The James Webb Telescope

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Summer Paper (Received full marks)

March 2, 2024

1 Introduction

The James Webb Telescope (JWST) shown in Figure 1 was a space telescope conceived by NASA and manufactured by Northrop Grumman (NASA 2018a) to conduct infrared astronomy to study the unexplored origins of the universe. The high-resolution instrumentation onboard the JWST allows it to capture electromagnetic radiation from distant objects that would be out of view from its predecessor, the Hubble Space Telescope (HST). Telescopes can often be referred to as *time machines*, because of their ability to observe light from distant objects as they appeared in the past. The HST was a very successful time machine that unlocked discoveries about "infant" galaxies and even the 2011 Nobel Prize (Nobel Foundation 2011). NASA sought to build on this success with an even more powerful time machine that could fill the gap in the electromagnetic spectrum left by the HST to analyse "newborn" galaxies and possibly unearth new astrophysics.

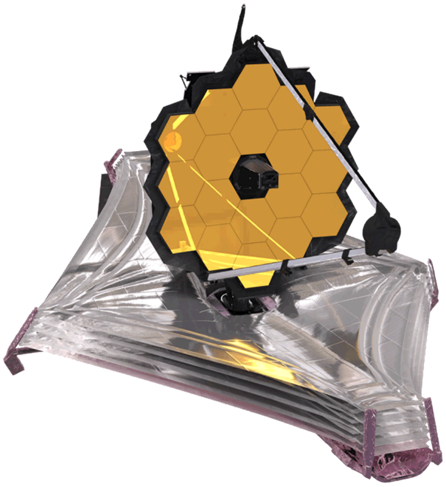

Figure 1: Rendering of the fully deployed James Webb Telescope. Courtesy of https://commons.wikimedia.org/wiki/File:JWST_spacecraft_model_3.png (Public Domain).

The technological advancements in high-sensitivity and resolution sensors have produced a powerful fleet of space-based telescopes that have uncovered the history of the universe, answering numerous questions and sparking new ones. NASA's Great Observatories program (NASA 2020) has deployed four of these space-based telescopes with powerful detection capabilities that specialise in certain wavelength bands of the electromagnetic spectrum. The HST was designed to focus on visible light and was later extended to support near-infrared (NASA 2001). Despite the incredible engineering feat by Lockheed Martin (NASA 2019d) the HST's Deep Field observations are optimised for the wavelengths of visible light (along with small quantities of infrared and ultraviolet) that are obstructed by cosmic debris (dust and gas clouds) during attempts to image the regions of the interstellar medium (ISM) responsible for star and planetary formation. JWST's deeper infrared capabilities will be able to cut through this debris and unlock discoveries of how planets and stars are formed. Infrared sensors will also allow JWST to capture primordial light that has been redshifted to infrared wavelengths due to the Doppler effect (Lemaitre 1979) that was previously not detectable by telescopes on Earth.

2 Background Scientific Information

The JWST has been deployed to focus on four major themes as in NASA (2019c), each aligning with significant scientific objectives. These objectives are integral to advancing our understanding of the universe and addressing current knowledge gaps.

2.1 Early Universe

Understanding the first galaxies is now possible by conducting ultra-deep infrared surveys of the universe with the JWST. Combined with spectroscopy and photometry methods to process and refine the results captured by the JWST, astronomers will be able to understand the composition, structure, and distribution of the earliest galaxies possibly unlocking knowledge about the formation of the universe and the nature of dark matter.

For example, by collecting data on the rotation curves of the earliest galaxies, astronomers can improve the theory that dark matter halos account for the non-uniform rotation speeds observed at varying distances from the center of a galaxy (Frenk et al. 1985). Should the data reveal differences between the rotation curves of modern galaxies and their ancient counterparts, it might suggest that dark matter properties have evolved over time. Such a finding could, in turn, influence the way astronomers model the isothermal density profile of dark matter surrounding galaxies (Begeman, Broeils, and Sanders 1991),

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1}, \tag{1}$$

where r_c is the core radius and ρ_0 is the central dark matter density.

Furthermore, a study into ancient dwarf galaxies[1] which have been observed to be dominated by dark matter (Carignan and Freeman 1988) (so-called "dark" galaxies) has the potential to unlock more knowledge of the nature of dark matter and its role as the "invisible" scaffolding of the universe.

2.2 Galaxies Over Time

The high-sensitivity camera and spectrograph on board the Mid-Infrared Instrument (MIRI) module of the JWST (NASA 2018b) in Figure 2.2 enables astronomers to compare the earliest galaxies with the grand spiral and elliptical structures we observe today. Understanding how galaxies evolved was previously hindered by the lack of data on "newborn" galaxies. Being a specialty of the JWST, this newly sourced data will help discover why earlier galaxies were often observed to be smaller and eventually merged to form the modern structures we see today (Dorminey 2009). It is now possible to analyse the broader impact of the merge

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[1] Some of the first galaxies to form in the universe before colliding with other galaxies.

events that have occurred to form nearly all massive galaxies since the universe was six billion years old (NASA 2008).

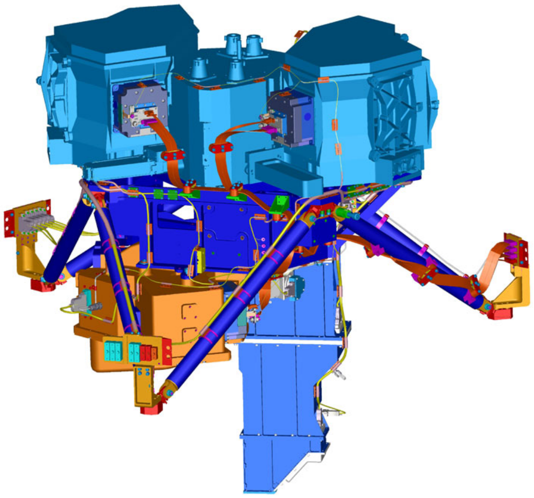

Figure 2: Engineering diagram of the Mid-Infrared Instrument (MIRI) module that sits on board the JWST at a nominal operating temperature of 7K. Courtesy of `https://webb.nasa.gov/images/miri.jpg` (Public Domain).

Moreover, astronomers can attempt to prove whether star formation is an internal galactical process or a consequence of interactions between other galaxies. Understanding the growth and evolution of galaxies will also help us understand the influence that supermassive black holes at their centre (Magorrian et al. 1998) have on the broader system and the role that dark matter accumulation has in galaxy formation, specifically the structure of Cold Dark Matter (CDM) halos (Navarro 1996).

2.3 Star Lifecycle

The HST captured many images of large nebulae that ultimately are stellar factories (Shu, Adams, and Lizano 1987). However, the dust from these nebulae obstructs the visible light being emitted from hidden stars in that region. The near-infrared capabilities of the HST allowed astronomers to take low-resolution peaks into the dusty cocoons of these stellar factories. JWST's 100x more powerful infrared hardware (NASA 2019b) will provide an even higher-resolution view inside these stellar factories possibly explaining why stars always form in groups and the role stellar accretion disks play in planetary formation (if any).

2.4 Other Worlds

The JWST aims to capture evidence to discover if organic life on planets outside of our solar system can exist through observing exoplanets that orbit the habitable zones of their host star and analysing their atmosphere for biosignatures (NASA 2019a). Capturing the infrared light of an exoplanet as they transit their bright host star (NASA 2016) with modern spectroscopy and chronographs will provide scientists with enough data to scan for life forms.

For the first time, fast-moving objects in our solar system can be tracked using the sophisticated software stack powering the JWST pointing control system. The image quality for moving targets is expected to be comparable to that for fixed targets (Milam et al. 2016). Tracking Mars and corroboration of results from NASA's Martian rovers and landers will help scientists understand the trace amounts of organic compounds in the Martian atmosphere and discover if life on Mars has ever existed.

3 Data Gathering

JWST's NIRCam (Near Infrared Camera) imaging acquired galaxy candidates at redshifts of $z \sim 9 - 15$ in the first year of operations (Castellano et al. 2022). This showed the unique infrared capabilities of JWST to discover galaxies at the high-redshift frontier. Two remarkably luminous galaxy candidates were observed at $z = 10.4^{+0.4}_{-0.5}$ and $z = 12.4^{+0.1}_{-0.3}$, forming the brightest and most distant stars ever observed (Naidu et al. 2022). Astronomers determined that these galaxies were forming stars at a rate of one hundred solar masses per year, which shows bright galaxies during much earlier epochs than previously anticipated.

As part of the unprecedented early release observations of the JWST, galaxies with redshifts of $z \sim 8$, belonging to the epoch of reionisation, were observed to have properties similar to local analogs (Schaerer et al. 2022). This could mean that the galaxy evolution process was already in place early in the history of the universe, suggesting it has been relatively stable over the past 13 billion years. The first JWST observations of gravitational lensing (Caminha et al. 2022) built off pre-testing from the HST (Coe et al. 2019) produced results that have helped astronomers reduce uncertainties in galaxy cluster mass measurements by 51%.

The data collected on exoplanets that have been confirmed to orbit in the habitable zone of their host stars will be the priority of the JWST deep imaging missions in search of biosignatures. Specifically, tidally locked rocky exoplanets will be analysed using a new scaling model to predict atmospheric heat distribution (Koll 2022). A tidally locked planet always has one side facing the star it orbits, creating a permanent dark and light side. The dark side can be cool enough to facilitate the formation of liquid water. With a more accurate atmospheric prediction model, astronomers will be able to accurately assess the habitability of exoplanets such as the TRAPPIST-1b and TRAPPIST-1e that orbit the TRAPPIST red dwarf star system discovered in 1999 (Gillon et al. 2016).

4 Scientific Contributions

The JWST represents a quantum leap in advancing our current scientific knowledge of the cosmos. By probing the early universe we have gained insight into the formation, composition, and distribution of the first galaxies. These insights allow astronomers and astrophysicists to refine their leading theories on concepts like dark matter and the origins of the universe. Furthermore, by imaging the earliest-born galaxies, astronomers can stress test the current proposed astronomical timelines of the universe and question whether periods like the reionisation epoch did last as long as we think. Exploring worlds beyond our solar system pushes the boundaries of science, adding new sophisticated analytical methods designed to process data from the JWST to make plausible conclusions about whether extraterrestrial life can exist on other planets.

5 Conclusion

The JWST has emerged as a beacon of scientific exploration, illuminating the mysteries of the cosmos and pushing the boundaries of our understanding. With its unprecedented capabilities, JWST not only has probed the early universe, providing profound insights into the formation of galaxies and challenging our notions of cosmic timelines, but has also embarked on a pioneering quest to explore other worlds in search of extraterrestrial life.

As we stand at the cusp of a new era in observational astronomy, the JWST's contributions reverberate across disciplines, refining theories on dark matter, shaping our comprehension of the universe's origins, and inspiring a re-evaluation of fundamental cosmic processes. In its quest to unravel the cosmic tapestry, the JWST not only extends our scientific frontiers, but beckons us to question, explore, and redefine our place in the vast expanse of the universe.

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