James Webb Space Telescope Fundamentals

Darryl D. Diptee

Embry-Riddle Aeronautical University

Executive Summary

Scheduled to be launched in 2013, the James Webb Space Telescope (JWST) will be most technologically advanced space observatory in operation. It will be launched and placed at the second Lagrange point some 1.5 million kilometers away on the Earth-Sun system allowing it to revolve around the Sun with the same period as the Earth. The JWST will have remote sensing abilities capable of capturing low frequencies of electromagnetic redshift which will offer answers pertaining to the beginning of the universe, the birth of galaxies, stars and planets. This paper will share the specifics of the JWST with supporting information to include: a brief history of space observatories, the fascinating discoveries of Edwin Hubble upon which the JWST draws its strength, fundamentals of electromagnetic radiation, spectroscopy and Lagrange points.

Space Observatories

Ever since Galileo first pointed a telescope towards the heavens in the early 1600s, it was quickly recognized that earth based space observatories had many limitations. For one, daylight typically eliminates any possibility of star gazing, so at least half the year is spent waiting for darkness. Then there are issues of cloud-cover, fog, rain, light pollution such as a full moon or street lights, and also the drawbacks of the atmosphere itself which may have light scattering effects. An interstellar observatory would avoid all these problems by orbiting the earth high above the atmosphere in the vacuum of space, allowing it to continuously capture images 24 hours a day, 365 days a year, limited only by design factors and possible malfunctions.

An astrophysicist named Lyman Spitzer, Jr. wrote a paper in 1946 about the benefits of an extra-terrestrial observatory, claiming that ultra-violet studies and measurements of distant galaxies would be possible. It wasn't until 1990 that the Hubble Space Telescope was launched and became the highly successful feat of human engineering responsible for magnificent images of our universe (Avnet, 2005). It is expected that JWST with its superior remote sensing abilities will unlock many of the secrets hidden by the universe.

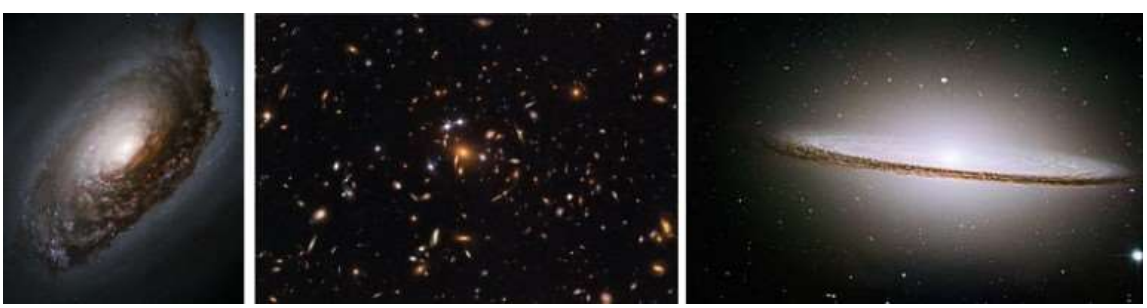

Figure 1. Images captured by the Hubble Space Telescope. *Note*. From "Hubble Site". No Copyright claimed by STScl in accordance with NASA contract.

Fundamentals of Electromagnetic radiation

The JWST will capture images from the depths of our universe by sensing various frequencies of electromagnetic (EM) radiation. Many people are intimidated by the concept of EM radiation because they think it is a complex and mysterious source of energy. While details on the subject can become rather intense, the concept is a very simple one. It is this concept that will allow the JWST to see into the early life of the universe.

Listed below are some basic facts about electromagnetic radiation (Lillesand, Kiefer, Chipman, 2004, p.6):

- Everything with a temperature greater than 0^{o} Kelvin emits EM radiation.
- All EM radiation travels at the speed of light.
- EM radiation exists as different frequencies and wavelengths which must follow the relationship: c (speed of light) = f (frequency of EM) x w (wavelength of EM)

To properly understand how the JWST will work, it is important to understand how EM radiation and heat are related. There is a theoretical limit to how cold anything in the universe can get, that point is called absolute zero and is represented as 0^{o} on the Kelvin scale (-273.15^{o} Celsius). Absolute zero is a theoretical point which can never be reached, but it is interesting to point out that in 2003 scientists were able to get within one billionth of a degree of absolute zero (Zielinski, 2008).

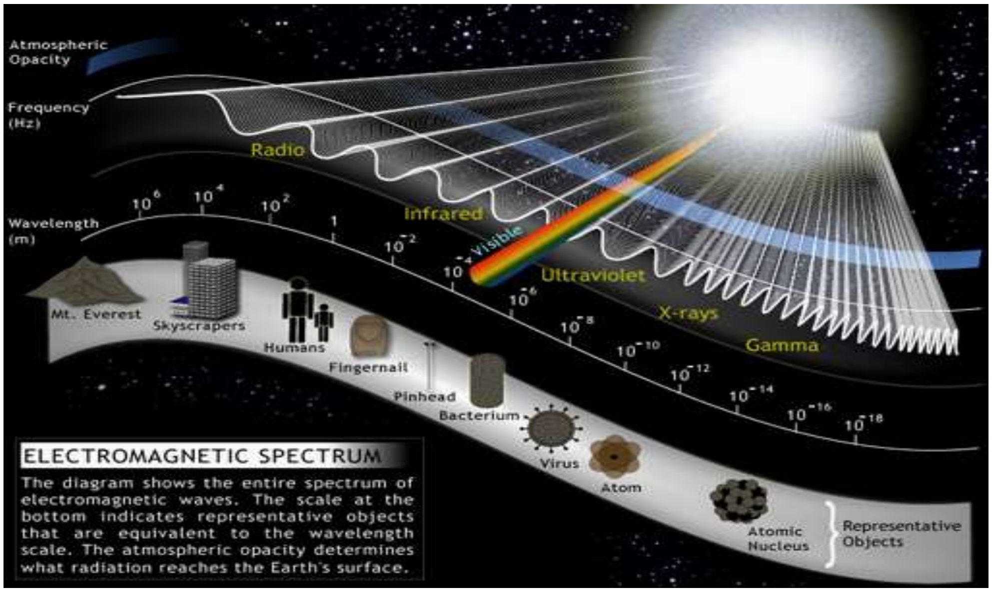

Figure 2. The Electromagnetic spectrum. *Note.* From "Living with a Star". Copyright 2002 by UC Regents.

It is known that anything that has a temperature greater than 0° Kelvin naturally emits electromagnetic radiation; as absolute zero can never be achieved; all things in the universe continuously emit some form of EM (Lillesand et al., 2004, p.6). Even as you read this paper your body is emitting low levels of EM radiation into its surroundings. The JWST developers factored this into the sunshield design which will keep the unit below the operating temperature of 40° Kelvin.

As the temperature of an object is increased however, so is the range of wavelengths over which EM radiation is emitted. The sun for example, radiates over all wavelengths from long radio waves to short gamma waves due to its intense heat, whereas the substantially cooler surface of the earth naturally radiates wavelengths between radio waves and infrared waves. Higher temperatures also result in dominant lower frequencies as can be seen by Figure 3. This can be easily verified by heating a piece of metal and seeing it progressively change to colors of shorter wavelengths: from a dull red, to orange, to yellow, and eventually to white (Lillesand et al., 2004, p.8).

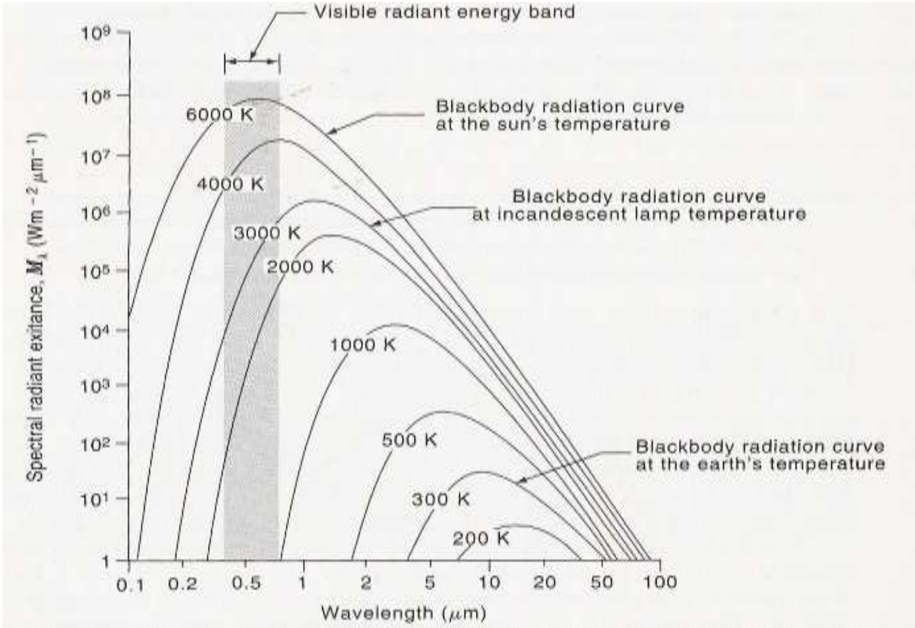

Figure 1.4 Spectral distribution of energy radiated from blackbodies of various temperatures. (Note that spectral radiant exitance M_λ is the energy emitted per unit wavelength interval. Total radiant exitance M is given by the area under the spectral radiant exitance curves.)

Figure 3. Spectral EM Distribution at various temperatures. *Note.* From "Remote Sensing and Image Interpretation" by Lillesand, Kiefer, Chipman, 2004, p.8. Copyright 2004 by John Wiley & Sons, Inc.

The JWST is designed to mainly sense frequencies in the infrared portion of the EM spectrum having wavelengths between 0.6 and 0.27 nanometers. All EM radiation adheres to the relationship: c = f x v where c is the speed of light, f is the frequency of EM and w is the wavelength of EM. This means that frequency and wavelength are indirectly proportional to each other, that is, as one increases - the other must decrease as the speed of light must be maintained. EM radiation travels at the speed of light though they may have different frequencies and wavelengths.

Discoveries of Edwin Hubble

Edwin Hubble was born in 1889 in Missouri, USA during a time where the Milky Way was considered the entire universe. After receiving a PhD in astronomy, he began working at

Mount Wilson Observatory in California which was the world's best observatory at the time. Hubble was able to prove by taking photographs with the 100 inch reflecting Hooker telescope that galaxies just like our Milky Way existed elsewhere in the universe. This was a revolutionary discovery at the time which lifted our limits on the size of the universe (Edwin Hubble, 2002). The data collected from the JWST will allow us to calculate the size of the universe with a fair degree of accuracy.

His greatest discovery didn't occur until 1929 after almost 10 years of collecting data when Hubble realized a pattern in the emission spectroscopy of distant galaxies. Most galaxies suffered from an emission spectroscopy redshift which increased the further away they were from earth. Put simply, not only were galaxies moving away from each other, but they seemed to gain speed with the more distance they traveled. This discovery gave rise to the current Big Bang Theory which states that all of the known universe once existed at a single point which exploded and evolved into what we know today (Edwin Powell Hubble, 2002). The science objective themes of the JWST address the theories of the Big Bang theory and the origins of life.

Emission Spectroscopy and Redshift

The galaxies the JWST will try to find are very, very old. The EM radiating from them may have been travelling for billions of years through space before it will get a chance to be captured by the JWST. As older galaxies recede with increasing velocity, their EM radiation becomes affected and is seen by increased wavelength. The JWST is designed to sense this “modified” EM radiation in hopes of seeing the universe’s oldest galaxies.

Each atomic element in the universe is unique due to the number of electrons and protons they contain. When the electrons of a particular element become energized, EM radiation is released at specific frequencies which can be located on the electromagnetic spectrum and is a unique "fingerprint" for that element. Energized sodium (Na) gas radiates in two frequencies (among others) at about 590 nanometer wavelength resulting in double yellow spectral lines in the visible range of the EM spectrum (Volland, 2005).

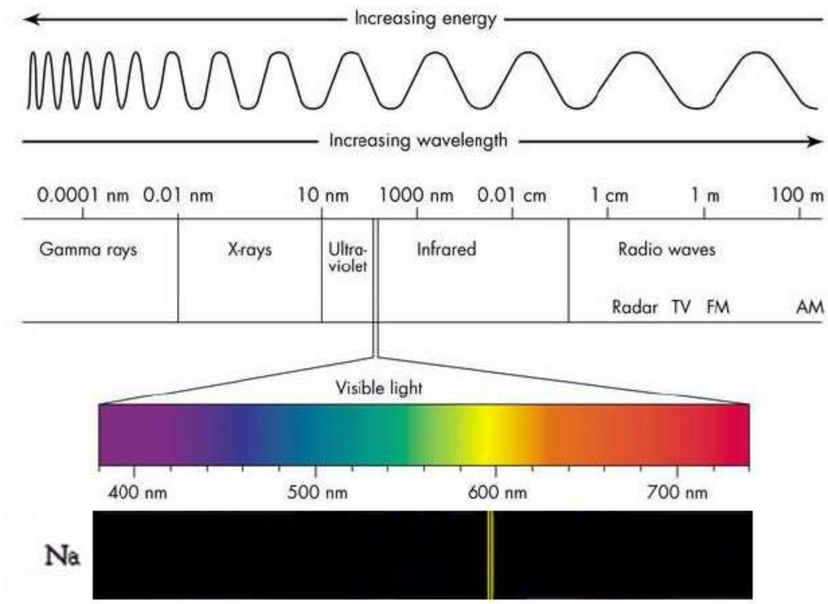

Figure 4. EM spectrum showing spectral lines of Sodium (Na). *Note.* From "Antoine Educational Website" by James Antoine, 2008. No copyright information listed.

When the source of EM radiation begins to move (for example, a galaxy moving away from the JWST), the wavelengths compress in the direction of movement and spread out in the opposite direction causing what is known as either a redshift or a blueshift. Blueshift is the result of compressed (shorter) wavelengths of an approaching EM transmitter, while redshift is due to stretched out (longer) wavelengths of receding EM transmitters (to help remember which is which, think blueshift is like blue car lights driving toward you and redshift is like red brake lights on a car as it drives away). Since the universe is expanding and most galaxies seem to be moving away from the Milky Way, there is a noticeable redshift in spectral data. The JWST will be most sensitive to the infrared spectrum which is the expected wavelengths of the oldest galaxies due to redshift. The amount of redshift (annotated by the character *"z")* can be used to calculate recession speeds (i.e. speeds at which galaxies are moving away), ages of galaxies and stars, and expansion of the universe. As an example, a redshift 1 galaxy (where $z = 1$) would be moving away from earth at 0.6 times the speed of light (Nave, 2006).

It should also be noted that from JWST's perspective, cosmic redshift tends to "slow" the relative time over which cosmic events occur. An event that occurs over two months in a distant galaxy with a high recessive velocity might appear to take 2 years when viewed by the JWST. This is because as the event unfolds the distances between galaxies increase substantially causing EM radiation to travel further with each passing moment, thus prolonging the time it takes for the images to be updated by the JWST (Mather, 2004).

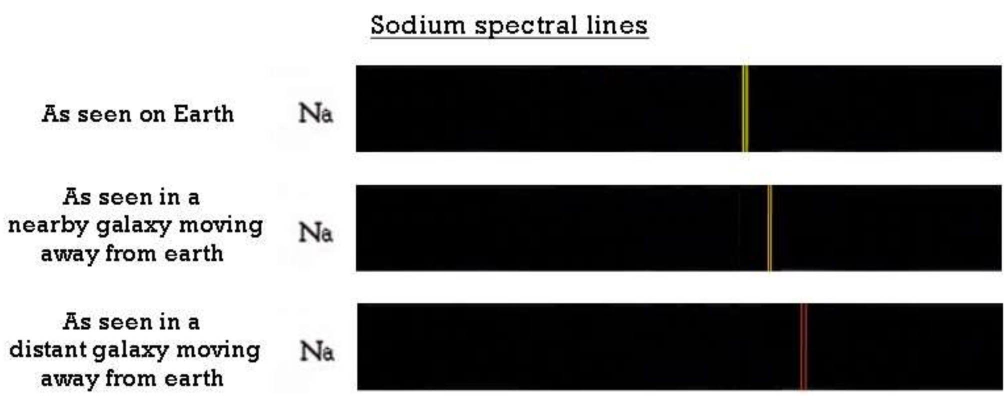

Figure 5. Example of sodium spectral lines showing redshift. *Note.* Copyright Darryl Diptee 2009.

Looking into the past

Images of stars and galaxies captured by JWST represent events that occurred when the EM was radiated, or in other words, these images are a picture of the very distant past. Even though EM radiation travels at the speed of light, the distances traveled are so great that it takes millions or even billions of years for that radiation to reach the JWST. According to the Big Bang theory, the oldest galaxies have the highest receding velocities resulting in large redshifts into the infrared and maybe even the radio portion of the EM spectrum. The JWST is designed to capture EM in the infrared range giving it unparalleled capability to view the universe at a very young stage (Stiavelli, 2005).

Lagrange Points

Unlike other space observatories, the JWST will not be placed in an orbit around the earth. Instead, it will be placed at Lagrange point two (L2) which will aid in the capturing the long wavelengths of the universe's oldest redshifted galaxies. In 1772 Joseph-Louis Lagrange discovered 5 points of equilibrium which exist between two large objects. L2 lies on the axis of the Earth-Sun system on the side furthest away from the sun. According to Kepler's Law, the further away an orbiting body is from its dominant source of gravitation the slower it will revolve around that source as gravitational strength decreases with distance. At the L2 point however, as the Sun and Earth are in a straight line they both exert gravitational forces in the same direction which can be considered to a combined stronger single force of gravitation. This increased gravitational field allows objects of insignificant mass such as the JWST (relative to the Earth and Sun) placed at the L2 point some 1.5 million kilometers away from the earth to make a complete orbit of the Sun in 365 days. The JWST will therefore remain on the axis of the Earth-Sun system which offers an excellent vantage point with which to study the universe (Cattrysse, 2004).

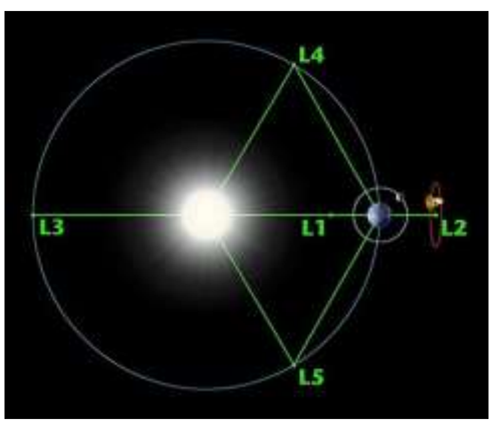

Figure 6. The five Lagrange Points on the Earth-Sun system. *Note.* From “SAFIR”, http://safir.jpl.nasa.gov/sun-earth-L2.shtml retrieved February 2009. Copyright 2009 by Caltech/JPL under NASA contract.

Specifications of the James Webb Space Telescope

When the JWST is launched to the L2 point in 2013, it will be the most advanced space observatory to date. It will house the following four remote sensing instruments which will be able to detect wavelengths ranging from 0.6 to 0.27 micrometers (μm) which are the wavelengths for the oldest galaxies due to expected redshift (Atcheson & Lightsey, 2004):

- NIRCam (Near Infrared Camera)
- NIRSpec (Near Infrared Spectrograph)
- MIRI (Mid Infrared Instrument)
- FGS (Fine Guidance Sensor)

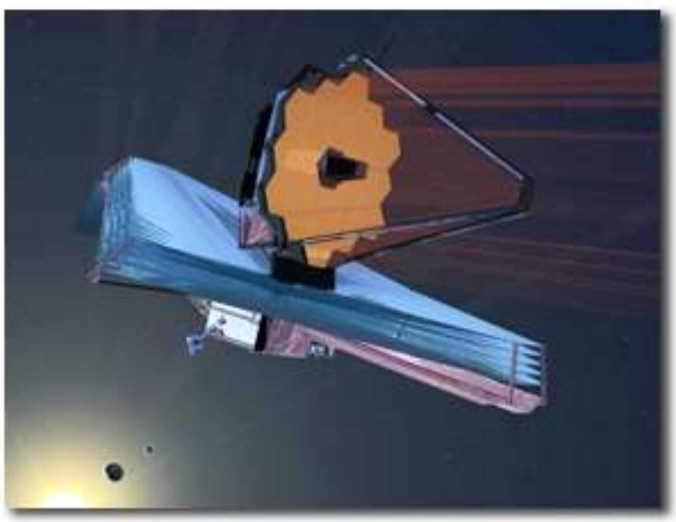

Figure 6. Artist's impression of the JWST at the L2 point. *Note.* From "JWST Observatory Architecture and Performance" by Nella, Atkinson, Bronowicki, Bujanda, Cohen, Davies, Mohan, Pohner, Reynolds, Texter, Simmons, Waldie, and Woods. Copyright 2004 by AIAA Inc.

Most of JWST's remote sensing capability will be in the IR range which will aid in the detection of some of the oldest and most redshifted galaxies in the universe greater than redshift 8 (Stiavelli, 2005). The main four main science mission themes of the JWST are (Mather, 2004):

1. The End of the Dark Ages: First Light and Reionization
2. The Assembly of Galaxies
3. The Birth of Stars and Protoplanetary Systems
4. Planetary Systems and the Origins of Life

One important requirement for the JWST to effectively complete its mission is an operating temperature below 40 Kelvin. Higher temperatures will cause the telescope itself to emit EM radiation which will interfere with the long wavelengths it will be sensing. Infrared (IR) radiation from distant galaxies can be masked by IR emissions from a "warm" JWST. The L2 point being a great distance from the Sun and a five layer sunshield the size of a tennis court are two steps taken to mitigate the problem of the JWST overheating (Nella et al., 2004).

The primary mirror on the JWST is made up of 18 individual Beryllium (Be) hexagonal segments which will be coated with gold plating. Beryllium has properties which work well in extremely low temperatures while gold offers excellent reflection of IR. Each of the segments when pieced together makes up the primary mirror, six of which will be folded when the JWST is placed into the rocket for launch (Long, Isaacs, Kinzel, Petro, Stanley, Stockman, 2006).

The projected lifespan of JWST is five years with many hoping it would operationally last at least 10 years due to the "slow motion" effects of cosmic redshifts. The L2 point lies far outside of the protection zone of the Earth's magnetic field, so proper precautions will be made to protect electrical equipment against harmful cosmic gamma bursts. Each day 229

Gigabits of compressed scientific data will be transmitted to Earth via the Deep Space Network (DSN) (Mather, 2004).

Conclusion

After the Big Bang the universe started expanding. Edwin Hubble discovered that not only was the universe expanding, but other galaxies had receding velocities that were proportional to their distances apart. This meant that galaxies gained speed as they were moving away from each other. According to Hubble's Law, the oldest galaxies in the universe will have the greatest redshift relative to their intense receding velocities. The JWST is designed to sense the Infrared EM radiation characteristic of these first galaxies.

The JWST will be launched to L2 stationing point on the Earth-Sun system in 2013 in hopes of capturing remote sensing imagery of the universe's first galaxies with large redshifts into the IR range of the EM spectrum. It needs to maintain a temperature below 40 Kelvin to avoid self radiating and thus masking scientific data. The location of the L2 position and the five layer sunshield will provide much needed protection from the sun's heat.

The main scientific themes of the JWST's mission will assist in determining the origins of the universe, how galaxies, stars and planets form and the origins of life. The data collected will be the furthest into the past mankind has ever seen as represented by the images of a younger universe.

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