Introduction to Astrophysics and Cosmology

Introduction to astrophysics - Basic concepts and units

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Unit of mass

What do you think?

Unit of mass

Astrophysics deals with objects that are generally very much larger or further than everyday objects.

For mass measurements **Solar mass** (the mass of the Sun) is used most often: $\boldsymbol{M_\odot}$

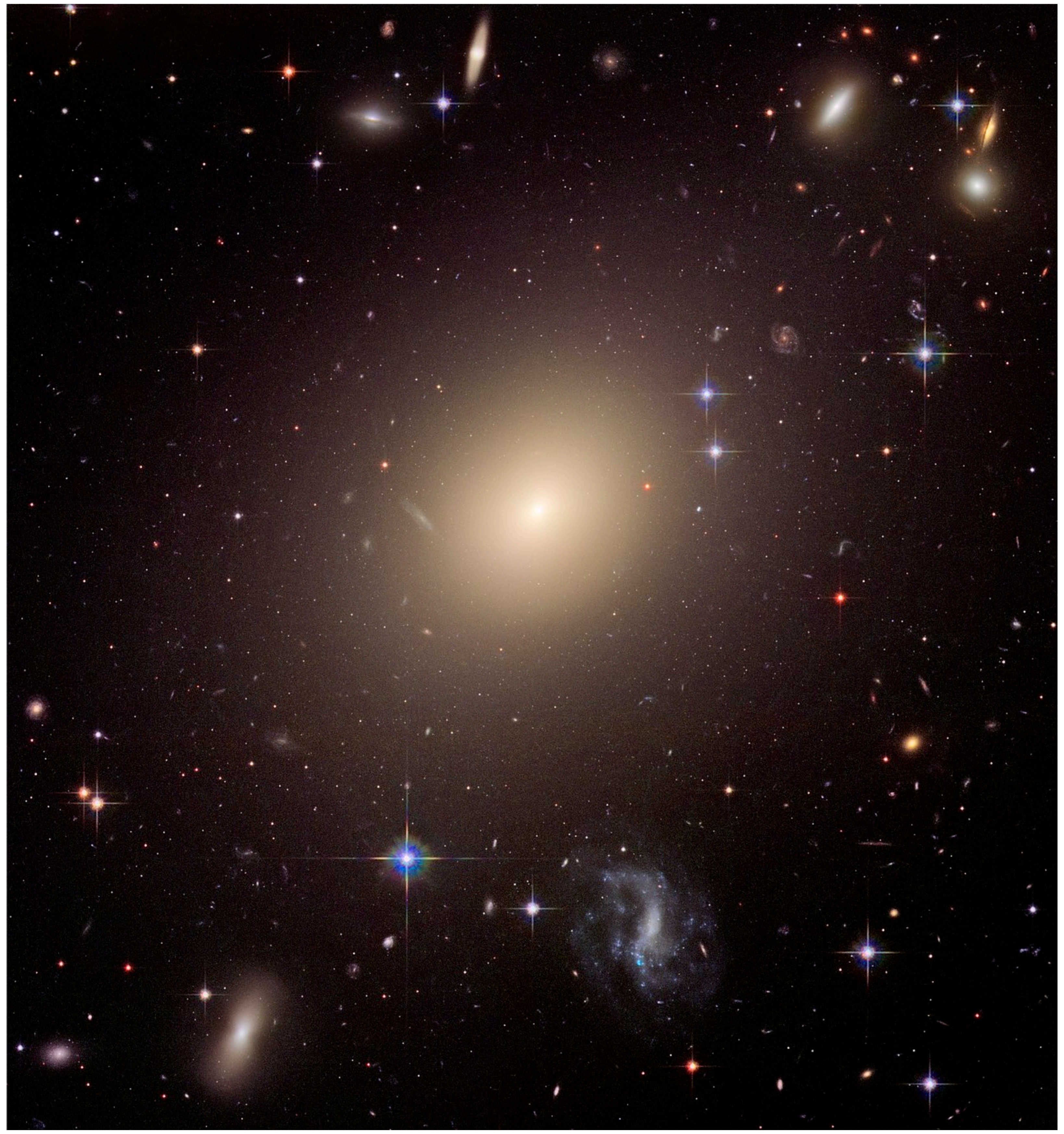
$M_\odot = 1.99 \times 10^{30}$ kg.

Examples:

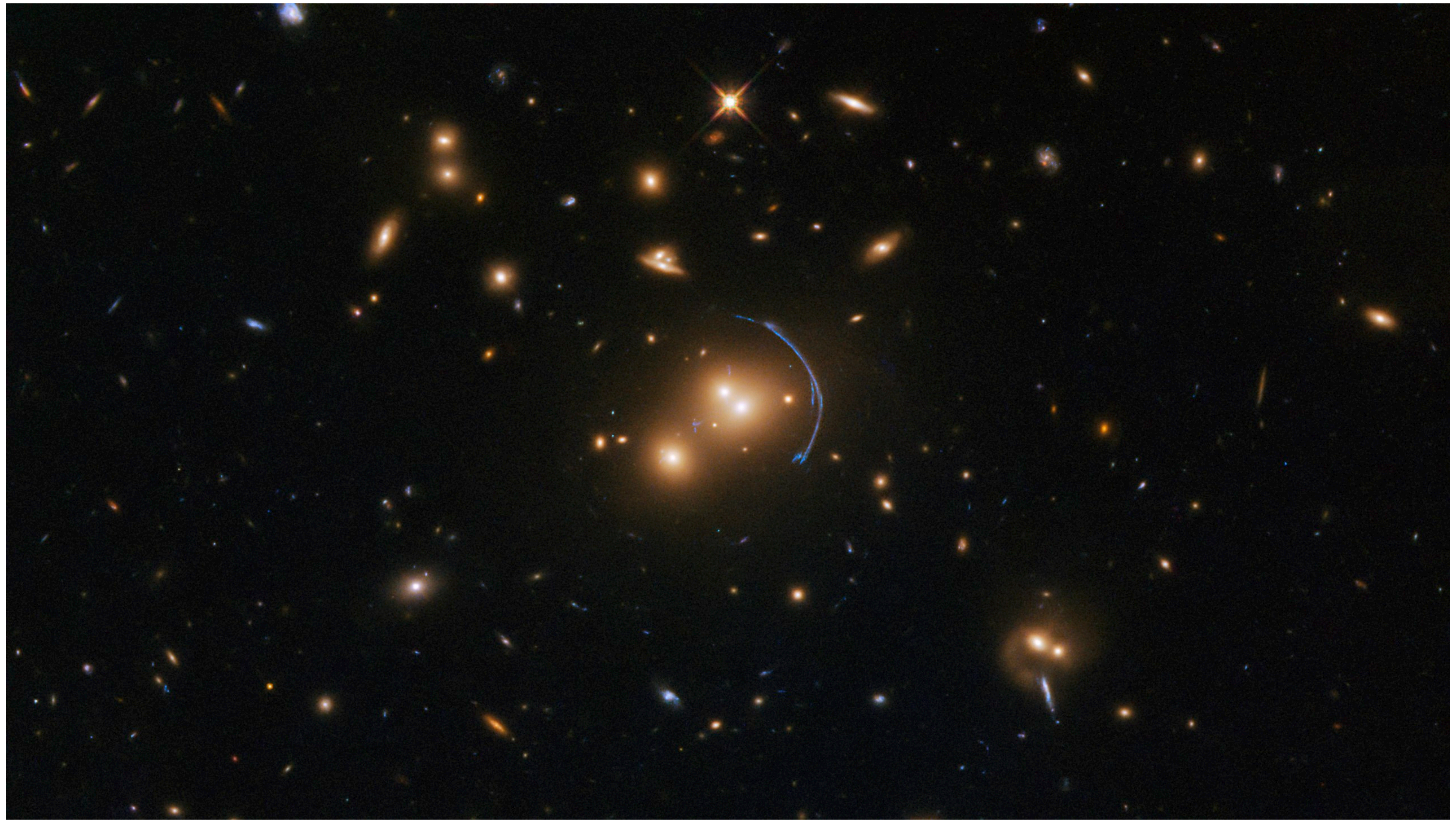
- The masses of most stars lie within a relatively narrow range from $0.1M_\odot$ to $20M_\odot$
- The mass of a typical galaxy can be $10^{11}M_\odot$.
- Globular clusters, which are dense clusters of stars having nearly spherical shapes, typically have masses around $10^5M_\odot$

Unit of mass

The mass of a typical galaxy can be $10^{11} M_{\odot}$.



The giant elliptical galaxy ESO 325-G004



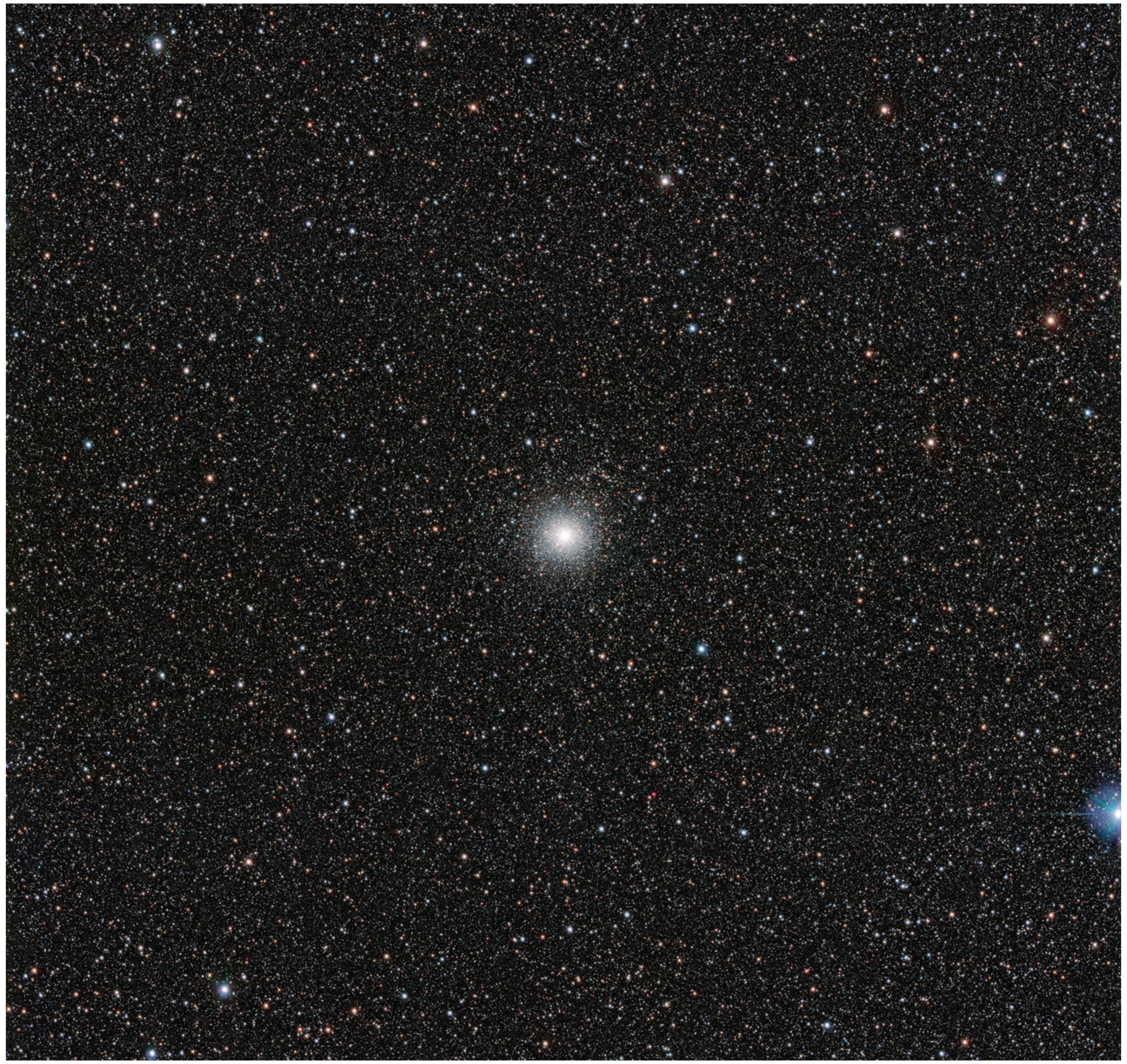
Galaxy cluster SDSS J1152+3313

NGC 4414, a typical spiral galaxy

Unit of mass

Globular clusters, which are dense clusters of stars having nearly spherical shapes, typically have masses around $10^5 M_\odot$

Globular cluster M54



Globular cluster M2

Unit of length

What do you think?

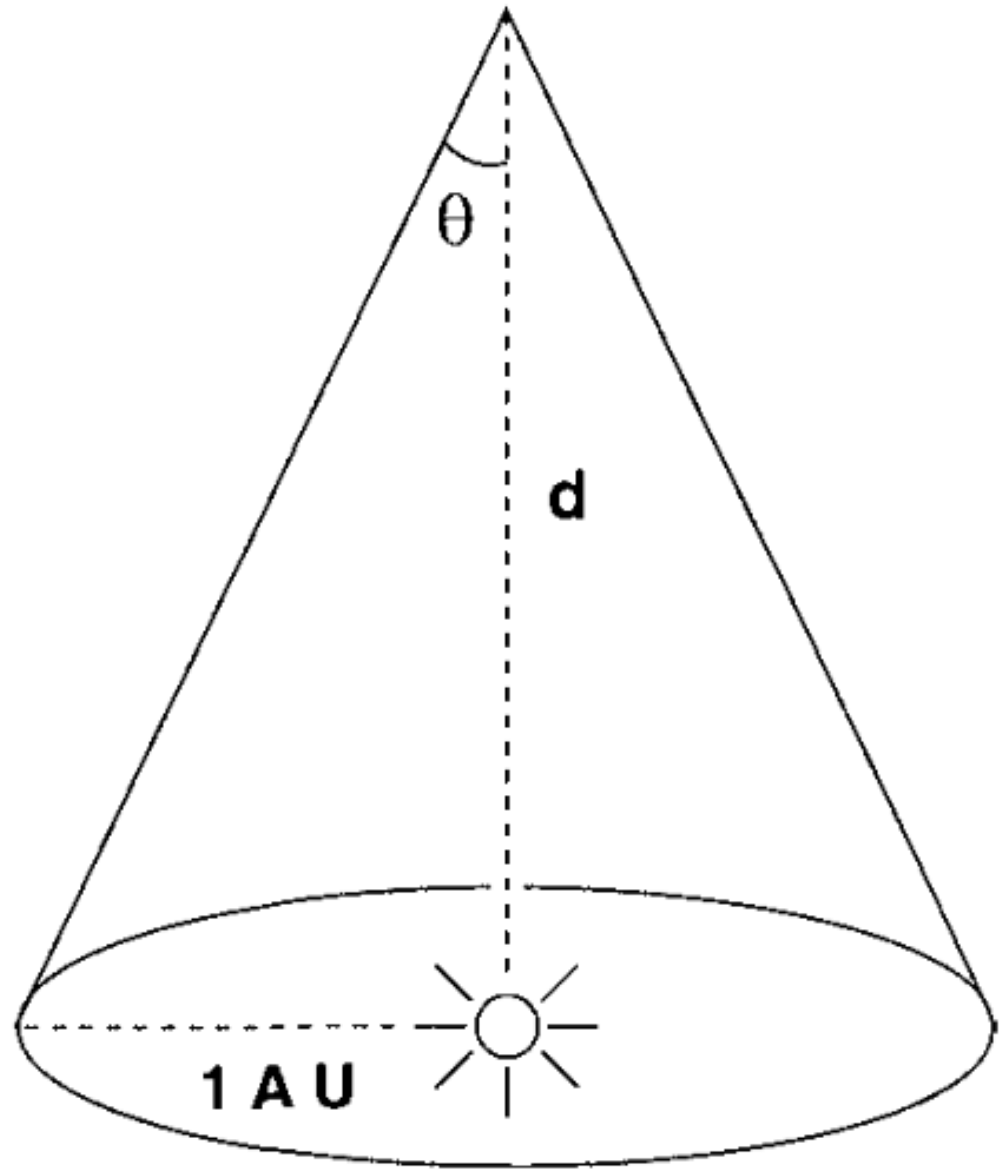
Unit of length

The average distance of the Earth from the Sun is called the ***Astronomical Unit*** (AU). Its value is:
AU = 1.50×10^{11} m.

As the Earth goes around the Sun, the nearby stars seem to change their positions very slightly with respect to the faraway stars. This phenomenon is known as ***parallax*.**

Let us consider a star on the polar axis of the Earth's orbit at a distance d away, as shown in the figure. The angle θ is half of the angle by which this star appears to shift with the annual motion of the Earth and is defined to be the parallax. It is given by

$$\theta = \frac{1\ \mathrm{AU}}{d}$$



Definition of a parsec (d)

The ***parsec*** **(pc)** is the distance where the star has to be so that its parallax turns out to be 1”. (1” is equal to $\pi/(180 \times 60 \times 60)$ radians)

pc = 3.09×10^{16} m.

Unit of length

It may be noted that 1 pc is equal to 3.26 light years (not used much in astronomy)

For even larger distances, the standard units are **kiloparsec** (10^3 pc, kpc), **megaparsec** (10^6 pc, Mpc) and **gigaparsec** (10^9 pc, Gpc).

Examples:

- The nearest star, Proxima Centauri, is at about a distance of 1.31 pc.
- Our Galaxy and many other galaxies like ours are shaped like disks with thickness of order 100 pc and radius of order 10 kpc. The geometric mean between these two distances, which is 1 kpc, may be taken as a measure of the galactic size.
- The Andromeda Galaxy, one of the nearby bright galaxies, is at a distance of about 0.74 Mpc.
- The distances to very faraway galaxies are of order Gpc

NGC 4565, an edge on spiral galaxy

Unit of time

What do you think?

Unit of time

Astrophysics uses many timescales from the age of the Universe is of the order of a few billion years to the same of pulsars which emit pulses periodically after intervals of fractions of a second.

Astrophysicists use **years** for large time scales and **seconds** for small time scales, the conversion factor being

$\text{yr} = 3.16 \times 10^7$ s.

gigayear (10^9 yr, Gyr) is often used

The stars typically live for millions to billions of years. The **age of the Sun is believed to be about 4.5 Gyr**.

Table 1.1 Approximate conversion factors to be memorized.

$M_\odot$	$\approx$	2×10^{30} kg
pc	$\approx$	3×10^{16} m
yr	$\approx$	3×10^{7}s

Celestial Coordinates

The sky appears as a spherical surface above our heads. We call it the ***celestial sphere***.

These coordinates are defined in such a way that faraway stars which appear immovable with respect to each other have fixed coordinates.

Position can be defined similarly to the latitude and longitude on Earth's surface. There are several astronomical coordinate systems in use.

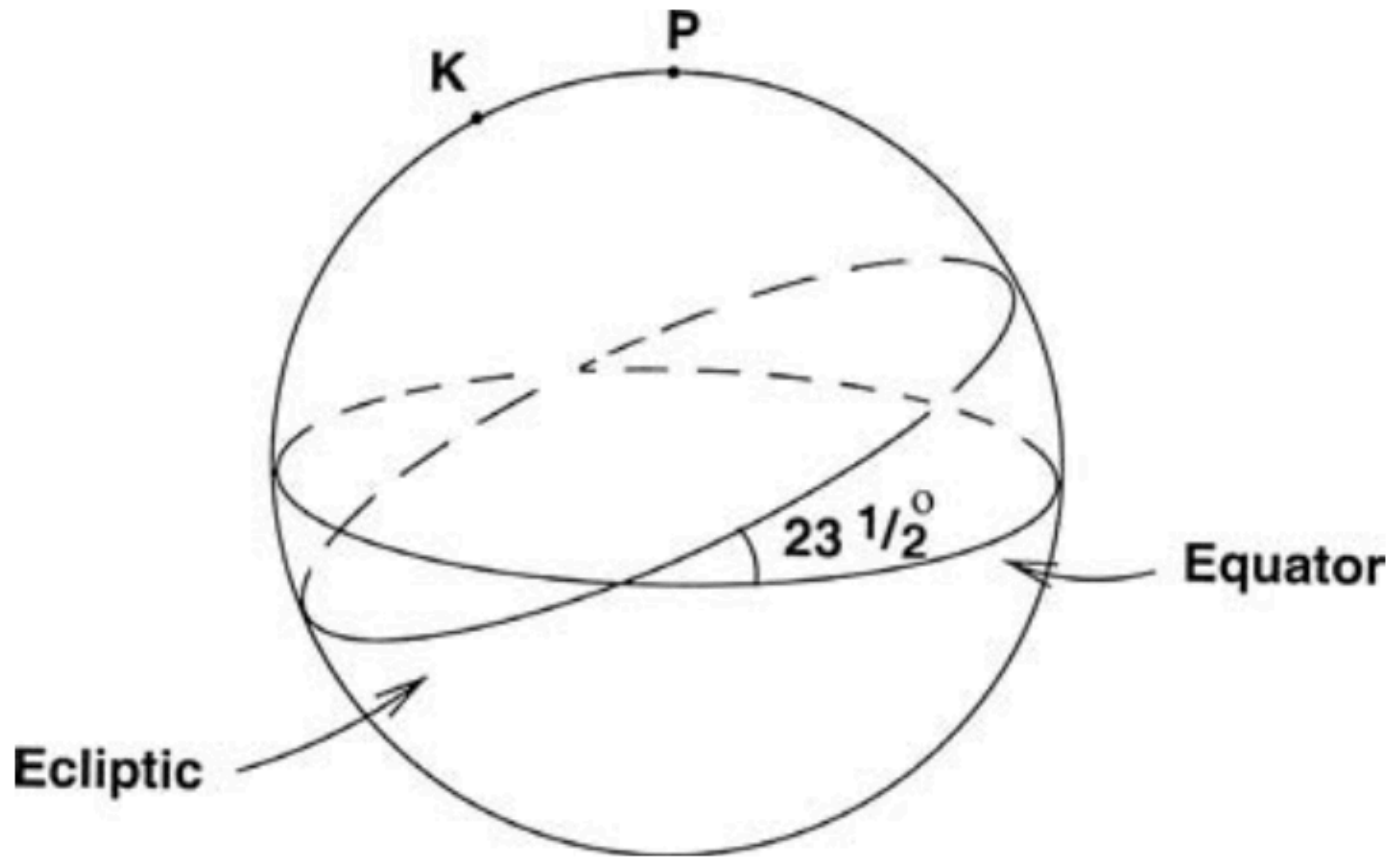
Equatorial coordinate system:

Declination (δ) ~ latitude

Right ascension (R.A.) ~ longitude

The points where the Earth's rotation axis would pierce the celestial sphere are called ***celestial poles***

The great circle on the celestial sphere vertically above the Earth's equator is called the ***celestial equator***

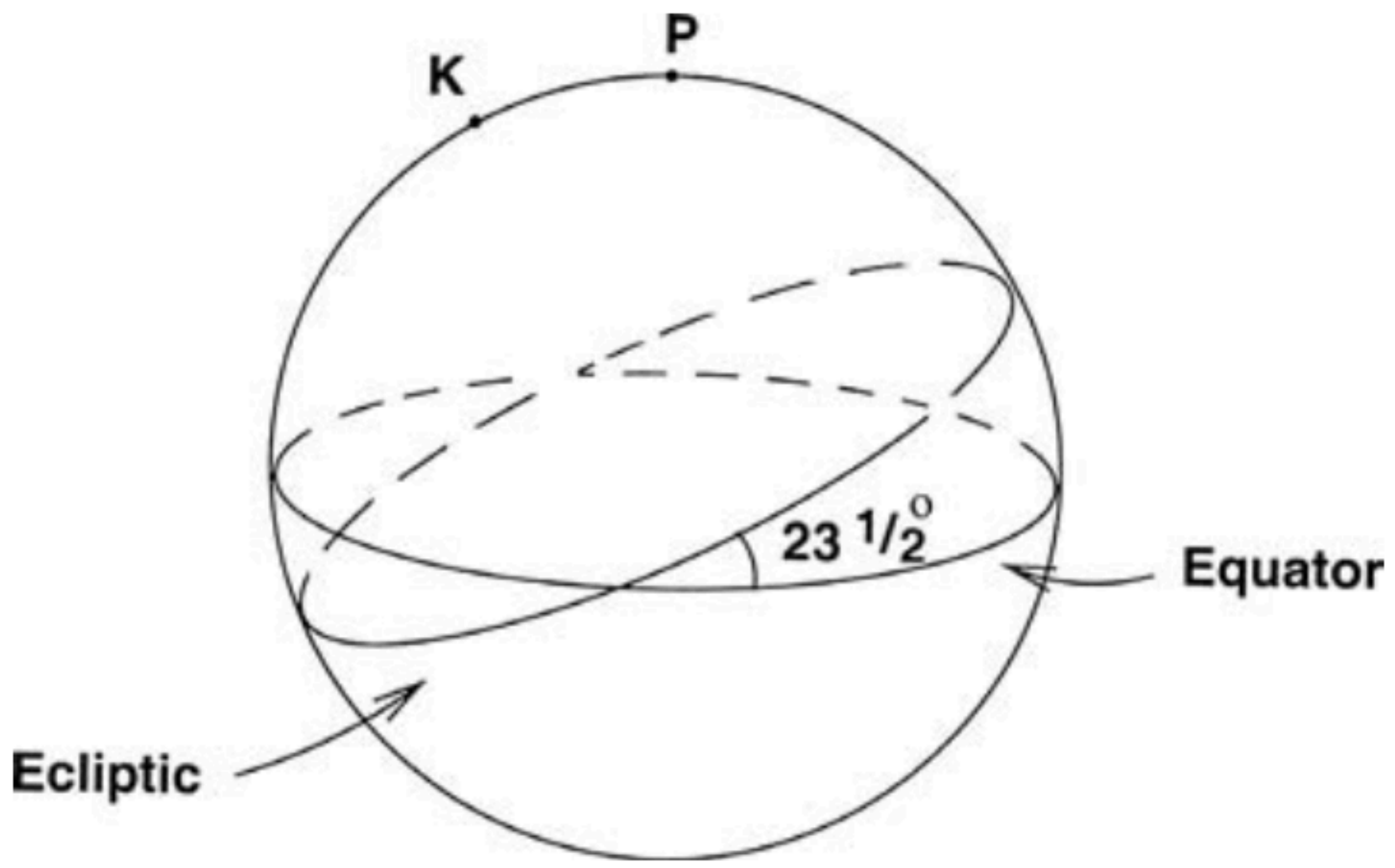


P is the celestial pole and K is the pole of the ecliptic.

Celestial Coordinates

Just as the zero of longitude is fixed by taking the longitude of Greenwich as zero, we need to fix the zero of R.A. for defining it.

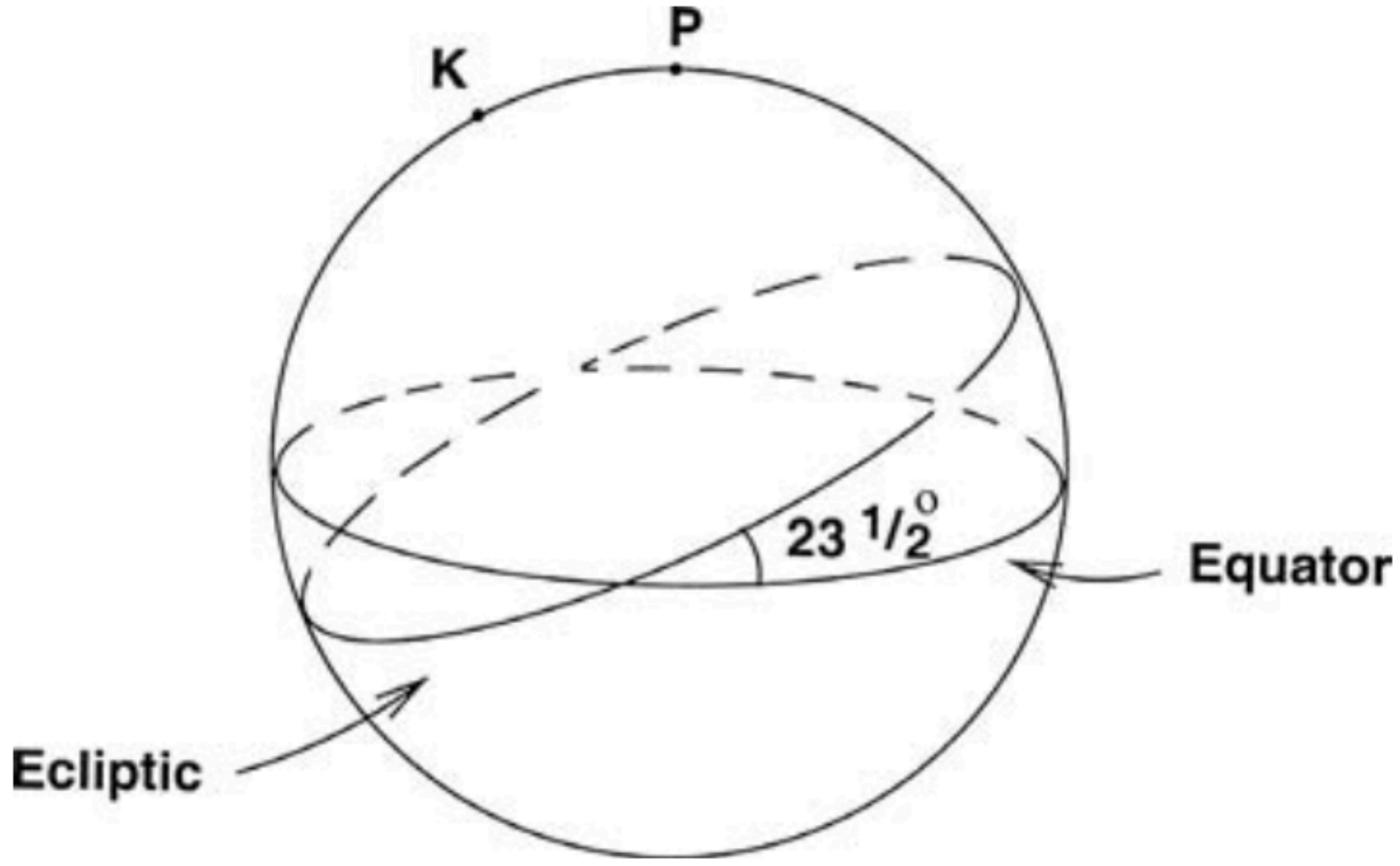
- This is done with the help of a great circle called the ***ecliptic***.
- Since the Earth goes around the Sun in a year, **the Sun's position with respect to the distant stars, as seen by us, keeps changing and traces out a great circle in the sky. The ecliptic is this great circle.**
- Twelve famous constellations (known as the *signs of the zodiac*) appear on the ecliptic. It was noted from almost prehistoric times that the **Sun happens to be in different constellations in different times of the year.**



P is the celestial pole and K is the pole of the ecliptic.

Celestial Coordinates

- The **celestial equator and the ecliptic are inclined at an angle** of about 23.5 deg and **intersect at two points**.
- **One of these points, lying in the constellation Aries, is taken as the zero of R.A.** When the Sun is at this point, we have the vernal equinox (spring equinox).
- It is a standard convention to express the R.A. in hours rather than in degrees.
- The celestial sphere rotates around the polar axis by 15 deg in one hour. Hence **one hour of R.A. corresponds to 15 deg**.



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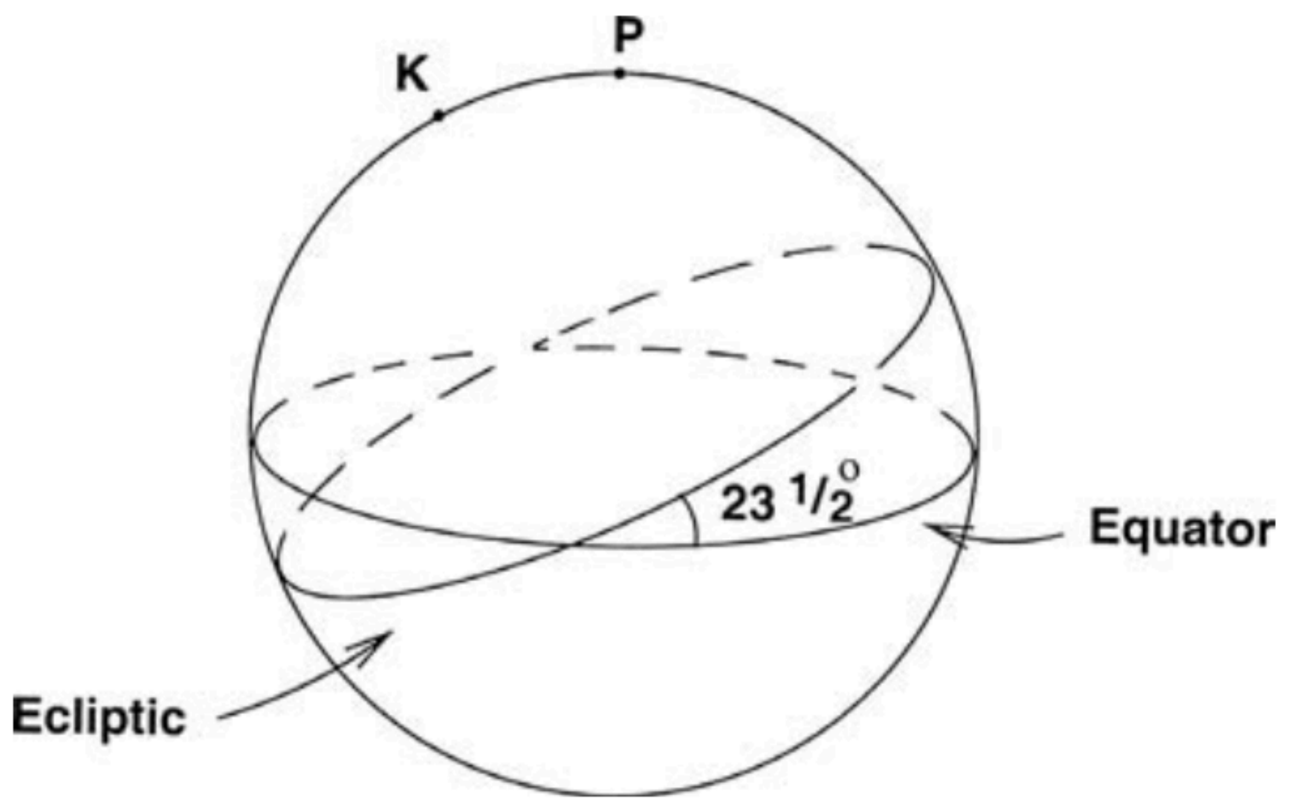
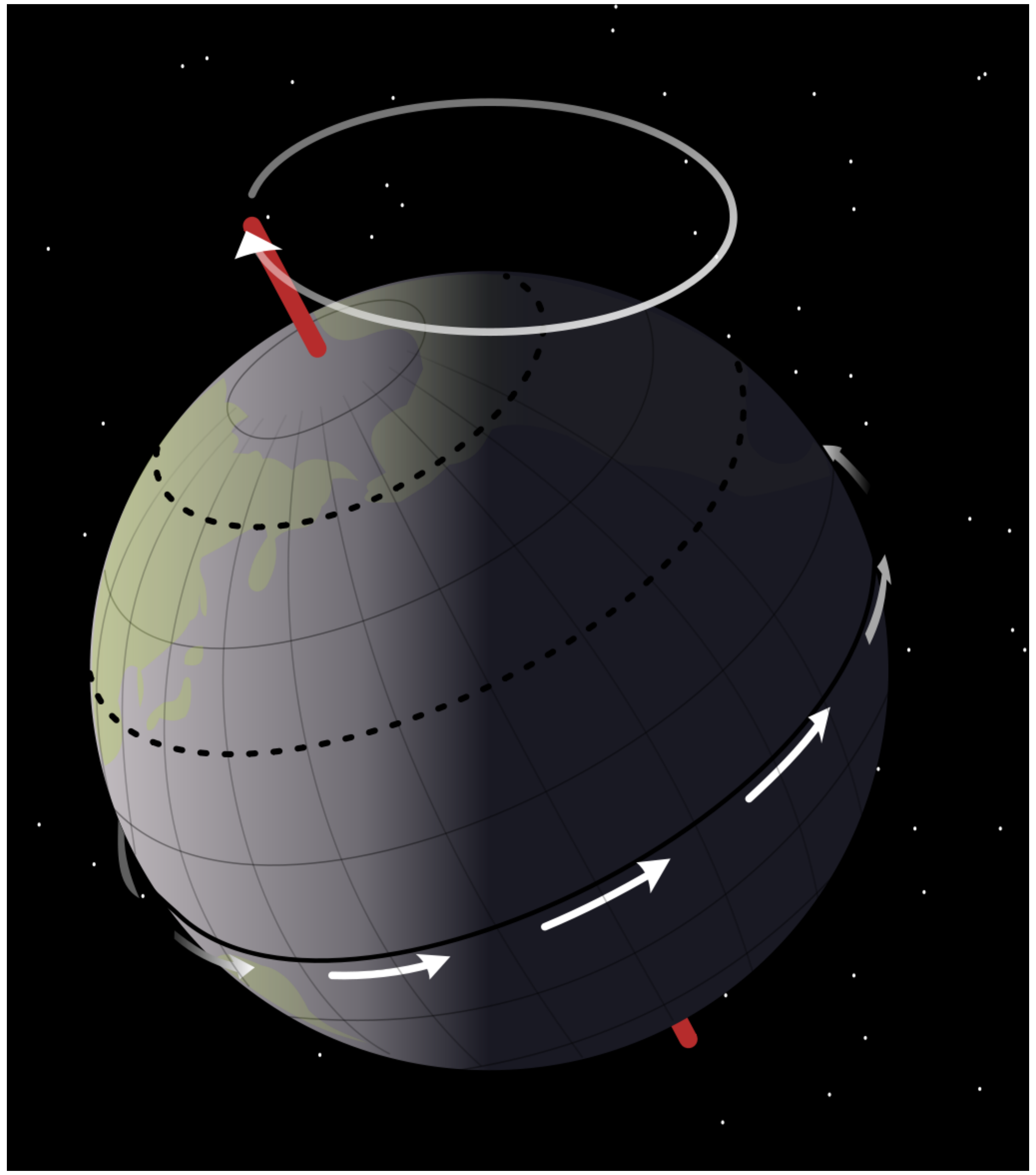
Celestial Coordinates



The declination and R.A. are basically defined with respect to the rotation axis of the Earth, which fixes the celestial poles and equator.

One problematic aspect of introducing coordinates in this way is that the **Earth's rotation axis is not fixed, but precesses around an axis perpendicular to the plane of the Earth's orbit around the Sun**. This means that the celestial pole (P) traces out an approximate circle in the celestial sphere slowly in about 25,800 years, around the pole *K* of the ecliptic.

This phenomenon is called ***precession*** and was discovered by Hipparchus (second century BC) by comparing his observations with the observations made by earlier astronomers about 150 years previously.



https://en.wikipedia.org/wiki/Axial_precession

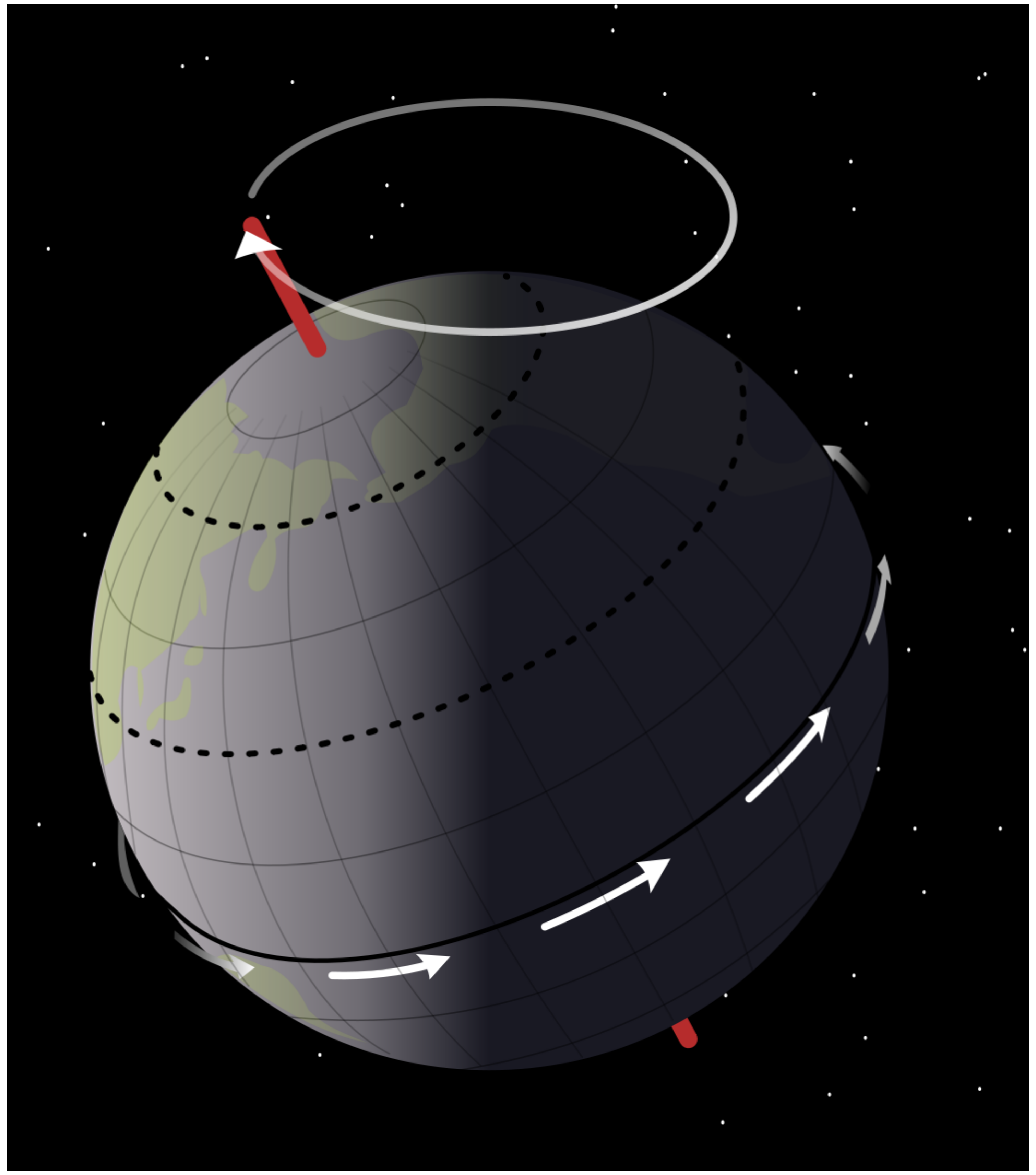
Celestial Coordinates

The precession is caused by the gravitational torque due to the Sun acting on the Earth and can be explained from the dynamics of rigid bodies.

Due to precession, the positions of the celestial poles and the celestial equator keep changing slowly with respect to fixed stars. Hence, **if the declination and the R.A. of an astronomical object at a time are defined with respect to the poles and the equator at that time, then certainly the values of these coordinates will keep changing with time.**

The current **convention** is to use the coordinates defined with respect to the positions of the poles and the equator in the year 2000 (J2000).

This equatorial coordinate system is very practical for telescopes for observing.



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Other coordinate systems

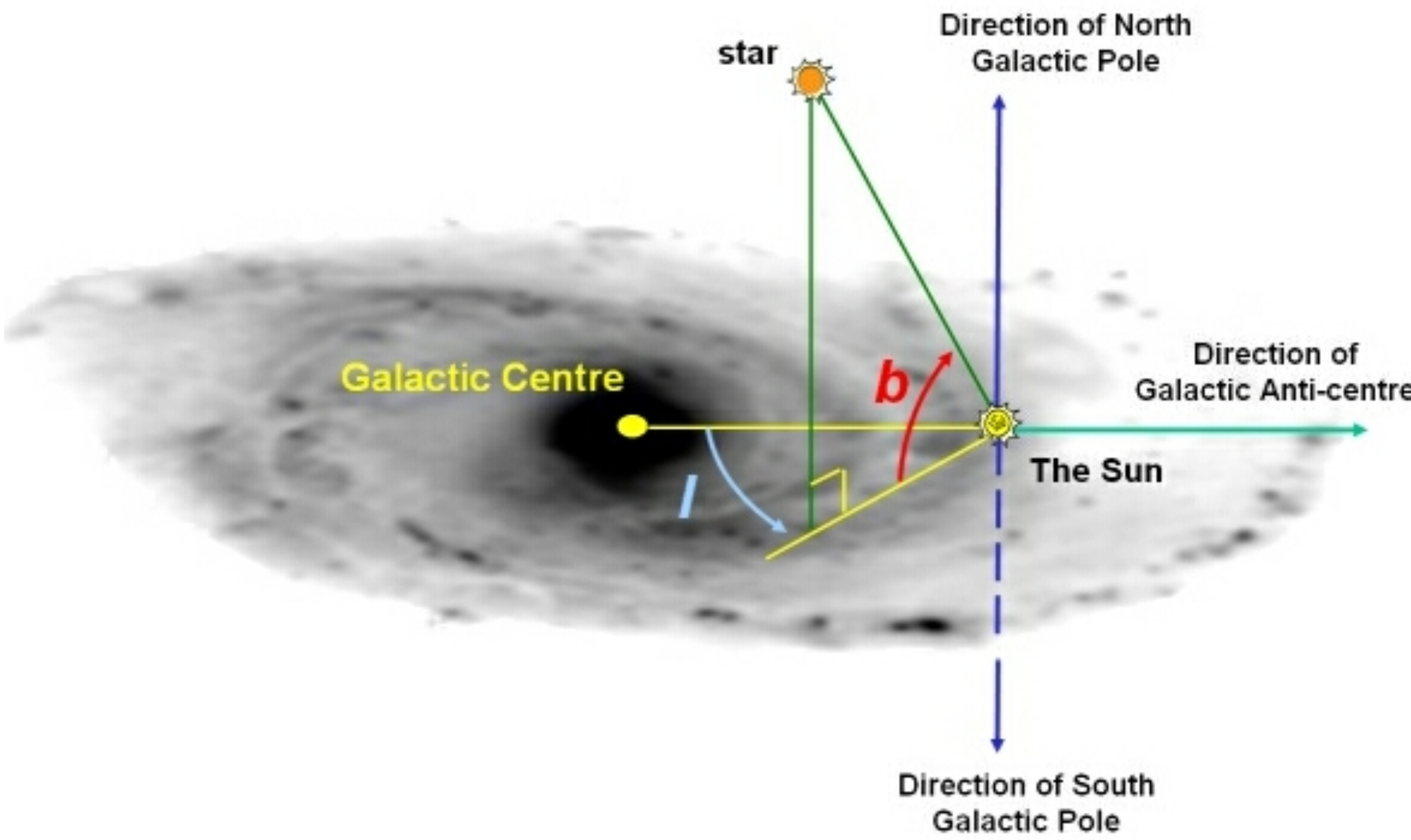
Which other coordinate systems are used?

Other coordinate systems

- There is another coordinate system, called ***galactic coordinates*****,** widely used in galactic studies. In this system, the plane of our Galaxy is taken as the equator and the direction of the galactic centre as seen by us (in the constellation Sagittarius) is used to define the zero of longitude. (Coordinates: l, b)

- **Galactic longitude (l)**: measures the angular distance of an object eastward along the galactic equator from the Galactic Center, measured in degrees.
- **Galactic latitude (b)**: measures the angle of an object northward of the galactic equator (or midplane) as viewed from Earth, measured in degrees

- The **supergalactic coordinate system** corresponds to a fundamental plane that contains a higher than average number of local galaxies in the sky as seen from Earth.



https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System

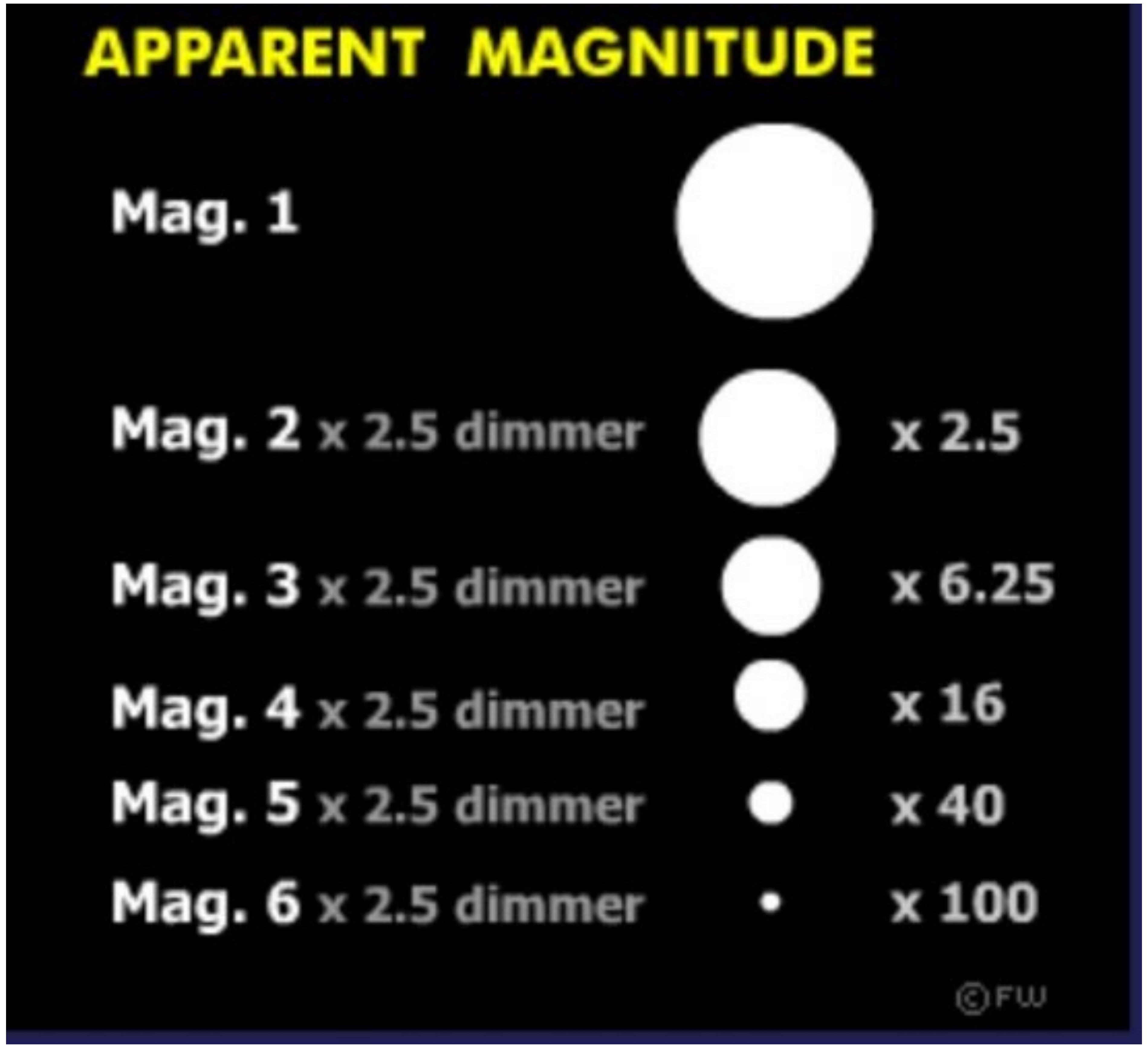
What do we use to quantify the brightness of objects?

The magnitude scale

The magnitude scale for describing apparent brightnesses of celestial objects is a **logarithmic scale**, because the human eye is more sensitive to a geometric progression of intensity rather than an arithmetic progression.

On the basis of naked eye observations, the Greek astronomer Hipparchus (second century BC) classified all the stars into **six classes** according to their apparent brightnesses.

A quantitative basis of the magnitude scale was given by Pogson (1856) by noting that the faintest stars visible to the naked eye are about 100 times fainter compared to the brightest stars. Since the brightest and faintest stars differ by five magnitude classes, **stars in two successive classes should differ in apparent brightness by a factor $(100)^{1/5}$.**



https://earthsky.org/astronomy-essentials/what-is-stellar-magnitude/

The magnitude scale

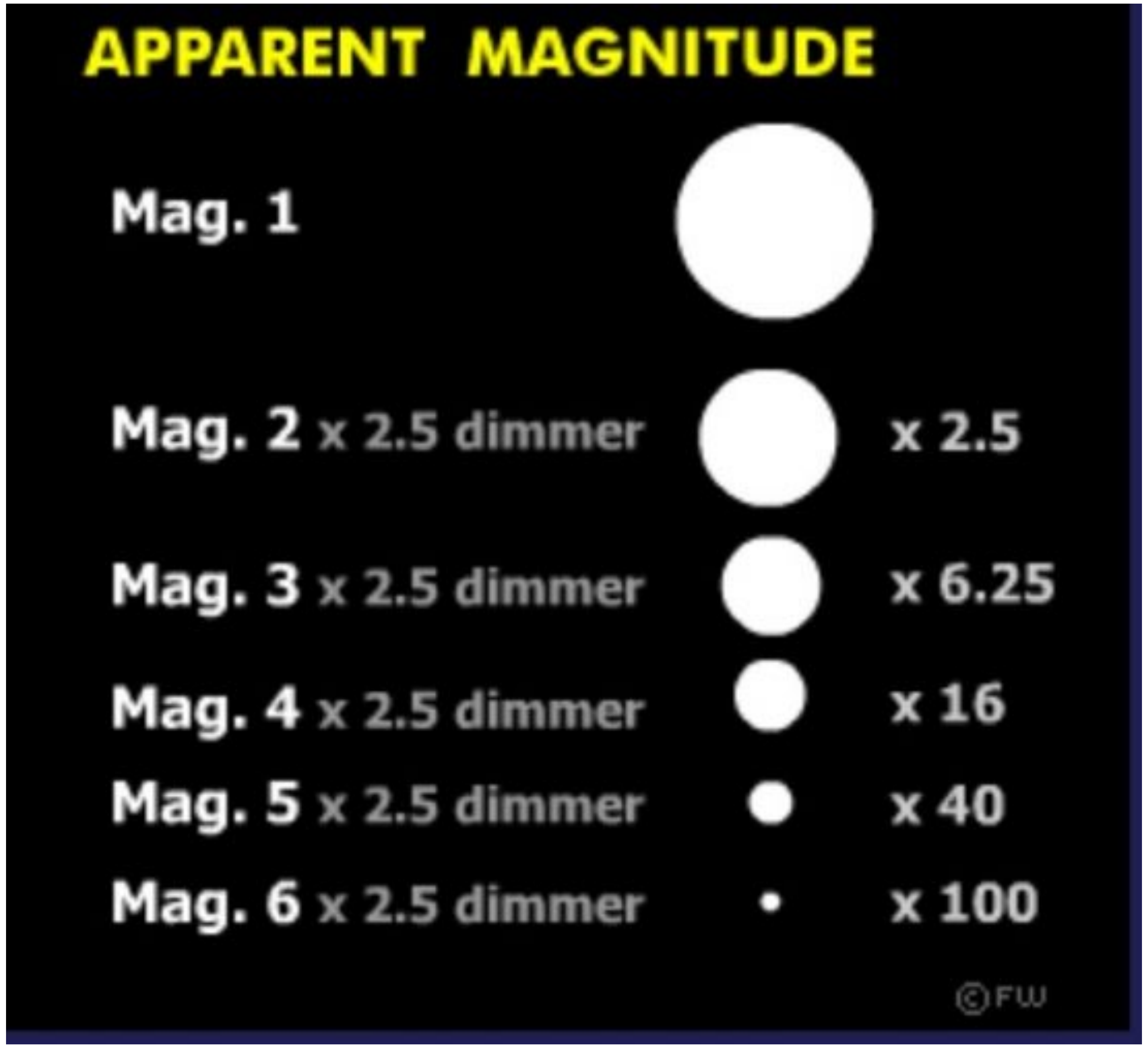
Suppose two stars have apparent brightnesses l_1 and l_2, whereas their magnitude classes are m_1 and m_2. It is clear that

$$\frac{l_2}{l_1} = (100)^{\frac{1}{5}(m_1 - m_2)}.$$

$$\boxed{m_1 - m_2 = 2.5 \log_{10} \frac{l_2}{l_1}.}$$

the definition of ***apparent magnitude* denoted m**, which is a **measure of the apparent brightness of an object in the sky.**

Note that the **magnitude scale is defined in such a fashion that a fainter object has a higher value of magnitude.**



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The magnitude scale

Since a star emits electromagnetic radiation in different wavelengths: what is the wavelength range over which we consider to measure its apparent brightness quantitatively?

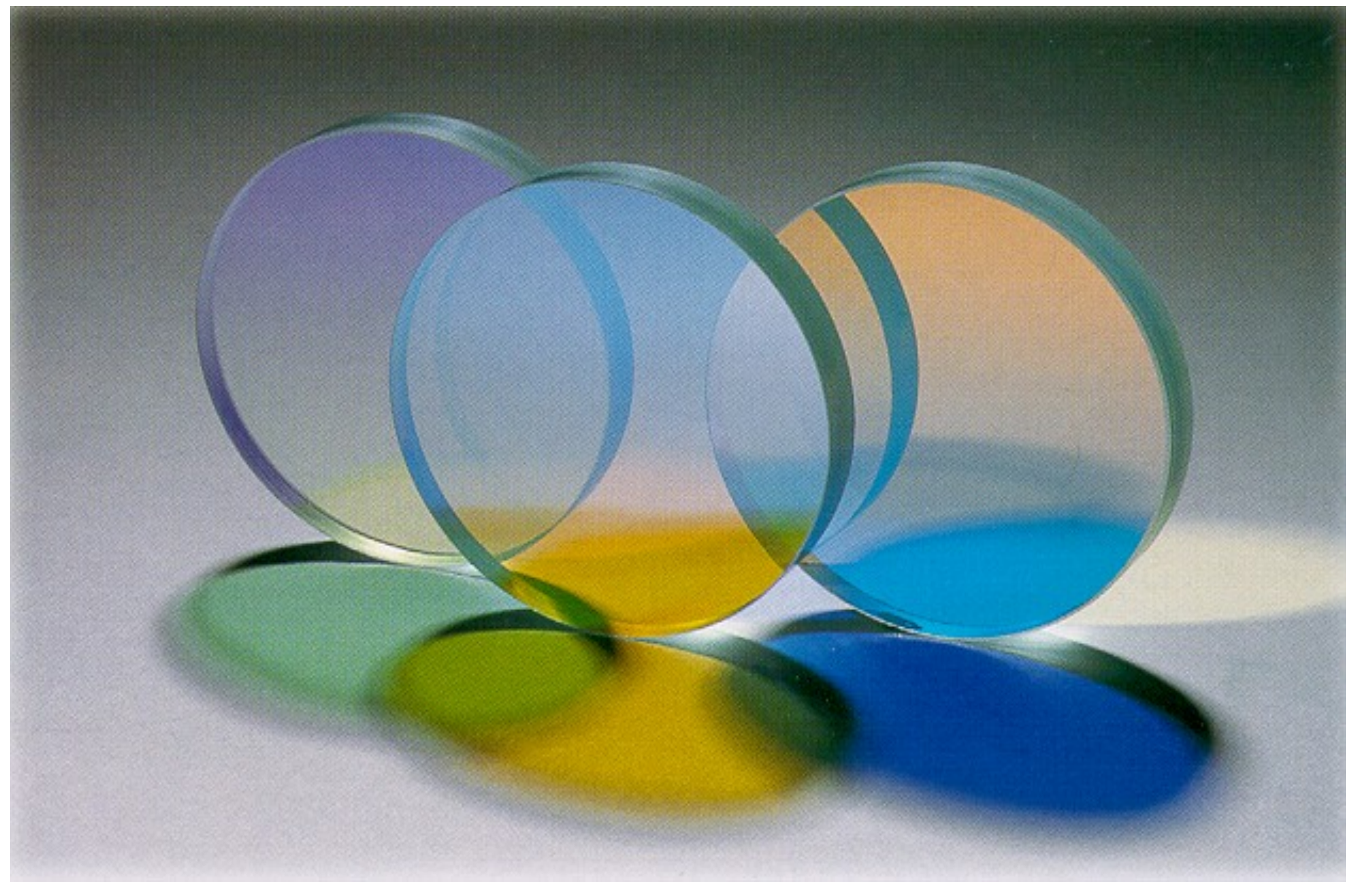
If we use apparent brightnesses based on the **radiation in all wavelengths, then the magnitude defined from it is called the *bolometric magnitude***. But this is not very practical to measure in practice.

A much more convenient system, called the **Ultraviolet–Blue–Visual system or the UBV system**, was introduced by Johnson and Morgan (1953) and is now universally used

- In this system, the **light from a star is made to pass through filters which allow only light in narrow wavelength bands around the three wavelengths**: 3650Å, 4400Å and 5500Å. From the measurements of the intensity of light that has passed through these filters, **we get magnitudes in ultraviolet, blue and visual, usually denoted by U, B and V** .
- Angstrom: 1Å = 10^{-10} m

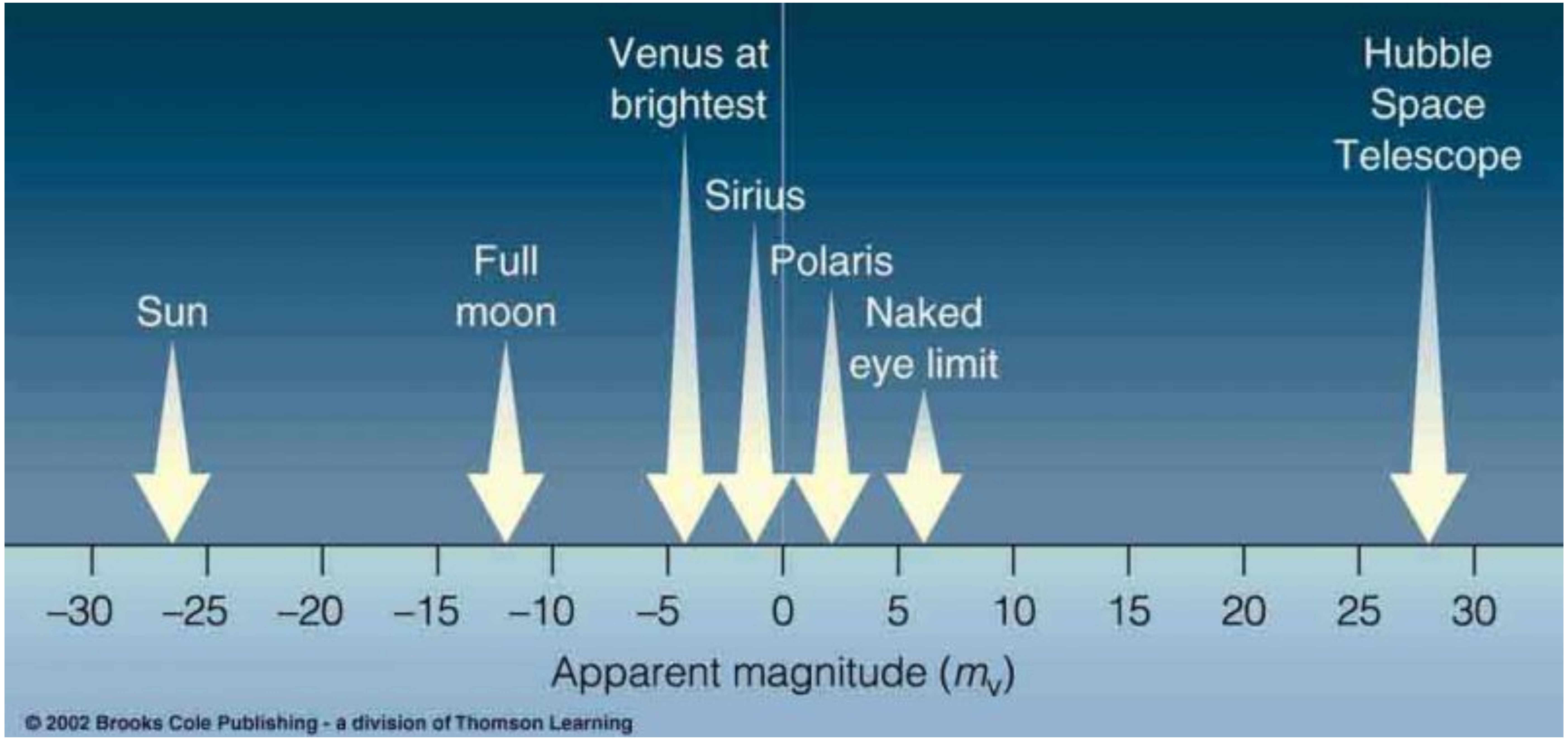
Typical examples of V magnitudes are:

- the Sun, $V = -26.74$;
- Sirius, the brightest star, $V = -1.45$;
- faintest stars measured, $V \approx 27$.



Ultraviolet filters for protecting a camera from ultraviolet radiation

The magnitude scale



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The magnitude scale

Suppose we consider a reddish star.

- It will have less brightness in B band compared to V band. Hence its B magnitude should have a larger numerical value than its V magnitude.
- So we can use **(B – V) as an indication of a star's colour.**
- The **more reddish a star, the larger will be the value of (B – V)**.

The **absolute magnitude** of a celestial object is defined as the magnitude it would have **if it were placed at a distance of 10 pc**. This is often used to denote the intrinsic brightness of objects.

The **relation between relative magnitude m and absolute magnitude M** can easily be found. If the object is at a distance d pc, then $(10/d)^2$ is the ratio of its apparent brightness and the brightness it would have if it were at a distance of 10 pc.

$$m - M = 2.5 \log_{10} \frac{d^2}{10^2} \quad \longrightarrow \quad \boxed{m - M = 5 \log_{10} \frac{d}{10}.}$$

Calculate the absolute magnitude

A star at a distance of 4 pc has an apparent magnitude 2. What is its absolute magnitude?

Given the fact that the Sun has a luminosity 3.9×10^{26} W and has an absolute magnitude of about 5, find the luminosity of the star.

$$m - M = 5\log_{10}\frac{d}{10}.$$

$$\frac{l_2}{l_1} = (100)^{\frac{1}{5}(m_1 - m_2)}.$$

Which star is redder

Vega and Deneb are two stars.

If the B-V colour of Vega is 0.0 and the B-V colour of Deneb is 0.09. Which star is redder?