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Galaxy Astrophysics

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Preface

This course provides a comprehensive overview of galaxy astrophysics, structured as follows:

- **Fundamentals** (approximately 10 hours)
 - Stars
- **Phenomenology** (approximately 25 hours)
- **Dynamics of Non-collisional Systems**
 - Elliptical galaxies
 - Galaxy clusters

Reference Textbooks:

- **Introductory**
 - Karttunen et al., “Fundamental Astronomy”
 - Schneider, P. (2015), “Extragalactic Astronomy and Cosmology”
- **Advanced**
 - Binney, J. & Merrifield, M., “Galactic Astronomy”
 - Binney, J. & Tremaine, S., “Galactic Dynamics”

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Introduction

When we observe the sky, we perceive it as a 2D surface, even though celestial objects actually exist in 3D space. To bridge this gap and measure distances in astronomy it is used a set of techniques known as the *distance ladder*. It consists of different methods, where each one relies on a specific physical phenomenon and is calibrated using the preceding method in the ladder. Only recently have precise instruments like ESA's Hipparcos (1989) and Gaia (2013) satellites enabled highly accurate stellar parallax measurements, with Gaia mapping distances to over a billion stars.

1.1 Reference Systems

To describe the position of an object in the sky, we need to define a reference system. For this purpose, astronomers often imagine all celestial objects as lying on a vast, imaginary *celestial sphere*, centered on the observer. Although this model has ancient origins, it remains extremely useful today. Since the celestial sphere is considered to have an infinite radius, we can ignore the small shifts caused by the Earth's rotation and orbit.

1.1.1 The Equatorial System

The equatorial coordinate system is defined by selecting a reference parallel and a reference meridian. The Earth's rotational axis remains nearly constant over time, so the equatorial plane (which is perpendicular to this axis) serves as a stable basis for a coordinate system that does not depend on the observer's location or the time of observation.

The celestial equator is the great circle where the celestial sphere meets the equatorial plane. The axis of this circle points toward the celestial poles. In the northern hemisphere, the north celestial pole is almost exactly aligned with the Earth's rotational axis and lies about one degree from Polaris. The angle between a star and the celestial equator (the equatorial plane) remains unchanged by the Earth's daily rotation. This angle is called the **declination** δ ($-90^\circ < \delta < +90^\circ$). For the second coordinate, we also need a fixed direction that is independent of the Earth's rotation. This direction is defined by the *vernal equinox* (Υ), which is the point on the celestial sphere where the Sun's path (the ecliptic) crosses the celestial equator at the moment of the spring equinox. The second coordinate is then defined as the angle measured eastward along the celestial equator from the vernal equinox. This angle is called the **right ascension** α (or R.A.), with values ranging from 0 to 24 hours.

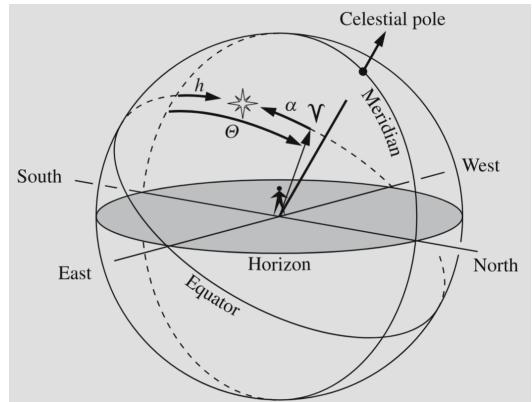


Figure 1.1: The Equatorial System [1]

The *sidereal time*, often denoted by Θ , measures the angle between the local meridian (The great circle on the celestial sphere that passes through both the celestial poles and the zenith of the observer) and the vernal equinox, increasing as the Earth rotates. For any celestial object, there is a simple and important relationship:

$$\Theta = h + \alpha$$

1.1.2 The Azimuthal System or Horizontal System

The azimuthal (or horizontal) system is defined relative to the observer's specific position on Earth. Its reference plane is the local *horizon* (the plane tangent to the Earth at the observer's location). Where this plane meets the celestial sphere forms the visible horizon. The point directly overhead is the *zenith*; the point directly beneath is the *nadir*.

Great circles passing through the zenith are called *verticals*, and each one meets the horizon at a right angle. As the Earth rotates, stars appear to rise in the east, reach their highest point (culminate) when they cross the *meridian* (the vertical circle connecting north, zenith, and south) and set in the west. The intersection points of the meridian with the horizon define the north and south directions.

In this system, one coordinate is the **altitude** (or elevation), a , the angle between the horizon and the object along its vertical circle. Altitude ranges from -90° to $+90^\circ$, and is positive above the horizon.

The second coordinate is the **azimuth**, A : the angle measured along the horizon from a fixed reference direction to the object's vertical circle. The reference is often north or south, and by convention the angle is measured clockwise (see tip below).

Since this system depends on both the observer's position and the time, the coordinates of the same star will be different for different observers and at different moments. For this reason, horizontal coordinates are not used in star catalogues.

💡 Tip: Azimuth direction

There are different conventions for the reference direction and sense of azimuth, so it is always important to verify which one is being used. Here, we measure azimuth clockwise from the south, as is common in astronomy.

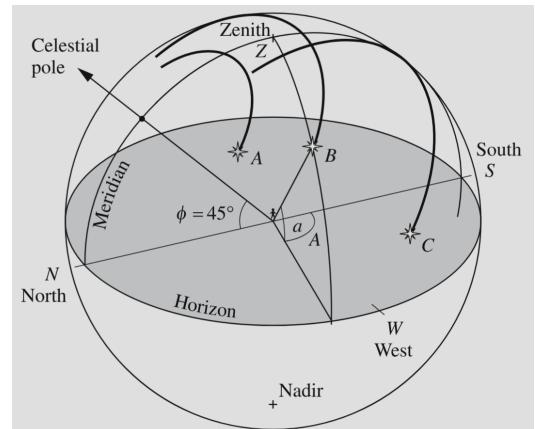


Figure 1.2: The Azimuthal System [1]

1.1.3 The Galactic System

For studies of the Milky Way Galaxy, the most natural reference plane is the plane of the Milky Way itself. Because the Sun lies very close to this plane, it is convenient to place the origin of the galactic coordinate system at the Sun.

The **galactic longitude** l is measured counterclockwise (analogous to right ascension) along the galactic plane, starting from the direction of the center of the Milky Way, which lies in the constellation Sagittarius. The **galactic latitude** b is measured from the galactic plane: it is positive towards the north galactic pole and negative towards the south.

⌚ Observation: Coordinate precision

If right ascension is given in hours, we need to provide one additional decimal place in seconds compared to the declination, to preserve equivalent angular accuracy. For example:

$$03^{\text{h}}\ 42^{\text{m}}\ 35.63^{\text{s}} \quad +42^\circ\ 32' 35.4''$$

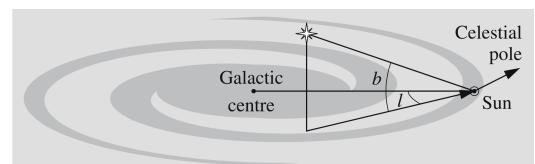


Figure 1.3: The Galactic System [1]

1.1.4 Coordinate perturbations

Even for a star fixed relative to the Sun, its observed coordinates may shift due to various perturbing effects. While altitude and azimuth change with Earth's rotation, even right ascension and declination are subject to small variations over time.

Precession and nutation

The Earth's rotational axis is not fixed in space; instead, it traces out a slow circular motion around the north pole of the ecliptic. This slow motion, known as **precession**, causes the celestial poles and equator to shift over time, completing a full cycle roughly every 25,800 years. As a result, the coordinates of stars change slowly: star catalogues must specify the equinox, or reference epoch, to which their coordinates refer.

Superimposed upon precession is a smaller, periodic oscillation of the axis called **nutation**. It is primarily caused by the gravitational pull of the Moon (and, to a lesser extent, the Sun) on Earth's equatorial bulge. This results in a short-term "nodding" motion, with the main period being about 18.6 years, as the Moon's orbital plane precesses.

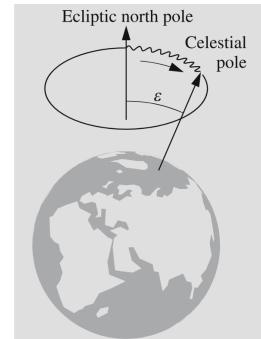


Figure 1.4:
Precession and
nutation

Mathematically, the precessional motion can be described using the concept of torque:

$$\vec{\tau} = \frac{d\vec{L}}{dt}$$

where \vec{L} is the angular momentum of the Earth, and $\vec{\tau}$ is the torque exerted mainly by the gravitational attraction of the Moon and Sun on the equatorial bulge. The change in angular momentum, $\Delta\vec{L}$, is perpendicular to \vec{L} , leading to a precession of the axis direction (rather than a change in tilt angle):

$$\Delta\vec{L} \perp \vec{L} \quad \text{and} \quad \vec{\tau} \perp \vec{L}$$

Both precession and nutation must be taken into account for precise astronomical coordinate systems, since they cause the celestial coordinate grid to shift over time.

Observation: The vernal equinox point

The vernal equinox point (Υ) is not fixed in space. Due to the precession of Earth's axis, it gradually shifts westward along the ecliptic by approximately $50.25''$ (arcseconds) per year. This slow drift means that the celestial coordinate system itself must be periodically updated to a reference epoch in star catalogs and astronomical calculations.

Aberration

Since the Earth is moving, the direction to a star appears to be shifted by a small angle due to the Earth's velocity. This effect is called **aberration**.

We can distinguish two types of aberration:

- **Annual aberration** is caused by the Earth's orbital motion around the Sun. This effect leads to a maximum apparent displacement of about $20.5''$ (arcseconds) in the direction of Earth's motion.
- **Diurnal (daily) aberration** is caused by the Earth's rotation about its axis. This produces a much smaller maximum displacement, about $0.32''$.

This phenomenon is usually already taken into account in the coordinates of the stars, so it is not necessary to correct for it.

Atmospheric refraction

Since light is refracted by the atmosphere, the direction of an object differs from the true direction by an amount depending on the atmospheric conditions along the line of sight.

If the object is not too far from the zenith, the atmosphere between the object and the observer can be approximated by a stack of parallel layers, each of which has a certain index of refraction n_i .

The zenith distance z of the object and the observed distance z_{obs} are related by the following equation:

$$n_0 \cdot \sin z_{obs} = n_1 \cdot \sin z_1 = \dots = 1 \cdot \sin z$$

where n_i are the indices of refraction of the different layers.

Let $R = z - z_{obs}$ be the *refraction angle*. It holds that:

$$\begin{aligned} n_0 \cdot \sin z_{obs} &= \sin z = \sin(z_{obs} + R) \\ &= \frac{\sin R}{\sim R} \cos z_{obs} + \frac{\cos R}{\sim 1} \sin z_{obs} \\ (\text{for small } R) \quad &\approx \sin z_{obs} + R \cos z_{obs} \end{aligned}$$

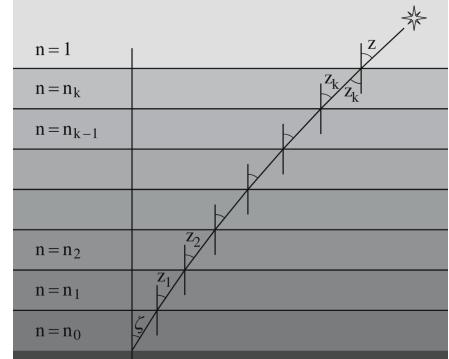


Figure 1.5: Refraction [1]

In addition to refraction, Earth's atmosphere also absorbs electromagnetic radiation, significantly impacting astronomical observations across various wavelengths:

- The **Troposphere** (0 – 10km), the lowest atmospheric layer, is composed primarily of H_2O , CO_2 , CO , N_2 , and O_2 . These molecules here strongly absorb light in the **infrared (IR)** region.
- The **Stratosphere** (10 – 80km) contains a significant concentration of ozone (O_3), which efficiently absorbs light in both the **ultraviolet (UV)** and **X-ray** regions.
- The **Ionosphere** (80 – 500km) is a region rich in ionized particles; it absorbs **radio waves**.

Beyond Earth's atmosphere, the **interstellar medium (ISM)**, composed of gas and dust, also absorbs and scatters electromagnetic radiation, particularly at **X-ray** and **UV** wavelengths.

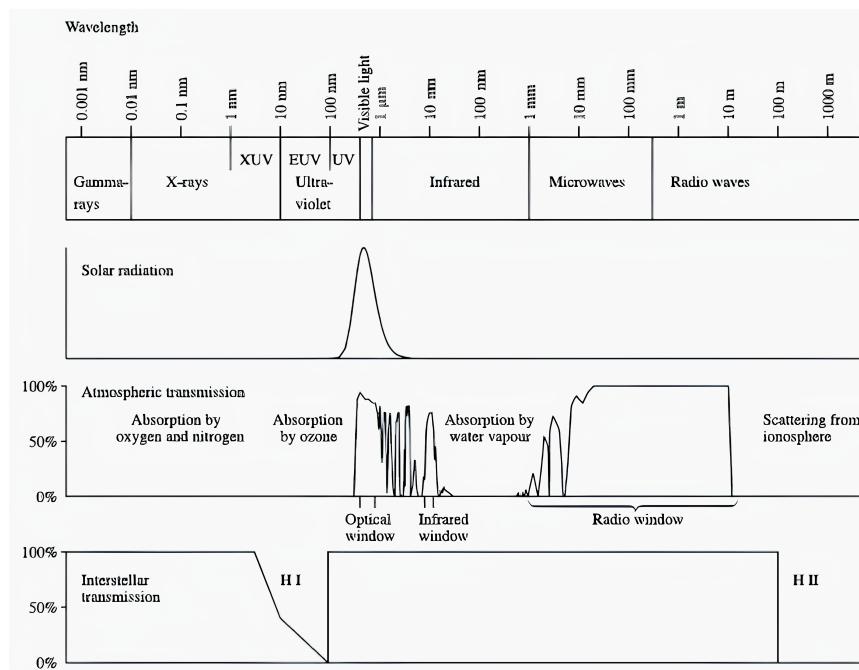


Figure 1.6: Atmospheric and interstellar absorption and transmission at different wavelengths: the top band shows the electromagnetic spectrum, followed by typical solar radiation at Earth; the third band displays atmospheric transmission with main absorption features (defining optical, infrared, and radio windows), while the bottom highlights interstellar absorption, especially by hydrogen, limiting UV and parts of the radio spectrum.

⌚ Observation: Zone of Avoidance

The **Zone of Avoidance** is the region near the Galactic plane ($|\alpha| \lesssim 10^\circ$) where absorption by dust and bright stars make optical observations of extragalactic objects very difficult.

Parallax

If we observe an object from different points, we see it in different directions. The difference of the observed directions is called the **parallax**. The parallax effect highly depends on the distance of the object. The closer the object, the greater the parallax.

Since the Earth is moving, if an observer observes a star after an interval of time, he will be looking at the object from a different angle. We can distinguish two kinds of parallax:

- **Diurnal (daily) parallax** is due to the change of direction due to the daily rotation of the Earth. The diurnal parallax also depends on the latitude of the observer; if the position is not specified, it is assumed to be at the equator.
- **Annual parallax** is due to the Earth's orbital motion around the Sun. The annual parallax is the maximum parallax effect and it is used to measure the distance of the stars.



Figure 1.7: The parallax π is the angle subtended by the Earth's equatorial radius as seen from the object [1]

⚠ Warning: Parallax correction

Usually, parallax correction is not taken into account in the coordinates of the star catalogues.

Over time, "parallax" and "distance" have practically become synonymous in astronomy, especially in the context of photometric parallax. In fact, parallax serves as the foundation for one of the most widely used units for astronomical distances: the parsec.

A **parsec** (pc) is defined as the distance at which an astronomical object would exhibit a parallax angle of $1''$ (one arcsecond), when measured from two points separated by 1 astronomical unit, that is, from opposite sides of Earth's orbit around the Sun six months apart.

Numerically, one parsec is approximately 3.26 light-years, or about 3.086×10^{16} meters.

Over time, advancements in astronomical instrumentation have enabled increasingly precise measurements of stellar parallax, allowing us to probe greater distances:

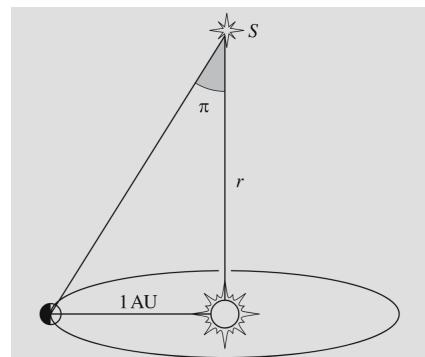


Figure 1.8: Parallax π of a star S is the angle subtended by the radius of the orbit of the Earth [1]

Method/Instrument	Parallax Precision	Distance Limit
From Earth	$\pi \approx 0.01''$	up to ~ 30 pc
Hipparcos satellite	$\pi \approx 0.001''$	up to ~ 1000 pc
Gaia mission	$\pi \approx 2 \cdot 10^{-4}''$	up to ~ 5000 pc (5 kpc)

Observation: *Parallax measurement*

The objects with the largest measured parallaxes are some of the stars nearest to the Sun. Some notable examples include:

- In 1838, Bessel measured the parallax of 61 Cygni: $\pi = 0.29''$
- Proxima Centauri, the closest star to the Sun: $\pi = 0.75''$

Bibliography

- [1] Hannu Karttunen et al. *Fundamental astronomy*. English. 5th ed. United States: Springer, 2007.