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Year 11 - 12

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SHE Task

James Webb Space Telescope

Stage 2 Physics

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Introduction

The James Webb Space Telescope (JWST) is humanity's newest and most advanced space telescope, designed to study the history of our universe. Developed collaboratively by NASA, the European Space Agency (ESA) and the Canadian Space Agency (CSA) since 1996, it is designed as the successor to the Hubble Space Telescope (HST) (*Gregersen, 2026*). It was launched in late December 2021, and spent roughly six months travelling to its orbital position, before its first images were released on 12 July 2022 (*ESA, 2022*). It has a nominal mission length of five years, though astronomers expect it to operate for over 10 years (*ESA, 2021a*). Unlike its predecessors, Webb uniquely orbits the Sun rather than the Earth, and analyses infrared light to see further, and thus deeper into the past, than ever before (*Gregersen, 2026*). This report will discuss how the development of the JWST is improving humanity's understanding of the universe.

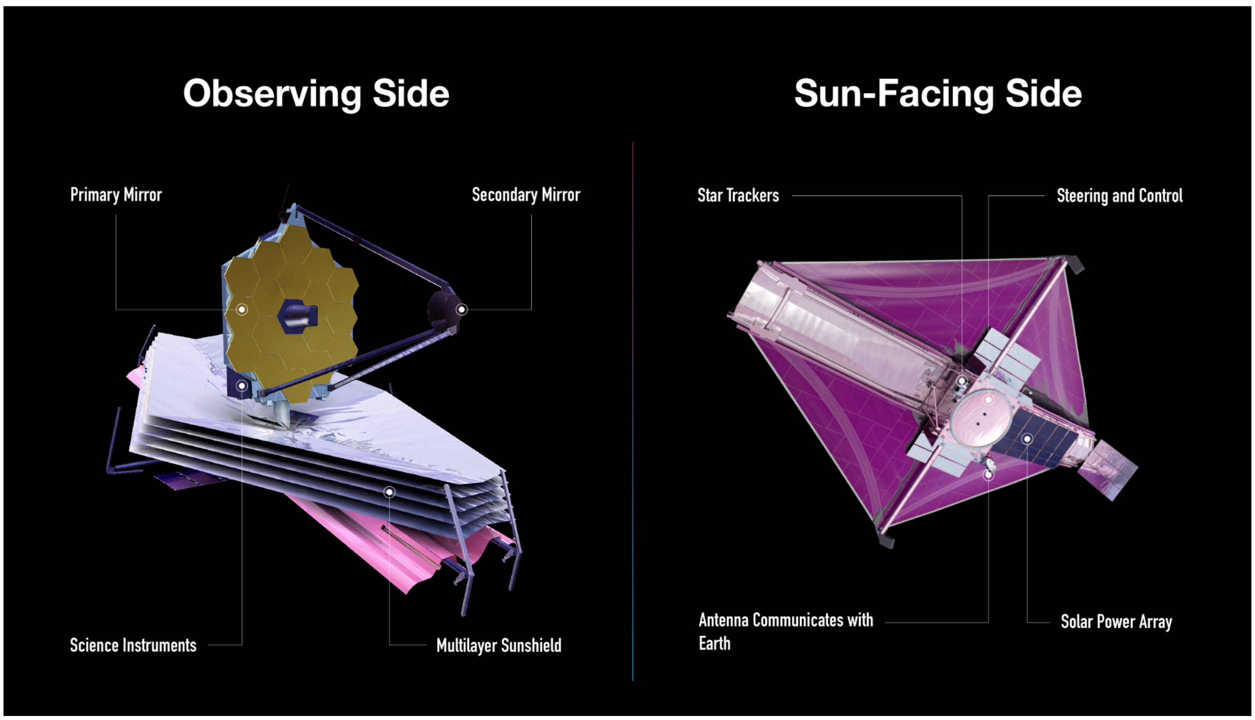

Figure 1: A labelled diagram of the JWST, depicting observing and sun-facing sides. Source: https://science.nasa.gov/asset/webb/diagram-of-the-james-webb-space-telescopes-main-components/

Science Background

To observe the earliest events of the universe, the JWST examines light emitted by the very first objects. Since the Big Bang, the universe has been constantly expanding, causing light from distant bodies to be redshifted, stretching it into longer wavelengths that appear redder to the eye (*ESA, 2021b*). The further away an object is, the greater this redshift effect. Therefore, the most distant bodies, which are of interest since they are the furthest back in time, emit light that is redshifted to such a degree that it now lies in the infrared (IR) part of the electromagnetic spectrum (*ESA, 2021b*). Webb must therefore observe in infrared, which requires it to be shielded from nearby sources of IR radiation, specifically the Sun, Earth, and Moon, since they could overwhelm the faint light from distant objects.

Hence, the telescope's orbit is a crucial factor for its successful function. It orbits the Sun from a point named Lagrange Point 2 (L2), which sits approximately 1.5 million kilometres from Earth, opposite to the Sun (see *Figure 2*) (*NASA, 2024a*). There are five Lagrange Points, but they share an identical characteristic: they are positions in space where the gravitational forces from two bodies (the Sun and Earth) provide the required centripetal force for a small object to move with them (*NASA, 2018*). This makes Lagrange Points ideal for long-term space missions like Webb's, as satellites positioned there require minimal fuel (*NASA, 2024a*).

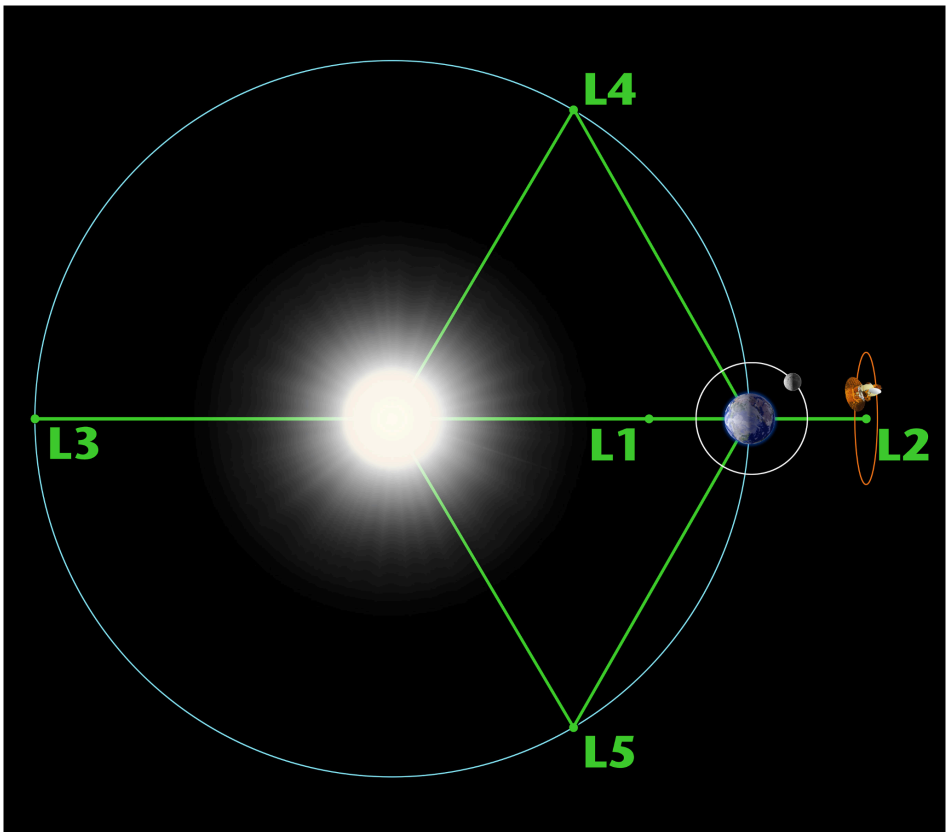

Figure 2: A diagram depicting the locations of all five Lagrange Points with reference to the Sun, Earth and Moon. Source: https://science.nasa.gov/resource/what-is-a-lagrange-point/

The JWST is specifically positioned at L2, since at this point, the Sun, Earth and Moon are always located behind Webb's sunshield (*NASA, 2024a*). This means the telescope is constantly shielded from IR radiation emitted by these bodies throughout its orbit, allowing for detailed deep space observations.

Webb requires a specific centripetal acceleration to maintain this orbit, which is determined as follows.

The velocity required for JWST's orbit can be calculated from:

$$v = \frac{2\pi r}{T} \ldots (1)$$

Since Webb orbits the Sun 1.5 million kilometres further than Earth, its orbital radius is:

$r_{Webb} = r_E + 1.5 \times 10^9$
$\approx 1.5 \times 10^{11} + 1.5 \times 10^9$
$\approx 1.515 \times 10^{11}$
$\approx 1.52 \times 10^{11}\, m\ (2\ s.f.)$

Webb's orbital period must match Earth's, which is
$= 365.25\, days \times 24\, hours \times 60\, minutes \times 60\, seconds$
$\approx 3.2 \times 10^7\, s.$

Using (1), the required velocity for JWST's orbit is:

$v = \frac{2\pi(1.52 \times 10^{11})}{3.2 \times 10^7}$
$\approx 29,845$
$\approx 3.0 \times 10^4\, ms^{-1}\ (2\ s.f.)\ tangential\ to\ its\ orbit$

The required centripetal acceleration for Webb to maintain this velocity is determined using:

$$a_c = \frac{v^2}{r} \ldots (2)$$

$a_c = \frac{(3.0 \times 10^4)^2}{1.52 \times 10^{11}}$
≈ 0.0059

$\approx 5.9 \times 10^{-3}\, ms^{-2}\ towards\ the\ Sun.$

At L2, this acceleration is provided by the combined gravitational forces from the Sun and Earth, and is therefore acceleration due to gravity (*Figure 3*).

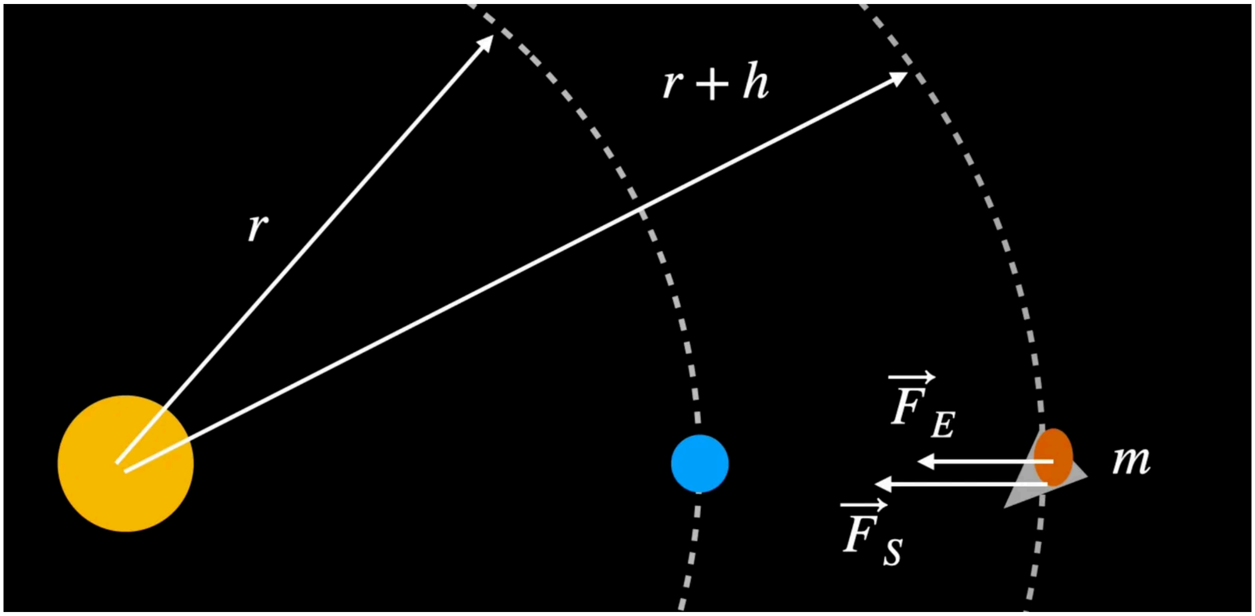

Figure 3: A force diagram depicting the gravitational forces ($\vec{F}_E$ from Earth and $\vec{F}_S$ from Sun) acting on the JWST (denoted m) at L2. Source: [*https://www.wired.com/story/the-physics-of-the-james-webb-space-telescope/*](https://www.wired.com/story/the-physics-of-the-james-webb-space-telescope/)

Using Newton's Second Law and Newton's Law of Universal Gravitation, the accelerations contributed by each body can be derived as:

$$F = G\frac{Mm}{r^2} \dots (3)$$

$$F = ma$$

$$\therefore a = \frac{F}{m}$$

$$\therefore a = \frac{G\frac{Mm}{r^2}}{m} \qquad \{\text{using } (3)\}$$

$$\therefore a = \frac{GM}{r^2}$$

Substituting values, acceleration due to Earth's gravity is:

$$a = \frac{(6.67 \times 10^{-11})(5.97 \times 10^{24})}{(1.50637 \times 10^{9})^2}$$

$$\therefore a = 1.75 \times 10^{-4}\ ms^{-2}\ towards\ the\ Sun$$

Similarly, for the Sun:

$a = 5.8 \times 10^{-3} ms^{-2}$ *towards the Sun*

Together, $a = 1.75 \times 10^{-4} + 5.8 \times 10^{-3} = 0.0059 \approx 5.9 \times 10^{-3} ms^{-2}$ towards the Sun.

Since this sum matches the required centripetal acceleration calculated previously, it proves the combined gravitational pull of the Sun and Earth is what enables the JWST to remain at L2.

However, Webb's orbit at L2 is meta-stable, meaning small perturbations from other masses, or imperfections in its course, will cause it to eventually drift away from this point (*NASA, 2024a*). To counteract this, Webb performs periodic course corrections, which result in Webb orbiting L2 in a three-dimensional loop, appearing as a halo when viewed from Earth - thus referred to as a halo orbit (*Figure 4*) (*NASA, 2024a*).

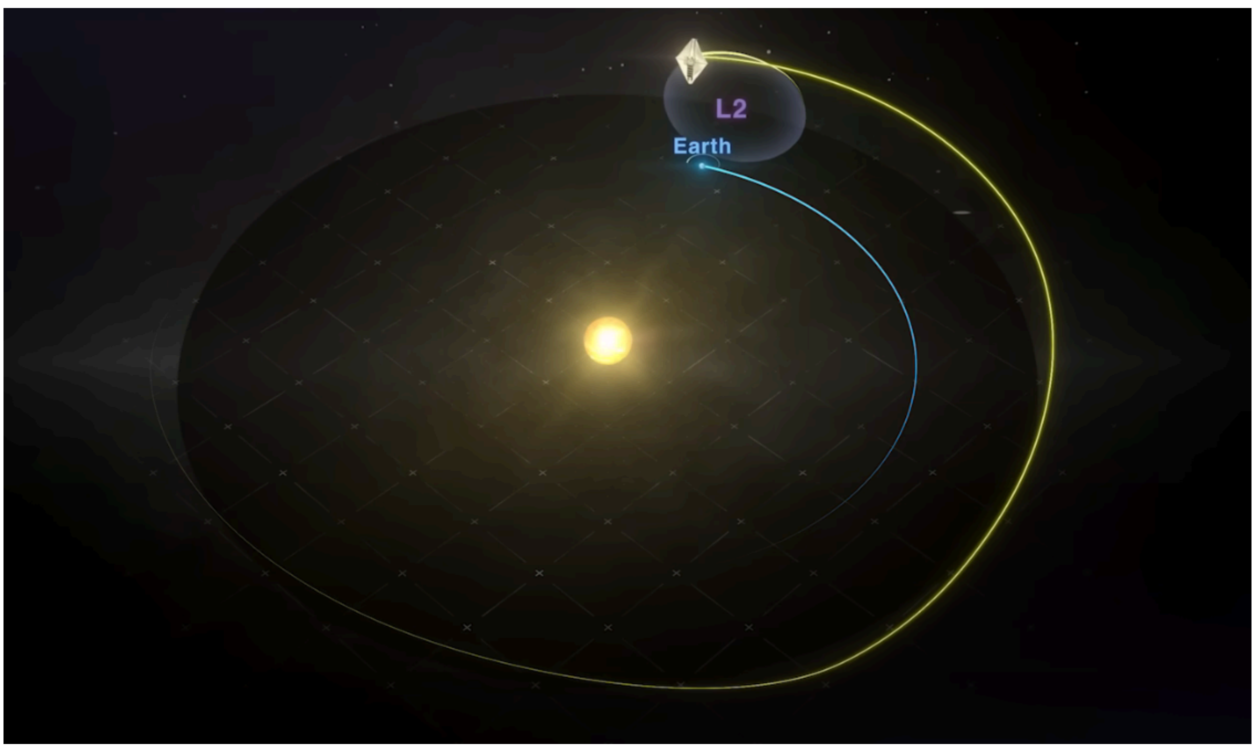

Figure 4: An image from an animation depicting the JWST's halo orbit at L2. Source: [*https://science.nasa.gov/mission/webb/orbit/*](https://science.nasa.gov/mission/webb/orbit/)

Development of Humanity's Scientific Understanding of the Universe

Scientific discoveries and breakthroughs are often driven by the development of new technologies. This is particularly true in astronomy: Galileo's use of the first telescopes, for example, provided direct evidence supporting the heliocentric model of the Solar System (*Whitworth, 2022*). The JWST is a prime modern example, since its infrared sensors are enabling observations of the distant universe that weren't possible with previous technology. In doing so, Webb is driving significant developments in humanity's understanding of early galaxy formation and exoplanets.

Early Galaxy Formation

To study early galaxies, astronomers must observe the most distant ones, since these are the oldest in the universe. However, because these galaxies are so distant, their light has been redshifted into the IR part of the electromagnetic spectrum. Previous telescopes, particularly the HST, lacked the technology to detect these wavelengths. However, Webb's infrared sensors can detect them, and since beginning observations in 2022, its discoveries have already prompted revisions to humanity's understanding of early galaxy formation.

Currently, the Lambda Cold Dark Matter (ΛCDM) model is the accepted model for cosmology (*Grayson et al, 2025*). It combines three major elements, the Cosmological Constant (Λ) associated with dark energy, cold (slow-moving) dark matter, and ordinary matter, to explain the universe's evolution from the Big Bang to today (*Perera, 2024*). According to this model, galaxies were thought to form hierarchically, meaning small structures formed first, then merged to form successively larger structures like galaxies (*Dayal et al., 2014*). In this model, baryons (subatomic particles formed of three quarks) fall into dark matter halos, invisible structures surrounding galaxies that make up most of their masses, where they cool and form stars, causing galaxies to slowly grow in brightness and mass (*Benson, 2010*) (*Wechsler & Tinker, 2018*). As a result, early galaxies were initially thought to have been relatively small and low in mass, emitting faint light, since not enough time had passed for more mature galaxies to form (*Benson, 2010*).

However, Webb's infrared cameras captured a large number of inexplicably bright early galaxies, which were initially dated to just 250 million years after the Big Bang (*Wright, 2024*). This challenged existing theories, including the ΛCDM model, which deemed this phenomenon impossible. But with more data from Webb, astronomers later revised this date to 1.2 billion years after the Big Bang, when galaxies were slightly more widespread (*Wright, 2024*). Nevertheless, the revised date is still too early for mature galaxies to have formed, meaning that JWST's observations of an unexpectedly high number of them are still puzzling scientists (*Smethurst, 2025*). It implies current theories, like the ΛCDM model, are possibly missing key processes of galaxy formation, which presents opportunities to deepen our understanding of the universe.

Exoplanet Features

Webb has also advanced our understanding of exoplanets - planets outside of the Solar System (*Lee, 2018*). Prior to the JWST, thousands of exoplanets had already been discovered, yet their compositions remained largely unknown (*NASA, 2025*). Earlier space telescopes like the Hubble could analyse key features of exoplanets, like composition, using emission spectroscopy, but only in the ultraviolet, visible, and near-infrared spectrum (*NASA, 2024b*). While this allowed it to discover elements like carbon and atomic oxygen on exoplanets, compounds like carbon dioxide and methane remained undetectable, since these exhibited an infrared emission spectrum which Hubble couldn't analyse (*Iowa State University, 2024*).

Detecting these gases is crucial, since alongside others like oxygen, these compounds are referred to as "biosignature gases" - gases produced by biological processes that accumulate in a planet's atmosphere to levels high enough to be detected by telescopes, indicating possible signs of life (*Seager et al., 2025*). Webb's infrared technology, unlike previous telescopes, enables it to find evidence of such compounds. This was demonstrated when the JWST captured the first clear evidence of carbon dioxide on WASP-39 b, a hot exoplanet roughly the size of Jupiter (*NASA, 2022*). Earlier telescopes had confirmed the presence of sodium, potassium and water vapour, but it was Webb's infrared sensitivity that allowed for carbon dioxide to be identified too (*NASA, 2022*). Since carbon dioxide is a biosignature gas, Webb's detection of it on WASP-39 b could have indicated potential signs of life - though its extreme heat later proved it to be uninhabitable (*ESA, 2024*). Nonetheless, the JWST's ability to detect biosignature gases is advancing our understanding of exoplanet habitability, and humanity's search for extraterrestrial life (*Greene et al., 2016*).

Beyond identifying signs of life, Webb's infrared technology is capable of tracing planet origins. A planet's atmospheric composition reflects the material it accreted from its protoplanetary disk - a rotating cloud of dust and gas remaining after its host star's formation (*Cridland et al., 2016*). Since regions of the disk vary in chemical composition, analysing an exoplanet's atmosphere can provide insights into where and how it formed (*Cridland et al., 2019*). Typically, a planet's atmosphere mirrors its host star's composition, since both formed from the same matter (*Sanchez et al., 2026*). However, Webb discovered exoplanet TOI-5205 b, a Jupiter-sized gas giant, to have a surprisingly metal-poor atmosphere despite its host star being metal-rich (*Cañas et al., 2026*) . This suggests the planet did not accrete material from its protoplanetary disk as current theories predict, indicating unknown formation processes, and demonstrating how Webb's observations are refining our understanding of planet formation.

Conclusion

Ultimately, the JWST has advanced humanity's understanding of the universe in ways that were previously impossible. Because of its special orbit at L2 and revolutionary infrared detection technology, Webb has enabled detailed analysis of exoplanet atmospheres and early galaxy formation, providing unprecedented insights into the origins of the universe and potential for life elsewhere.

Word Count (excl. references and calculations): 1498 Words

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