

ME 476

Solar Energy

UNIT THREE

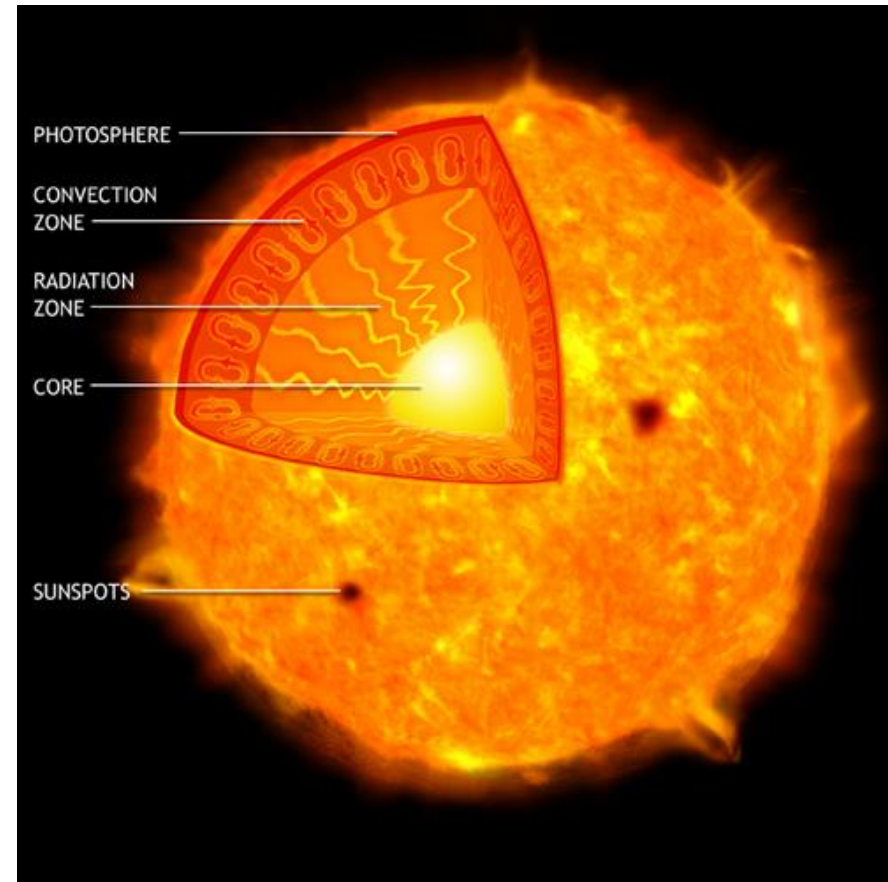
SOLAR RADIATION

- What is the sun?
- Radiation from the sun
- Factors affecting solar radiation
 - **Atmospheric effects**
 - **Solar radiation intensity**
 - **Air mass**
 - **Seasonal variations**
- Calculating time
- Solar angles

What is the Sun?

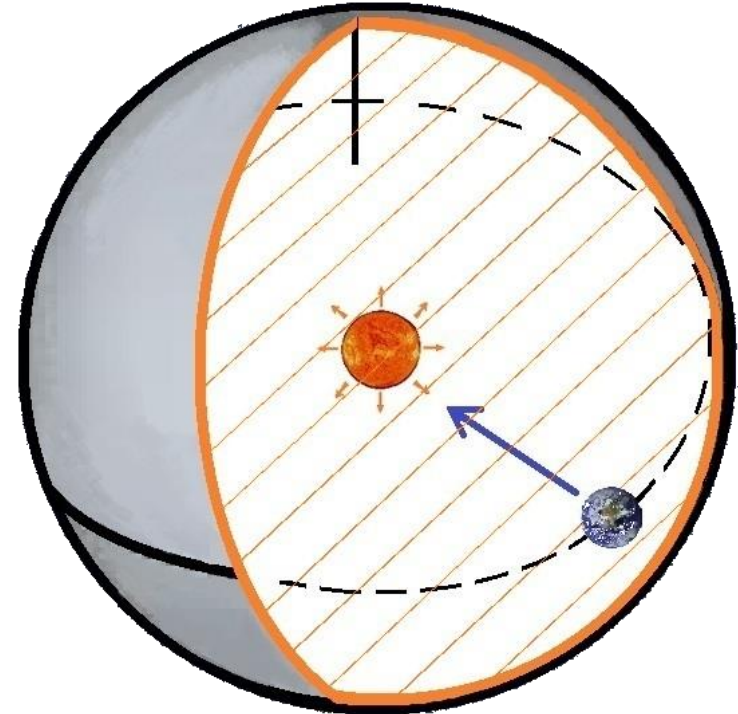
3

- The sun is a gaseous body composed mostly of hydrogen and some helium.
- The huge gravitational force causes intense pressure and temperature at the core.
- These conditions initiate nuclear fusion reactions.
- The sun fuses hydrogen into helium at its core and the resulting energy radiates outward.
- Energy is convected to the photosphere



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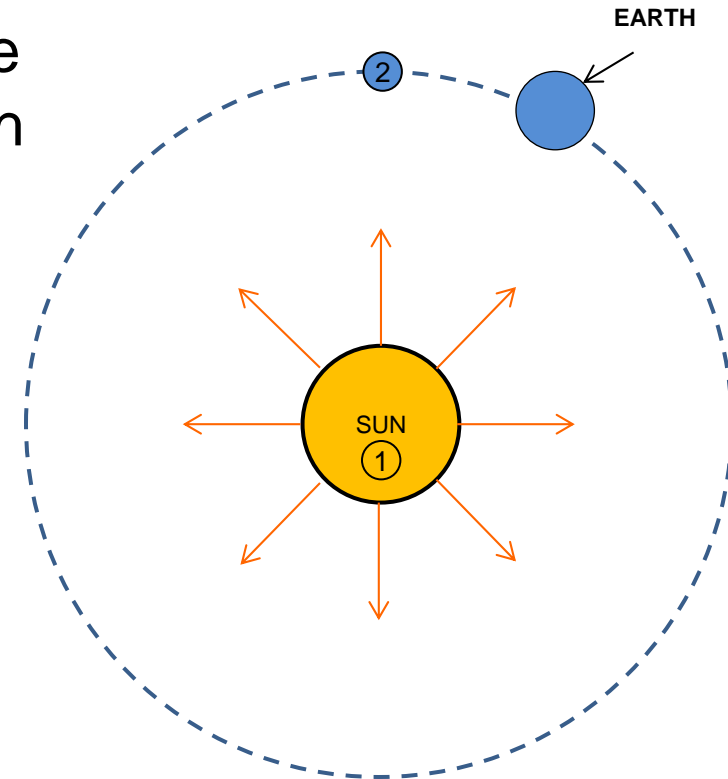
- The surface of the photosphere is at about 5777 K.
- Once the energy reaches the surface of the photosphere, it escapes to space by radiation.
- The sun is considered a blackbody.
- It radiates diffusely (uniformly) in all directions.
- All the energy leaving the sun's surface will reach a sphere containing earth.



- The net radiation heat transfer between the sun's surface (1) and the surface of the sphere containing earth (2) is given by:

$$\dot{Q}_{1 \rightarrow 2} = A_1 F_{1 \rightarrow 2} \sigma (T_1^4 - T_2^4)$$

- $F_{1 \rightarrow 2} = 1$
- $A_1 = 4 \pi r_1^2$, where r_1 is the radius of the sun (6.955×10^8 m)
- T_2 is negligible
- The total rate of heat transfer leaving the sun's surface and reaching Surface 2 is: 3.84×10^{26} W.



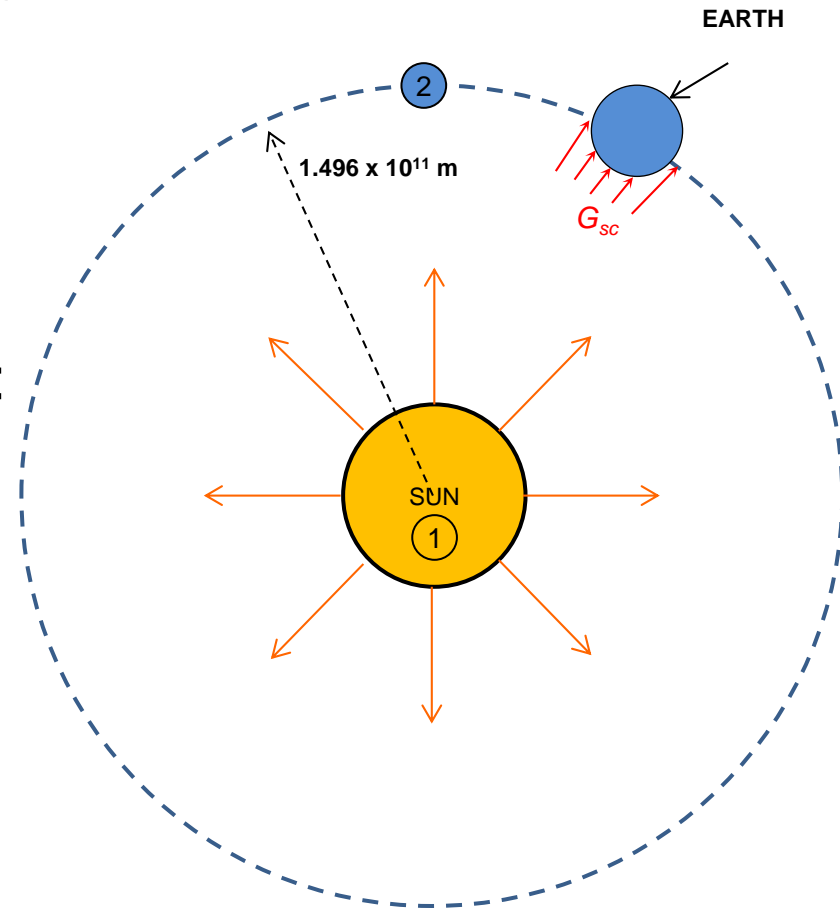
Solar Constant

7

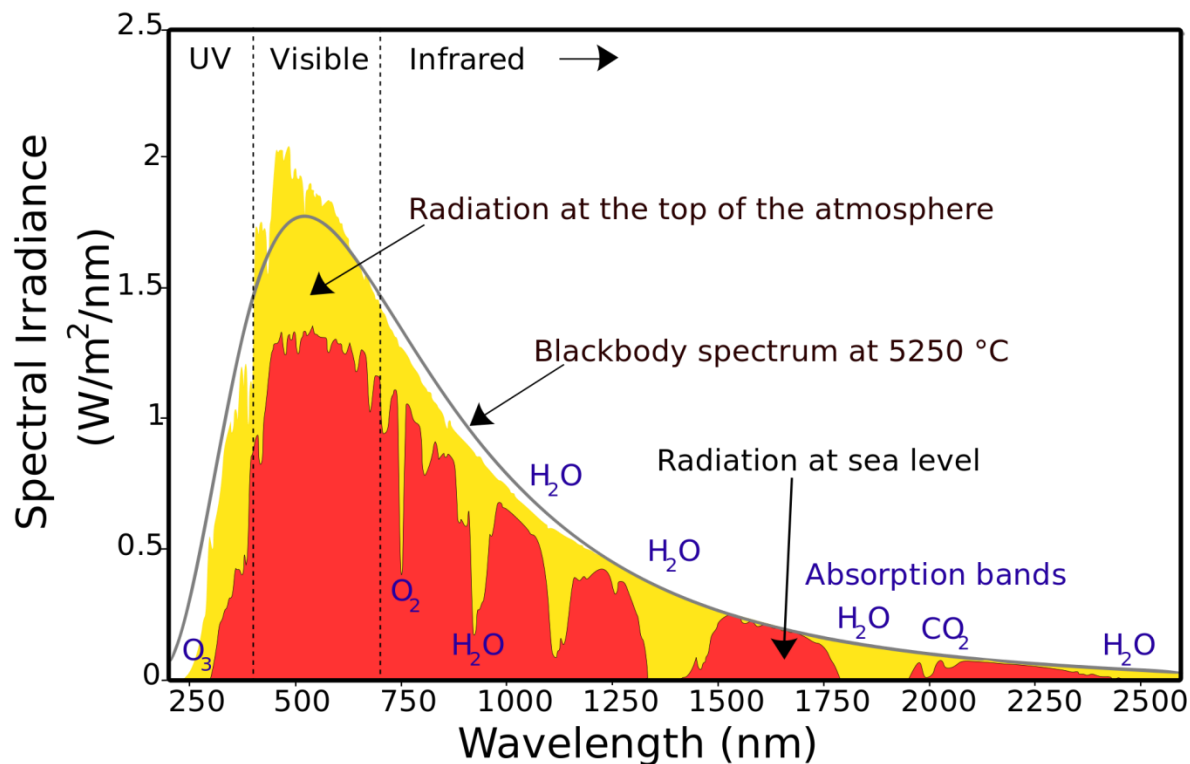
- The average distance between the sun and earth is 1.496×10^{11} m.
- This distance is called an ***astronomical unit*** (AU).
- The irradiance (G_{sc}) incident on Surface 2 (including earth) will be:

$$G_{sc} = \frac{\dot{Q}_{1 \rightarrow 2}}{A_2} = \frac{\dot{Q}_{1 \rightarrow 2}}{4\pi r_2^2}$$

- The value of G_{sc} is 1367 W/m^2 .
- This value is called the ***Solar Constant***.



- The solar radiation spectrum closely matches the spectrum of a blackbody (but only at the top of the atmosphere).
- Once solar radiation penetrates the atmosphere, the spectrum is affected by the presence of gases.
- For example, ozone (O_3) greatly reduces ultraviolet radiation.

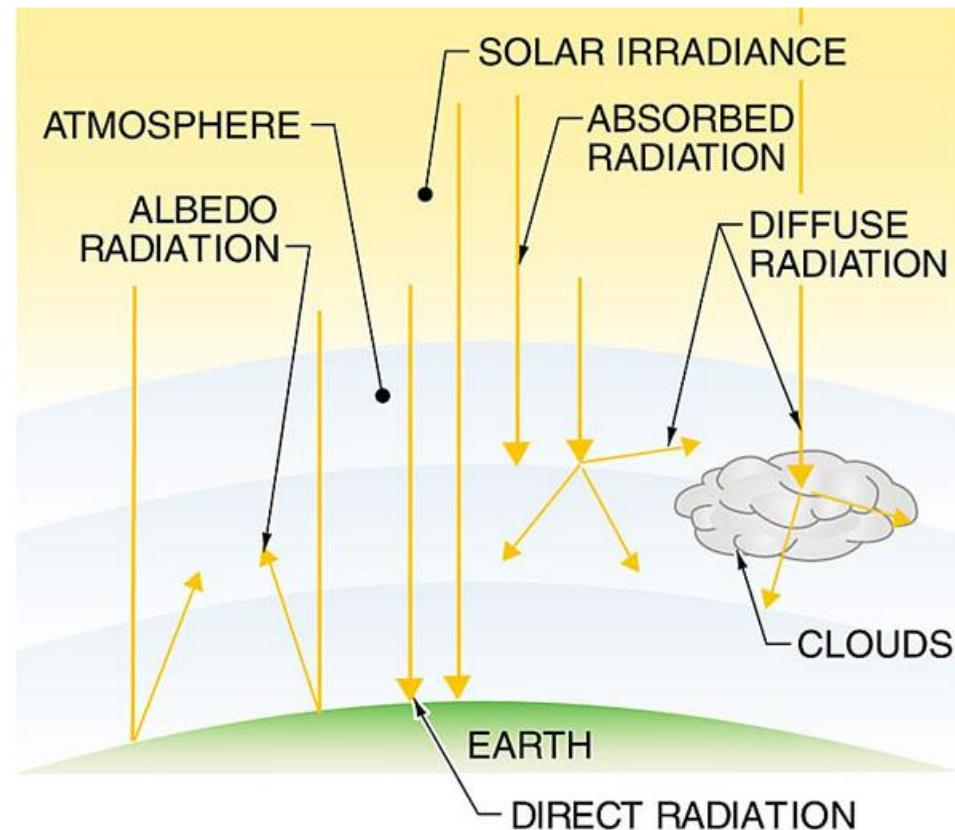


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Atmospheric Effects

10

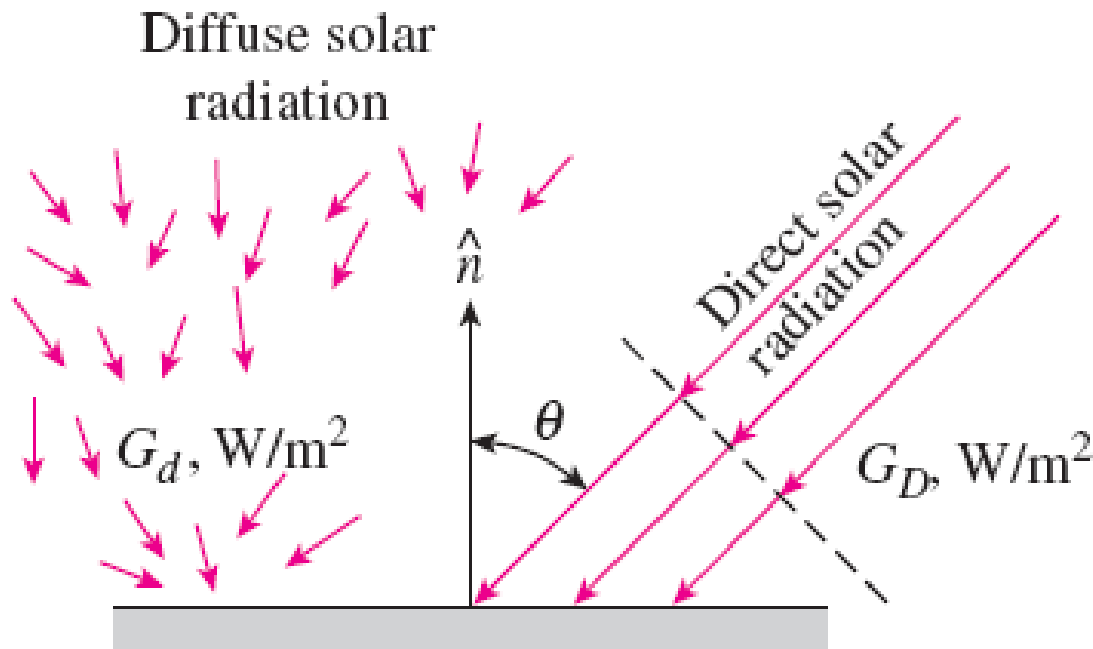
- The solar irradiance reaching the earth's surface is affected by:
 - **Suspended particles (e.g. dust)**
 - **Gases in the atmosphere**
 - **Clouds**
- These substances can:
 - **Absorb solar radiation**
 - **Reflect solar radiation**
 - **Scatter solar radiation**



Atmospheric Effects

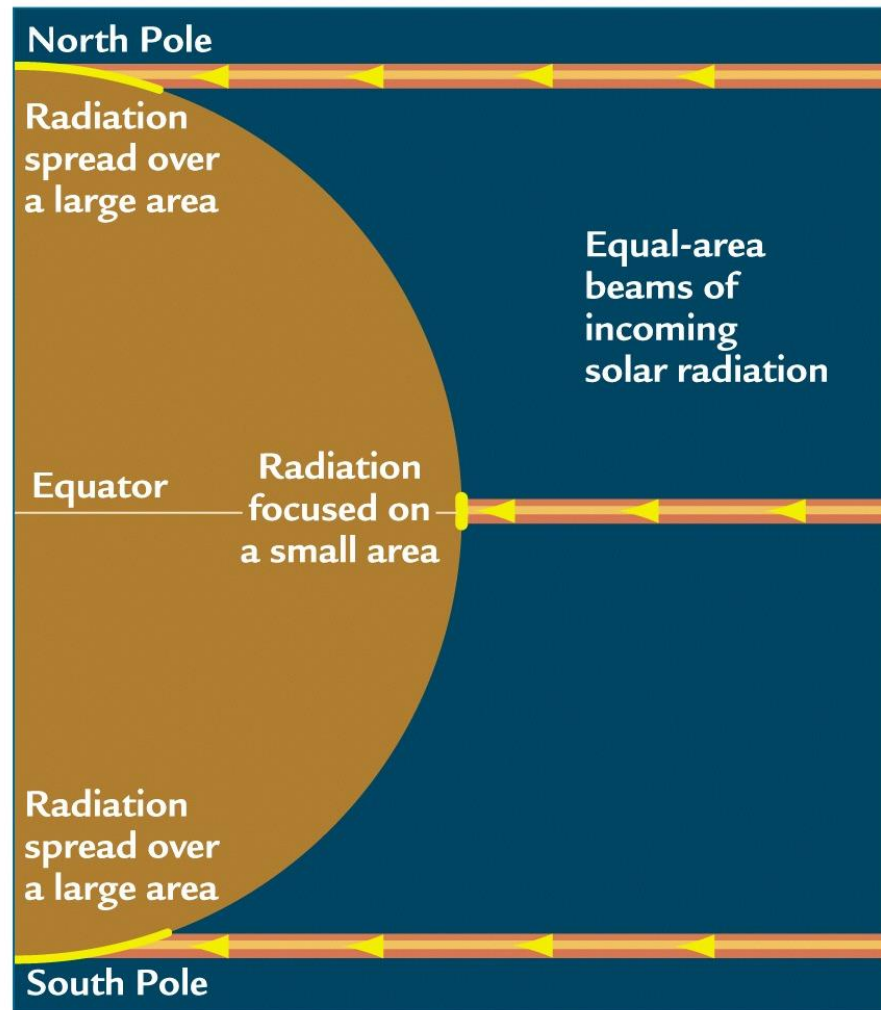
11

- Solar radiation not affected by these substances reaches the earth's surface as **direct radiation**.
- Remaining radiation reaching the surface is **diffuse radiation**.
- Total of direct and diffuse radiation is called **global radiation**.



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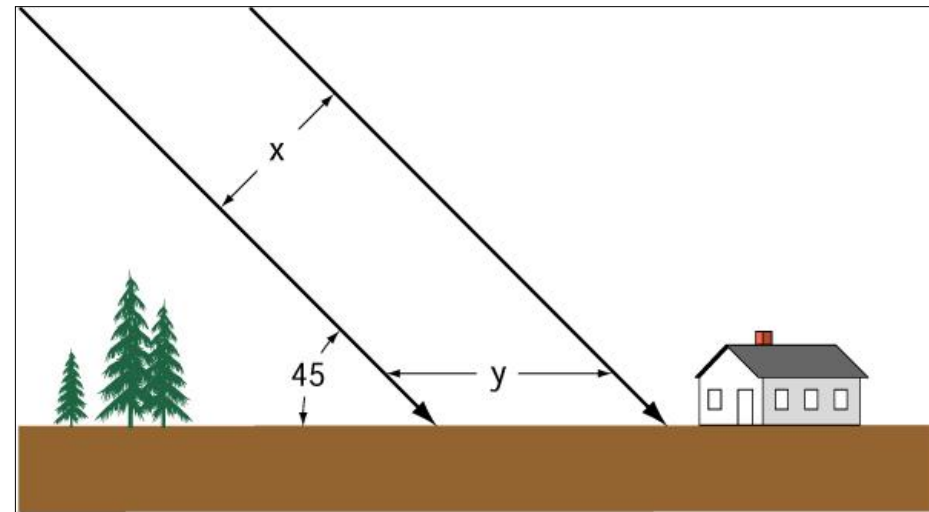
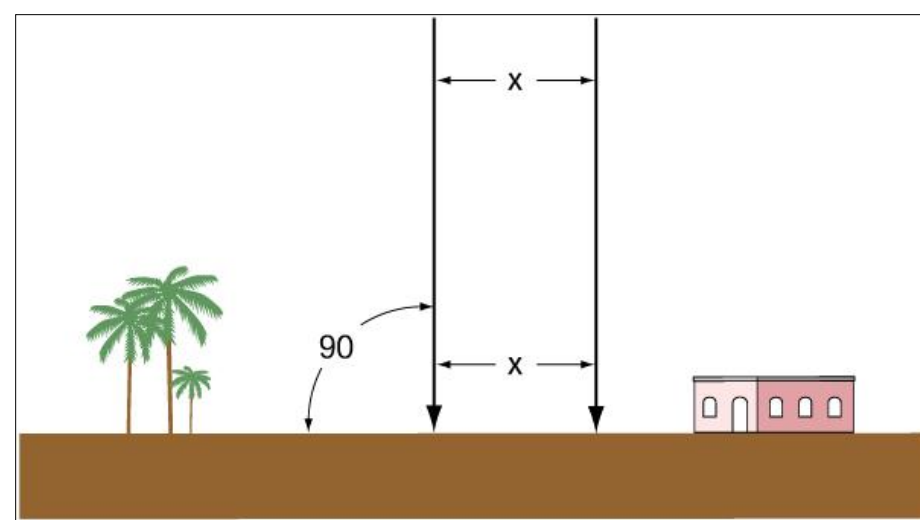
- Solar irradiance (G) incident on the earth's surface in the normal direction is focused on a small area.
- If the same (G) is incident at a different angle, it will be spread over a larger area.
- This means that the solar intensity in the normal direction is highest.
- Solar intensity at high **latitudes** is lower.



Solar Radiation Intensity

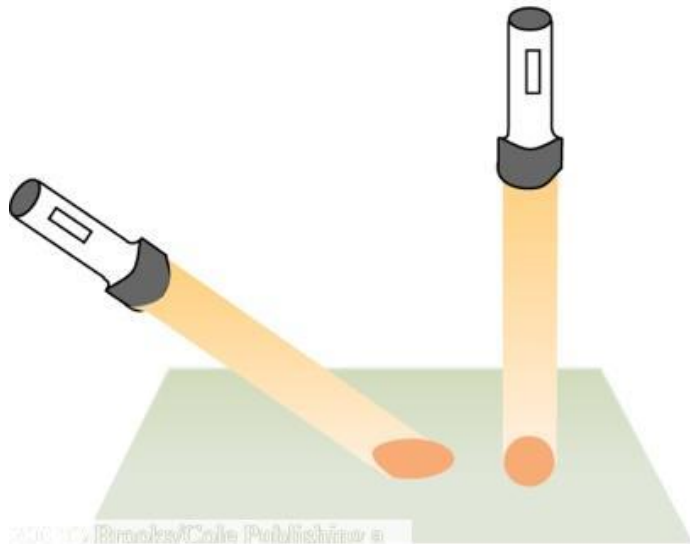
14

- This also means that solar intensity is higher in the middle of the day (e.g. at noon) than in the early morning or late afternoon.

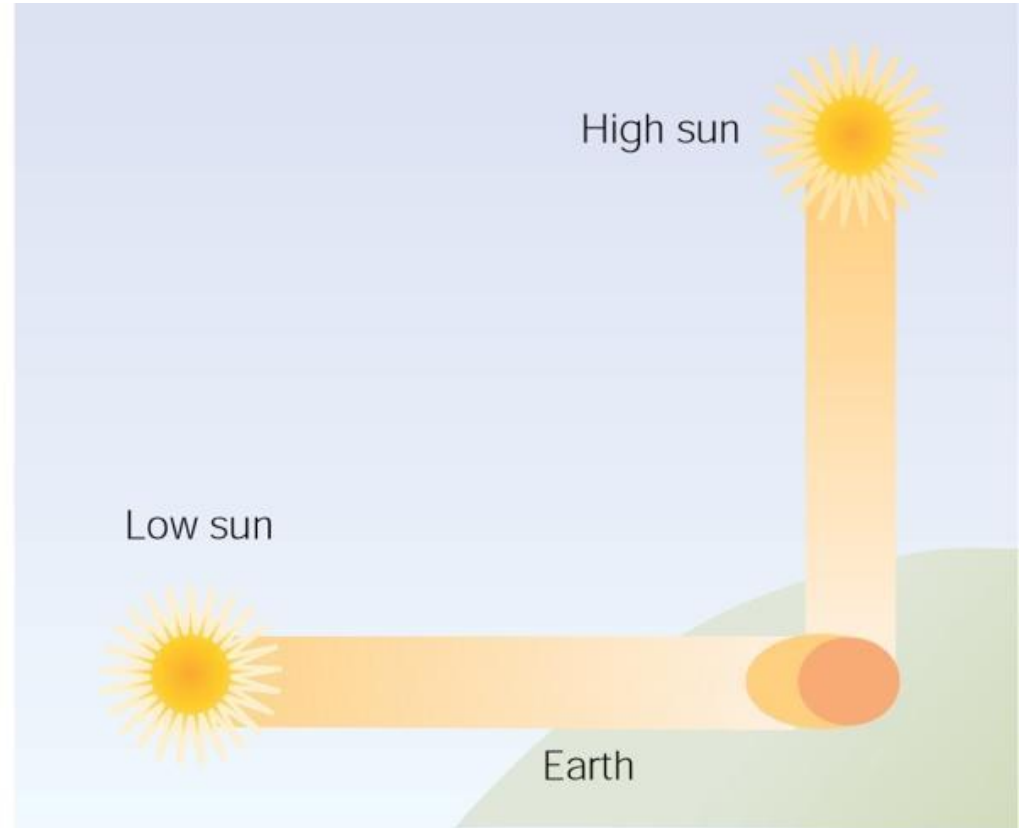


Solar Radiation Intensity

15



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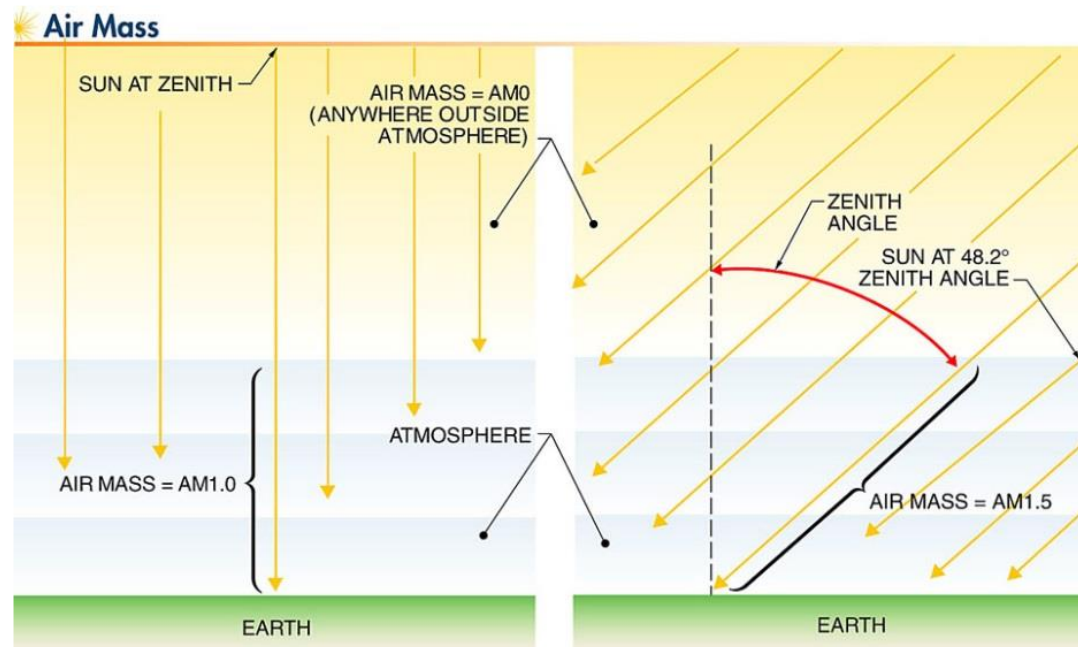


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Air Mass

17

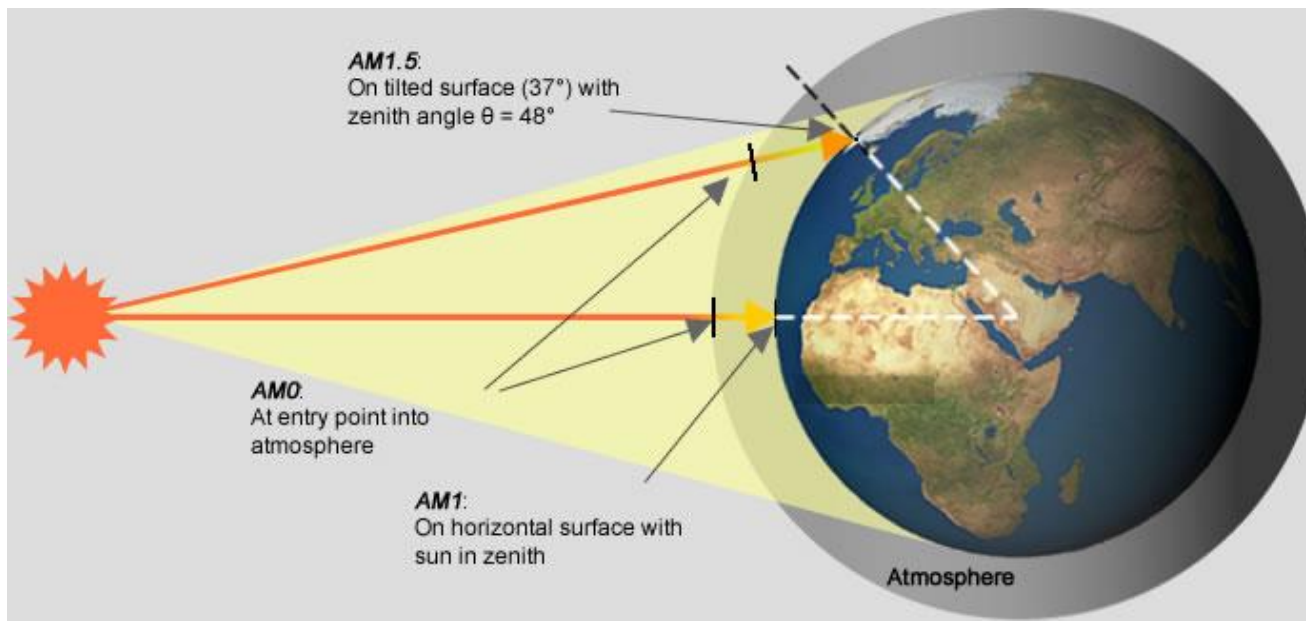
- The amount of solar radiation interacting with the atmosphere depends on how much atmosphere it passes through.
- When the sun is directly overhead (at **zenith**), the amount of atmosphere that the sun's rays pass through is at a minimum.
- As the sun approaches the horizon, the sun's rays must pass through a greater amount of atmosphere.
- This phenomenon is characterized by the **air mass**.



Air Mass

18

- The larger the air mass, the more solar radiation will be absorbed (or reflected) by the atmosphere
- This reduces the quantity of solar irradiance reaching the earth's surface.
- The larger air mass also changes its wavelength composition
- This is the reason for the change in the sun's color in early morning and late afternoon.

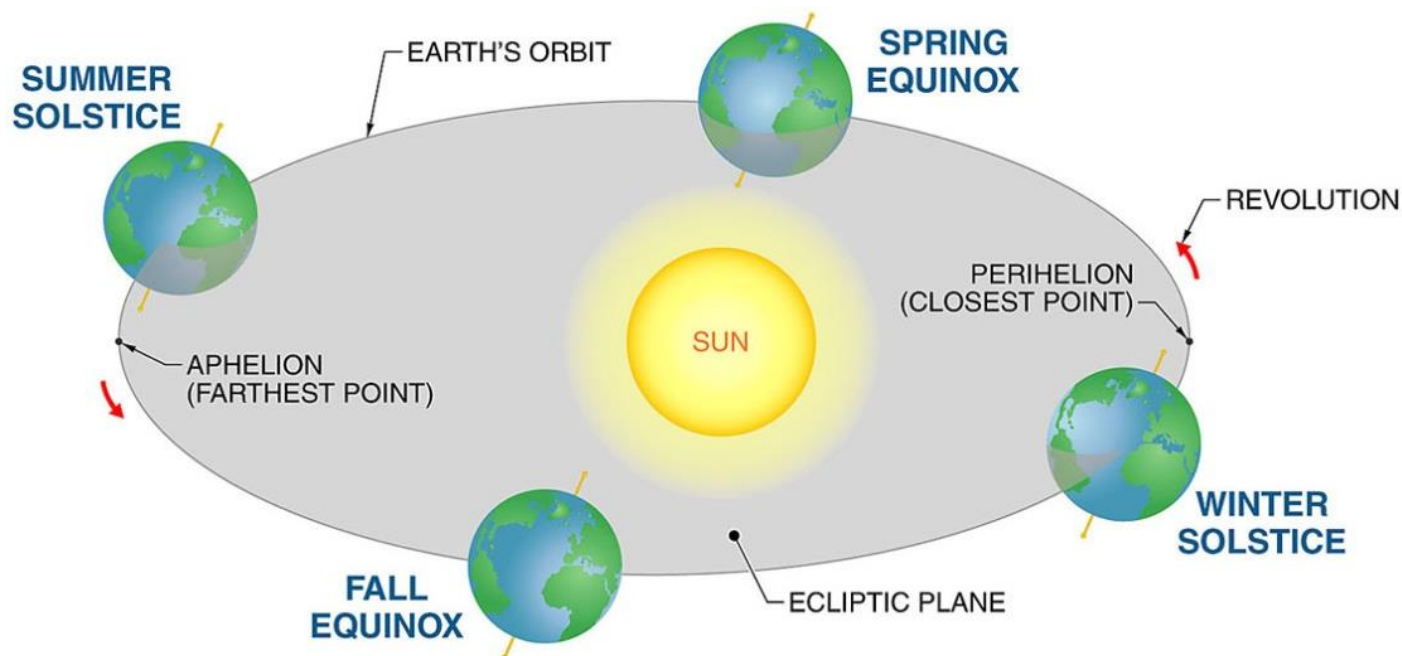


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Seasonal Variation of Solar Radiation

20

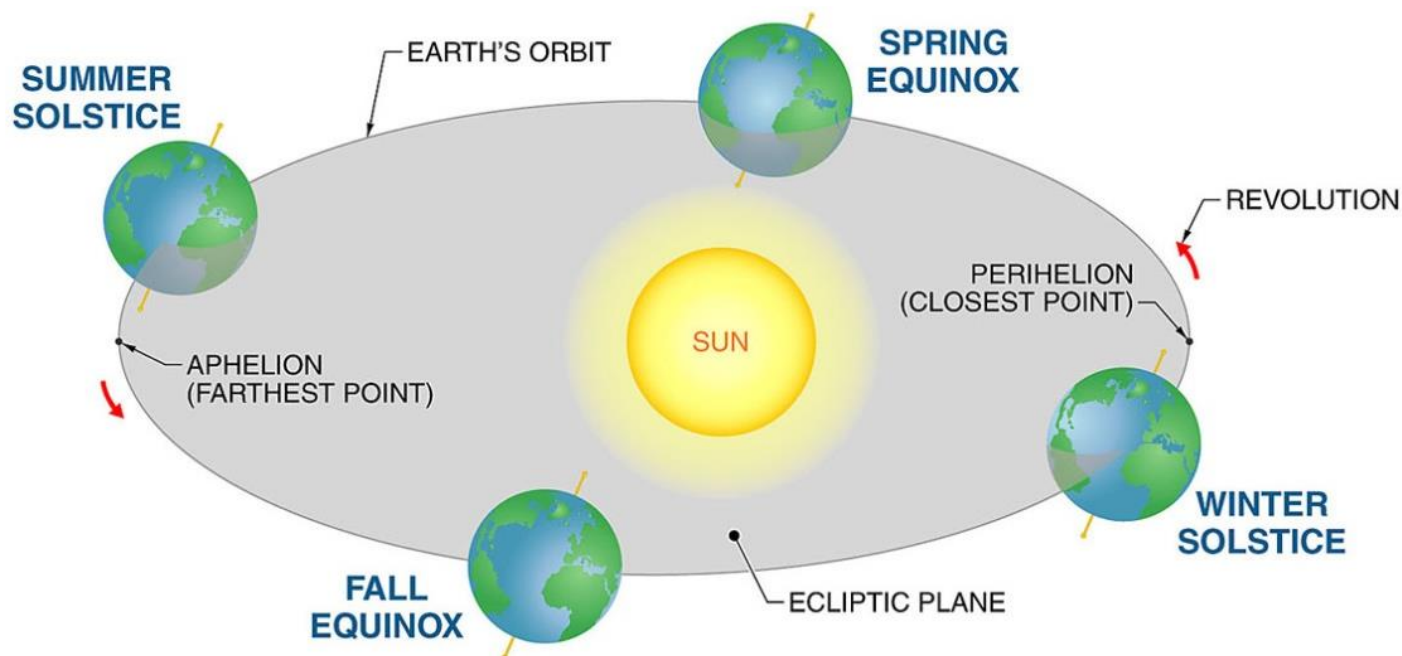
- The earth rotates around the sun in an elliptical orbit.
- The plane formed by the earth's rotation around the sun is called the ***ecliptic plane***.
- The earth's axis is tilted by 23.5° to the ecliptic plane.
- Because of this tilt, the lengths of day and night vary throughout the year.



Seasonal Variation of Solar Radiation

21

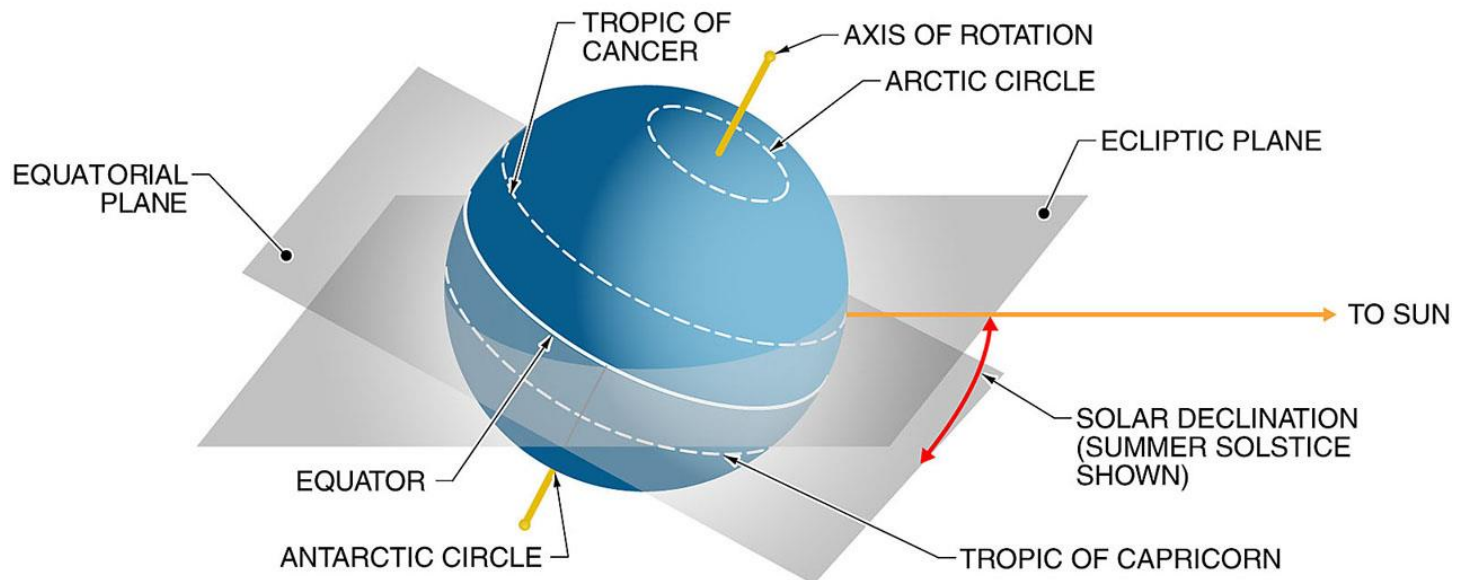
- The point at which the day is shortest in the northern hemisphere is called **winter solstice**.
- The point at which the day is longest in the northern hemisphere is called **summer solstice**.
- The two points at which day and night have equal lengths are called the **spring equinox** and **fall equinox**.



Sun's Declination

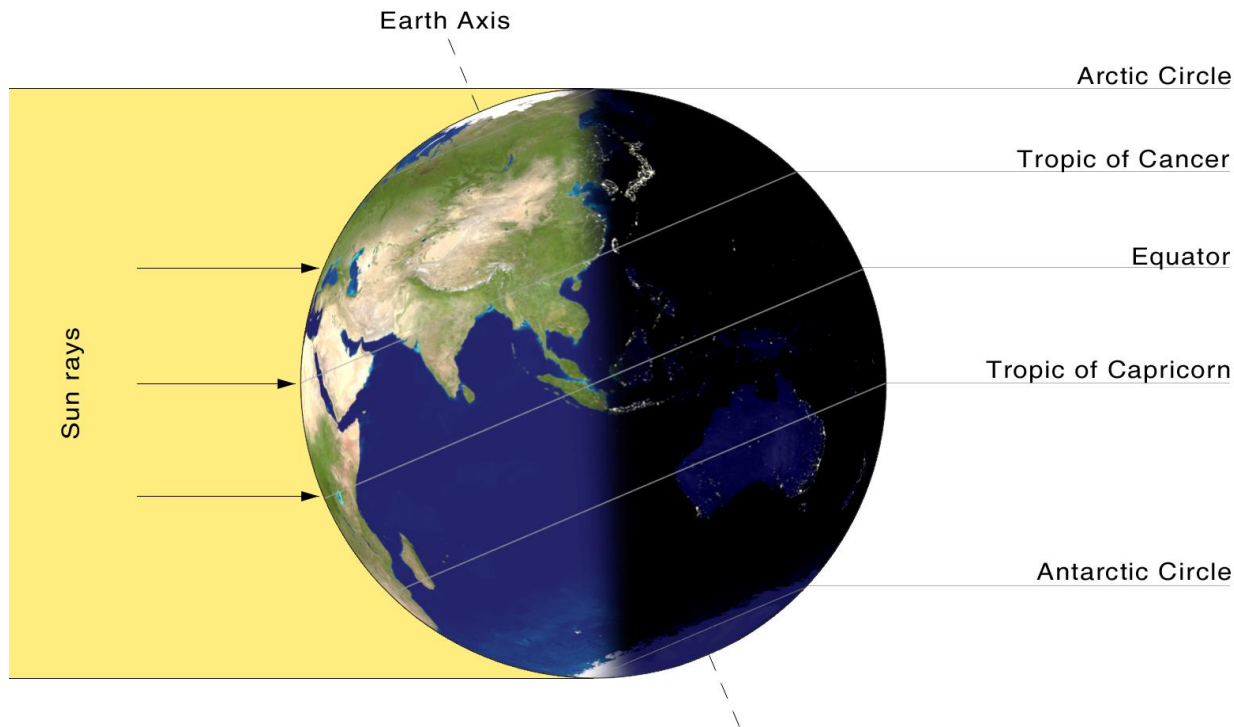
22

- The **equatorial plane** is the surface cutting through the earth's equator.
- **Solar declination** is the angle between the equatorial plane and the rays of the sun.
- The angle of solar declination changes continuously as Earth orbits the sun, ranging from -23.5° to $+23.5^\circ$ (positive when the northern hemisphere is tilted toward the sun).



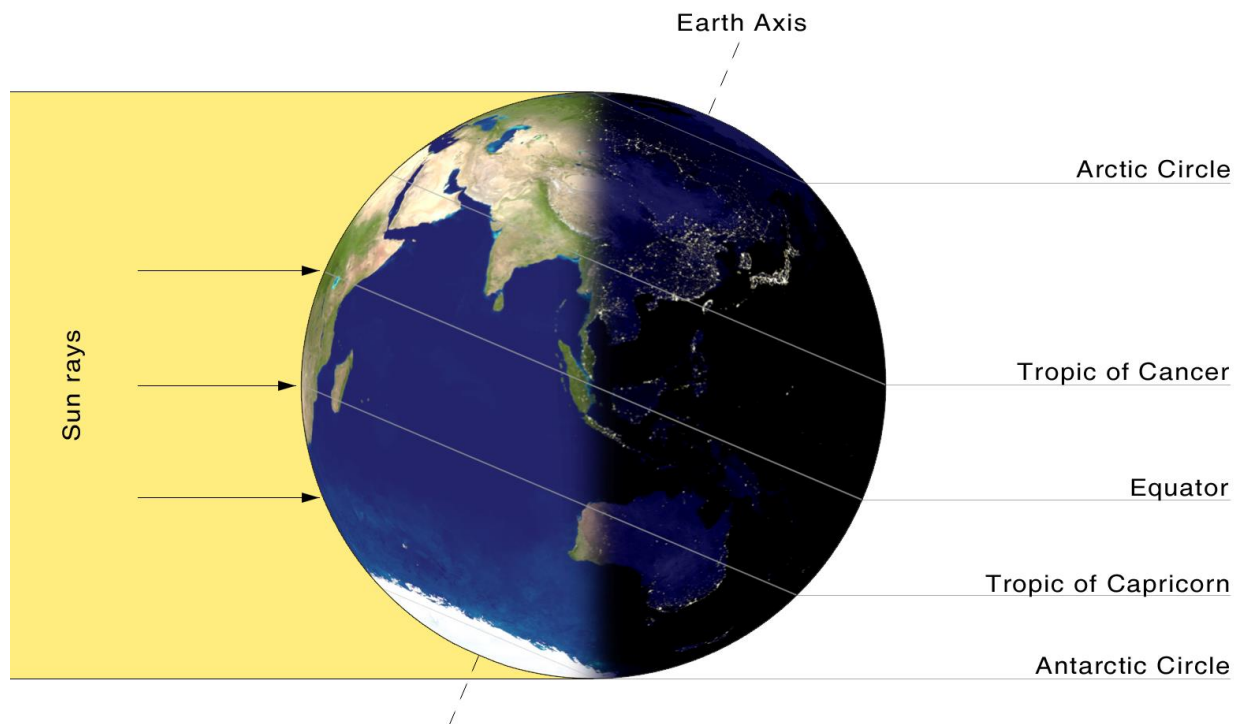
Summer Solstice

- At summer solstice, the sun's rays are perpendicular to the tropic of cancer.
- Daytime is longest in the northern hemisphere.
- Daytime is shortest in the southern hemisphere.



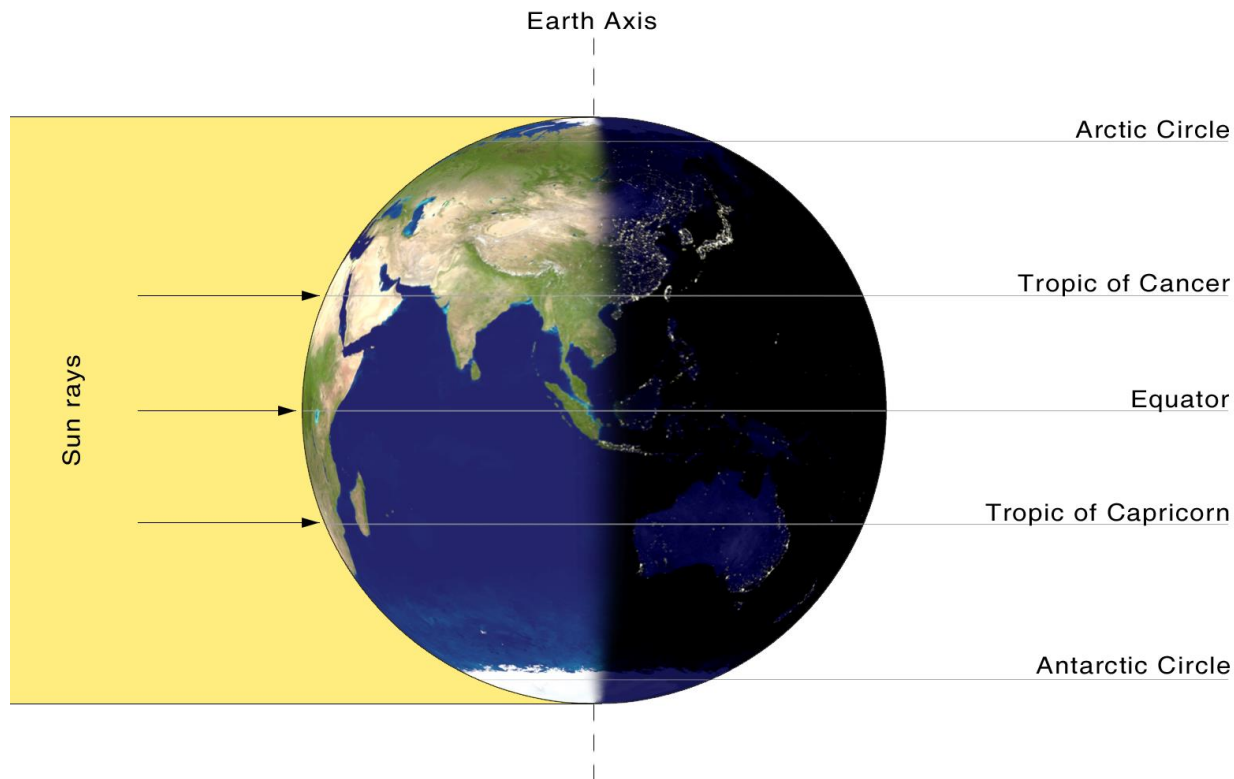
Winter Solstice

- At winter solstice, the sun's rays are perpendicular to the tropic of capricorn.
- Daytime is shortest in the northern hemisphere.
- Daytime is longest in the southern hemisphere.



Spring and Fall Equinoxes

- At spring and fall equinoxes, the sun's rays are perpendicular to the equator.
- Day and night have equal lengths.

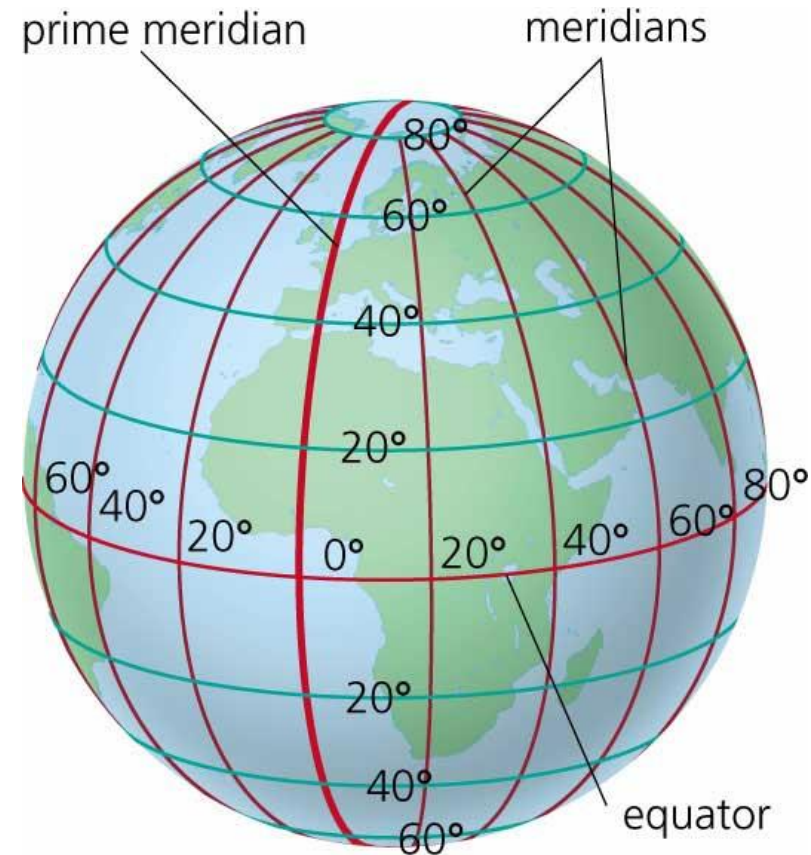


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Lines of Longitude

27

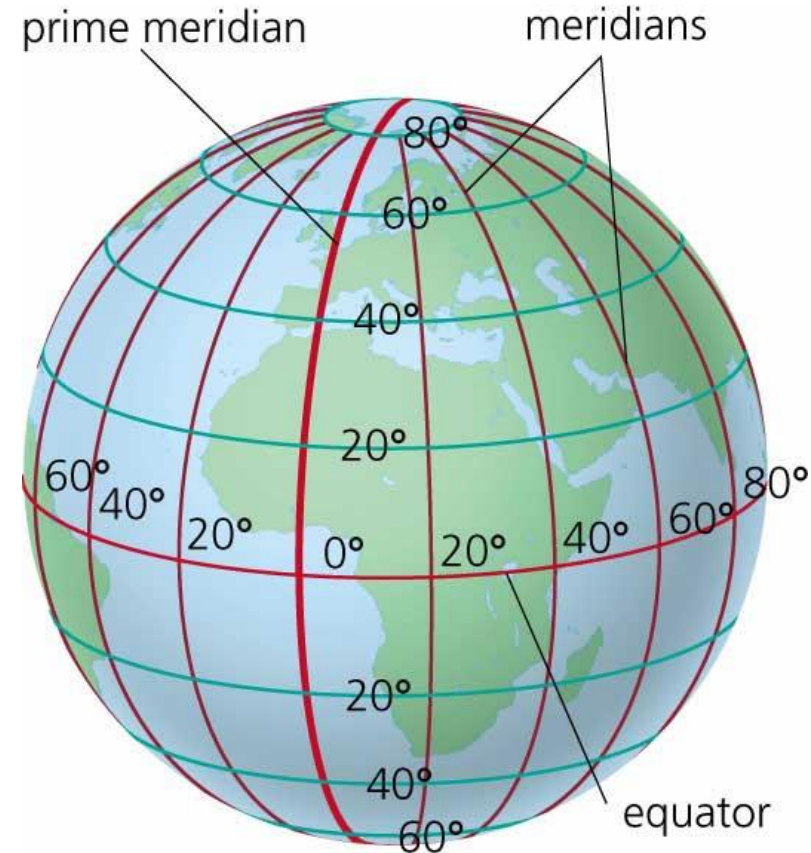
- **Lines of longitude** start at the north pole and end at the south pole.
- Lines of longitude are also called **meridians**.
- There are 360 meridians, one for each degree.
- The meridian passing through Greenwich is called the prime meridian, and it is given the value of 0° .
- Riyadh is approximately 46° east of the prime meridian.



Lines of Longitude

28

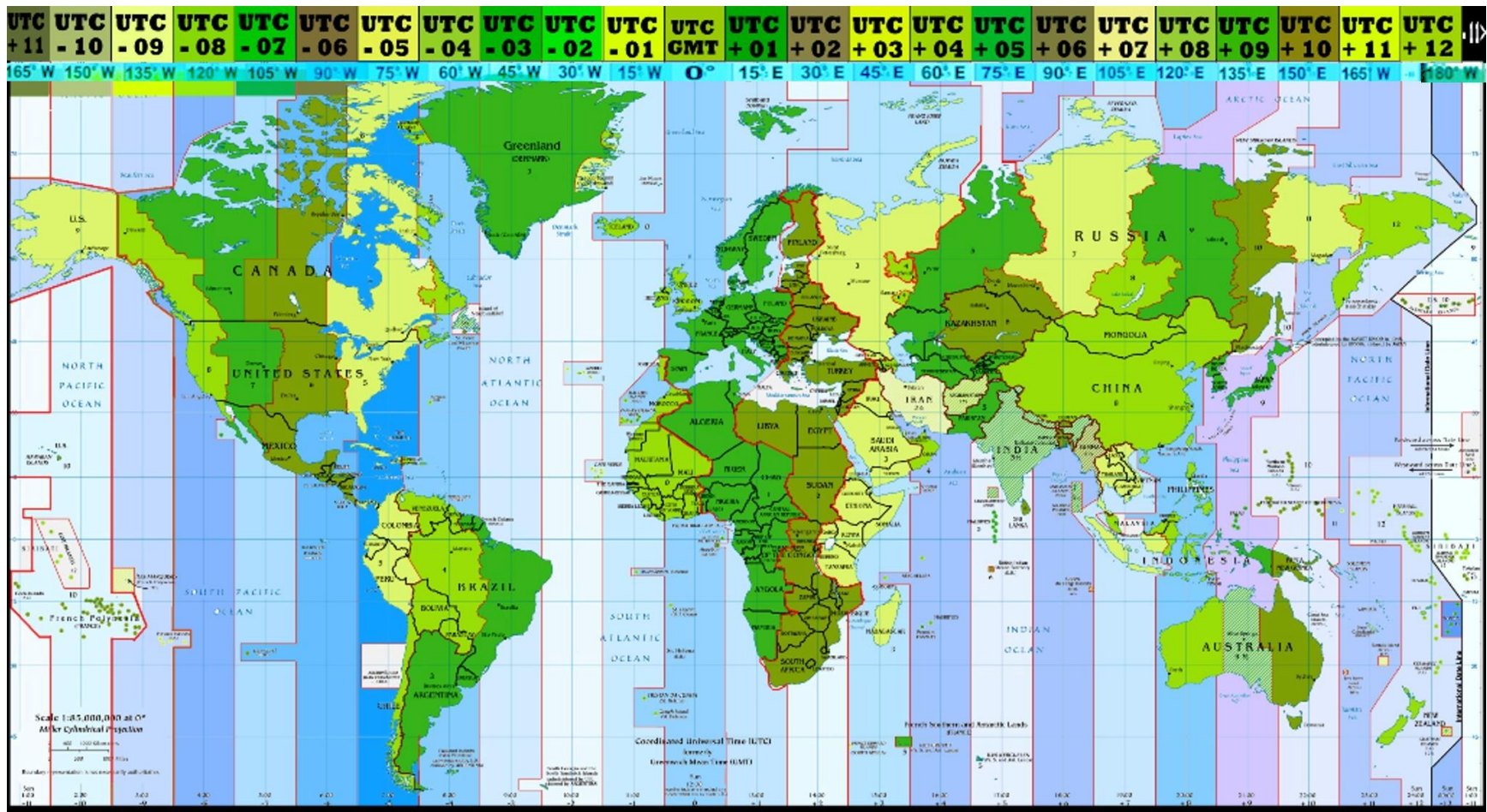
- As the earth turns once around its axis, it passes through 360 meridians.
- Moving from one meridian to the next takes 4 minutes.
- 15 degrees of longitude correspond to 1 hour.
- **Example:** If the time in Greenwich is 10:00, the time in a city 30° east will be 12:00, and the time in a city 45° west will be 7:00.



What about the time in locations between?

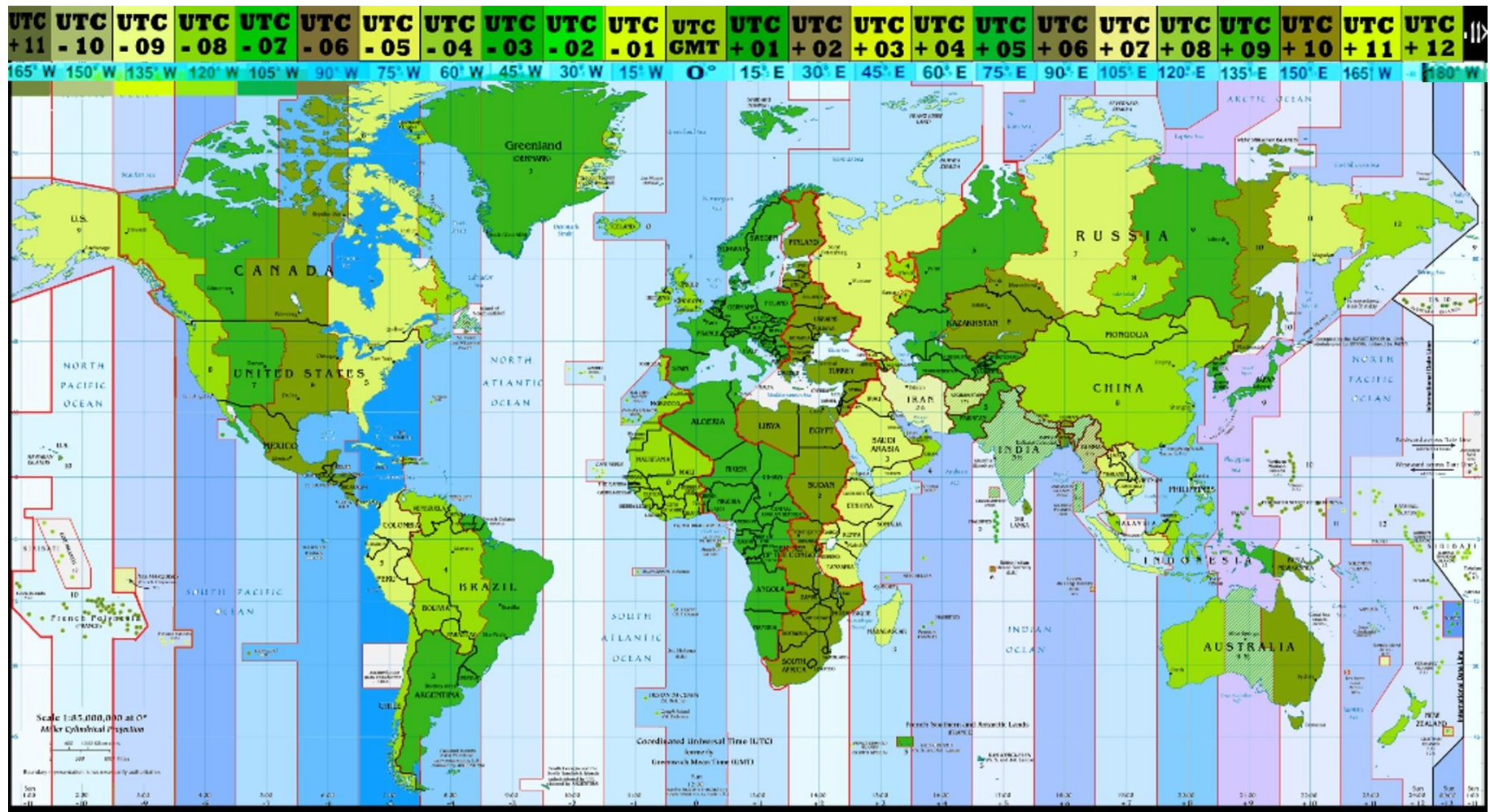
Standard Time

- To simplify calculation of time and avoid an infinite number of times throughout the world, Standard Time was introduced
- Clocks are usually set for the same reading throughout a zone covering approximately 15° of longitude



Standard Time

- The time at the center of the zone is called ***standard time***
- Zones are 15° apart



- Solar time is the time used in calculating the sun's position.
- Solar time does not coincide with standard time.
- In solar time, 12:00 always represents the time when the sun is exactly halfway through the sky.
- This time is called **solar noon**.
- The time of Dhuhr Athan is solar noon.

- It is necessary to convert standard time to solar time by applying two corrections
 1. Constant correction for the difference in longitude between the observer's meridian (longitude) and the meridian on which the local standard time is based
 2. Equation of time, which takes into account the changes in the earth's rate of rotation

- Local solar time at a given location is denoted by LST

$$LST = \text{Local Standard Time} - \underbrace{(L_L - L_S)(4 \text{ min/deg W})}_{\text{Correction for Longitude}} + \underbrace{EOT}_{\text{Correction for Rate of Earth Rotation}}$$

Correction for
Longitude

Correction for
Rate of Earth
Rotation

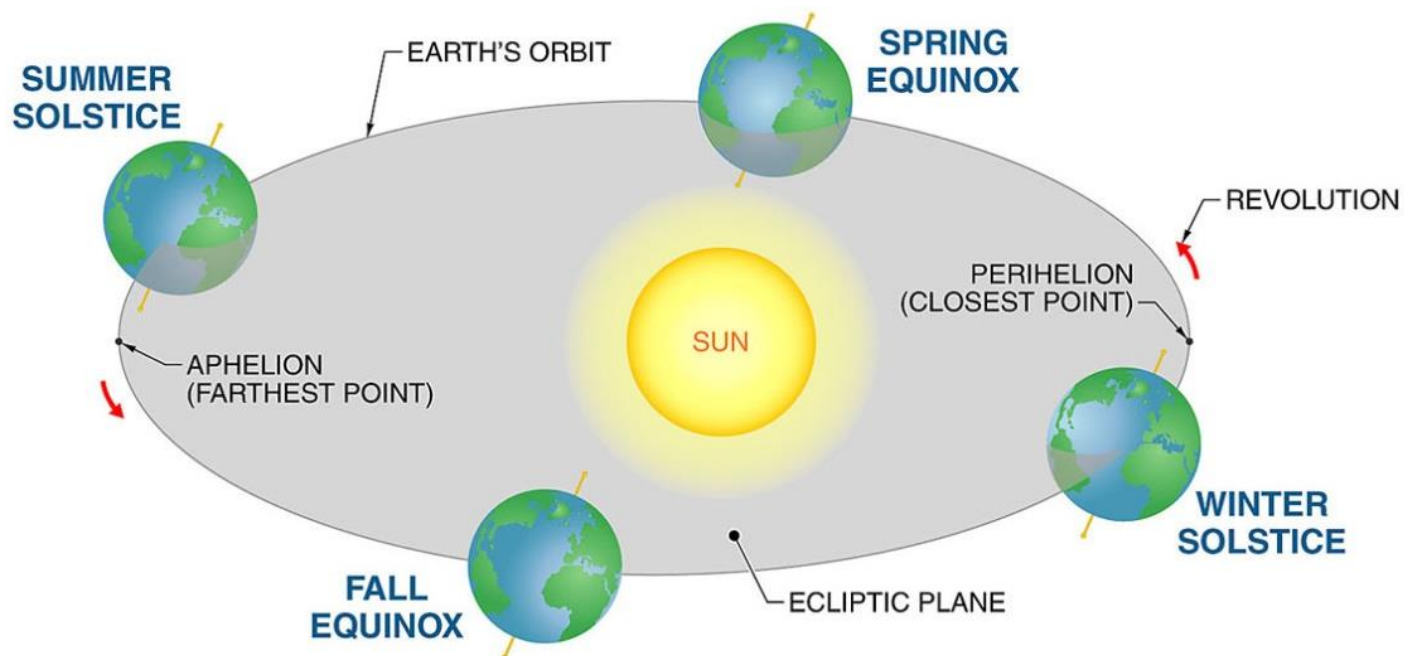
Where:

- L_L is the longitude at the given location
- L_S is the longitude at the standard meridian for the time zone
- deg W means moving in the western hemisphere
 - If a location is in the eastern hemisphere, (4) becomes (-4)
- EOT is called the Equation of Time

Equation of Time

34

- Earth moves in an elliptical (not circular) orbit around the sun, moving faster near Perihelion than at Aphelion.
- This affects solar time.
- The correction used to account for this phenomenon is called Equation of Time (EOT)



- EOT can be found from:

$$EOT = 229.2 (0.000075 + 0.001868 \cos N - 0.032077 \sin N - 0.014615 \cos 2 N - 0.04089 \sin 2 N)$$

Where:

$$N = (n - 1)(360/365)$$

n is the day of the year

EOT for the 21st of each month:

	Equation of Time, min	Declination, degrees	$A,$ $\frac{\text{Btu}}{\text{hr-ft}^2}$	$A,$ $\frac{\text{W}}{\text{m}^2}$	$B,$ Dimensionless	$C,$
Jan	-11.2	-20.2	381.0	1202	0.141	0.103
Feb	-13.9	-10.8	376.2	1187	0.142	0.104
Mar	-7.5	0.0	368.9	1164	0.149	0.109
Apr	1.1	11.6	358.2	1130	0.164	0.120
May	3.3	20.0	350.6	1106	0.177	0.130
June	-1.4	23.45	346.1	1092	0.185	0.137
July	-6.2	20.6	346.4	1093	0.186	0.138
Aug	-2.4	12.3	350.9	1107	0.182	0.134
Sep	7.5	0.0	360.1	1136	0.165	0.121
Oct	15.4	-10.5	369.6	1166	0.152	0.111
Nov	13.8	-19.8	377.2	1190	0.142	0.106
Dec	1.6	-23.45	381.6	1204	0.141	0.103

Time Calculation Examples

- If the local standard time in Makkah is 9:45am on February 21st, calculate the solar time:

SOLUTION

- L_S is 45° east
- L_L for Makkah is 39.8° east
- Correction for longitude: $(39.8 - 45) \times (-4) = 20.8$ min
- EOT = -13.9 min (from table or equation)

$$\rightarrow \text{LST} = 9:45 - (20.8 \text{ min}) - 13.9 \text{ min} \approx 9:10$$

$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4 \text{ min/deg W}) + EOT$$

Correction for
Longitude

Correction for
Rate of Earth
Rotation

Time Calculation Examples

- What is the time of Dhuhr Athan in Riyadh on February 21st?

SOLUTION

- L_S is 45° east, and L_L for Riyadh is 46.7° east
- Correction for longitude: $(46.7 - 45) \times (-4) = -6.8$ min
- EOT = -13.9 min (from table or equation)
- LST at Dhuhr Athan is solar noon, which is always 12:00
 - $12:00 = \text{Local Standard Time} - (-6.8 \text{ min}) - 13.9 \text{ min}$
 - $\text{Local Standard Time} = 12:00 + 13.9 - 6.8 \approx 12:07$

$$\text{LST} = \text{Local Standard Time} - \underbrace{(L_L - L_S)(4 \text{ min/deg W})}_{\text{Correction for Longitude}} + \underbrace{EOT}_{\text{Correction for Rate of Earth Rotation}}$$

Correction for
Longitude

Correction for
Rate of Earth
Rotation

Time Calculation Examples

- If the local standard time in Atlanta, Georgia is 3:00pm on November 21st, calculate the solar time:

SOLUTION

- L_S is 75° west
- L_L for Atlanta is 84.4° west
- Correction for longitude: $(84.4 - 75) \times (4) = 37.6$ min
- EOT = 13.8 min (from table or equation)

$$\rightarrow \text{LST} = 15:00 - (37.6 \text{ min}) + 13.8 \text{ min} \approx 14:36$$

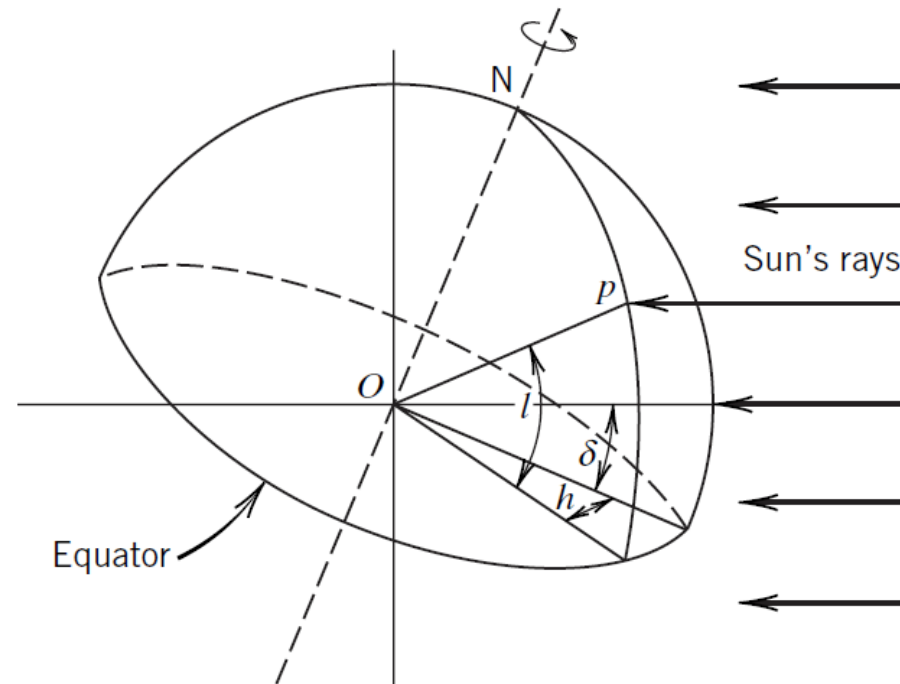
$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4 \text{ min/deg W}) + EOT$$

Correction for
Longitude

Correction for
Rate of Earth
Rotation

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- Solar angles

- The location of the sun is determined by:
 - **Location on earth**
 - **Day of the year**
 - **Time of the day**
- It is convenient to describe these three quantities by angles:
- Location on earth is determined by latitude (l)
- Day of the year is determined by declination angle (δ)
- Time of the day is determined through solar time by the hour angle (h)



- The declination angle can be determined as follows:

$$\delta = 0.3963723 - 22.9132745 \cos N + 4.0254304 \sin N - 0.3872050 \cos 2N + 0.05196728 \sin 2N - 0.1545267 \cos 3N + 0.08479777 \sin 3N$$

Where:

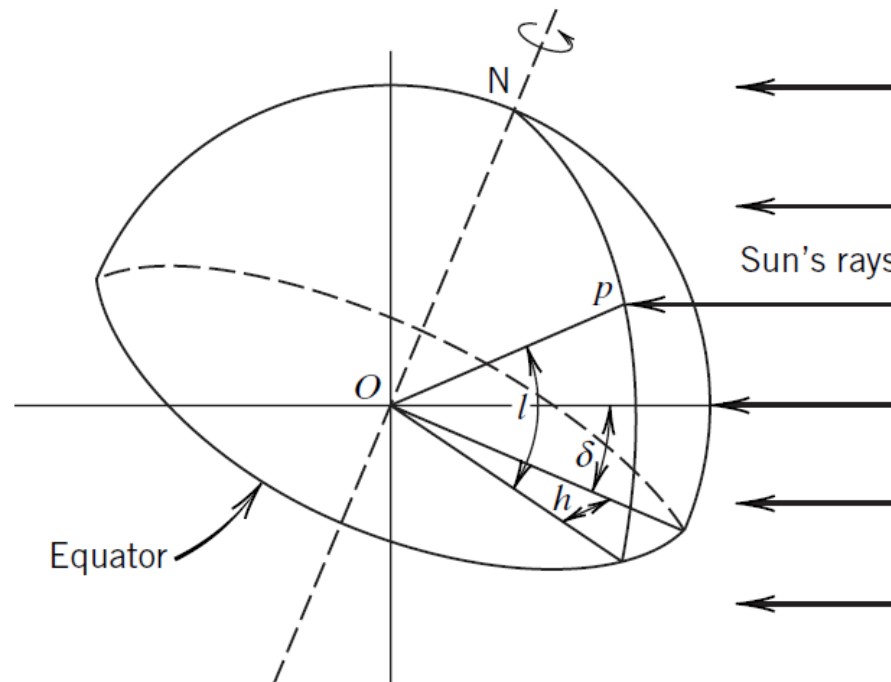
$$N = (n - 1)(360/365)$$

n is the day of the year

Hour Angle

43

- The *hour angle* h is the angle between the projection of P on the equatorial plane and the projection on that plane of a line from the center of the sun to the center of earth.
- 15° of hour angle corresponds to one hour of time.



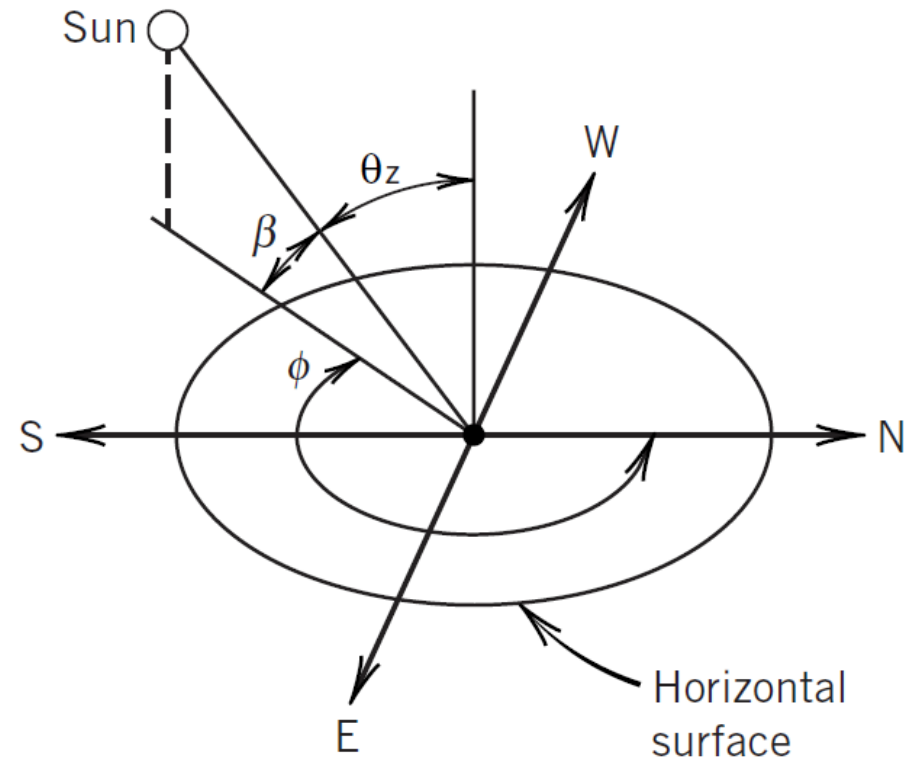
Hour Angle

44

- The hour angle is set to zero at local solar noon
- The hour angle is considered negative in the morning and positive in the afternoon.
- The maximum value of hour angle is at sunset
- The minimum value of hour angle is at sunrise
- The magnitude of hour angle at sunrise and sunset on a given day are identical.
- The hour angle is calculated by:

$$h = (\text{LST} - 12:00) \times 15^\circ/\text{hour}$$

- The sun's location in the sky can be determined from the following information:
 - **Latitude (l)**
 - **Declination angle (δ)**
 - **Hour angle (h)**
- The most convenient way to describe the sun's location in the sky is by using two angles:
 - Solar **elevation (or altitude) angle (β)**
 - Solar **azimuth angle (ϕ)**

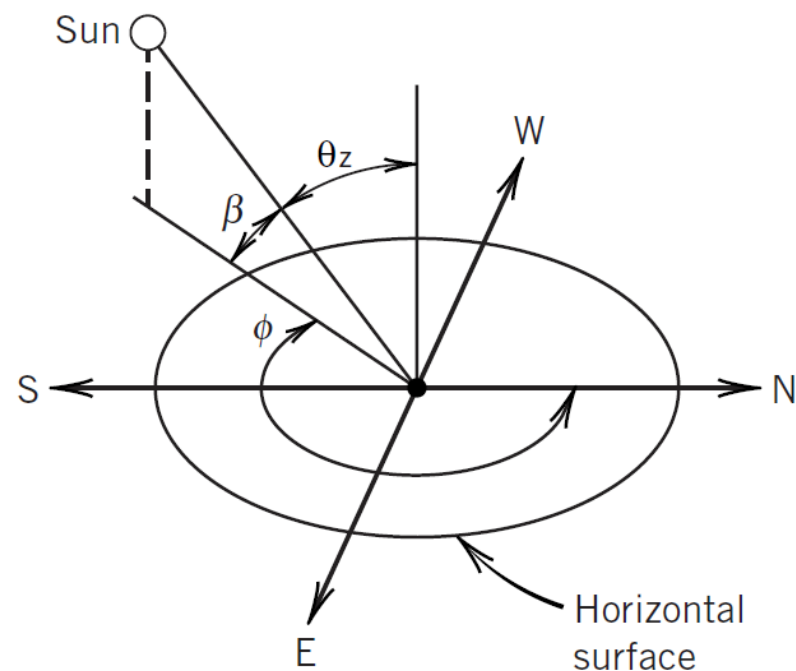


- The **solar elevation angle** is the angle between the sun's ray and the projection of that ray on a horizontal surface
- At sunrise and sunset, the solar elevation angle is 0° .
- It can be found from:

$$\sin \beta = \cos l \cos h \cos \delta + \sin l \sin \delta$$

- The daily maximum elevation angle occurs at noon (β_{noon}).
- It is given by:

$$\beta_{\text{noon}} = 90 - |l - \delta| \text{ degrees}$$

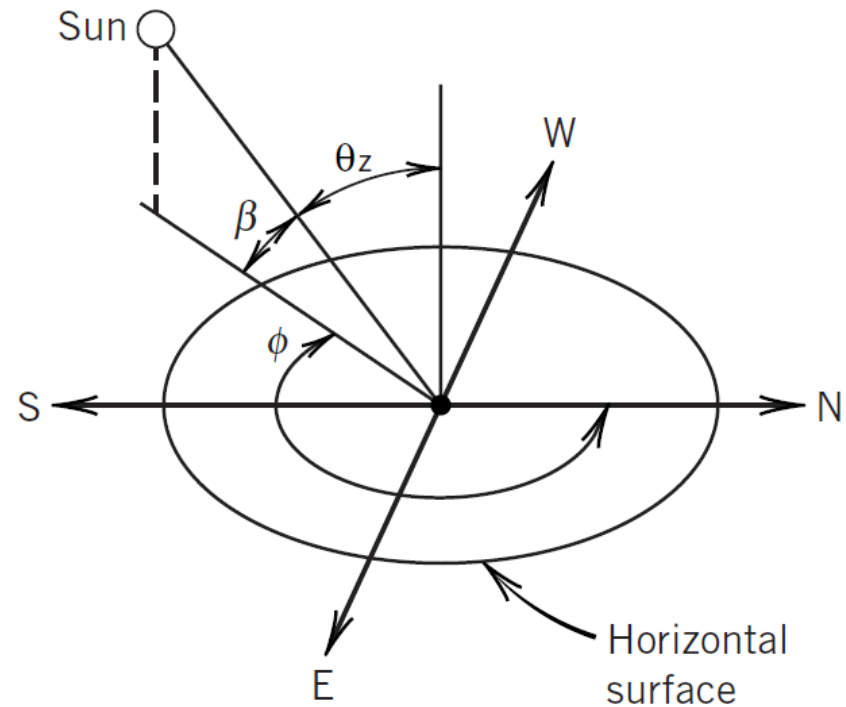


Sun's Zenith Angle

47

- The sun's **zenith angle** (β_z) is the angle between the sun's rays and a perpendicular to the horizontal plane at point P .

$$\beta + \theta_z = 90 \text{ degrees}$$

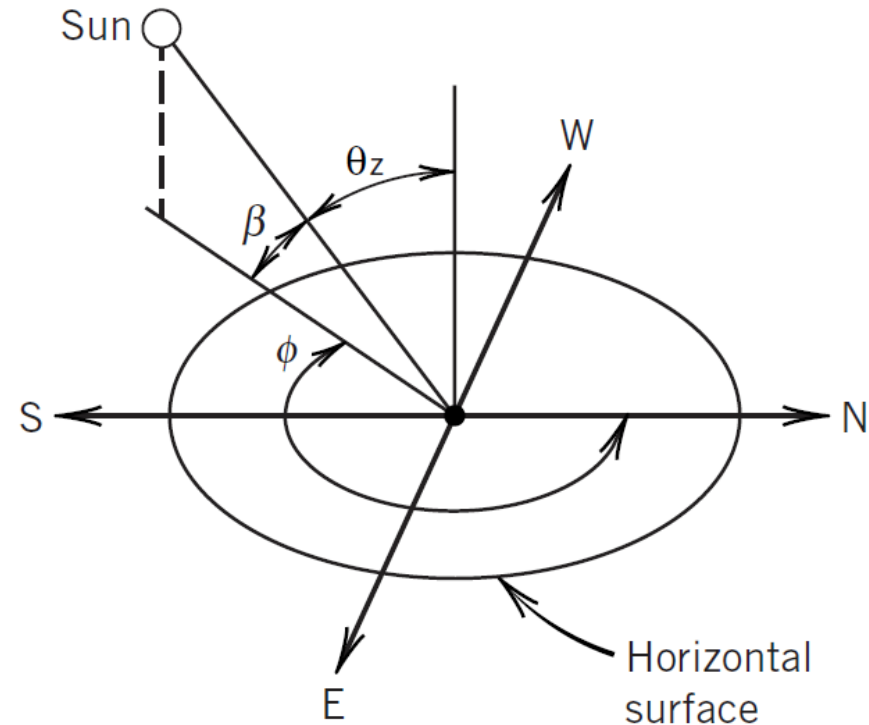


Solar Azimuth Angle

48

- The **solar azimuth angle** (ϕ) is the angle in the horizontal plane measured, in the clockwise direction, between north and the projection of the sun's rays on the horizontal plane.
- The solar azimuth angle can be found from:

$$\cos \phi = \frac{\sin \delta \cos l - \cos \delta \sin l \cos h}{\cos \beta}$$



For Riyadh on February 21st, calculate sunset time (in standard time).

SOLUTION

At sunset, the elevation angle $\beta = 0^\circ$

Latitude of Riyadh: $l = 24.6^\circ$

Declination angle on February 21st: $\delta = -10.8^\circ$

$$\sin \beta = \cos l \cos h \cos \delta + \sin l \sin \delta$$

$$\sin (0) = \cos (24.6) \times \cos (h) \times \cos (-10.8) + \sin (24.6) \times \sin (-10.8)$$

$$\rightarrow h = 85^\circ$$

$$h = (\text{LST} - 12:00) \times 15^\circ/\text{hour}$$

$$\rightarrow \text{LST} = 17:40$$

$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4 \text{ min/deg W}) + EOT$$

$$\text{Local Standard Time} = 17:40 + (46.7 - 45) \times (-4) + 13.9$$

$$\rightarrow \text{Local Standard Time} \approx 17:47$$

For Riyadh on February 21st, calculate the azimuth angle at sunset

SOLUTION

The solar azimuth angle is given by:

$$\cos \phi = \frac{\sin \delta \cos l - \cos \delta \sin l \cos h}{\cos \beta}$$

At sunset, the elevation angle $\beta = 0^\circ$

Latitude of Riyadh: $l = 24.6^\circ$

Declination angle on February 21st: $\delta = -10.8^\circ$

Hour angle (found from previous example): $h = 85^\circ$

$$\cos (\phi) = \sin (-10.8) \times \cos (24.6) - \cos (-10.8) \times \sin (24.6) \times \cos (85)$$

$$\rightarrow \cos (\phi) = -0.206 \text{ (second quadrant)}$$

$$\rightarrow \phi = 101.9^\circ \text{ OR } 258.1^\circ$$

The first solution represents sunrise, and the second represents sunset.

$$\rightarrow \phi = 258.1^\circ$$