Summer Project

SINGULARITY MOSAIC

Midterm Report

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Contents

1 History of Astronomy

1.1 The Ancient Greeks

The astronomy of the ancient Greeks was closely linked to mathematics. Greek astronomers sought to create geometrical models that could imitate the appearance of celestial motions.

1.1.1 Pythagoras (570–495 BCE)

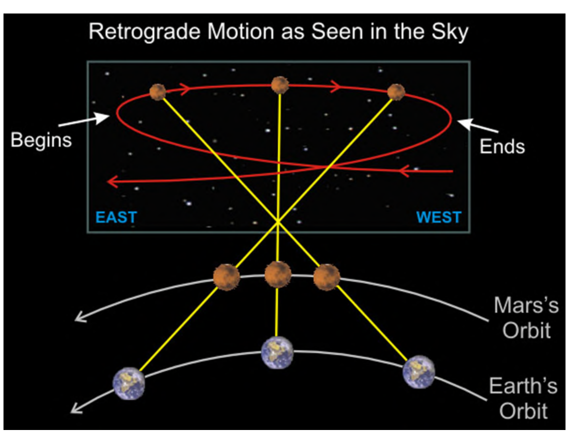
Pythagoras placed astronomy as one of the four mathematical arts, the others being arithmetic, geometry, and music. By his time, the five planets visible to the naked eye—Mercury, Venus, Mars, Jupiter, and Saturn—had long been identified. Pythagoras was among the first to propose that the Earth was round, a theory later proved around 330 BCE by Aristotle. However, many people continued to believe the Earth was flat until the mid-1600s CE.

1.1.2 Aristotle's Theories

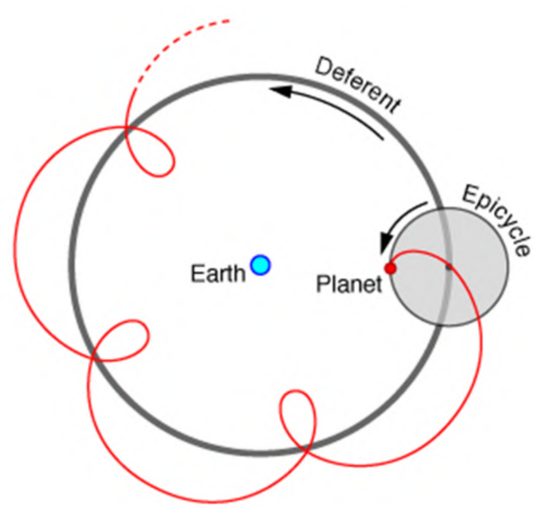
- The Earth was at the center, with the Sun, Moon, stars, and planets orbiting on separate spheres encasing each other and spinning at different rates.
- Their motion was caused by a supernatural being.
- Earth was a sphere (evidenced by the shadow on the moon during an eclipse) and non-moving (since we could not feel its motion and falling objects would not drop straight down).
- Geocentric universe: Earth-centered model of the Universe.

1.2 Retrograde Motion

Retrograde motion refers to the apparent backward movement of a celestial body (like a planet) against the background of distant stars, as observed from Earth. This "backwards" movement is an illusion caused by Earth's own orbital motion around the Sun.



(a) Retrograde Motion



(b) Epicycle Model

Comparison of Retrograde Motion and the Epicycle Model

As Earth orbits the Sun, its perspective on other planets changes. When Earth overtakes a slower-moving outer planet, the outer planet appears to move backward. For example, Mars, being an outer planet, moves more slowly than Earth in its orbit. When Earth overtakes Mars, Mars appears to move backward in the sky during its retrograde period.

1.3 Different Theories

1.3.1 Aristotle's Ideas

- Heavy objects fall faster than light objects.
- Objects have inertia—all objects prefer to be at rest.
- The heavens are perfect and immutable.
- All heavenly objects travel about the Earth at a constant speed in a perfect circle.

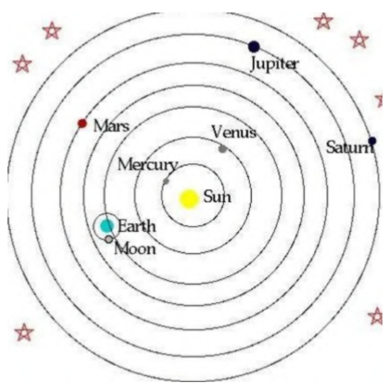
To explain retrograde motion: Earth is at the center (stationary), the Sun and Moon orbit the Earth, and planets move at a constant speed around epicycles. Epicycles orbit around Earth at a constant speed in a circle called a deferent. The combination of orbital and epicyclic motion creates retrograde motion.

1.3.2 Ptolemy (90–168 CE)

Ptolemy proposed a more complicated geocentric model, keeping Earth slightly off-center at a point called the eccentric. Epicycles only move at constant speed around the deferent when viewed from the equant.

1.3.3 Copernicus

Copernicus introduced the heliocentric view of the Universe. He completed his book in 1530, but it was published in 1543, the year he died.



The Heliocentric Model

1.3.4 Tycho Brahe (1546–1601 CE)

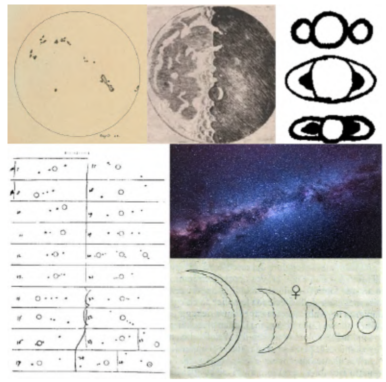
- Detected and corrected several serious errors in standard astronomical tables.
- Discovered a supernova in the constellation Cassiopeia.
- Provided the most complete and accurate observations available without a telescope.
- Did not accept Copernicus's model of the Universe.

1.3.5 Kepler (1571–1630 CE)

Kepler, Tycho's assistant, had full access to Tycho's data. He discovered that orbits are elliptical, not circular, and formulated three laws of planetary motion.

1.3.6 Galileo (1564–1642 CE)

Galileo was a key figure in modern astronomy. He provided crucial observations that proved the Copernican hypothesis. He used a telescope to challenge Aristotle's view of the universe.



Galileo's discoveries using Telescope

Galileo conducted experiments:

- Dropping balls to measure gravity.
- Rolling balls to examine inertia.
- Observing the sky through a telescope.

He observed sunspots, mountains and craters on the Moon, the 'ears' of Saturn, four moons orbiting Jupiter, the stars of the Milky Way, and the phases of Venus. Mercury and Venus both show phases because their radius of revolution is shorter than that of Earth.

1.3.7 Sir Isaac Newton (1642–1727 CE)

Newton built on Galileo's ideas to show that the laws of motion are the same on the heavens and on Earth. He completed the synthesis of astronomy and physics, formulating three new laws of motion based on the existence of gravity.

1.3.8 Edwin Hubble (1889–1953 CE)

Hubble measured the distance to observed celestial objects, discovered that the Milky Way is one of many galaxies, and provided evidence that most distant galaxies are moving away from us.

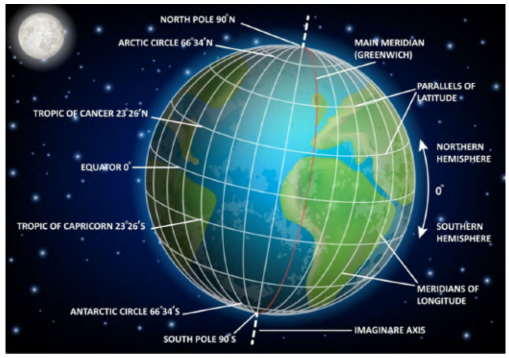
1.3.9 Georges Lemaitre (1894–1966 CE)

Lemaitre suggested the Big Bang theory. Unlike an explosion, the Big Bang was an expansion of space itself—all distances in the universe stretch out at the same rate. Any two galaxies separated by distance X recede from each other at the same speed, while a galaxy at distance $2X$ recedes at twice that speed.

2 Coordinate Systems – A Guide to the Cosmos

2.1 Geometrical Coordinate System

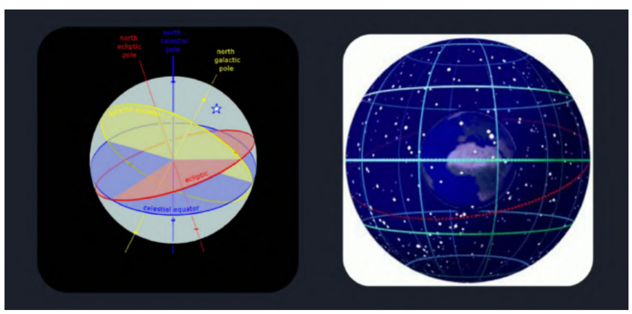
This system allows any location on Earth to be specified by its latitude and longitude. It is essential for mapping, navigation, and understanding Earth's geography.



Earth's latitude and longitude coordinate system.

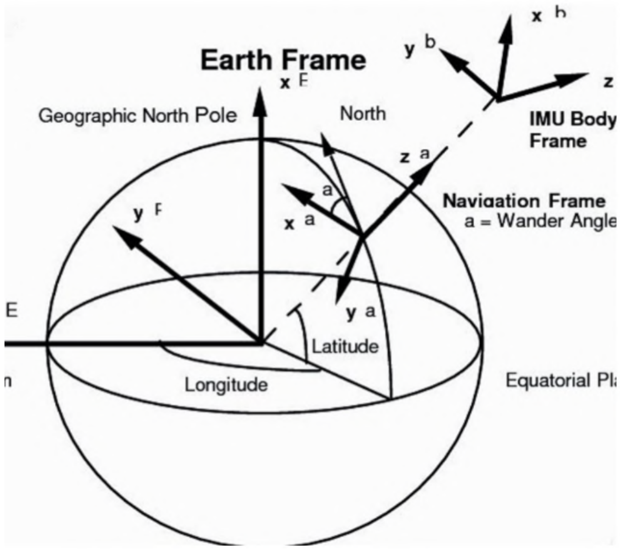
2.2 Astronomical Coordinate System

A framework used to locate celestial objects in the sky, based on the celestial sphere. Key reference planes include the celestial equator, the ecliptic, and the galactic equator. Celestial poles mark the sky's north and south points. Using coordinates like right ascension and declination, astronomers can precisely identify and track objects.



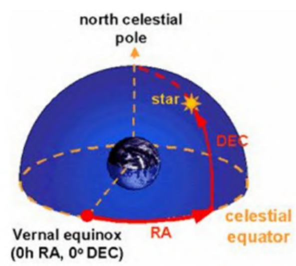
The celestial sphere and astronomical coordinate systems.

2.3 Reference Frames



Earth's latitude and longitude coordinate system.

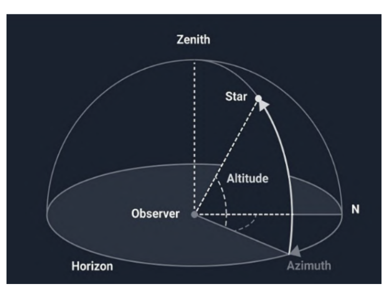
Equatorial Coordinate System:



The celestial sphere and astronomical coordinate systems.

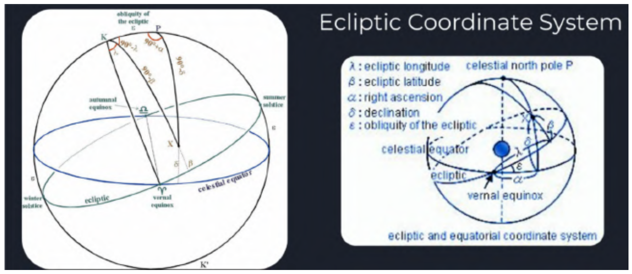
Earth is centered inside the imaginary celestial sphere. The celestial equator is the projection of Earth's equator onto this sphere. The position of a star is specified by Right Ascension (RA) and Declination (DEC). The north celestial pole is directly above Earth's North Pole.

Alt-Az Coordinate System:



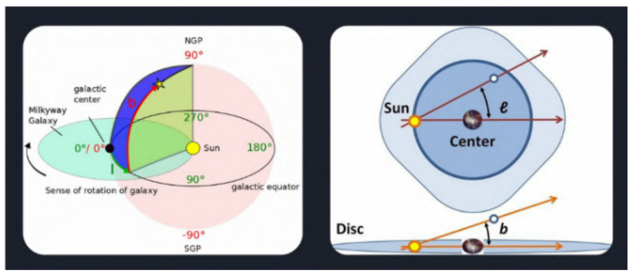
The Horizontal Coordinate System defines a star's position by altitude (height above the horizon, from 0° to 90° at the zenith) and azimuth (compass direction along the horizon, measured clockwise from North). The zenith is the point directly overhead.

Ecliptic Coordinate System:



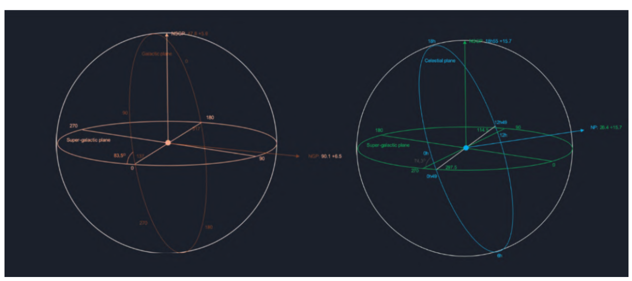
Based on the plane of Earth's orbit around the Sun (the ecliptic). Useful for tracking planets and Solar System objects, with positions given by ecliptic longitude and latitude. Reference points are the vernal equinox and ecliptic poles.

Galactic Coordinate System:



Used to locate objects within the Milky Way, based on the plane of the galaxy. The galactic equator is the reference plane, and the galactic center is the zero point for longitude.

Supergalactic Coordinate System:



A spherical reference frame for mapping galaxy clusters and superclusters. Its equator aligns with the supergalactic plane, tilted about 83.5° relative to the Milky Way's galactic plane.

3 Telescope Handling

1. **Setup the Tripod:** Find level ground, away from direct lights and with a clear view of the sky. Adjust the tripod legs to the desired height, ensuring all legs are fully locked. Gently press down on the tripod to make sure it doesn't shift or wobble. If our tripod has a spreader, we secure it for added stability.

2. **Polar Alignment:** Polar alignment allows us to observe celestial objects for longer periods. In the North, find the North Star (Polaris). It's near the end of the handle of the Little Dipper (*Ursa Minor*). Adjust the mount's polar axis (usually marked on equatorial mounts) so it points directly at Polaris. We use the altitude and azimuth adjustment screws for fine-tuning. Use a polar scope (if available) for more precise alignment.

3. **Balancing the Telescope:** Secure the telescope to the mount. Unlock the RA axis and move the telescope so that it's horizontal. Slide the counterweights along the shaft until the telescope stays balanced when released. Unlock the Dec axis and move the telescope tube forward or backward in its cradle/rings until it balances horizontally. Once balanced, we lock both axes.

4. **Finding Objects:** Celestial objects move across the sky, so you need to accurately point your telescope to their current position. Use star charts or astronomy apps to find the RA and Dec coordinates of your target. Use the slow-motion controls or hand knobs to move the telescope to the desired RA and Dec. Align the finder scope with the main telescope to help center objects.

5. **Focusing:** Start with a low-power eyepiece for a wider field of view. Slowly turn the focus knob until the object comes into sharp focus. For higher magnification, switch to a higher-power eyepiece and refocus as needed.

6. **Fine-Tuning:** Even with polar alignment, you may need to make small adjustments to keep objects centered as the Earth rotates. Gently turn the RA and Dec knobs to keep the object centered in the eyepiece. If your mount has tracking motors, engage them for automatic tracking. Otherwise, adjust manually as needed. For astrophotography or high-magnification viewing, precise tracking is essential. Make small, smooth corrections to maintain your view.

4 Deep Sky Objects

4.1 White Dwarfs

White dwarfs are the final evolutionary stage of low to medium-mass stars—those with masses up to around 8 times that of the Sun. After such a star exhausts the hydrogen and helium in its core through nuclear fusion, it expands into a red giant. During this phase, the outer layers of the star are blown away into space, forming a beautiful cloud of gas known as a planetary nebula. What remains is the hot, dense core: a **white dwarf**.

Despite their name, white dwarfs are not always white—they gradually cool and fade over time, transitioning from white to blue-white, and eventually to reddish tones as they lose heat. At formation, their surface temperatures can be over 100,000 K, but since they no longer undergo fusion, they slowly radiate away their stored thermal energy.

Figure 2: Image of a White Dwarf. (Source: NASA)

4.1.1 Properties

- **Mass**: Typically between 0.6 and 1.4 times the mass of the Sun. The upper limit is known as the **Chandrasekhar limit** ($\sim$1.4 $M_\odot$).
- **Size**: Roughly the size of Earth—about 1% of the Sun's radius ($\sim$7000–10,000 km).
- **Density**: Extremely dense—about 10^6 g/cm^3. A teaspoon of white dwarf material would weigh several tons on Earth.
- **Composition**: Primarily carbon and oxygen nuclei with a sea of degenerate electrons. Some may be helium or oxygen-neon-magnesium based.

4.1.2 Degeneracy Pressure

A white dwarf is prevented from collapsing further by a quantum mechanical force known as **electron degeneracy pressure**. According to the *Pauli Exclusion Principle*, no two electrons can occupy the same quantum state simultaneously. As gravity compresses the star, electrons resist being forced into the same state, providing pressure independent of temperature. This effect allows white dwarfs to remain stable without nuclear fusion.

4.1.3 Cooling and Final Fate

With no energy source, white dwarfs slowly radiate their residual heat into space. Over billions of years, they cool and dim, eventually becoming **black dwarfs**—cold, dark, and inert. However, the universe is not yet old enough for any black dwarfs to exist, so all white dwarfs still glow faintly.

4.1.4 Astrophysical Significance

- White dwarfs serve as **cosmic clocks**: By modeling their cooling rates, astronomers estimate the ages of stellar populations.
- In binary systems, if a white dwarf accretes enough matter from a companion and surpasses the Chandrasekhar limit, it may explode as a **Type Ia supernova**, which is a standard candle in cosmology.
- White dwarfs provide key insights into stellar evolution, quantum mechanics under extreme conditions, and the chemical evolution of galaxies.

4.2 Neutron Stars

Neutron stars are the incredibly dense remnants of massive stars that were originally between 8 and 20 times the mass of the Sun. When such a star reaches the end of its life, it undergoes a catastrophic supernova explosion, ejecting its outer layers into space. The core collapses under its own gravity, compressing protons and electrons into neutrons—a process called **neutronization**. The result is a compact, neutron-rich object known as a **neutron star**.

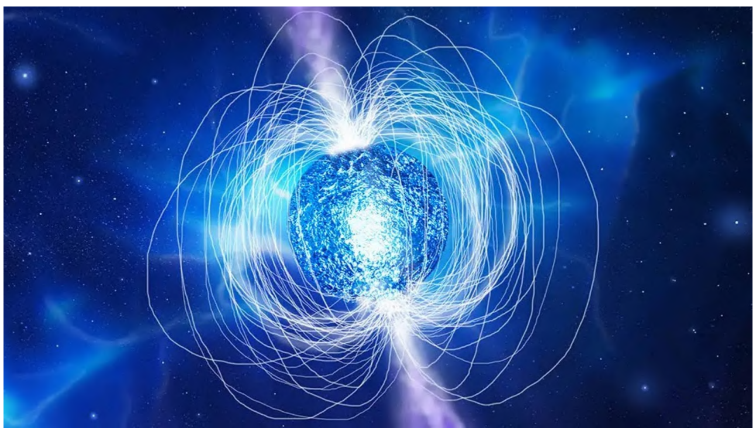


Figure 3: Illustration of a neutron star with magnetic field lines.

4.2.1 Properties

- **Mass:** Typically between 1.4 and 3 solar masses.
- **Radius:** About 10–12 kilometers—comparable to the size of a city.
- **Density:** Up to 10^{17} kg/m^3, similar to the density of atomic nuclei. A sugar-cube-sized piece of neutron star matter would weigh about a billion tons on Earth.
- **Magnetic Fields:** Among the strongest in the universe, often exceeding 10^8 Tesla—trillions of times stronger than Earth's magnetic field.

4.2.2 Structure

Neutron stars have a layered internal structure:

- **Outer crust:** A solid lattice of heavy atomic nuclei embedded in a sea of electrons.
- **Inner crust:** Neutrons begin to drip out of nuclei, forming a neutron-rich fluid.
- **Core:** A superfluid of neutrons with possible exotic states of matter like *hyperons*, *kaon condensates*, or even a **quark-gluon plasma**.

4.2.3 Rotational and Magnetic Phenomena

Newly formed neutron stars can spin incredibly fast, up to several hundred times per second. When aligned with strong magnetic fields, these rotating stars can emit beams of radiation from their magnetic poles—an effect observed as **pulsars**.

4.2.4 Scientific Significance

Neutron stars are astrophysical laboratories for extreme physics:

- They allow us to test **general relativity** in intense gravitational fields.
- Their behavior helps constrain the **equation of state (EoS)** of nuclear matter.
- The collisions of neutron stars, known as **kilonovae**, produce gravitational waves and create heavy elements like gold and platinum.

4.3 Pulsars

Pulsars are a fascinating class of neutron stars that emit regular beams of electromagnetic radiation from their magnetic poles. As the star spins, these beams sweep across the sky. When one of the beams points toward Earth, we detect it as a pulse—hence the name **pulsar**.

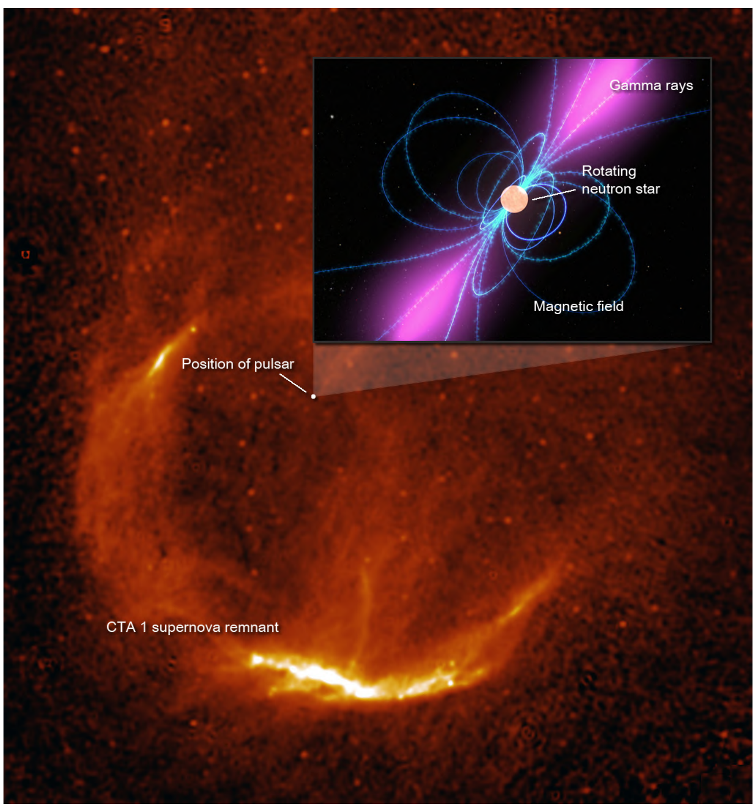


Figure 4: Image of a pulsar emitting radiation beams from its poles.

4.3.1 Discovery

Pulsars were first discovered in 1967 by **Jocelyn Bell Burnell** and **Antony Hewish** using a radio telescope. Initially dubbed "LGM" (Little Green Men) due to their regular pulses, they were soon recognized as a new class of astrophysical object.

4.3.2 Mechanism

A pulsar is a highly magnetized, rotating neutron star. Its magnetic axis is not aligned with its rotational axis. As it spins, the magnetic poles emit focused beams of radiation—usually in radio, X-ray, or gamma-ray wavelengths. This configuration causes the beams to sweep across space, much like the beam of a lighthouse. If Earth lies in the path of these sweeping beams, we observe regular flashes of radiation.

4.3.3 Types of Pulsars

Pulsars are classified based on their rotation period:

- **Normal Pulsars**: Rotation periods typically range from 0.1 to 1 second. These are often relatively young neutron stars.
- **Millisecond Pulsars (MSPs)**: These pulsars spin at incredible speeds, with periods between 1 and 10 milliseconds. They are often found in binary systems and are believed to have been "spun up" by accreting matter from a companion star.

4.3.4 Scientific Importance

Pulsars serve as **precise cosmic clocks**. Their regular pulses can be more stable than atomic clocks, making them useful tools for:

- Testing theories of **general relativity**, especially in binary systems.
- Detecting **gravitational waves** via timing irregularities in pulsar arrays (Pulsar Timing Arrays).
- Studying the **interstellar medium** by analyzing how their pulses are affected as they travel through space.

Pulsars have deepened our understanding of neutron stars, extreme magnetic fields, and the fundamental laws of physics under the most extreme conditions known in the universe.

4.4 Black Holes

Black holes are among the most mysterious and extreme objects in the universe. They are regions in space where gravity is so strong that not even light can escape, making them invisible to direct observation. Black holes are typically formed when very massive stars (greater than about 20 times the mass of the Sun) end their lives in catastrophic supernova explosions, leaving behind a gravitationally collapsed core.

4.4.1 Types of Black Holes

Black holes are classified based on their mass:

- **Stellar Black Holes:** Formed from collapsed massive stars; mass ranges from $\sim$3 to 100 solar masses.
- **Intermediate-Mass Black Holes:** Hypothetical black holes with masses between 10^2 and 10^5 $M_\odot$.
- **Supermassive Black Holes:** Found at the centers of galaxies; masses range from 10^6 to 10^{10} $M_\odot$.
- **Primordial Black Holes:** Hypothetical black holes formed in the early universe due to high-density fluctuations shortly after the Big Bang.

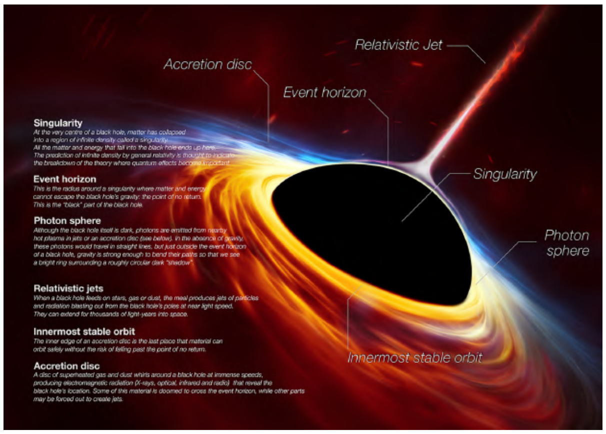


Figure 5: Simulated image of a black hole with accretion disk.

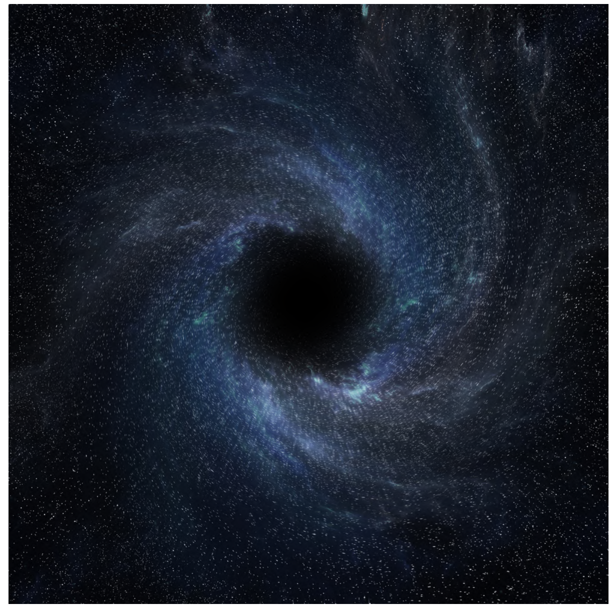


Figure 6: Visual Representation of Space-Time Warped by a Black Hole.

4.4.2 Key Features

- **Event Horizon:** The spherical boundary around a black hole beyond which nothing—not even light—can escape. It marks the "point of no return."
- **Singularity:** The center of a black hole, where gravity compresses all the mass into a point of infinite density and zero volume. The known laws of physics break down here.
- **Hawking Radiation:** A theoretical quantum mechanical process proposed by Stephen Hawking, suggesting that black holes can slowly lose mass and energy over time by emitting radiation, eventually leading to their evaporation.

4.4.3 Detection Methods

Black holes cannot be seen directly, but their presence is inferred through:

- **Gravitational effects** on nearby stars and gas clouds.
- **X-ray emissions** from hot gas spiraling into them via accretion disks.
- **Gravitational wave signals** observed during black hole mergers (first detected by LIGO in 2015).

4.4.4 Scientific Importance

Black holes offer deep insights into both general relativity and quantum mechanics. They:

- Serve as natural laboratories for studying extreme gravity.
- Help us understand galaxy formation (supermassive black holes may regulate galaxy growth).
- Raise fundamental questions about the nature of space, time, and information (e.g., the information paradox).

4.5 Quasars

Quasars, short for **quasi-stellar objects**, are among the brightest and most energetic phenomena in the universe. They appear star-like in visible light but emit enormous amounts of energy—far more than entire galaxies. Quasars are powered by **supermassive black holes** at the centers of young, active galaxies that accrete surrounding matter at astonishing rates.

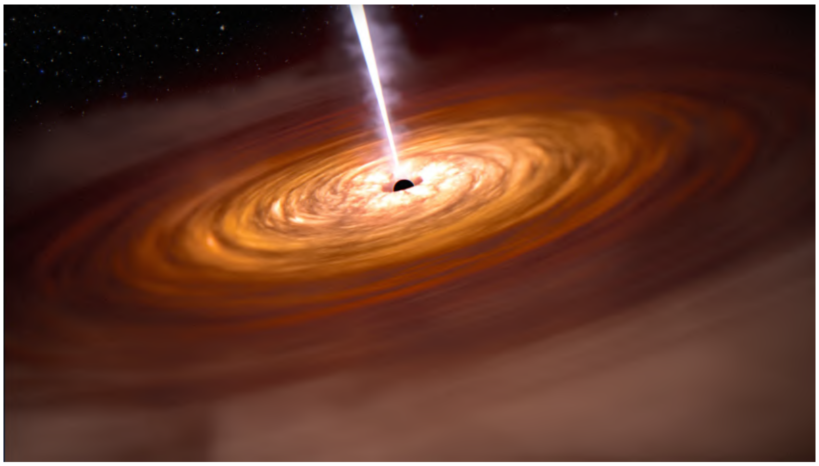


Figure 7: Hubble Quasar (Source: NASA)

4.5.1 Luminosity

Quasars can shine with luminosities up to 10^{14} times that of the Sun. Despite their compact size (comparable to our Solar System), they outshine the galaxies that host them. They are visible across billions of light-years and are often used as cosmic beacons to probe the distant universe.

4.5.2 Structure

Quasars are believed to consist of the following components:

- **Supermassive black hole:** Typically 10^6 to 10^{10} solar masses.
- **Accretion disk:** A rapidly spinning disk of gas and dust heated to millions of degrees as it spirals into the black hole.
- **Dusty torus:** A thick, doughnut-shaped structure of obscuring dust around the accretion disk.
- **Relativistic jets:** High-energy plasma jets ejected perpendicular to the disk, often stretching thousands of light-years.

4.5.3 Discovery

Quasars were first identified in the 1960s through their unusual radio signals and optical spectra. The redshifts in their light revealed that they were extremely far away, indicating they must be incredibly luminous to be visible from such distances.

4.5.4 Scientific Importance

Quasars offer unique insights into the early universe:

- Most known quasars existed billions of years ago, making them valuable tools for studying the universe's infancy.

- They help scientists understand the growth of **supermassive black holes** and their role in **galaxy formation**.
- Quasar light passing through intergalactic matter allows us to study the composition and distribution of matter in the early universe.

4.5.5 Modern Relevance

Even today, quasars remain important in cosmology and astrophysics. Ongoing surveys like the Sloan Digital Sky Survey (SDSS) and data from telescopes such as the James Webb Space Telescope continue to reveal new quasars and deepen our understanding of their properties and evolution.

5 UV interferometry

5.1 The UV Plane and Spatial Frequency Domain

In an interferometric array, each pair of antennas forms a *baseline*, characterized by its vector separation projected on the plane perpendicular to the source direction. For a monochromatic observation, the components of this projected baseline (measured in wavelengths) define coordinates (u, v) in the spatial frequency domain, or *UV plane*.

5.1.1 Visibility Function

The fundamental equation in radio interferometry is:

$$V(u,v) = \iint I(l,m) e^{-2\pi i(ul+vm)} \frac{dl\, dm}{\sqrt{1-l^2-m^2}}, \tag{1}$$

where:

- $V(u, v)$ is the complex visibility,
- $I(l, m)$ is the sky brightness distribution in direction cosines (l, m),
- (u, v) are the baseline components in units of wavelength.

This is essentially a 2D Fourier transform of the sky brightness distribution (under small-angle approximation where $\sqrt{1-l^2-m^2} \approx 1$).

5.1.2 Fourier Inversion and Imaging

To reconstruct the sky image from visibilities, one inverts the Fourier transform:

$$I(l,m) = \iint V(u,v) e^{2\pi i(ul+vm)} du\, dv. \tag{2}$$

However, due to practical limitations, we cannot sample the entire UV plane, leading to incomplete data. The observed image is therefore a convolution of the true sky brightness with the *point spread function* (PSF) or synthesized beam.

5.2 UV Coverage and Array Configuration

5.2.1 Earth Rotation Synthesis

Earth's rotation causes the projected baselines to trace elliptical paths over time. This rotation effectively improves UV coverage for a fixed array. Observing a source for several hours yields a denser sampling of the UV plane.

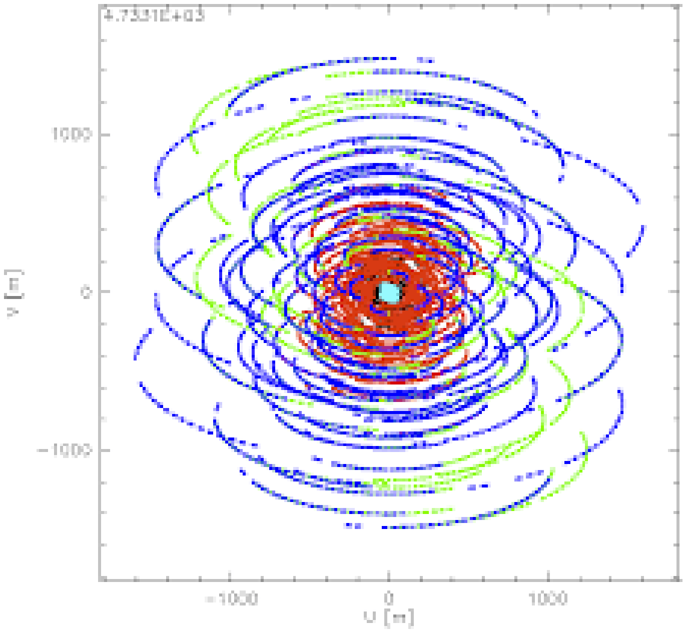


Figure 8: Example UV coverage for an interferometric array over a 6-hour observation.

5.2.2 Impact of UV Coverage

The fidelity of the reconstructed image depends heavily on how well the UV plane is sampled:

- Sparse UV coverage results in high sidelobe levels and artifacts.
- Uniform or dense coverage leads to a cleaner synthesized beam and better image quality.

5.2.3 Array Design and UV Optimization

Different array configurations (e.g., Y-shaped in the VLA or ring-shaped in ALMA) are designed to maximize UV coverage over time and optimize imaging performance for specific science goals. The inclusion of both short and long baselines allows sensitivity to extended structures and fine details, respectively.

5.3 Deconvolution and Imaging Algorithms

Incomplete UV coverage means the dirty image is a convolution of the true image with the dirty beam. Algorithms such as CLEAN and MEM (Maximum Entropy Method) are used to iteratively remove the effects of the PSF:

- **CLEAN** models the image as a collection of point sources and subtracts their contribution iteratively.
- **MEM** imposes entropy-based priors to infer the most probable image given the data.

These techniques attempt to recover the original sky distribution from incomplete visibility data.

6 Very Long Baseline Interferometry (VLBI)

Very Long Baseline Interferometry (VLBI) is an advanced form of radio interferometry that uses telescopes separated by **thousands of kilometers** to achieve **unprecedented angular resolution**. It is the technique behind the **Event Horizon Telescope (EHT)** and other high-precision astronomical observations.

6.1 How VLBI Works

6.1.1 Telescopes Spread Across the Globe

- Multiple radio telescopes (often on different continents or even in space) observe the same cosmic object simultaneously.
- Example: The EHT includes telescopes in Hawaii, Chile, Spain, Antarctica, and Mexico.

6.1.2 Independent Recording with Atomic Clock Precision

- Unlike traditional interferometers, VLBI telescopes **do not communicate in real time**.
- Each telescope records incoming radio waves onto high-speed hard drives.
- **Hydrogen maser atomic clocks** synchronize the data with nanosecond precision.

6.1.3 Data Transport & Correlation

- After observations, hard drives are shipped to a central processing facility (e.g., MIT Haystack Observatory or MPIfR in Germany).
- A **correlator supercomputer** aligns the data streams, accounting for:
  - Earth's rotation (which changes telescope positions over time)
  - Atmospheric delays
  - Tiny clock errors

6.1.4 Constructing an Image from Interference Patterns

- The correlator measures **fringes** (interference patterns) between telescope pairs.
- These fringes encode information about the brightness and structure of the observed object.
- Advanced algorithms (e.g., **CLEAN, Bayesian imaging, or machine learning**) reconstruct the final high-resolution image.

6.2 Why VLBI is Special

6.2.1 Extreme Resolution

- Resolution depends on the **longest baseline** (distance between telescopes)
- Formula:
$$\text{Resolution (radians)} \approx \frac{\lambda}{D}$$
  where:
  - λ = wavelength of observation
  - D = maximum baseline (e.g., Earth's diameter for EHT)
- Example: The EHT at **1.3 mm wavelength** achieves **20 microarcseconds** resolution - enough to spot a **donut on the Moon from Earth!**

6.2.2 No Physical Connection Needed

- Unlike connected interferometers (e.g., ALMA), VLBI telescopes operate independently, allowing **global or even space-based baselines**.

6.2.3 Best for Studying Compact Objects

- VLBI excels at imaging extremely small but bright regions, such as:
  - Black hole shadows (EHT's images of M87* and Sgr A*)
  - Quasar jets
  - Masers (cosmic microwave lasers) in star-forming regions

6.3 Challenges of VLBI

6.3.1 Requires Perfect Synchronization

- Atomic clocks must stay synchronized within **nanoseconds**; even tiny errors blur the image.

6.3.2 Massive Data Rates

- Each telescope records **64 gigabits/second** (petabytes per observation)
- Data must be shipped on hard drives - too large to transmit electronically

6.3.3 Atmospheric Interference

- Water vapor distorts millimeter-wave signals, so telescopes are placed in high, dry locations (e.g., Atacama Desert, South Pole)

6.3.4 Complex Data Processing

- Combining signals from widely spaced telescopes requires supercomputers and sophisticated algorithms

6.4 Famous VLBI Projects

Project	**Purpose**	**Key Achievement**
Event Horizon Telescope (EHT)	Imaging black holes	First images of M87* (2019) and Sgr A* (2022)
VLBA (Very Long Baseline Array)	High-resolution radio astronomy	Maps cosmic jets, measures galaxy distances
RadioAstron (Space VLBI)	Space-ground interferometry	Highest-resolution images ever (baselines ¿ Earth diameter)

6.5 Future of VLBI

- **Adding More Telescopes** (e.g., Africa, Greenland) to improve image quality
- **Higher Frequencies** (e.g., 0.8 mm) for sharper black hole images
- **Space VLBI** (e.g., upcoming **Millimetron mission**) for even longer baselines

6.6 How the Event Horizon Telescope Collects Data

6.6.1 Global Telescope Network

The **Event Horizon Telescope (EHT)** is not a single instrument, but an array of radio observatories spread across the globe, forming a coordinated global network. This includes:

- ALMA and APEX in Chile
- IRAM 30m in Spain
- SMA and JCMT in Hawaii
- LMT in Mexico
- SPT at the South Pole
- NOEMA, SMT (Arizona), and others

Purpose: The aim is to create a virtual telescope with a baseline as large as the Earth's diameter, achieving extremely high angular resolution capable of imaging the surroundings of a black hole's event horizon.

Why Earth-sized? Angular resolution depends on both the observing wavelength and the distance (baseline) between telescopes. The larger the baseline, the finer the detail that can be resolved—this is the principle behind *very long baseline interferometry (VLBI)*.

6.6.2 Data Collection and Timing

Signal Capture

Each telescope targets the same object—like M87* or Sagittarius A*—and collects radio waves from the hot gas and plasma swirling around the black hole (the accretion disk).

- Observations are made at a frequency of 230 GHz, corresponding to a wavelength of 1.3 mm.
- This frequency lies in the millimeter/submillimeter band, ideal for penetrating cosmic dust.

Time Synchronization

- Each observatory uses a **hydrogen maser atomic clock** for precise timekeeping.
- These clocks have an accuracy of 1 part in 10^{15}, allowing synchronization to billionths of a second.
- This ensures coherent combination of wavefronts despite vast distances between telescopes.

6.6.3 Data Storage

Volume

- Each site collects 4–5 petabytes of raw digitized radio signal data over several nights.
- All data is timestamped precisely using atomic clocks.

Transport

- Due to massive data volume, internet transfer is impractical.
- Data is stored on helium-cooled hard drives.
- These drives are physically transported to central processing locations.
- For example, data from the South Pole Telescope is flown out only after the Antarctic winter ends.

6.6.4 Correlation and Processing

Once all the hard drives are gathered, the data is processed using powerful **correlators**, or specialized supercomputers.

Correlation Process

- Align timestamps to correct for Earth's rotation and signal arrival delays.
- Use interference patterns (fringes) across all telescope pairs (baselines).
- Reconstruct the phase and amplitude of the incoming radio waves.

Output

- The output is a "visibility" dataset—a complex map representing wave interference patterns.
- This is not an image, but raw interferometric data ready for image reconstruction.

6.6.5 Image Reconstruction

The final step is converting visibility data into a meaningful image.

Algorithms Used

- CLEAN
- MEM (Maximum Entropy Method)
- Regularized Maximum Likelihood

These iterative algorithms compensate for missing data and noise to generate the most probable image from observed signals.

Results

- In April 2019, EHT released the first image of a black hole (M87*), showing a bright ring and a dark central region—the shadow of the event horizon.
- In 2022, the EHT released the image of Sagittarius A*, the supermassive black hole at the center of the Milky Way.
- These are not direct photographs but reconstructions from massive radio datasets via interferometry.

7 Clean Algorithm

7.1 CLEAN Algorithm: Use and Introduction to Dirty Image and Dirty Beam

7.1.1 Introduction

Radio astronomy enables us to study celestial objects by detecting radio waves emitted from space. Unlike optical telescopes, radio telescopes often use arrays of antennas, combining their signals to achieve higher resolution. However, the first image produced from such data is not a true representation of the sky but is instead a **dirty image**, which is blurred and contains artifacts due to the instrument's limitations. The blurring pattern is known as the **dirty beam**. To overcome these issues and reveal the true structure of astronomical sources, astronomers use the CLEAN algorithm—a transformative technique in radio astronomy.

7.1.2 Dirty Image: What Is It and Why Does It Occur?

A **dirty image** is the initial image produced after processing the raw data from a radio interferometer. This image is created by performing an inverse Fourier transform of the measured visibilities (the data collected by the telescope array). However, due to incomplete coverage of the spatial frequency domain (the "uv-plane"), the resulting image is not a perfect representation of the sky. Instead, it is convolved with the **dirty beam**, causing the following issues:

- **Blurring:** The dirty image is smeared, making point sources appear spread out.
- **Artifacts:** Sidelobes and spurious features appear, which do not correspond to real astronomical sources.
- **Reduced Contrast:** Faint sources may be masked by the noise and artifacts.

This happens because the array cannot sample all possible spatial frequencies, leading to incomplete information and, hence, an imperfect image.

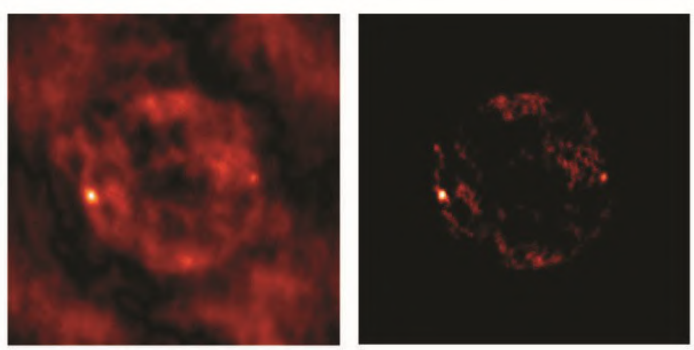


Figure 9: Example of a Dirty Image (left) and a Clean Image (right)

7.1.3 Dirty Beam: The Source of Blurring

The **dirty beam** (or point spread function, PSF) is the response of the telescope array to a single point source. It is essentially the instrument's "fingerprint"—a 2D pattern that shows how a true point source would appear in the dirty image. The dirty beam typically has a central peak (the main lobe) surrounded by weaker, oscillating features called sidelobes. These sidelobes are responsible for the spurious marks and confusion in the dirty image.

Key characteristics of the dirty beam:

- **Shape:** Determined by the configuration of the antenna array and the sampling of the uv-plane.

- **Sidelobes:** Cause false signals and make it difficult to distinguish real sources from artifacts.
- **Central Peak:** Corresponds to the main response to a point source.

7.1.4 Mathematical Perspective

Mathematically, the dirty image $D(x, y)$ is related to the true sky brightness $I(x, y)$ by convolution with the dirty beam $B(x, y) : D(x, y) = I(x, y)B(x, y)$

The CLEAN algorithm attempts to invert this convolution, reconstructing $I(x, y)$ from $D(x, y)$ and $B(x, y)$.

7.1.5 The CLEAN Algorithm: Step-by-Step Explanation

The CLEAN algorithm is a foundational deconvolution technique used in radio interferometry to address the limitations imposed by incomplete sampling of the UV plane. The observed image, or *dirty image*, is the convolution of the true sky brightness distribution with the instrument's *dirty beam* (the point spread function, PSF). The goal of CLEAN is to iteratively remove the effects of the dirty beam and reconstruct a model of the true sky image. This process is organized into two distinct computational stages: the **minor cycle** and the **major cycle**.

7.1.6 Minor Cycle

The minor cycle is a fast, image-plane operation where the algorithm searches for the brightest pixel in the current residual image, which is presumed to correspond to a point source. A scaled version of the PSF is subtracted from the residual image at the location of this peak. This subtraction is usually controlled by a *loop gain* factor γ (typically $\gamma \sim 0.1$), meaning only a fraction of the peak is removed in each iteration. The corresponding component is added to the CLEAN model.

Because the minor cycle uses a simplified or truncated version of the PSF for efficiency, it is only an approximation and can lead to inaccuracies for complex or extended emission. The minor cycle continues for a fixed number of iterations or until a stopping threshold is reached.

7.1.7 Major Cycle

To correct for the approximations introduced in the minor cycle, the major cycle performs a more accurate update of the residual image. This is done by transforming the current CLEAN component model into the visibility domain using a forward Fourier transform, comparing it against the measured visibilities, and then computing the inverse Fourier transform to generate a new residual image.

The major cycle ensures that the residuals reflect the true differences between the modeled and observed visibilities, not just the image-plane discrepancies. Although more computationally expensive due to the need for full Fourier transforms, the major cycle is crucial for maintaining accuracy, especially in the presence of extended emission or strong sidelobes.

7.1.8 Combined Workflow

The CLEAN algorithm proceeds as an alternation between minor and major cycles:

1. Begin with the dirty image and the dirty beam.
2. Perform several iterations of the minor cycle to remove the brightest features.
3. Invoke the major cycle to update the residual image using the full visibility data.
4. Repeat this cycle until the residual image meets a defined convergence criterion.
5. Convolve the CLEAN components with an idealized *clean beam*, typically a Gaussian fitted to the main lobe of the PSF.
6. Add the final residual image to the convolved model to form the *restored image*.

This separation into major and minor cycles enables the CLEAN algorithm to balance computational efficiency with deconvolution accuracy, making it suitable for processing large interferometric datasets across a wide range of source complexities.

7.1.9 Advantages of CLEAN

- **Removes Artifacts:** Significantly reduces the sidelobes and spurious features.
- **Improves Resolution:** Recovers the true structure of sources, revealing details hidden in the dirty image.
- **Widely Adopted:** The algorithm is a standard tool in radio astronomy and is implemented in most data reduction pipelines.

7.1.10 Illustrative Example

Suppose an array observes a region of the sky with two point sources. The dirty image will show two main peaks, each surrounded by sidelobes due to the dirty beam. The CLEAN algorithm will:

- Identify the brightest peak, subtract the dirty beam from that location, and record the component.
- Move to the next brightest peak (possibly the second source), repeat the subtraction, and record.
- Continue until the image is cleaned of significant sidelobes, leaving only noise.

7.1.11 Why Is CLEAN Essential in Radio Astronomy?

Without CLEAN, radio astronomers would struggle to interpret their data. The dirty image can be misleading, with real sources obscured by artifacts. CLEAN enables:

- **Accurate Source Identification:** Real astronomical features are revealed, allowing for precise studies of galaxies, quasars, and other objects.
- **Quantitative Analysis:** Flux densities, positions, and structures can be measured reliably.
- **Scientific Discovery:** CLEAN has been crucial in many discoveries, such as imaging black hole shadows and mapping cosmic jets.

Table 1: Summary Table

Term	Meaning	Notes
Dirty Image	Initial, blurry image from radio data	Contains real sources + artifacts
Dirty Beam	Blurring pattern (PSF) from telescope array	Has central peak and sidelobes
CLEAN Algorithm	Iterative process to remove dirty beam effects	Produces clear, artifact-free image
Clean Image	Final, deconvolved image	True representation of the sky

8 Installing CASA

8.1 Part A: Install WSL and Ubuntu on Windows

1. Enable WSL

Open PowerShell as Administrator and run:

```
wsl --install
```

This installs WSL 2 with the default Ubuntu distribution. Restart your system if prompted.
If WSL is already installed, update and configure it:

```
wsl --update
wsl --set-default-version 2
```

2. Install Ubuntu

If Ubuntu is not installed automatically, install it from the Microsoft Store:

1. Open Microsoft Store
2. Search for `Ubuntu`
3. Click `Install`

After installation, launch Ubuntu and set your username and password when prompted.

8.2 Part B: Install CASA in Ubuntu (WSL)

3. Download CASA

Go to the official CASA download page:
`https://casa.nrao.edu/casa_obtaining.shtml`
Download the appropriate tarball, for example:
`casa-6.7.0-31-py3.12.el8.tar.xz`

4. Move File to Linux Filesystem

In Ubuntu (WSL terminal), move the downloaded file from your Windows filesystem to the Linux home directory:

```
cd /mnt/c/Users/<YourUsername>/Downloads
mv casa-6.7.0-31-py3.12.el8.tar.xz ~/
cd ~
```

Replace <YourUsername> with your actual Windows username.

5. Extract the CASA Package

```
tar -xf casa-6.7.0-31-py3.12.el8.tar.xz
cd casa-6.7.0-31-py3.12.el8
```

6. Run CASA

Launch CASA using its launcher script:

```
./bin/casa
```

Note: You may see warnings like:
`optional configuration file not found, continuing CASA startup without it`
These are generally safe to ignore.

7. (Optional) Add CASA to PATH

To make CASA easier to launch in the future:

```
nano ~/.bashrc
```

Add this line at the end of the file:

```
export PATH="$HOME/casa-6.7.0-31-py3.12.el8/bin:$PATH"
```

Then save and reload your shell:

```
source ~/.bashrc
```

Now you can simply type:

```
casa
```

to launch CASA.

8.3 Troubleshooting

8.3.1 Problem: HTTPSHandler Import Error

Cause: Running CASA with the wrong Python environment. **Fix:** Always start CASA using its launcher:

```
./bin/casa
```

8.3.2 Problem: Startup Warnings

You may see messages about missing configuration files. These are typically harmless and safe to ignore.

9 CASA codes for visualizing EHT data for M87*

9.1 Why Combine Only Low-Band (lo) Data and Not Low With High (hi)?

When processing EHT data in CASA, it is common practice to combine only the low-band (lo) datasets separately from the high-band (hi) datasets. This separation is important for both scientific accuracy and technical consistency.
Reasons:

Band	Combine With	Reason
lo	lo only	Same frequency; safe for uv-plane and imaging combination
hi	hi only	Preserves high-band calibration and frequency integrity
lo + hi	With caution	Requires frequency regridding, calibration matching, and scientific justification

9.2 CASA codes to visualize uv data

1. **Importing UVFITS Files:**
The `importuvfits` command converts raw UVFITS files into CASA's Measurement Set (MS) format:

```
importuvfits(fitsfile="SR1_M87_2017_095_lo_hops_netcal_StokesI.uvfits", vis="M87_095_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_096_lo_hops_netcal_StokesI.uvfits", vis="M87_096_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_100_lo_hops_netcal_StokesI.uvfits", vis="M87_100_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_101_lo_hops_netcal_StokesI.uvfits", vis="M87_101_lo.ms")
importuvfits(fitsfile="SR1_M87_2017_095_hi_hops_netcal_StokesI.uvfits", vis="M87_095_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_096_hi_hops_netcal_StokesI.uvfits", vis="M87_096_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_100_hi_hops_netcal_StokesI.uvfits", vis="M87_100_hi.ms")
importuvfits(fitsfile="SR1_M87_2017_101_hi_hops_netcal_StokesI.uvfits", vis="M87_101_hi.ms")
```

2. **Inspecting Metadata:**
Use `listobs` to examine the MS structure and metadata:

```
listobs(vis="M87_095_lo.ms")
```

3. **Plotting UV Coverage:**
The `plotms` tool is used to visualize the *uv-coverage*, revealing array geometry:

```
plotms(vis="M87_095_lo.ms", xaxis="u", yaxis="v", avgtime="1e8", avgscan=True, coloraxis="
    spw")
```

4. **Fixing Metadata Issues:**
`mstransform` is used to generate corrected MS files, resolving pointing table inconsistencies:

```
mstransform(vis="M87_2017_095_lo.ms", outputvis="M87_2017_095_lo_fixed.ms", datacolumn="
    data")
mstransform(vis="M87_2017_096_lo.ms", outputvis="M87_2017_096_lo_fixed.ms", datacolumn="
    data")
mstransform(vis="M87_2017_100_lo.ms", outputvis="M87_2017_100_lo_fixed.ms", datacolumn="
    data")
mstransform(vis="M87_2017_101_lo.ms", outputvis="M87_2017_101_lo_fixed.ms", datacolumn="
    data")
```

5. **Renaming Field Names:**
Unique field names are assigned before concatenation:

```
tb.open("M87_2017_095_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_095"])
tb.close()
tb.open("M87_2017_096_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_096"])
tb.close()
tb.open("M87_2017_100_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_100"])
tb.close()
tb.open("M87_2017_101_lo_fixed.ms/FIELD", nomodify=False)
tb.putcol("NAME", ["M87_101"])
tb.close()
```

6. **Concatenating Measurement Sets:**
   Multiple MS files are merged using `concat`, preserving field names and time order:

```
concat(vis=vis=["M87_2017_095_lo_fixed.ms", "M87_2017_096_lo_fixed.ms","
    M87_2017_100_lo_fixed.ms","M87_2017_101_lo_fixed.ms"],
   concatvis="M87_combined_distinct.ms",
   timesort=True, respectname=True, copypointing=False)
```

7. **Plotting Combined Data:**

```
plotms(vis="M87_combined_distinct.ms", xaxis="u", yaxis="v",
   coloraxis="field", avgchannel="9999", avgtime="9999")
```

8. **Final Combination and Visualization:**
   A final MS is created by concatenating all ‘lo‘ datasets. The same plotms command helps assess the overall UV coverage for imaging.