



COMPARATIVE ANALYSIS BETWEEN THE HUBBLE SPACE TELESCOPE AND THE JAMES WEBB SPACE TELESCOPE

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Abstract: The purpose of this study is to explore the significant improvements that humanity's second space telescope, The James Webb Space Telescope (JWST), has undergone since the installation of the Hubble Space Telescope (HST). It analyses the light gathering power (LGP) of both telescopes, the resolution of the images captured, the different camera detection systems, and finally the difference in spectroscopy and how the new Near Infrared Spectrograph on the JWST allows for simultaneous imaging of the cosmos. The results found were that JWST had about 7 times the LGP of HST. The JWST has a better or equal resolution of images depending on the wavelength. Finally, advancement in technology in the form of 'Microshutters' has allowed for simultaneous imaging of multiple celestial objects at once on the JWST.

Keywords: *Light gathering power, spectroscopy, camera detection systems, resolution, spectrograph, microshutters.*

Subject: Astronomy & Astrophysics

Introduction:

The purpose of this study is to provide a comparative analysis of the James Webb Space Telescope (JWST) and the Hubble Space Telescope (HST). There is no doubt that space telescopes are quintessential for the development of a unified theory in physics. This is primarily because space telescopes provide a better view of the universe. Telescopes on earth are unable to detect many different wavelengths due to the presence of various greenhouse gases that absorb these radiations.^[1]

The HST has long been humanity's primary link to interstellar space. It has provided scientists with remarkable images of the universe. Recently, NASA launched the JWST at the L2 Lagrange Point of the Earth and Sun system. It, however, begs the question: Was the installation of another space telescope necessary? If so, what significant advantage does the James Webb Space Telescope offer? This paper aims to answer these questions.

Wavelengths and Detection Abilities:

The JWST varies in many technical aspects from the Hubble. A major difference is that the JWST is sensitive to longer wavelengths (0.6-28.3 microns).^[2] The telescope observes the cosmos in the near-infrared and mid-infrared region of the Electromagnetic Spectrum.^[3] The HST, however, is sensitive to shorter wavelengths such as the ultraviolet, visible region and parts of the near-infrared region of the Electromagnetic Spectrum (up to 2.4 microns).^{[4][5]} The need for infrared sensitive telescopes is indispensable as they help scientists improve their understanding of the universe. Many objects in the universe are so cold that they cannot be observed in the visible light spectrum. They primarily radiate in the infrared spectrum. Consequently, they can only be detected by IR sensitive telescopes. Moreover, many of the atomic particles radiate at the infrared wavelengths.^[6]

¹ Blue Shift: Falling under the observations of Doppler's Effect, a blue shift is defined as the displacement of lines of the spectrum towards to part of the spectrum which contains shorter wavelengths. This usually occurs when a body moves towards the detecting body. It is visible on a cosmic scale as light takes years to reach the observing body.

Detecting the chemical composition of the universe could provide some insight on its formation. IR sensitive telescopes can also scrutinize exoplanet atmospheres, explore the birth of the first stars and younger galaxies that formed in the beginning of the universe.^[3] As we observe things millions of light years away, we are seeing how those things looked millions of years ago.^[7] It is equivalent to looking back in time. This phenomenon exists due to the concept of Hubble expansion. Until 1929, it was expected that galaxies move in an erratic fashion, hence, if observed, there would be near to equal amounts of blueshifts¹ and redshifts² in the sky. However, Edwin Hubble's observations showed most galaxies to be red shifted.^[8] Moreover, he also found that the size of the red shift, i.e., velocity of the galaxy, was directly proportional to the galaxy's distance away from the observer [Figure 1].

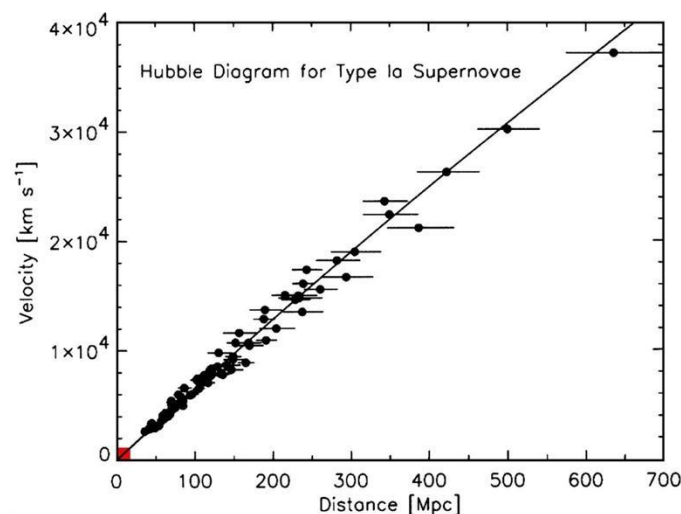


Figure 1: Hubble's observations have seen to be sustained through new research, as seen above^[9].

Owing to the Hubble Expansion, the light that travels through the universe gets stretched, increasing the wavelength towards the Infrared Regions. Thus, utilizing a space telescope that detects infrared signals makes it possible to truly see back in time.

² Red Shift: Falling under the observations of Doppler's Effect, a red shift is defined as the displacement of lines of the spectrum towards the part of the spectrum which contains longer wavelengths. This usually occurs when a body moves away from the detecting body. On a cosmic scale, it is visible as light takes years to reach the observing body.

Diffraction:

Diffraction is an important phenomenon to understand resolution, which will be talked about during the comparative analysis. Diffraction is defined as the spreading out of a wave as it passes through any obstacle or aperture.^[10] The phenomenon follows Huygens's principle that every point on a wavefront is a source of secondary spherical wavelets. These spread out at the speed of light in the forward direction.^[11] At times, due to an obstacle, portions of the wave are scattered in random directions. The secondary waves can interfere with each other, causing a series of constructive and destructive bands of light. This phenomenon is called diffraction.^[12] A common diffraction pattern looks something like this:^[13]

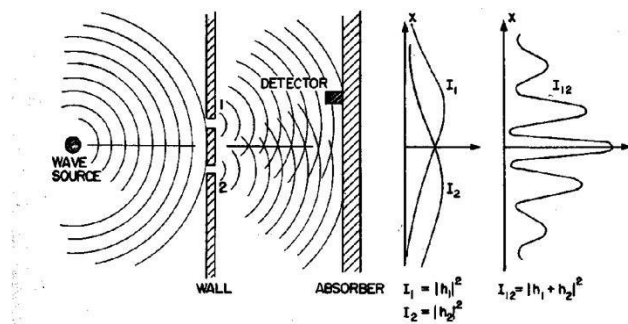


Figure 2: How a common diffraction pattern of any wave source appears to look like ^[13].

The peaks are known as maxima whilst the depressions are known as minima.

Finally, the main questions arise: What changes were made in the JWST to make significant improvements possible? What were these significant improvements?

The JWST utilizes very special instruments: Near Infrared Cameras (NIRcam), Mid Infrared Instrument (MIRI), Near Infrared Spectrograph (NIRSPEC) and a NIR imager & slit less spectrograph.^[14] The HST utilizes the Advanced Camera for Surveys (ACS), Wide Field Camera 3 (WFC3), Cosmic Origins Spectrograph (COS), Space Telescope Imaging Spectrograph (STIS) & Fine Guidance Systems (FGS) to capture their images.^[15] Other than their detection systems and differences in the sophisticated designs, both telescopes are reflecting telescopes that conceptually work the same.^[16] This research will

investigate how the difference in the external and internal engineering design, size of the mirrors and camera detection all contribute to a new and improved space telescope in the JWST.

Processing and Analysis:

As a method of comparative analysis is conducted, it is important to consider certain commonalities between the two said objects in question: The HST and the JWST.

Reflecting Telescopes:

A major basis of analysis can be built from the fact that both space telescopes, as mentioned earlier, are reflecting telescopes, i.e., they are built with mirrors instead of any glass lens as its primary material. More specifically, they are Cassegrain-type reflector telescopes.^{[17][18]} There is a simple reason behind the implementation of this idea. As seen from Newton's experiment with a glass prism, when white light passes through a glass, it splits into its constituent colors. These colors fall into the visible spectrum of the broad Electromagnetic Spectrum. However, glass absorbs all other wavelengths, including certain types of ultraviolet and infrared emissions which fall in wavelengths that are lower and higher than the visible spectrum respectively.^{[19][20]} Consequently, a reflecting telescope's use would be more effective. Moreover, for telescopes like the JWST and the HST, it is more likely that the requisite lens thickness would be very high. This is because the thickness of a lens has a strong positive correlation with the power of that lens (Fotouhi et al., 2015).^[21] The problem would arise when thick lenses would have to be mounted on top of a space telescope. Their tremendous weight would make it expensive and inefficient to utilize in the space telescope, corroborating the usage of reflector telescopes which have lighter mirrors.

A Cassegrain-type telescope is quite unique in its design and structure. Its primary mirror is like the Newtonian telescope: a concave parabolic shape. However, it utilizes a convex hyperboloidal secondary mirror which increases its focal length and makes the focus more easily accessible.^[22]

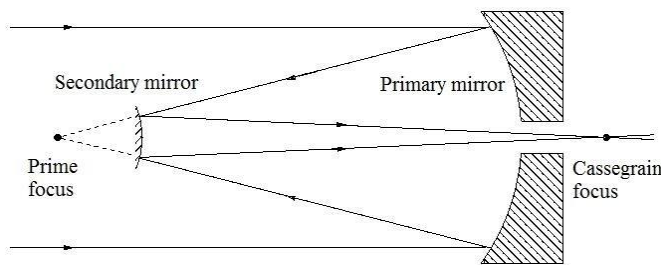


Figure 3: The internal structure of a Cassegrain Reflector Telescope ^[22]

After laying down the commonality between these two space telescopes, it is now possible to investigate the major differences between the two telescopes.

To investigate whether the JWST offers any significant advantage over the HST, 4 parameters will be analyzed: The maximum wavelength detectable, resolution of images, power, and the external structure of both telescopes with their link to any 3 of the aforementioned.

Light Gathering Power & its Implications:

One of the stark contrasts found between the JWST and the HST, is the size of the primary mirror. Mirrors are important in all reflecting telescopes as they collect and focus all the light received, towards a concentrated spot.^[23] The engineers wanted to mount a mirror that was larger in size than the HST. Mounting more mirrors than the HST, however, would make the JWST too heavy to launch into orbit. This is because the mirrors of the HST were built with ultra-low expansion glass coated with thin layers of magnesium fluoride and aluminum.^{[24][25]} Thus, scientists came up with a mirror made from Beryllium. It was lightweight and strong, making this the perfect material for the mirrors of the JWST.^[26] Consequently, scientists were able to mount a mirror of a larger size on the JWST. the HST contains a primary mirror that is 2.4 meters across, whilst the JWST contains a primary mirror that is 6.5 meters across.^[26] With a larger primary mirror, it is possible to capture more light. In essence, it is possible to see farther back in time as the mirror can capture larger distances.^[16] In order to understand why the size of the primary mirror allows the capture of more light, it is important to understand the light gathering power (LGP) of any telescope. By literature, light gathering power is the ability of any telescope to capture more

amount of light than the human eye.^[27] It is expressed as a ratio of the area of the telescope to the area of the human eye.^[27] Consequently, the LGP is highly dependent on the area of the objective.^[28] The objective in the case of the HST and the JWST is their primary mirror. Instead of the human eye, however, a ratio can also be found between the two telescopes themselves, by dividing the areas of both primary mirrors. This would give an idea LGP of the JWST in comparison to the HST. Knowing that both mirrors are somewhat circular gives us a better idea of their area:

area of primary mirror of the HST

$$= \frac{\pi d^2}{4} = \frac{3.1416(2.4)^2}{4} = 4.52m^2$$

Similarly,

area of primary mirror of the JWST

$$= \frac{\pi d^2}{4} = \frac{3.1416(6.5)^2}{4} = 33.2m^2$$

Dividing both areas,

$$\frac{33.2}{4.52} = 7.34$$

Thus, the light gathering power of the JWST is around 7.34 times that of the HST, which means it can gather more light in a given time interval. Hence, looking farther back in time.

Camera Detection Systems:

As the JWST can see farther back in time due to an LGP of about 7 in comparison to the HST, it is logical to believe that the instruments present in both telescopes will also be different. The JWST must have cameras that are able to receive, detect and process signals of a higher wavelength than the HST.

As mentioned earlier, the JWST contains 4 main instruments: MIRI, NIRcam, NIRSPEC and a NIR imager & slit less spectrograph. Out of these 4 instruments, NIRcam is the main imager of the

JWST.^[29] NIRcam has multiple roles and different observation modes, these include: imaging, coronagraphy³, and spectroscopy.^[30] The wavelength coverage of NIRcam depends on the observing mode parameters. There are two main wavelength channels that the NIRcam covers: the short wavelength channel which ranges from 0.6-2.3 μm , and the long wavelength channel which ranges from 2.4-5.0 μm .^[31] Two channels are required to detect different wavelength signals. The range of all NIRcam observational modes lie between 0.6-5.0 μm and only vary according to the wavelength channel.

In contrast, the HST has two main imagers which work in harmony to capture images. These are the ACS and the WFC3. The ACS has 3 wavelength channels, namely: WFC, HRC and SBC.^[32] The WFC3, however, has 2 channels, namely: UVIS and NIR.^[33] The specific wavelength ranges that these imagers can capture is as follows:

ACS:^[32]

Channel	Wavelength Range Captured (μm)
WFC	0.350 - 1.05
HRC	0.200 - 1.05
SBC	0.115 – 0.180

Table. 1.

WFC3:^[33]

Channel	Wavelength Range Captured (μm)
UVIS	0.200 - 1.00
NIR	0.850 – 1.70

Table. 2.

In comparison, NIRcam captures a wider range of signals than ACS and WFC3, and logically so. It is important to understand that the HST does not require an instrument such as NIRcam in its structure as the

primary mirror cannot capture that extent of redshifted light. Thus, while the ACS and WFC3 are effective for the HST, an improvement was required while installing the instruments in the JWST. These improvements came in the form of NIRcam, as seen above, and the Mid Infrared Instrument (MIRI).

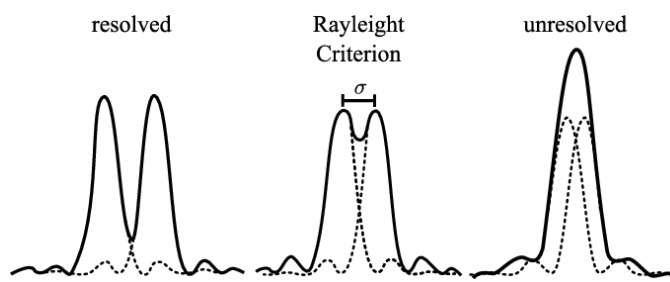
As stated earlier, the JWST can not only venture in the near infrared region, but also the mid infrared region. MIRI helps detect wavelengths in the Mid Infrared Region. MIRI has the ability to detect signals coming from as far as 25.5 μm , showing a significant improvement in the range of detection.^[34]

Resolution:

Another important factor to consider is the clarity of the images captured by the space telescopes. Clarity of any image is usually measured by its resolution. Higher the resolution, better the image quality. In digital terms, resolution is defined as the number of pixels per inch in an image.^[35] Consequently, the higher the resolution, the better. In the realm of optical instruments, however, the definition of resolution tends to differ. In microscopes and telescopes, resolution is used to define the ability of the optical instrument to distinguish detail.^[36] Two objects are said to be resolved if they can be distinctly identified at a particular distance.

How can one determine the distance or minimum angle for resolution to occur? It is done via the Rayleigh's Criterion. The Rayleigh's Criterion states that any two images are resolvable if the central maxima of the diffraction pattern of one object is directly over the first minimum of the diffraction pattern of the second object.^[37]

Diagrammatically,^[38]



³ Coronagraphy: It is the process of utilizing a coronagraph. A coronagraph is a telescoping attachment which is used to block out the direct light emitted by stars to resolve nearby objects.

This technique is often used to detect exoplanets and planetary systems in the outer ends of the galaxy.

Figure 4: The Rayleigh's Criterion diagrammatically explained via diffraction patterns ^[38]

The ability of a telescope to resolve an image is labelled as its resolving power.^[39] The basis of calculating resolving power revolves around the minimum resolvable angle θ . θ , in this case is the minimum angle that must be created between the observer/telescope and the two objects that are tested.

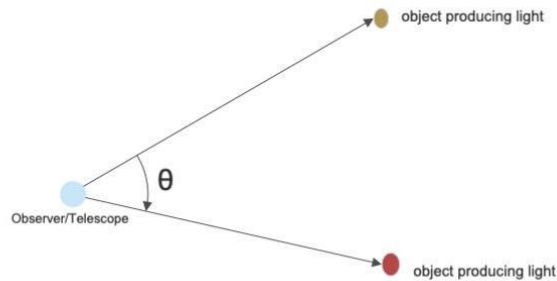


Figure 5: Observing the minimum angle required in a particular condition, to see two light emitting bodies distinctly.

Scientifically, if θ is greater than or equal to the angle of the first diffraction minimum, resolution is possible.

For an object with a circular aperture, Resolution is possible when ^[40]

$$\theta \geq 1.22 \frac{\lambda}{b}$$

Where λ is the wavelength and b is the diameter of the aperture

Logically, considering the above equation, the desire would be to make θ as small as possible while still being greater than $1.22 \frac{\lambda}{b}$ to see images far away clearly. This can be done in 2 ways: ^[39]

1. Decreasing the observable wavelength [λ reduces]
2. Making the objective diameter large [b increases]

On both space telescopes, the HST and JWST, b is determined by the diameter of the primary mirror as it is the objective being compared. Thus, b remains constant for both telescopes and cannot be changed, leaving only the observation wavelength to be modifiable.

The highest resolution that the HST can attain is about 0.04 arcseconds (per pixel) on its UVIS channel of the WFC3,^[33] and the lowest resolution is on its Near Infrared channel at about 0.13 arcseconds.^[33] Hubble's range of resolution lies approximately between 0.05-0.1 arcseconds.^[41]

The JWST, however, has the lowest pixel scale of 0.032 arcseconds (per pixel) in its shorter waveband, i.e., the Near Infrared.^[42] In the Mid Infrared region, however, the resolution reduces. It is about 0.11 arcseconds.^[43] It is important to note that these slight changes in arcseconds does not mean that the image quality has a blatant difference. They are still quite clear.



Image Left: MIRI captures an image of a deep field. Right: The same image captured by NIRcam of the JWST ^[44].

From these observations, it can also be concluded that the resolution of images captured by JWST will either be equal to better than the HST. If an image of the same wavelength was to be captured by both telescopes, the JWST would have a higher resolution as the diameter of its primary mirror is much larger than that of the HST.

However, in regions which the HST doesn't capture, for example the Mid Infrared Region, the resolution of the image captured by JWST might be equal to that of

a normal image captured by the HST in the Near Infrared region.

Both space telescopes, however, do not only rely on their primary mirror's diameter and the observable wavelength to determine or increase the resolution of images. Thanks to technological advances, interferometers were invented and helped massively increase the resolution of images.

Interferometers are virtual instruments. They are formed by combining two or more telescopes.^[45] In very brief terms, if there are two sensors working together, the images captured by both telescopes, which are detected as waves, interfere with each other, creating fringe patterns. These fringe patterns can be converted to an even higher resolution image.^[45]

The HST can detect binary star systems via the use of interferometers. The HST uses its Fine Guidance Sensors as interferometers.^[46] The JWST, however, utilizes 3 different interferometers, namely: Electronic Speckle Pattern Interferometer (ESPI), High Speed Interferometer (HSI) and the Multi-Wave Interferometer.^[47] Multi-Wave Interferometers are primarily used to increase the resolution of images.^[48]

Conclusively, when considering resolution, the JWST prevails in quality. For a common wavelength detected by both telescopes, the JWST provides images of higher resolution than the Hubble.

NIRSPEC vs. STIS:

NIRSPEC is the spectrograph instrument on the James Webb Space Telescope while STIS is currently operational on the Hubble Space Telescope. Spectrographs are instruments that separate incoming light by its characteristic properties, wavelength or frequency, and records it to form a spectrum.^[49]

Light travels through a small opening in the spectrograph after which it gets reflected by a mirror, directly onto a diffraction grating. The white light, here, gets split into its constituent elements, reflect off another mirror and reach a photodetector. This photodetector converts the photons into signals which the computer can measure, determining the strength of specific wavelengths.^[50]

Spectrographs thus inform our understanding of the atmosphere, temperature and motion of planets, stars,

galaxies and cosmic dust.^[51] They do not capture any images in high resolution. However, as stated above, this is not their main function.

While both the NIRSPEC and STIS are useful and provide valuable information about exoplanets and chemical properties of stars, NIRSPEC has some special upgrades.

As the JWST can venture far and wide into the cosmos, it will capture a lot of images. In order to study all the light captured by the mirror in 5 years, the NIRSPEC is designed to analyze and observe 100 objects at once. This is a ability unique to the NIRSPEC, known as the multi-object spectrograph capability.^[52] To make this possible, however, new technology had to be invented. This new technology named "microshutter system" controlled how light entered the NIRSPEC.^[52]

The microshutter system are tiny windows with shutters.^[53] They have lids which open and close when a magnetic field is applied. Each of these lids can be controlled individually, meaning scientists can specifically block certain portions of the sky. This ability of the microshutter allows NIRSPEC to do spectroscopy on 100 objects simultaneously.^[54] This makes it easier to analyze more images in lesser time, increasing the efficiency of the JWST.

Results and Discussion:

Both telescopes, being reflector telescopes, are created using the same fundamental concepts. Thus, making comparisons becomes less daunting.

The primary mirror of the JWST, being significantly larger in diameter, allows more light to be captured in a given interval of time. As a result, the Light Gathering Power of the JWST is about 7 times that of the HST. This was done by calculating the ratios between the areas of the primary mirrors.

As the JWST has more LGP than the HST, its camera detection systems must also be able to account for these higher bands of wavelengths. Thus, there is a difference in the camera detection systems used in the JWST and HST.

There are also differences in the resolution of the images captured by both telescopes. JWST might have a resolution that is better or equal to that of the HST as

resolution depends on wavelength and size of the primary mirror.

Advancements in recent technology has allowed for the invention of Microshutter systems which allow the NIRSPEC of the JWST to simultaneously capture images of 100 objects, the first of its kind to do so.

Conclusions:

The JWST can see farther back in time, much clearer and offers researchers with new opportunities and avenues to explore more about the unknown mysteries of the universe. It has better resolution because the resolution of images depends on the wavelength of the image being detected as well as the size of the objective. In the case of the JWST, its primary mirror, objective, is larger, giving it an edge. The advantage of NIRSPEC over The Space Telescope Imaging Spectrograph (STIS) is the invention of technology known as 'Microshutters'. They block light from entering the spectrograph, hence allowing for imaging of 100 objects simultaneously, something that's never been done before. In conclusion, the JWST has provided significant improvements to space imaging. While its predecessor - Hubble - served, and continues to serve, as a pillar for humanity's understanding of the universe, the JWST has a much more advanced external and internal engineering design which provides a substantial advantage to scientists whilst analyzing the cosmos.

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