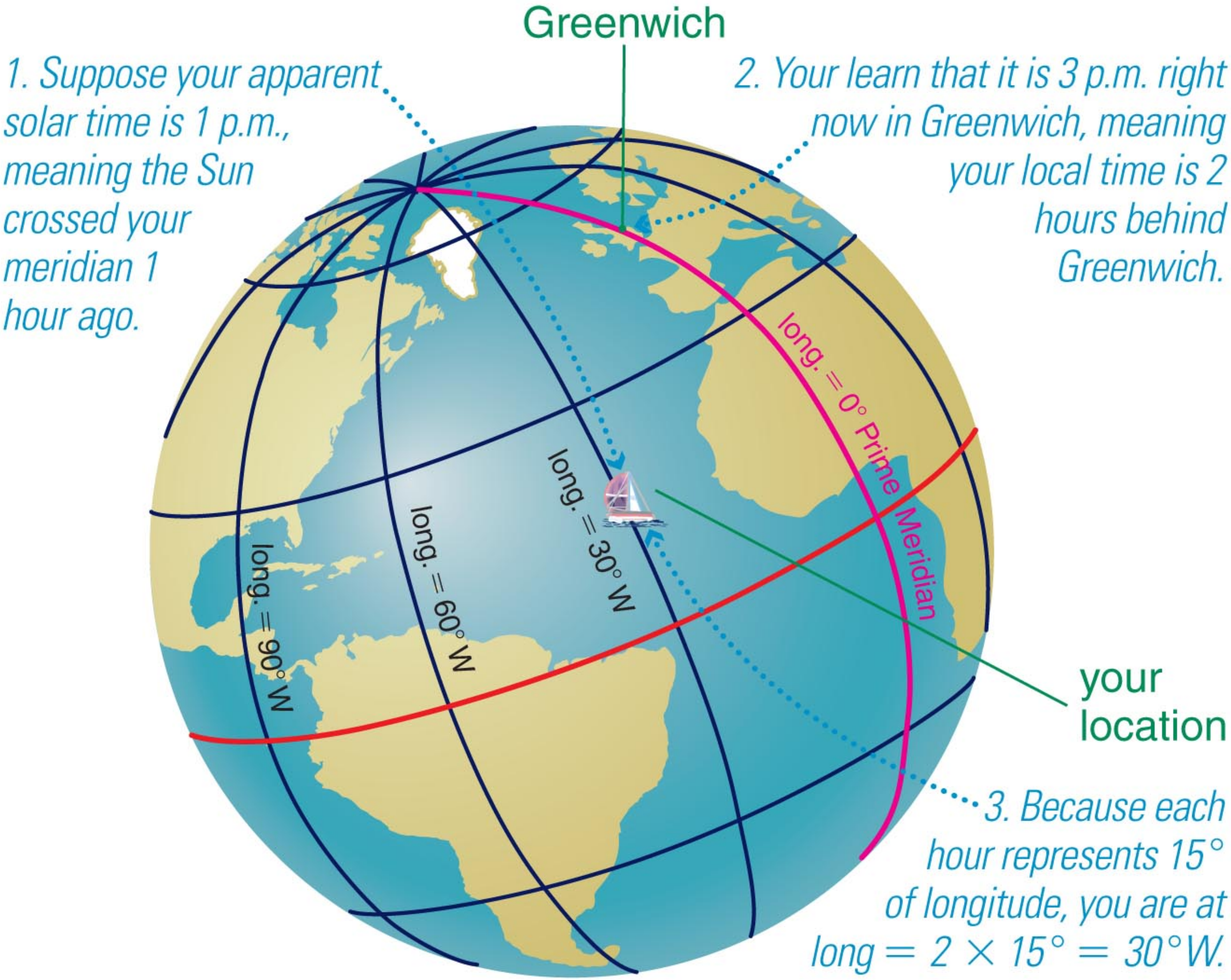
- Use Sun's declination over the year (0 on March equinox)
- Measure altitude of Sun when crossing the central meridian
- Subtract declination from Sun's altitude to find the altitude of the CE
- Use Rule 1 for CE: altitude = 90^o - latitude



b Diagram showing how you can find your latitude by knowing the date and measuring the Sun's altitude when it crosses the meridian. You know that you are in the Southern Hemisphere because the CE crosses the meridian in the North.

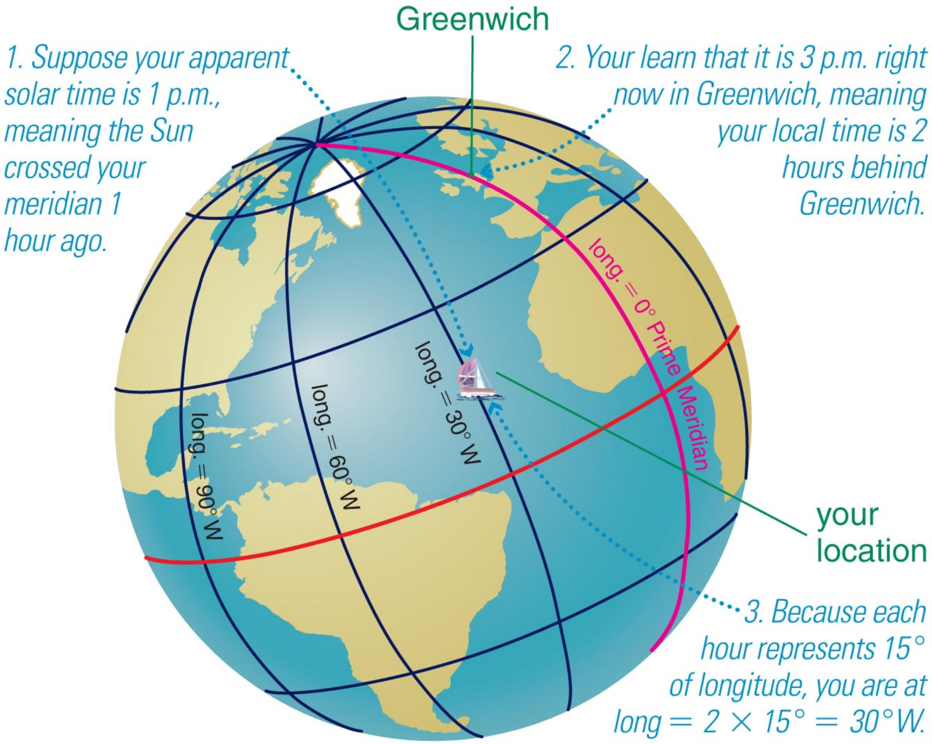
Caveat: Solar declination changes throughout the year

How can you determine your longitude?



How can you determine your longitude?

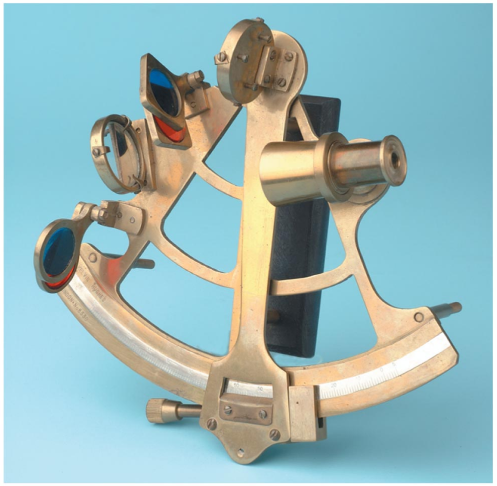
- To determine your longitude, you need to know <u>both</u> the apparent solar time and the time at some other known longitude (by convention, Greenwich, at the outskirts of London, England)



Celestial Navigation in Practice

- In practice, there are three real difficulties.
  - One must be able to accurately measure angles on the sky.
  - One must know celestial coordinates of stars.
  - One must have an accurate clock— ***this was the biggest challenge for early navigation!***

a The faceplate of an astrolabe. Many astrolabes had sighting sticks on the back for measuring positions of bright stars.



d A sextant.

What have we learned?

- **How can you determine your latitude?**
  - By finding the altitude of the celestial pole in your sky, or finding where known objects cross your meridian.
- **How can you find your longitude?**
  - By finding apparent solar time and comparing that to the time at a known longitude.