JAMES WEBB SPACE TELESCOPE

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Abstract. *The James Webb Space Telescope (JWST) is the latest Space Observatory that features advanced cutting edge technology, including infrared light detection instruments that capture images of distant objects which wavelength elongated due to the expansion of the universe, faint young stars and exoplanets.*

Key Words*: infrared light, redshift, cryogenic temperatures, heat radiation, fine allignment, allignment correction, nominal course.*

Introduction

The James Webb Space Telescope (JWST) is a joint project between NASA, European Space Agency and the Canadian Space Agency. Its first mention was in 1989 as a replacement for the Hubble Telescope and its launch being planned for 2005. The construction began only in 2004. With several delays, it finally got launched after nearly three decades in 2021. The James Webb Space Telescope was launched on an Ariane 5 rocket from French Guiana on the 25th of December 2021 at 12:20 GMT. The key feature of the telescope is detecting infrared light. The primary goals of the Telescope is to study the formation of galaxies, stars and planets in the universe, to see through dense dust nebulae and to study objects that are redshifted into the infrared spectrum.

The Second Lagrange Point

James Webb Space Telescope will orbit the second Earth-Sun Lagrange point or L2. This point is in itself empty, yet it is a mathematical deduced point where an object can orbit the sun with the same period as the earth, even though it is situated at a greater distance. This is possible due to the overlap of both sun's and earth's gravitational force that cancels out the centripetal force. Earth and moon reflected light from the sun, is strong enough to damage satellite's equipment. L2 provides a perspective from where the sun, earth and moon are seen in the same direction, therefore the telescope will only have to shield that one direction.

The general equation of forces at L2:

$$F_{sun} + F_{earth} = F_{centripetal} \tag{1}$$

From this we can deduce that:

$$\frac{M_{sun}}{(R+r)^2} + \frac{M_{earth}}{r^2} = \frac{M_{sun}(R+r)}{R^3} \tag{2}$$

Solving for r we get a distance of approximately 1.6 million km.

F_{sun} - gravitational force of Sun
F_{earth} - gravitational force of Earth
$F_{centripetal}$ - centripetal force at the L2
M_{earth} - mass of earth
M_{sun} - mass of sun
R - distance from earth to sun
r - distance from earth to L2

The Telescope is powered by solar energy, therefore it needs to adopt an orbit around L2 in order to not stay in Earth's shadow. L2 is an unstable equilibrium point and if the telescope passes L2, the centripetal force will overcome the forces of gravity throwing its orbit off, therefore the satellite must orbit slightly away from L2, closer to the Earth.

Deployment of The Space Telescope and its Instruments

After its launch and shedding off the booster rocket, an automatic process of two days begins. First step is the deployment of the solar array. The telescope will then go off of battery power and start generating its own power. The Mid Course Correction Burn 1a compensates for the intentional underburn of the Ariane rocket. The underburn is by design due to the possibility of too much thrust from Ariane 5 that would require the satellite to turn around, which would expose all the instruments and optics to the heat of the sun. The last step is the deployment of the Gimbaled Antenna Assembly, pointing back to Earth, allowing all the other deployments to be controlled manually from the ground. After 30 days from its launch, JWST executes the insertion burn into the orbit around L2.

James Webb Space Telescope is designed to capture infrared light. Infrared light is heat energy. In order to detect the faint light coming from space, the telescope itself must be very cold, otherwise its own heat emmisions will interfere with the readings.

Webb's sunshield allows the telescope to passively cool down bellow 50 K, by radiating its heat into space and reflecting sun's light. The sunshield consists of five layers, the first one being the hottest. The vacuum from the gaps is an excellent insulator and will allow for the heat radiated by the membranes to be reflected back into space (figure 1).

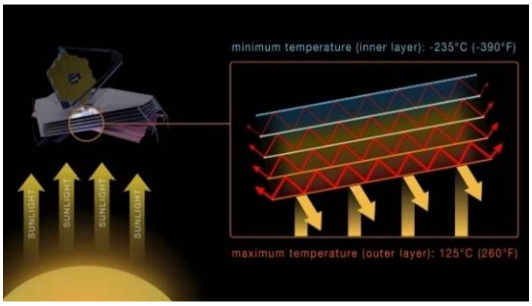

Figure 1. Here it shows how heat is reflected and dissipated back into space [1]

The sunshield is made out of thin lightweight material of Kapton E with specific coatings. Kapton is a polyimide tape that has high heat-resistance and tolerates a wide range of temperatures from 4 K to 673 K. Each layer is coated with aluminum for its high reflectivity. The first two layers facing the sun have a doped-silicon coating. Doping is a process where a small amount of a different material is mixed in during the Silicon coating making it electrically conductive. It is therefore grounded to the rest of JSWT to not build up static electric charge. Silicon also has a high emissivity [2]. The role of the fifth layer is mostly for the margin of error, to account for imperfections and micro-meteoroids that can tear through one of the membranes [3].

The membrane material is durable, but even a small hole can get bigger. By using a special process called a Thermal Spot Bond, where areas are melted together, it reinforces strips of membrane material and stops the tears from „spreading". This way a grid-like pattern of „rip-stops" is created that isolates the area of damage [4].

JWST is too large to fit into a rocket in its functioning state, therefore it was designed to unfold as an origami. The deployment of the sun shield takes eight days, firstly, the two forward and aft pallet structures are unfolded to their full length. The aft momentum flap is deployed to stabilize the telescope's orbit and rotation by using the photon pressure of the sun. The protective membranes covers of the sunshield are unfolded. The mid-booms are deployed expanding the sunshield to its full kite shape. After tensioning the membranes, the sunshield is fully secured into position finalizing the sunshield deployment step 10 days after launch.

JWST includes a primary, secondary, tertiary and a Fine Steering Mirror (FSM). Three strong struts of about 8 meters, fixate the secondary mirror right in front of the primary mirror. They are made out of carbon fiber composite, hollow, with a thickness of about one millimeter. The secondary mirror is perfectly rounded in a convex shape with a diameter of 0.74 m. The secondary mirror plays an important part in reflecting and focusing the light from the primary mirror to the concave aspheric tertiary mirror (figure 2). The light will then be reflected to the FSM which is a high quality mirror used to stabilize the image [5].

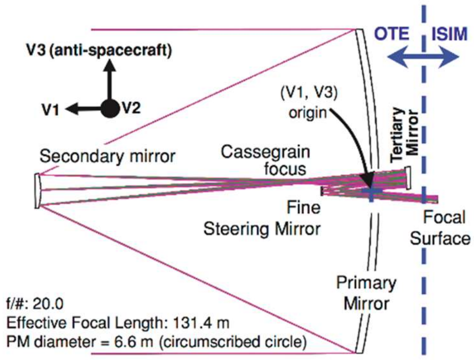

Figure 2. How light is redirected into the instrument system [5]

JWST's primary mirror has a diameter of 6.5 m and an area of 25.4 m^2, comprised out of 18 hexagonal shaped mirrors. The primary mirror segments are mounted on a graphite-composite backplane structure. Two „wings" both supporting three mirror segments, deploy and latch firmly into their permanent positions on the first few weeks.

Each of the primary mirror segments possess six actuators which are tiny mechanisms composed of precision motors and gears. They are used to move the mirror surfaces so that all 18 can be aligned to each other. Each primary mirror segment has one special „force" actuator. The force actuators enable the segments to have the same center of curvature [6].

The mirrors themselves are made out of beryllium, lightweight, stiff and good at holding its shape to temperature changes. Each mirror substrate is nearly 5 centimeters thick. The reflective side is polished to an average roughness of 20 nm. It is coated with a 100 nm thin layer of pure gold due to its efficiency of reflecting infrared light. By putting the mirrors inside a vacuum chamber and vaporizing a small quantity of gold, it is deposited finely on the mirror. A thin layer of amorphous glass is deposited on top of the gold to protect it from scratches. One mirror segment has a mass of 20 kg, while a full segment assembly is about 40 kg [6].

Periodic Wavefront Sensing and Control (WS&C) keep the primary mirrors aligned and in phase. Due to the stable space environment, the wavefront sensing system atchitecture is different from large telescopes on the ground. The Space Telescope does not suffer from atmospheric disturbances and gravity-induced deformations, instead JWST only needs corrections to temperature changes that cause slight thermal expansion or contraction. After launch and deployment, the segments and science instruments will be misaligned up to several milimeters. An iterative process will bring the mirrors to an allignment of nanoscale accuracy. WS&C will begin once the telescope and instruments have cooled sufficiently toward their operating temperatures. The first high quality images will be first achieved by NIRCam, it being the main wavefront sensing sensor. During routine science operations, the wavefront will be monitored periodically taking about 1%-2% of observatory time [7].

JWST houses four different infrared light detection instruments: Near Infrared Camera (NIRCAM), Mid-Infrared Instrument (MIRI), Fine Guidance Sensor/Near Infrared Imager and Slitless Spectograph (FGS/NIRISS), Near Infrared Spectograph (NIRSPEC).

NIRCAM is Webb's primary imager covering a wavelength range from 0.6 to 5 μm (figure 3). It can detect light from the earliest stars and galaxies in the process of formation, the population of stars in nearby galaxies, young stars in the Milky Way and Kuiper Belt objects. NIRCAM is equipped with coronagraphs that allows to detect faint objects near a central bright object, such as stellar systems by blocking the brighter object’s light. With this, astronomers can detect exoplanets and determine their characteristics [8].

MIRI provides observers with coverage of mid-infrared wavelengths from 4.9 to 28.8 µm (figure 3). Imaging can be obtained with 9 broad-band filters. The sensitive detectors of the camera will be able to see the redshifted light of galaxies, newly forming stars, faintly visible comets and objects in the Kuiper Belt. The spectograph will provide new physical details of the distant objects it will observe. The nominal operating temperature of the MIRI is 7 K, which cannot be reached using passive cooling by radiating heat into space, therefore Webb carries a cryocooler dedicated to cooling MIRI’s detectors [9]. The cooling is a two-step process, a pulse tube precooler lowers the instrument’s temperature to 18 K, and then a Joule-Thomson Loop heat exchanger cools it to the desired 7 K. The cooler requires a low vibration in order to not disturb the optical allignments. The cooling system has only two moving parts, two 2-cylinder horizontally opposed piston pumps that are finely balanced and tuned, being in nearly perfect opposition, vibration is mostly cancelled-out, therefore minimized. FGS allows Webb to fixate the telescope precisely, for obtaining high-quality images [10].

NIRISS is used for first light detection, exoplanet detection and characterization, and exoplanet transit spectroscopy. FGS/NIRISS detects a wavelength range of to 0.8 to 5 µm (figure 3), it is a specialized instrument with three main modes that are specialized to address different wavelength ranges [11].

NIRSPEC functions over a wavelength range of 0.6 to 5 µm (figure 3). The spectograph disperses light from an object onto a spectrum. By analyzing its spectrum, it can tell us a lot about its properties, temperature, mass, chemical composition. JWST must stare for hundreds of hours at faint distant galaxies so it collects enough light to form a spectrum. NIRSPEC is designed to observe 100 objects simultaneously in order to optimize the time spent [12]. For this, engineers developed a new microshutter technology which controls how light enters the NIRSPEC. The microshutters can be opened and closed individually by use of a magnetic field to view or block a portion of the sky. With this kind of control over the light, the instrument can do multiple spectroscopies on so many objects simultaneously. Using the microshutters, the instrument can block brighter light to „give way” for the fainter light [13].

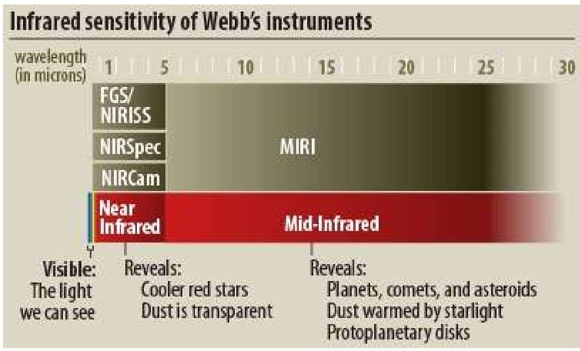

Figure 3. Wavelength Covering of Webb’s Instruments [14]

Conclusion

JWST is unique through its design, innovative technologies and time spent for its construction and preparation. Due to its size, the telescope had to be folded up as an origami, and deployed through an iterative process that takes 6 months. Scientists had to equip the observatory with several cryogenic resistant technologies and make sure that the functionality of the telescope does not diminish when put in practice. The telescope needs to identify objects that are so far, their light has shifted into the infrared spectrum. That means, it has to be extremely stable and precise on nanometer level, in order to capture usable information. Scientists will be able to study the formation of galaxies, stars, identify exoplanets, study dark matter behaviour, etc.. James Webb Space Telescope can discover things we have never thought could be possible, it can completely turn around our understanding of physics.

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