Chapter 2  The Earth and the sky

2.1  Imaginary Celestial sphere

For objects very far away from us, they appear to be of equal distance from us (Fig. 2-1) — in fact, an illusion. Look at the following example:

Suppose you are standing under the “Rice cooker” (飯煲) of Science Centre, and looking at the main library (Fig. 2-1 Top). Mr. A and Mr. B are now standing at two corners of Signal Fire Terrace (烽火台) (Fig. 2-1 Bottom). Although Mr. A is nearer and Mr. B is farther away from you, they seem to be of the same distance from you. It appears to be because they are very far away from you.

✓ Similarly, since all stars are extremely far away from us, they appear to be of the same distance from us. Consequently, it seems that we are at the centre of a huge imaginary sphere, the stars are attached to the surface of that sphere — celestial sphere (天球). (Fig. 2-2)

✓ All celestial bodies are imagined to attach to the inside of a very large hollow sphere surrounding the earth.

✓ This is a convenient model of the sky for mapping the apparent positions and motions of celestial bodies as seen from the Earth.
In order to define the positions of stars on the celestial sphere, one specifies the coordinates of a star by

✓ **Declination** (DECL, \( \delta \)) and **Right Ascension** (RA, \( \alpha \)), which are similar to latitude and longitude on earth respectively (Fig. 2-3).

✓ DECL is measured in degrees: \( 0 \leq \delta \leq 90^\circ \) for northern celestial hemisphere, whereas \( -90^\circ \leq \delta \leq 0 \) for southern celestial hemisphere.

✓ RA counts from the vernal equinox 春分點 eastward. One should assume vernal equinox is a fixed point on the celestial sphere at this moment. (Section 2.5 for the details) RA is measured in hours, minutes, and seconds.

\[
24 \text{ hr} = 360^\circ, \text{ or } 1 \text{ hr} = 15^\circ \\
1 \text{ hr} = 60 \text{ min} \\
1 \text{ min} = 60 \text{ sec}
\]

✓ **Apparent sizes and separations** of celestial bodies are measured in angles:

\[
1 \text{ circle} = 360^\circ \text{ (degrees)}, \\
1^\circ = 60^\prime \text{ (minutes)}, \\
1^\prime = 60^\prime\prime \text{ (seconds)}.
\]

For example, apparent diameters of the Sun and Moon is about 0.5\(^\circ\) (Fig. 2-4), the width of a finger at arm’s length \( \approx 1^\circ \), that of the fist at arm’s length \( \approx 10^\circ \).
If the Earth were not spinning (rotate about its own axis), we always see a stationary celestial sphere, i.e., all the stars on the celestial sphere will not move. However, it is definitely not true. Our Earth does self-rotate! Because of the self-rotation (once a day) of the Earth, the celestial sphere appears to rotate once a day, so one may define:

- **Celestial poles:** The north celestial poles (NCP) and south celestial poles (SCP) of the celestial sphere located, respectively, above the north and south poles of the Earth. The poles specify the axis of daily rotation of the celestial sphere. (Fig. 2-3)

- **Polaris** (北極星) is a bright star close to the north celestial pole, so Polaris appears almost stationary during the daily rotation.

- **Celestial equator:** It is an imaginary plane, which divides the celestial sphere into the north and south hemispheres. (Fig. 2-3)

2.2 Daily motion (周日運動)

We know that the Earth is not stationary, but self-rotating (自轉) from West (W) to East (E), i.e., counter-clockwise as seen from above the North Pole. Before we discuss the self-rotation of the Earth, let us talk about several phenomena first.

- Imagine that you are at the North Pole of the Earth, the polar star Polaris then locates directly above you. All stars appear to move on horizontal circular paths in counter-clockwise. (Fig. 2-5)

- At the South Pole of the Earth, Polaris locates directly under you. You see all stars are moving on horizontal circular paths but in clockwise direction (Fig. 2-6).
At equator, Polaris locates at the northern horizon. (Fig. 2-7 Right) Because of the self-rotation of the Earth, the celestial sphere, which carries all stars, appears to move along vertical circles. (Fig. 2-7 Left)

As mentioned previously, Polaris is close to the north celestial pole, it appears almost stationary. Stars near Polaris circulate around it anticlockwise. On the other hand, in the south hemisphere Polaris is below the horizon, so it can never be seen in the south hemisphere.

No matter where the circular path is, the star always spend one day to complete one cycle since the Earth self-rotates once a day. This daily circular motion is called the Daily motion (周日運動) of stars.

Moreover, as the Earth is self-rotating (自轉) from West (W) to East (E), i.e., counterclockwise as seen from above the North Pole, celestial bodies appear to move in opposite direction (E to W) in the sky, e.g., the Sun rises in the E and sets in the W.

In general, at certain latitude (Fig. 2-8 Right), one see the polar star Polaris locates at an angle above the horizon (Fig. 2-8 Left Up). Because of the self-rotation of the Earth (Fig. 2-8 Left Bottom), the celestial sphere, which is carrying celestial bodies, rotate about the Polaris. (Fig. 2-8 Left Up)
Position of Polaris depends on the observer location on the Earth, e.g., an observer at north pole sees Polaris directly overhead (Fig. 2-5); an observer at equator sees Polaris at the northern horizon (Fig. 2-7), or more generally (Fig. 2-9),

The angle of Polaris above the horizon = latitude of the observer

Can you verify if it is correct for an observer is at the poles or equator?

Stars to be seen also depend on the observer’s location on Earth. For example, observers at the North Pole can see stars of $\delta > 0$ only. Observers at equator can see all stars. Can you see why?

For an observer at a latitude $L$ (Fig. 2-10), he can never see a star of $\delta < -(90^\circ - L)$, i.e., stars close to the S celestial pole never rises. On the other hand, he can always see a star of $\delta > 90^\circ - L$, i.e., stars close to the N celestial pole never sets. Stars that never rise or set are called circumpolar star 拱極星. (Fig. 2-11)
2.3 Keeping track of Time

Suppose you are at latitude $L$, you see Polaris at an angle $L$ above the northern horizon as discussed previously (Fig. 2-12). In addition, relative to an observer’s horizon, one may define

- **Zenith** (天頂): the point directly overhead of the observer.
- **Meridian** (子午線): a great circle passing through the *north, south celestial poles* and the *zenith* of an observer. (Fig. 2-12)

*Important:* Since the zenith and meridian are defined with respect to an observer, so the zenith and meridian are *fixed* relative to the observer, no matter the celestial sphere (together with all stars) is *rotating*. (Fig. 2-13)

How to define *one day*? You may have heard that one-day is defined as the time for the earth to self-rotate once. It is in fact called *sidereal day*.

- **Sidereal day** (恆星日): The time between successive passages of any distant across the observer’s meridian. It is in fact equal to the self-rotation period of the Earth.

Traditionally we want the system of timekeeping used in everyday life to reflect the position of the Sun in the Sky. For example, thousands of years ago, the sundial was invented to keep track of the Sun. It is because the Sun’s position determines whether we are awake or asleep and whether it is time for breakfast or dinner. Hence, it is quite obvious to define *apparent solar day* for time keeping.
Apparent solar day: The time between two successive passages of the Sun across the observer’s meridian. Noon and midnight are defined, respectively, as the Sun crosses the upper and lower meridian. It is a timekeeping using the daily motion of the Sun.

However, the Sun is not a good timekeeper! It is because the length of an apparent solar day varies.

After one sidereal day, the Earth has self-rotated once, but the Sun is not at the observer’s meridian (Fig. 2-14). A has to wait for the earth to self-rotated a bit more (about 1°) to see another passage of the Sun across his meridian; hence, an apparent solar day is slightly longer than a sidereal day.

To make it more complicated, the Earth’s orbit is not a prefect circle, but an ellipse, the Earth moves faster when closer to the Sun. (I shall discuss it in details in chapter 5) As a result, the length of an apparent solar day varies from one time of a year to another! How can we design a clock to measure the apparent solar day?

In order to avoid these difficulties, one may define

Mean sun: It is an imaginary object that moves uniformly in a perfect circular orbit. One should see that the object sometimes ahead of the real Sun, sometimes behind.

Mean solar day: The time between two successive passages of the mean Sun across the meridian. It is exactly 24 hours. Our alarm clock or wristwatch measures mean solar day.

In fact, one shows that 1 sidereal day = 23 hr 56 min of mean solar time. Thus, it explains why a star rises at the eastern horizon 4 minutes earlier each day.
✓ **Universal Time (UT):** Mean solar time at Greenwich (a seaport just outside of London)

✓ **Time zones** are defined by meridians of longitude, each zone being 15° (1 hr) wide. Within a zone, it has the same **Standard Time**. This is what we use in our daily life.

✓ **Standard Time (ST):** the mean solar time for a meridian of longitude at the centre of the zone. For example, Hong Kong Standard Time = UT + 8 hour. (Fig. 2-15)

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![Fig. 2-15: Time Zones in North America.](image)
Constellations

- **Constellations**: Visual groupings of stars (Fig. 2-16). Modern definition: Regions on the celestial sphere with well-defined boundaries. Totally 88 today, some added in modern days (e.g., Telescopium 望遠鏡座).

- Usually no real correlation among the stars in the same constellations; they could be very far away from one another (Fig. 2-17).

- They rise and fall with the rotation of the celestial sphere because of the self-rotation of the earth.

- Which constellations one can see depend on the observer’s location and reason. For example, an observer living in the northern hemisphere on earth can never see some southern constellations (they never rise above the horizon), but he/she can always see some constellations around the NCP as they never set.

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**Fig. 2-16**: (a) The constellation of Orion. The brightest stars are connected to form the outline of a hunter. (b) An actual photograph of this region.

**Fig. 2-17**: The true space locations of the stars in Orion, in 3-dimensions. Stars in the constellation are actually very far away from one another. They just appear to be in about the same direction as seen from the earth.
Star charts

✓ **Map**: for looking *from up to down* at a region on the earth surface.

✓ **Star chart**: for looking *from down to up* at a region on the celestial sphere. As a result, West on the right and East on the left (Fig. 2-18)

✓ The centre of the star chart represents the **zenith** (天頂); whereas the edge of the star chart represents the horizon. As the earth rotates, we see different parts of the celestial sphere at different times. We need to use another star chart after some time. Fig. 2-19 shows a star chart of April - June 2004, which can be downloaded from Hong Kong Observatory.
2.4  Apparent motions of the Sun

- **Daily motion:** The sun moves across the sky daily because of the self-rotation of the earth. The celestial sphere rotates *together with* the Sun and all the stars *once a day*.

- **Yearly motion:** Because the earth revolves around the Sun, the Sun appears to drift *eastwards* of the celestial sphere slowly throughout a year. As a result, the Sun moves across the background of stars on the celestial sphere, passing through 13 constellations, completing a path called the *ecliptic* 黃道 (Fig. 2-20).

   At night, we can only see constellations at the *opposite* side of the sun, e.g., we can see Gemini (雙子座) in January, but *not* Sagittarius (人馬座).

*Fig. 2-20: As the earth moves in its orbit, we see the sun in front of different constellations. In January the sun is in front of Sagittarius, but by March it has moved along the ecliptic to Aquarius. The ecliptic is the projection of the earth's orbit onto the celestial sphere.*
2.5 **Seasons and the calendar**

The Earth’s equatorial plane is not parallel to its orbital plane around the Sun, but it makes an angle of $23.5^\circ$ with the orbital plane (Fig. 2-21). On the Earth we observe that the Sun appears to drift slowly in the celestial sphere once a year, and the ecliptic makes an angle of $23.5^\circ$ with the celestial equator (Fig. 2-22).

Four locations along the ecliptic defining the seasons (Fig. 2-23):

*Vernal equinox* (春分) 21/3: The point where the Sun crosses the celestial equator moving northward.

*Summer solstice* (夏至) 22/6: The Sun is farthest North, and it makes an angle of $23.5^\circ$ with the equatorial plane northwards.

*Autumnal equinox* (秋分) 23/9: The point where the Sun crosses the celestial equator moving southward.

*Winter solstice* (冬至) 22/12: The Sun is farthest South, and it makes an angle of $23.5^\circ$ with the equatorial plane southwards.
Do you notice that there is longer daytime in summer in North hemisphere? In fact, the inclination of the Earth’s rotation axis is the main reason for seasons.

- When the Sun travels to summer solstice, the sunlight comes from the north of the equatorial plane at the greatest angle 23.5°, so and it has the *longest daytime* in North hemisphere, but the *shortest daytime* in South hemisphere. (Fig. 2-24)

- When the Sun travels to winter solstice, the sunlight comes from the south of the equatorial plane at the greatest angle 23.5°, and it has the *shortest daytime* in North hemisphere, but the *longest daytime* in South hemisphere. (Fig. 2-25)

Can you guess when the Sun travels to summer or winter solstice, vernal or autumnal equinox, how long of the daytime at equator is?
Summer and winter

✔ Furthermore, at noon on the day of the summer solstice, the Sun shines from nearly overhead in Northern hemisphere. Like the light from a flashlight shining nearly straight downward, the summer sunlight is not spread out very much. (Figure 2-26 a) On the day of the winter solstice, sunlight strikes the ground at a steep angle and spreads out in Northern hemisphere. (Figure 2-26 b) Thus, the ground receives less energy per square meter from the winter Sun than from the summer Sun. Hence, it is hotter in June than in December in Northern hemisphere. But why is it hotter in December in Australia?

Sun rise and set

✔ Because the Earth revolves around the Sun, the Sun appears to drift along the ecliptic on the celestial sphere slowly throughout a year. (Fig. 2-27)
✔ On the vernal equinox (or autumnal equinox), the Sun appears to move along the celestial equator as it self-rotates. (Fig. 2-28)

Question: Where does the Sun move along as observed at equator?
At equator, i.e., latitude of 0°, the Sun is moving along a vertical circle from the east to west.
When the Sun is positions from \( C \) (vernal equinox) to \( E \) (summer solstice), the Sun appears to move in a plane parallel to the celestial plane, but shifting northward; (Fig. 2-29) Similarly, when the Sun is positions from \( A \) (winter solstice) to \( C \) (vernal equinox), the Sun appears to move in a plane parallel to the celestial plane, shifting northward too. (Fig. 2-30)

After summer solstice, the Sun appears to move along the celestial plane, but shifting southward.

Question: How does the Sun move as observed at equator?

**Calendar**

- **Tropical year**: The time required for the Sun to return to the vernal equinox, about 365.2422 mean solar days, so one added Feb.29 to every calendar year that is divisible by four, i.e., 366 days. But it still produces an error of about 3 days in every 400 years!

- Only the century years divisible by 400 are leap years (29 days in Feb). For example, 1700, 1800, and 1900 were not leap years; the year 2000 is a leap year. This is **Gregorian calendar**, which we use now. But it still produces an error of about 1 day in every 3300 years!!
2.6 Brightness of celestial bodies

- **Magnitude scale**: lower magnitude of a star, brighter it is, e.g., a star of magnitude one is brighter than that of magnitude two, star of magnitude –1 is brighter than that of 0.

- Magnitude is a measurement of light intensity $B$ (light energy received per unit time per unit area). Each magnitude differs by an intensity ratio of about 2.5. For example, a star of magnitude one is about 2.5 times brighter in intensity than that of magnitude two; the intensity ratio is then about 100 times for two stars with magnitude difference of 5. (Details will be discussed in Chapter 8.)

- **Apparent magnitude** 視星等: magnitude as measured on the Earth (Fig. 2-31). Objects closer to the Earth look brighter, and those farther away look dimmer. Analogy, a close candle may appear brighter than a far street lamp. Therefore, apparent magnitude does not give a measure of the intrinsic brightness. It only measures the apparent brightness of a body (the amount of light energy received on Earth). For convention, $m = 0$ is chosen for Vega (織女星).

![Fig. 2-31: The scale of apparent visual magnitudes extends into negative numbers to represent the brighter objects. The sun has an apparent magnitude of about -27; it is the brightest celestial object as seen from the earth.](image)

- **Absolute magnitude** 絕對星等: magnitude as if all stellar objects were placed at a distance of 10 pc from the Earth. Absolute magnitude measures the intrinsic brightness of a celestial body, i.e., the amount of light energy emitted by the body.
2.7 Planets

- They do not emit light, and they shine by reflecting sunlight.
- Planets move around the Sun in nearly circular orbits, except Mercury and Pluto.
- Their orbits lie in nearly the same plane as the Earth’s, except Pluto. (Fig. 3-32)
  Therefore, planets appear to move near the ecliptic. They all move within the zodiac (黃道帶), a band of width 18° centred on the ecliptic. (Fig. 3-33)
- Planets closer to the Sun move faster and have shorter orbital periods. For example, the period of the Earth is 1 year; that of Mars is about 1.9 years; that of Saturn is about 29 years.
- Inner planets (Venus and Mercury) are closer to the Sun than the Earth. They can be observed for a short time just after sunset as evening stars above the western horizon, or just before sunrise as morning stars above the eastern horizon. (Figs. 3-34, 35)
2.8 Precession

- Interesting! The Pole star is changing. The self-rotational axis of Earth currently points towards the star Polaris. One finds Thuban (α Draco 天龍座) was the Pole star in 5,000 years ago, and it will point to Vega 12,000 years later (Fig. 3-36).

- Nevertheless, the precession of the Earth’s axis is very slow. It takes about 26,000 years per cycle. Because the Earth is not a perfect sphere, the gravity of the moon and the sun will produce torques on the earth. It is similar to the precession of the spinning top. (Fig. 3-37, 38)