Understanding space telescopes

Learners' Space Astronomy

Contents

Introduction

In the first module, we got an overview of what astronomical imaging entails. In this module, we shall understand the significance of telescopes, both space and ground-based, and how they aid in improving our understanding of the universe.

The history of telescopes and aided sky-watching is nothing short of marvelous. In 1608, the Netherlands became an unexpected epicenter for an astronomical revolution through the ingenuity of three spectacle-makers. Hans Lippershey, Zacharias Janssen, and Jacob Metius, all independently stumbled upon a groundbreaking device: the refracting telescope. This marvel utilized a combination of lenses and tubes to bring the heavens closer, forever altering our perspective of the universe.

News of this contraption, with its converging objective lens and diverging eyepiece, spread like wildfire across Europe. Galileo Galilei, the renowned astronomer, wasted no time in acquiring one. He then revolutionized astronomy by turning his attention to the night sky with his improved refracting telescope, boasting superior lenses. These advancements led to groundbreaking discoveries that challenged the prevailing understanding of the cosmos. He unveiled the existence of Jupiter's moons, the phases of Venus, and the intricate details of our own Moon's surface.

However, these early telescopes had limitations. The lenses used suffered from chromatic aberration, a phenomenon that caused a fuzzy image. In 1668, another brilliant mind, Isaac Newton, devised a solution. He constructed a telescope that employed a curved mirror instead, ushering in the era of the reflecting telescope. This design eliminated chromatic aberration and provided a clearer view of the cosmos.

William Herschel, armed with a powerful reflecting telescope he built himself in 1789 (featuring a massive 1.2-meter primary mirror), embarked on groundbreaking celestial exploration. This telescope led to a monumental discovery – a new world – literally. He stumbled upon Uranus, a giant planet previously unknown to humanity. Herschel's success with his giant telescope paved the way for the development of even more impressive astronomical instruments.

The 19th century witnessed fierce competition to build the most powerful telescopes. The "Leviathan of Parsonstown," a behemoth of a reflecting telescope completed in 1845 with a staggering 1.8-meter mirror, dominated astronomical observations for decades. But the 20th century brought a paradigm shift – telescopes rocketed into space!

Lyman Spitzer, a visionary scientist, dreamt of a telescope unhindered by Earth's atmospheric distortions. In 1968, his dream became a reality with the launch of the Orbiting Astronomical Observatory (OAO-2), the first successful space telescope. This marvel operated in ultraviolet wavelengths, pioneering a new era of celestial observation.

The launch of the Hubble Space Telescope (HST) in 1990 marked a golden age in astronomy. Hubble's sophisticated design, featuring a suite of mirrors and corrective optics, allowed it to capture a vast range of wavelengths, including visible, ultraviolet, and near-infrared. This powerful gaze pierced the veil of space, revealing unprecedented details of distant galaxies, the universe's age, and even the existence of a mysterious force known as dark energy.

Space became a crowded yet productive place for telescopes, each with a unique specialty. Launched in 1999, the Chandra X-ray Observatory utilized its X-ray vision to investigate the universe's high-energy regions, while the Spitzer Space Telescope (launched in 2003) focused on the cool and faint objects in the infrared spectrum, like protoplanetary disks and distant galaxies. Joining the party in 2013, the Gaia spacecraft meticulously mapped our Milky Way galaxy, creating a precise three-dimensional map of over a billion stars.

The story continues in 2021 with the launch of the James Webb Space Telescope (JWST), the highly anticipated successor to Hubble. JWST's primary mirror, significantly larger than Hubble's, and its focus on the infrared spectrum promise to unveil the secrets of the early universe, the atmospheres of alien worlds, and the formation of stars and galaxies. The future beckons with telescopes like the Nancy Grace Roman Space Telescope (expected to launch by May 2027), designed to delve deeper into the mysteries of dark energy, dark matter, and exoplanets.

With the extensive history of the telescope behind us, we will now jump into studying in greater depths the ones we can use to photograph the nightsky today, In this module, we will cover:

- Challenges faced in astronomical imaging owing to factors like continuum emission and several other sources of limitations
- A qualitative comparison between ground-based and space telescopes
- A deep dive into the two space telescopes at the helm of astrophotography globally: Hubble space telescope and the James Webb space telescope
- Comparative study of these two space telescopes and how they complement each other to provide a complete picture of the universe

Continuum emission

Like all electromagnetic radiation, continuum emission results from the acceleration of charged particles. While line emission results from atomic processes that only have very specific quantised energies, continuum emission results from processes where the energy exchange is not quantised and so the photons emitted may have a continuous energy distribution.
There are two main types of continuum emission:

- **Thermal radiation**: Which depends on the temperature of the emitter (eg. blackbody radiation).
- **Non-thermal radiation**: Which does not depend on the temperature of the emitter (eg. synchrotron radiation).

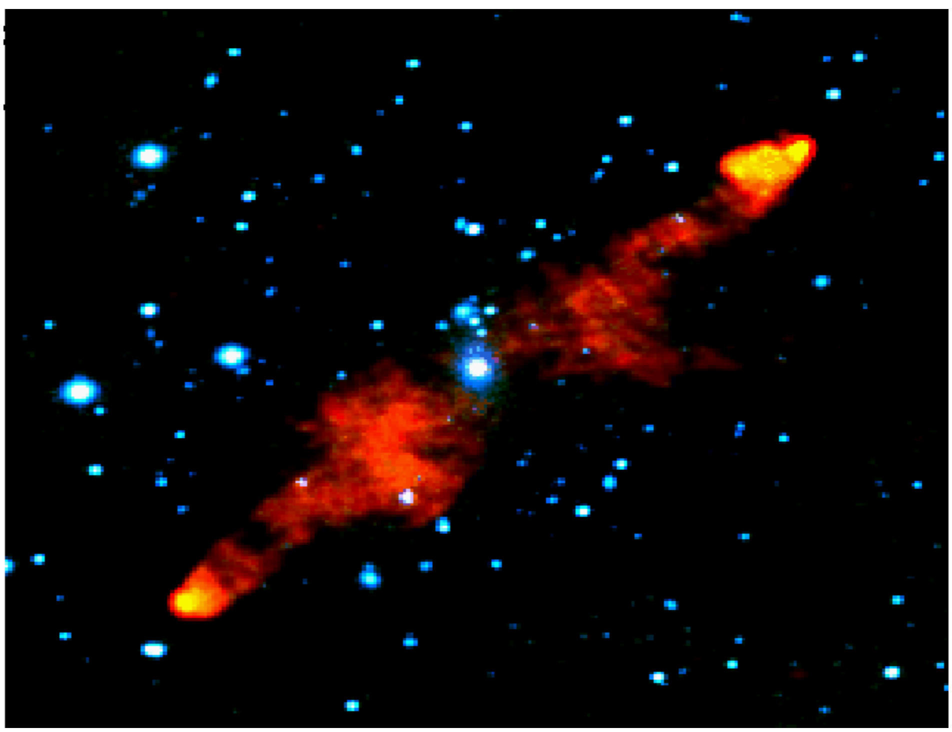

Figure 2.1: Credit: A. Koekemoer, R. Schilizzi, G. Bicknell and R. Ekers (ATCA)/ATNF

Thermal radiation

At short radio wavelengths, thermal emission sources dominate the sky, while non-thermal process dominate at long radio wavelengths. As we shall see, the shape of the spectrum of thermal and non-thermal radiation differs, making it easy to determine the emission mechanism of a source.

Other types of radio thermal radiation include free-free radiation, and other types of nonthermal radio radiation include maser emission. (Note that there are many types of thermal and non-thermal radiation mechanisms that do not emit radio photons, such as thermal Compton scattering and non-thermal Bremsstrahlung, both of which emit X-ray photons.)

Thermal radiation and blackbodies

All objects with temperatures above absolute zero have some internal motion: the atoms in solids are vibrating and the molecules in gases are zooming around and bumping into each other. The hotter the body, the faster the vibrations or the more collisions occur. Since accelerating charged particles (like the electrons in atoms) emit electromagnetic radiation, all bodies above absolute zero emit thermal radiation. Thermal radiation just means that a body's emission spectrum is determined by its temperature. The simplest (and most ideal) case of thermal emission is that of a blackbody.
Absolute zero = 0 K = -273°C

Non-thermal radiation

While thermal emission depends on the temperature of the emitting source, non-thermal emission depends on other things, such as the relative proportions of excited states of atoms and magnetic field strength. Examples of non-thermal radiation include synchrotron radiation, maser emission, and Compton scattering. Astrophysical non-thermal sources like low-luminosity accretion flows like Sgr A* at our Galactic center contribute to non-thermal radiation.

Requirements and limitations

Sensitivity:

- **Definition:** Sensitivity in astronomy refers to a telescope's ability to detect faint objects. This depends on the telescope's design, the efficiency of its detectors, and the amount of background noise.
- **Limitation Factors:**
  - **Atmosphere:** Earth's atmosphere absorbs and scatters light, reducing the sensitivity of ground-based telescopes. This is particularly problematic for infrared and ultraviolet observations.
  - **Detectors:** The efficiency of a detector (quantum efficiency) and its noise characteristics (thermal noise, readout noise) play critical roles in determining sensitivity.

  Resource: Estimation of Sensitivity of Optical Telescopes

Atmosphere:

- **Impact:** Atmospheric conditions such as turbulence, water vapor, and airglow can significantly distort and absorb incoming light, leading to blurred images and loss of detail.
- **Solution:** Adaptive optics systems on ground-based telescopes correct for atmospheric distortion in real-time, improving image clarity. Space telescopes avoid these issues entirely by operating outside Earth's atmosphere.
  Resource: Astronomical seeing

Spatial resolution:

- **Definition:** Spatial resolution is the ability of a telescope to distinguish between two closely spaced objects. Higher resolution allows for more detailed observations of celestial objects.
- **Limitation Factors:**
  - **Defraction limit:** The theoretical limit to resolution based on the wavelength of light and the diameter of the telescope's aperture, described by the formula $\theta = 1.22\lambda/D$
  - **Atmospheric disturbance:** As described in the atmosphere point.

  Resource: HyperPhysics- Diffraction limit

Ground and space-based telescopes

In the quest to explore and understand the cosmos, astronomers face numerous challenges primarily due to the limitations imposed by the Earth's atmosphere. This atmosphere, while nurturing life on our planet, acts as a significant barrier that distorts and obscures the light from celestial objects, making it difficult to achieve the clarity and precision necessary for detailed astronomical observations.

Additionally, certain wavelengths of light, such as ultraviolet and infrared, are absorbed by the atmosphere and are inaccessible to ground-based telescopes. These obstacles hinder our ability to study distant galaxies, observe the birth of stars, and uncover the secrets of black holes.

The need to overcome these barriers has driven the development of advanced techniques and technologies in astronomy, allowing us to push the boundaries of our knowledge and explore the universe in unprecedented detail.

Ground-based Telescopes

Ground-based telescopes are located on Earth's surface and employ sophisticated optics to capture and analyze celestial light. These observatories come in various sizes and configurations, from small amateur telescopes to large professional facilities like the Keck Observatory in Hawaii.

- **Cost-Effectiveness and Flexibility:** Building and operating ground-based telescopes generally incur lower costs compared to their space-based counterparts.
- **Ease of Maintenance and Upgrades:** Ground-based telescopes benefit from the advantage of easy accessibility for maintenance and upgrades. Instruments can be repaired, instruments can be calibrated, and new technologies can be integrated without the need for complex space missions.
- **Adaptive Optics:** To compensate for atmospheric turbulence, ground-based telescopes employ adaptive optics systems. These systems use deformable mirrors to counteract the effects of atmospheric distortion, resulting in improved image quality and resolution.

Challenges of Ground-Based Telescopes Despite their advantages, ground-based telescopes also face challenges:

- **Atmospheric Interference:** Earth's atmosphere introduces turbulence, light pollution, and absorption of specific wavelengths, which can degrade the quality of observations. Techniques such as adaptive optics and site selection help mitigate these effects, but they cannot completely eliminate atmospheric interference.
- **Observational Constraints:** Ground-based telescopes are subject to weather conditions, daytime limitations, and seasonal variations, which restrict their observational capabilities. These constraints can limit the amount of usable observing time and affect long-term studies.

Figure 4.1: Keck Observatory in Mauna Kea, Hawaii

Space telescopes

Space telescopes operate above the Earth's atmosphere, eliminating atmospheric interference and allowing for clearer, more detailed observations. They can observe wavelengths that are absorbed by the atmosphere, such as ultraviolet and infrared.

Example:

- **Hubble Space Telescope (HST):** Has provided detailed images of the universe, operating in ultraviolet, visible, and near-infrared wavelengths. It has significantly advanced our understanding of cosmology through its high-resolution observations and numerous groundbreaking discoveries.

- **James Webb Space Telescope (JWST):** Set to be the premier observatory of the next decade, JWST focuses on infrared astronomy with a larger mirror and more advanced instruments than Hubble.

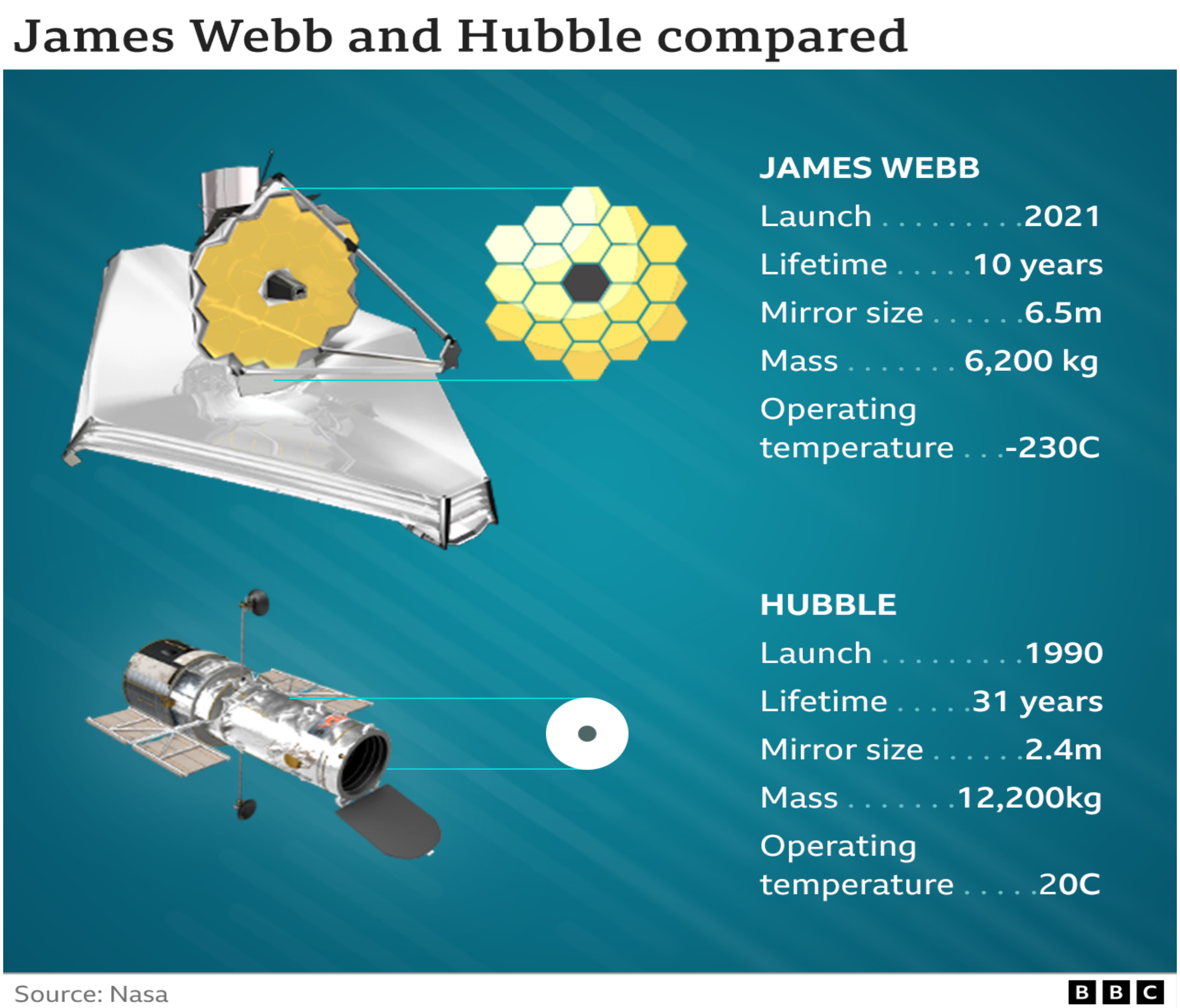

Figure 4.2: JWST and HST comparison

Hubble Space Telescope (HST)

Launched on April 24, 1990, aboard the Space Shuttle Discovery, the Hubble Space Telescope has revolutionized our understanding of the cosmos. Positioned in low Earth orbit, Hubble avoids atmospheric distortion, enabling it to capture incredibly detailed images across ultraviolet, visible, and near-infrared wavelengths. Over its three decades of operation, Hubble has made numerous groundbreaking contributions to astronomy.

Figure 4.3: HST

Advantages

- **Unobstructed view:** The Hubble Space Telescope operates above the Earth's atmosphere, at an altitude of approximately 547 kilometers (340 miles), providing it with a clear and unobstructed view of the universe. Unlike ground-based telescopes, Hubble is free from the distortions and absorption caused by the atmosphere, such as light pollution, weather conditions, and atmospheric turbulence. This allows it to capture sharper and more detailed images of celestial objects.

- **High resolution:** Hubble's 2.4-meter (7.9 feet) primary mirror, combined with its suite of advanced instruments, enables it to achieve high spatial resolution. This means it can resolve fine details in distant galaxies, nebulae, and other astronomical phenomena. The clarity and precision of Hubble's images have significantly advanced our understanding of the universe's structure and dynamics, providing insights into phenomena that are often beyond the reach of ground-based telescopes.

- **Capability to Capture Ultraviolet, Visible, and Near-Infrared Light:** Hubble's instruments are designed to observe the universe in a broad range of wavelengths, including ultraviolet (UV), visible, and near-infrared (NIR) light. This versatility allows it to study a variety of astrophysical processes. For example, UV observations can reveal hot, young stars and active galactic nuclei, while NIR observations can penetrate dust clouds to unveil star formation regions and the cores of galaxies.

Challenges

- **Limited by size:** The Hubble Space Telescope's primary mirror, although large for its time, is 2.4 metres (7.9 feet) in diameter. This size limits the amount of light Hubble can collect, which affects its ability to observe very faint objects. While Hubble's mirror allows for significant observational power, newer telescopes like the James Webb Space Telescope (JWST) have larger mirrors (JWST's mirror is 6.5 metres) that can collect more light and provide greater sensitivity and resolution.

- **Older technology compared to JWST:** Hubble was launched in 1990, utilising technology from the 1980s. While it has undergone several servicing missions to upgrade its instruments and extend its operational life, some components are now outdated. The James Webb Space Telescope (JWST), launched in 2021, is equipped with state-of-the-art technology and is designed to surpass Hubble in many areas, particularly in infrared astronomy. JWST's advanced capabilities will allow it to explore new frontiers that Hubble cannot reach.

Notable contributions

- **Deep field images:** One of Hubble's most famous contributions is its series of Deep Field images. By pointing Hubble at a small, seemingly empty patch of sky for extended periods, astronomers were able to capture images of thousands of distant galaxies, some as far as 13 billion light-years away. The Hubble Deep Field (1995), Hubble Ultra Deep Field (2004), and eXtreme Deep Field (2012) have provided unprecedented views of the early universe, revealing a wealth of information about galaxy formation and evolution.

- **Precise distance measurements:** Hubble has played a crucial role in refining the cosmic distance ladder, which astronomers use to measure the distance to faraway galaxies. By observing Cepheid variable stars and Type Ia supernovae, Hubble has helped determine the Hubble constant, the rate at which the universe is expanding. These precise measurements have led to the discovery of dark energy, a mysterious force that is accelerating the expansion of the universe.

- **Observations of exoplanets and galaxies:** Hubble has made significant contributions to the study of exoplanets, detecting their atmospheres and analysing their compositions. It has observed transits of exoplanets across their host stars, providing valuable data on their atmospheres and potential habitability. Additionally, Hubble has provided detailed images and spectra of distant galaxies, enhancing our understanding of their structure, dynamics, and star formation processes.

Resources: HST's contribution to astrophotography

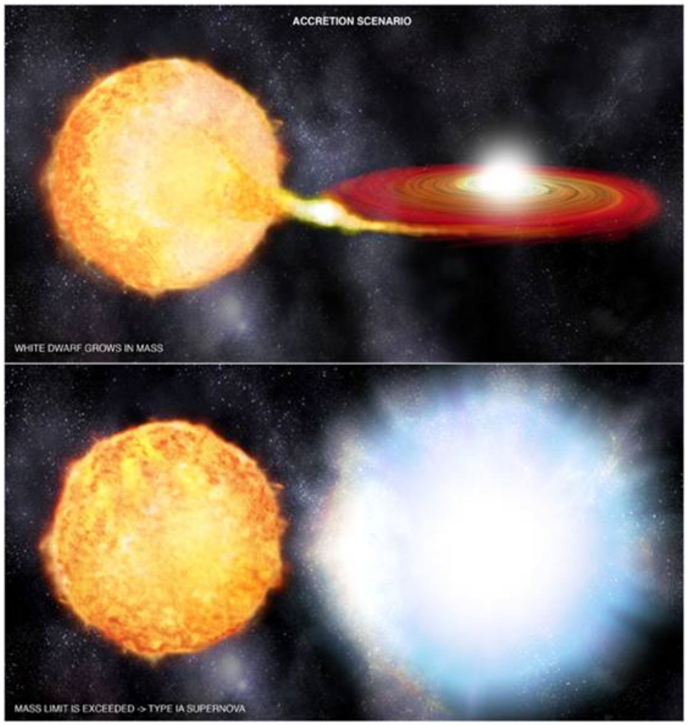

Figure 4.4: Type Ia supernova

James Webb Space Telescope (JWST)

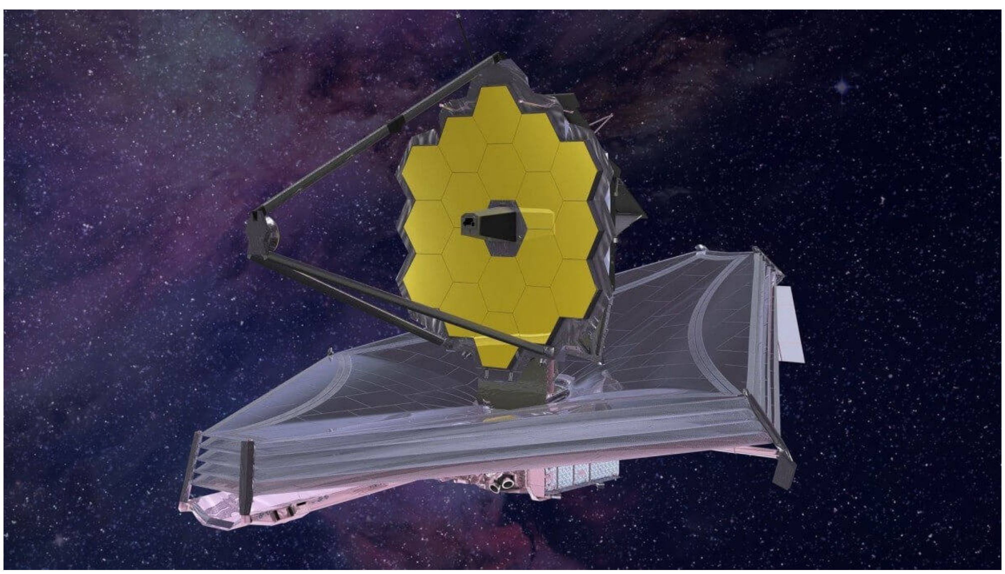

Figure 4.5: JWST

Advantages

- **Advanced Technology (Infrared Focus):** The James Webb Space Telescope is equipped with state-of-the-art technology designed to excel in infrared astronomy. Its primary scientific goals require observations in the infrared spectrum, which allows it to peer through dust clouds that obscure visible light and observe objects at much greater distances and redshifts. This infrared capability enables JWST to study the formation and evolution of galaxies, stars, and planetary systems, as well as to search for the faint heat signatures of exoplanets.

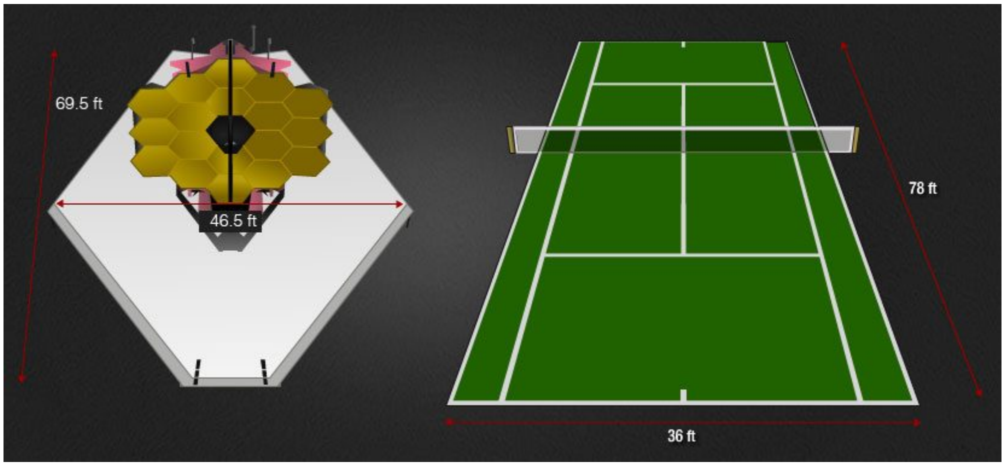

Figure 4.6: Size comparison of JWST

- **Larger Mirror (6.5 Metres):** JWST's primary mirror is 6.5 metres (21.3 feet) in diameter, significantly larger than Hubble's 2.4-meter mirror. This larger mirror allows JWST to collect more light, improving its sensitivity and enabling it to observe fainter objects. The segmented mirror design, which unfolds after launch, provides a much larger collecting area without exceeding the size limitations of the launch vehicle.
- **More Sensitive Instruments:** JWST is equipped with four highly sensitive scientific instruments: the Near Infrared Camera (NIRCam), the Near Infrared Spectrograph (NIRSpec), the Mid-Infrared Instrument (MIRI), and the Fine Guidance Sensor/Near InfraRed Imager and Slitless Spectrograph (FGS/NIRISS). These instruments provide unprecedented sensitivity and resolution across the infrared spectrum, enabling detailed studies of distant galaxies, star-forming regions, and exoplanet atmospheres.

Challenges

- **Mainly Operates in the Infrared Spectrum:** While JWST's infrared focus provides significant advantages, it also presents challenges. Infrared detectors must be kept extremely cold to function correctly, requiring complex and sensitive cooling systems. This limits the telescope's ability to observe in the visible and ultraviolet spectra, where Hubble excels. Additionally, the infrared observations require careful shielding from the Sun, Earth, and Moon to maintain the necessary low temperatures.
- **Extreme Cooling Requirements:** To observe in the infrared spectrum, JWST's instruments must be cooled to extremely low temperatures, around 40 Kelvin (-233 degrees Celsius). This is achieved using a combination of passive cooling with a large sunshield and active cooling for the mid-infrared instrument (MIRI). The sunshield, the size of a tennis court, is crucial in blocking heat from the Sun and Earth, but its deployment is a complex and high-risk process. Any failure in the cooling system could compromise the mission's scientific goals.

Notable contributions

- **Detailed Studies of the Early Universe:** JWST is designed to look back over 13.5 billion years to see some of the first stars and galaxies that formed after the Big Bang. Its advanced infrared capabilities allow it to observe the earliest stages of galaxy formation and provide insights into the evolution of the universe. This will help scientists understand the processes that led to the formation of the first stars, galaxies, and black holes.
- **Formation of Stars and Planetary Systems:** JWST's infrared sensitivity allows it to peer into dense molecular clouds where stars and planetary systems are born. It can observe the earliest stages of star formation, track the growth of protoplanetary disks, and study the chemical composition of these environments. This will enhance our understanding of how stars and planetary systems, including our own solar system, form and evolve over time.
- **Atmospheric Analysis of Exoplanets:** One of JWST's most exciting capabilities is its ability to analyse the atmospheres of exoplanets. By observing the starlight that passes through an exoplanet's atmosphere during a transit, JWST can detect and measure the presence of various molecules, such as water, carbon dioxide, and methane. This will help scientists determine the composition, structure, and potential habitability of exoplanets, advancing the search for life beyond our solar system.

Documentaries:

- PBS - Nova: "The Ultimate Space Telescope"
- Netflix - "The Most Unknown" (Features segments on JWST's development and potential discoveries)

Human achievements and advancements due to JWST

JWST represents one of humanity's most ambitious space projects, built through the collaboration of NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). The technological innovations developed for JWST, such as its segmented mirror and sunshield, have pushed the boundaries of engineering and have set new standards for future space telescopes. The discoveries made by JWST are expected to revolutionise our understanding of the universe, from the origins of the first galaxies to the potential for life on other planets.

JWST's contributions to astronomy and space science will be monumental, providing unprecedented data that will inform and inspire future generations of scientists and engineers. Its success in overcoming engineering challenges and its potential to answer some of the most profound questions about the cosmos are a testament to human ingenuity and curiosity.

Resources

Space-Based and Ground-Based Telescopes: A Collaborative Approach

Space-based and ground-based telescopes are not mutually exclusive but rather complementary in their capabilities. They serve different purposes and work together to provide a more comprehensive understanding of the universe. Space telescopes, with their unobstructed views and access to multiple wavelengths, excel in producing high-resolution images and capturing data on celestial objects and events that are inaccessible from the ground. Ground-based telescopes, on the other hand, offer cost-effective observation and the ability to adapt and upgrade technology easily, allowing for long-term monitoring of specific targets and large-scale surveys. For example, ground-based telescopes can provide follow-up observations and complementary data to space-based missions, validating and refining scientific findings.

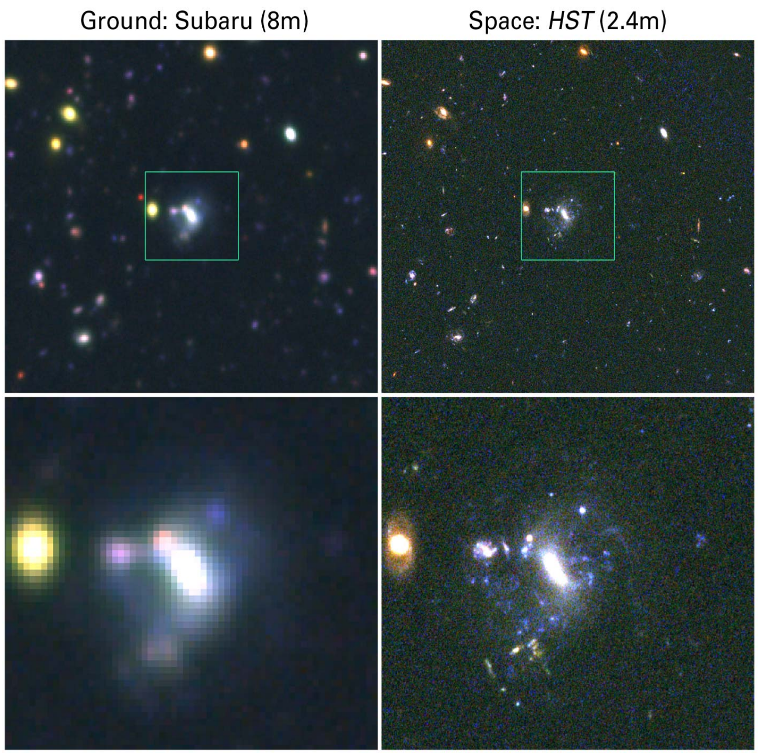

Figure 4.7: Resolution difference between ground-based telescopic imaging and HST

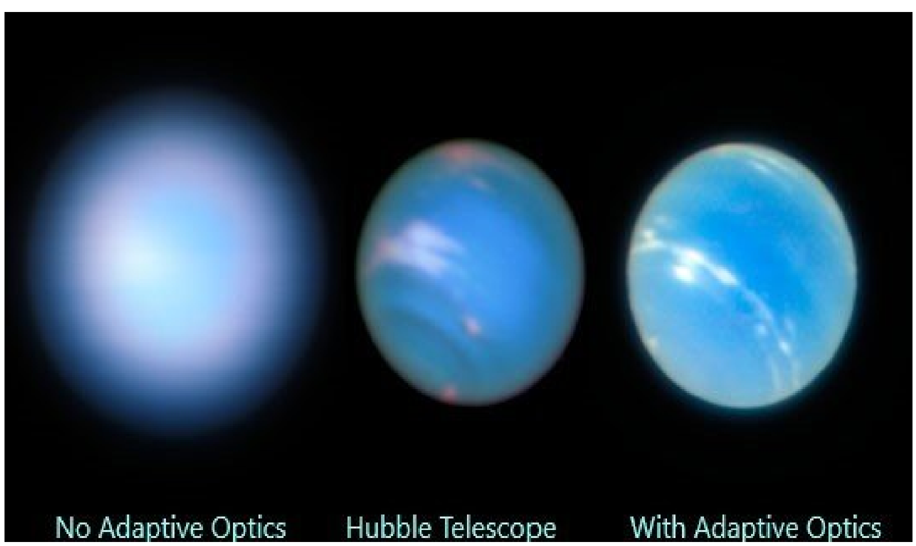

Figure 4.8: With and without adaptive optics

Comparative analysis of HST and JWST

The JWST and Hubble are complementary in their functionality as they work together to give us a comprehensive picture of the universe, from its earliest moments to the wonders that exist around us today. We shall look into three aspects of comparison for the HST and JWST:

1. Positioning in space
2. Wavelength of operation
3. Differences in structure, resolution and sensitivity

1. **Positioning in space**

   Hubble space telescope:

   - **Positioning:** Hubble orbits in Low Earth Orbit (LEO) at an altitude of approximately 547 kilometres (about 340 miles).
   - **Advantages of LEO:** The placement allows for easy servicing missions and relatively low communication delays with Earth.
   - **Disadvantages of LEO:** The telescope is still subject to some atmospheric drag and radiation, which can affect observations.

   James Webb space telescope:

   - **Positioning:** JWST orbits the Sun-Earth Lagrange Point 2 (L2), approximately 1.5 million kilometres from Earth in the direction opposite to the Sun.
   - **Advantages of L2:** This unique positioning allows JWST to maintain a stable orbit with minimal fuel consumption and to utilise a large sunshield to protect its instruments from solar radiation.
   - **Disadvantages of L2:** The distance makes servicing missions impractical, and the telescope must rely on its initial deployment and instruments.

Figure 5.1: Hubble's orbit

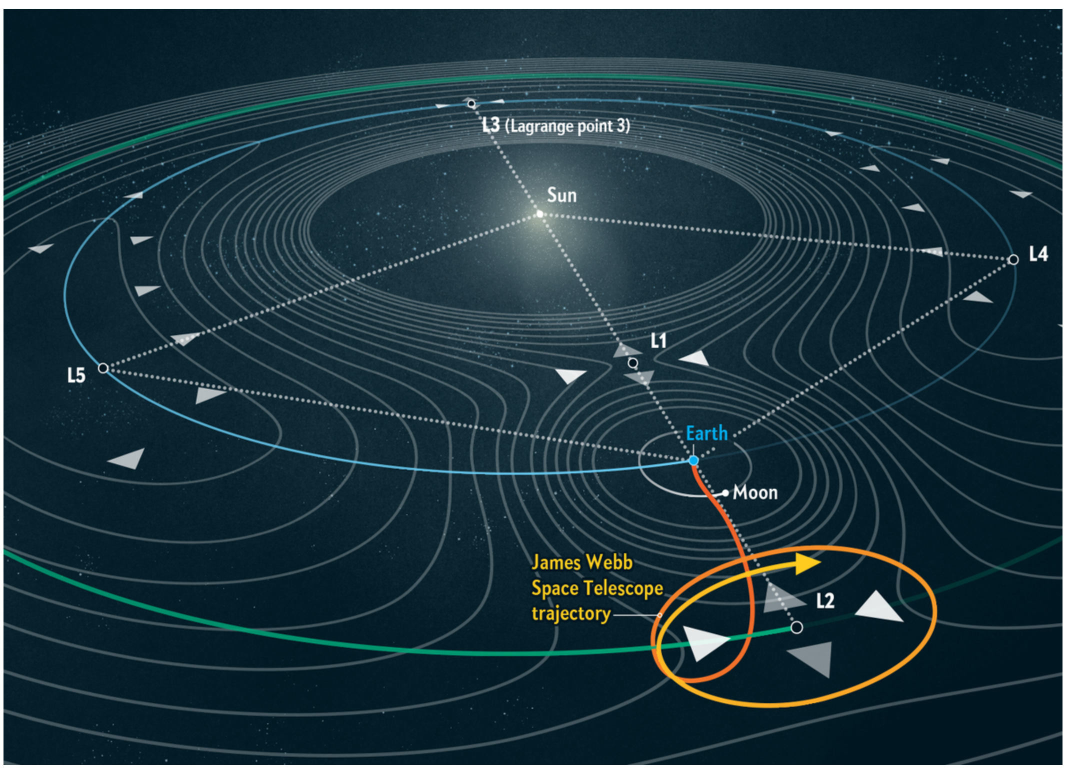

Figure 5.2: JWST at L2

UNIQUE POSITIONING OF JWST: The James Webb Space Telescope is unique in its positioning as it orbits the Sun-Earth Lagrange point 2, or L2 for short. L2 is approximately 1.5 million kilometres from Earth in the direction opposite to the sun. Lagrange points are positions in space where objects sent there tend to stay put.
At Lagrange points, the gravitational pull of two large masses precisely equals the centripetal force required for a small object to move with them. These points in space can be used by spacecraft to reduce fuel consumption needed to remain in position. The L2 orbit allows JWST to use a large sunshield to protect its instruments from solar radiation. This is crucial for infrared observations, as it keeps the telescope extremely cold, which is necessary to detect faint heat signals from distant celestial objects.

2. **Wavelength of operation**

Hubble space telescope:

- **Wavelength range:** Hubble observes light at primarily optical and ultraviolet wavelengths, ranging from about 200 nanometers (nm) to 2.4 microns.
- **Observations:** This range allows Hubble to study a variety of phenomena, including young, hot stars emitting ultraviolet light and visible light from various cosmic objects.
- **Unique observations:** Hubble's range has enabled it to capture some of the most iconic images of the universe, such as the Pillars of Creation and the Hubble Deep Field.

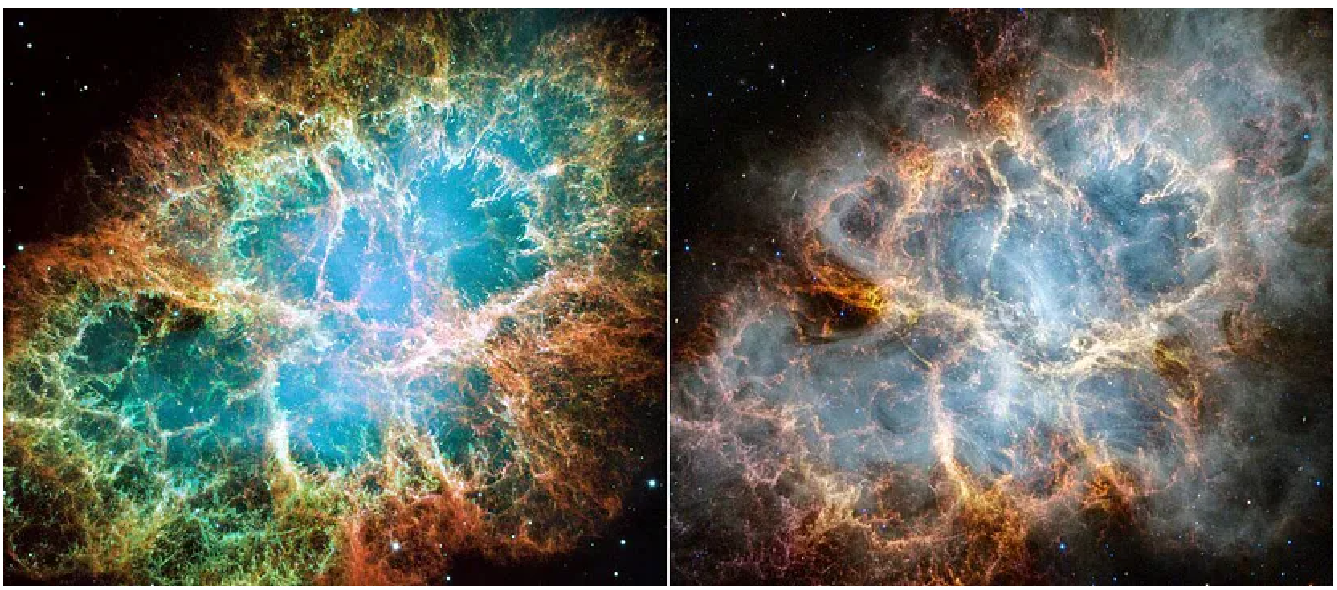

Figure 5.3: Crab nebula: L: 2005 Hubble optical wavelength image, showcasing its appearance in visible light with a blend of vibrant colors and intricate patterns. R: Image from the James Webb Space Telescope's NIRCam and MIRI instruments

James Webb space telescope:

- **Wavelength range:** JWST is designed to detect primarily infrared light, covering wavelengths from about 600 nm to 28 microns.

- **Observations:** The infrared focus allows JWST to peer through cosmic dust clouds and observe the heat emitted by distant objects, making it ideal for studying the early universe, star formation, and the atmospheres of exoplanets.
- **Unique observations:** JWST's infrared capabilities will enable it to observe phenomena that are invisible in visible light, such as the first galaxies formed after the Big Bang.

Figure 5.4: Carina nebula: HST vs JWST

Conclusion: Hubble's broad wavelength range from ultraviolet to near-infrared allows for a wide variety of astronomical observations, while JWST's infrared focus lets it explore regions of the universe obscured by dust and distant in time and space. Each telescope's wavelength coverage complements the other, providing a more comprehensive understanding of the cosmos.

3. **Differences in structure, resolution and sensitivity**

Hubble space telescope:

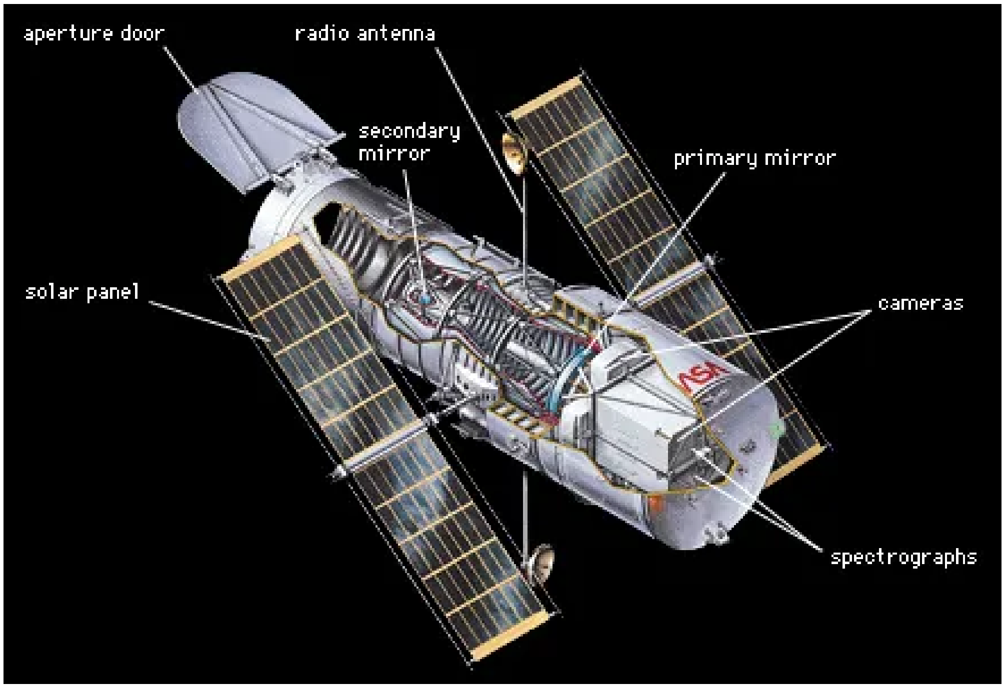

Figure 5.5: Parts of HST

- **Structure:** Hubble's structure includes a 2.4-meter primary mirror and various instruments designed for visible and ultraviolet observations.

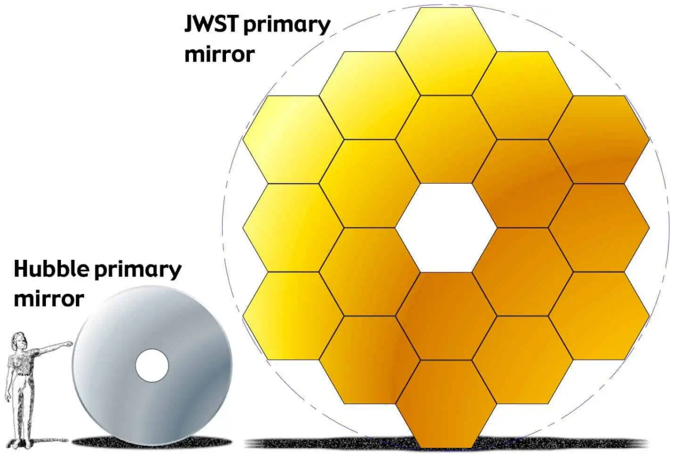

Figure 5.6: Primary mirrors of HST and JWST

- **Resolution and sensitivity:** Hubble has provided the world with stunning images for decades and has high angular resolution, allowing it to capture sharp images of distant galaxies and other celestial objects.

- **Achievements:** Hubble's significant contributions include determining the rate of expansion of the universe, observing the formation and evolution of galaxies, and studying exoplanets and their atmospheres.

James Webb space telescope:

- **Structure:** JWST features a 6.5-meter primary mirror, much larger than Hubble's, and is equipped with cutting-edge detectors and four scientific instruments: NIRCam, NIRSpec, MIRI, and FGS-NIRISS.

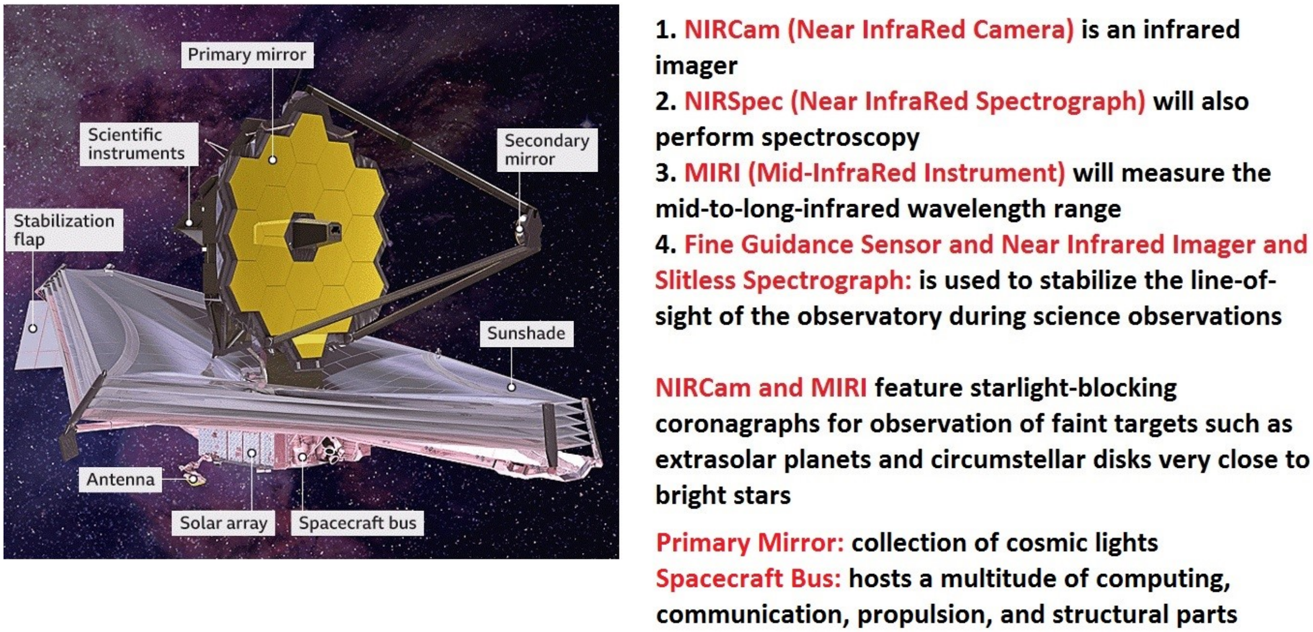

Figure 5.7: Parts of JWST

- **Resolution and sensitivity:** JWST's larger mirror provides more surface area to collect light, significantly improving its sensitivity and allowing it to observe much fainter objects. It can detect objects 10 billion times fainter than the faintest stars visible with no telescope, or 10 to 100 times fainter than what Hubble can observe.

- **Achievements:** JWST is designed to "see" the first stars and galaxies that formed in the early universe, study the formation of stars and planetary systems, and analyse the atmospheres of exoplanets for potential signs of life.

Conclusion: JWST's larger mirror and more advanced instruments give it a distinct advantage in terms of resolution and sensitivity, allowing it to observe much fainter and more distant objects than Hubble. While both telescopes provide sharp images, JWST's capability to look deeper into the infrared spectrum enables it to see much farther back in time, offering new insights into the early universe and the formation of cosmic structures.

Future of telescopes and astronomical imaging

The Nancy Grace Roman Space Telescope
The Nancy Grace Roman Space Telescope, formerly the Wide Field InfraRed Survey Telescope (WFIRST), is a NASA observatory designed to settle essential questions in the areas of dark energy, exoplanets, and infrared astrophysics. Expected to be launched by May 2027 to L2, it is designed for a five-year mission. The telescope has a primary mirror that is 2.4 meters in diameter (7.9 feet) and is the same size as the Hubble Space Telescope's primary mirror. The Roman Space Telescope will have two instruments:

- **Wide Field Instrument:** The Wide Field Instrument (WFI) is a 300-megapixel infrared camera that will have a field of view that is 100 times greater than the Hubble infrared instrument, capturing more of the sky with less observing time. With its 18 detectors, each Roman image will capture a patch of the sky bigger than the apparent size of a full Moon. Hubble's infrared images, taken with its Wide Field Camera 3, are about 200 times smaller. Even Hubble's widest exposures, taken with the Advanced Camera for Surveys, are nearly 100 times smaller. Over the first five years of observations, Roman will image over 50 times as much sky as Hubble covered in its first 30 years, surveying the sky up to 1,000 times faster than Hubble can while maintaining similar sensitivity and infrared resolution. It will perform a microlensing survey of the inner Milky Way to find 2,600 exoplanets.

- **The Roman Coronagraph instrument and its objectives:** The light from an exoplanet, as it would be seen in reflected starlight, is fainter than the host star by factors of 100,000,000 or more, and well beyond the reach of today's observatories on the ground or in space. The Roman Coronagraph is a system of masks, prisms, detectors, and even self-flexing mirrors built to block out the glare from distant stars and directly image the planets in orbit around them. It will be the first high-performance coronagraph system in space capable of imaging directly mature gas giant exoplanet systems (similar to our own Jupiter) in reflected starlight, paving the way to a future possible NASA mission aimed at imaging and characterizing faint Earth-like planets.

  Current ground-based and space-based instruments are limited to the detection of bright (self-luminous) young exoplanets, a million times fainter than their host star and located >0.3 arc seconds away. A successful Coronagraph technology demonstration, i.e., just meeting its threshold technical requirement (TTR), will be capable of detecting planetary companions 10 million times fainter than their host star and located >0.3 arcseconds away.

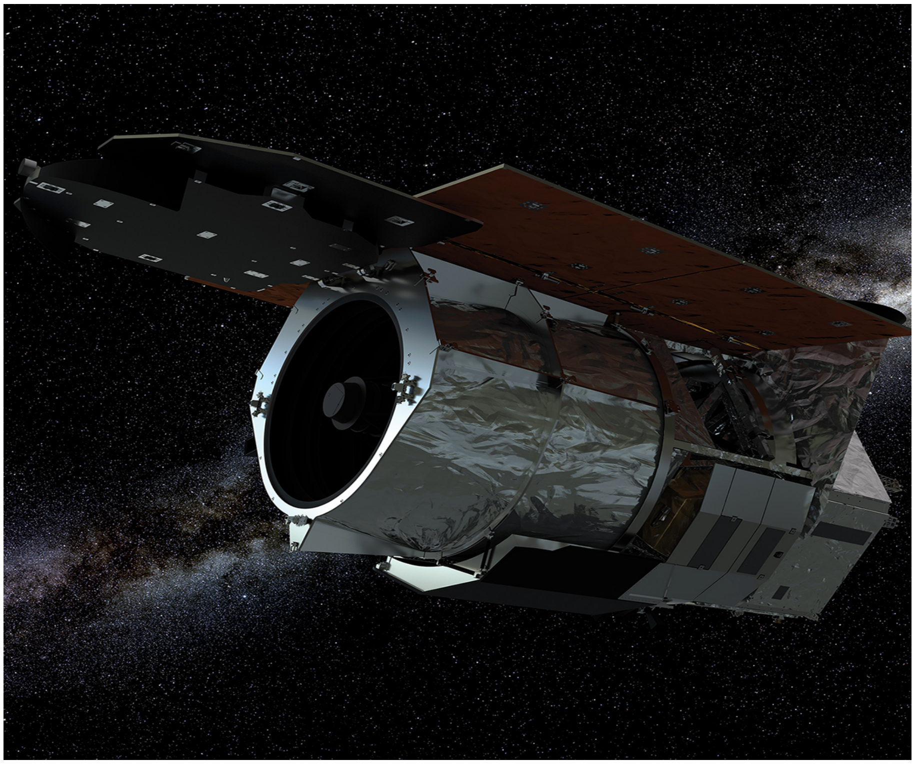

Figure 6.1: Nancy Grace Roman space telescope

Performance models based on current lab results predict the Coronagraph would be capable of detecting planetary companions a billion times fainter than their host star and located >0.15 arcseconds away. The Coronagraph provides a crucial stepping stone in the preparation of future missions aiming to image and characterize Earth-like planets 10 billion times fainter than their host star and located 0.1 arcseconds away. Coronagraph observations will advance community goals in exoplanet astronomy and how it will validate key technologies for future exoplanet missions, now envisioned as HabEx and LUVOIR.

Deep dive (More resources)

- Why are the mirrors of JWST hexagonal?
- Why are the mirrors of JWST gold plated?
- Simulation to understand JSWT and HST