# Calculating the Solar Radiation Intensity from a Sun to Planets

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## Abstract

As NASA and other organizations prepare for space exploration and the settlement of Mars, solar radiation is brought about as a major consideration. While Earth has factors that shield it from receiving dangerous amounts of solar radiation, other planets differ. This project consists of making calculations using known constants and gathered data to quantify the solar radiation intensity planets receive from the Sun within the solar system.

## I. Introduction

In 1969, the Apollo 11 mission successfully landed a crew of two astronauts on the surface of the Moon. Prior to this achievement, other missions before, such as Apollo 8, collected and gathered data about the Moon's radiation environment utilizing Personal Radiation Dosimeters (PRDs) inside astronaut suits [1]. These preparations were made to ensure the safety of the crew as they were sent to areas that were outside of Earth's magnetosphere, placing them in areas of higher radiation exposure.

With the development of technology, there has been an increase in advancing the exploration of other planets both within and outside the solar system. For instance, Kepler-186f was discovered with the use of the Kepler space telescope using the transit method, where a star's light is dimmed intervalley to indicate a planet orbiting a star [2]. In 2017, the Artemis program was formed with the goal of establishing a long-term outpost on the Moon for future expeditions to Mars [3]. As these plans carry out, radiation becomes a larger issue as radiation measurements vary from planet to planet depending on factors such as atmospheres and distance to the Sun. This research project aims to utilize the solar radiation intensity (SRI) equation to calculate each planet's SRI in the solar system with the use of data, showcased through an application which was programmed.

## II. Background

### A. Defining Radiation

Radiation travels at the speed of light and can either be a wave or particle in the form of sound, heat, or light [4]. There exist two types of radiation: ionizing radiation and non-iodizing radiation. Ionizing radiation has greater energy that non-ionizing radiation as electrons are removed from atoms and molecules, while non-ionizing is the opposite [5]. Both can cause the breakdown of DNA, leading to the damage of tissues in the body. Humans are exposed to radiation through everyday activity, such as phone or microwave usage. In the instance of a human body absorbing a large dosage of radiation, acute radiation syndrome (ARS) can occur with the possibility of cancer [6]. These possible consequences contribute to the necessity of ensuring human safety when traveling into space.

### B. Difference Between Solar Radiation and Solar Irradiance

Solar radiation refers to the radiant energy that the Sun emits, while solar irradiance refers to the power that is received from the Sun per unit area [7]. Both contribute to the understanding of determining a planet's potential to sustain life. Figure 1 below conveys the range of radiation that is emitted through solar radiation as Earth receives it. Solar radiation consists of different types of energies that range from high to low on the electromagnetic spectrum, as shown in figure 1 [16].

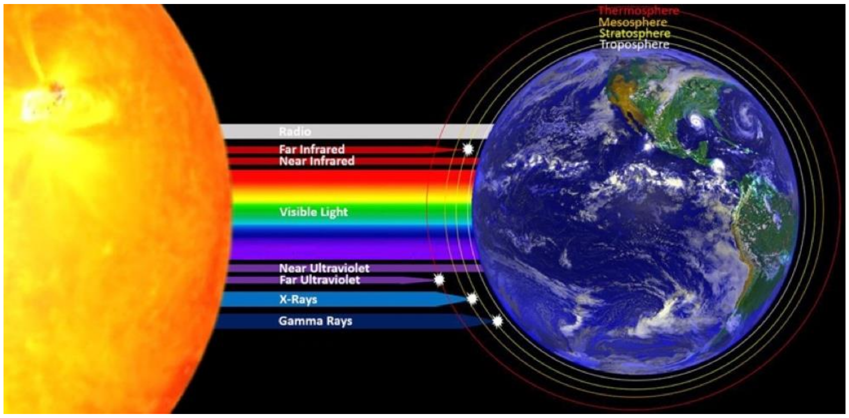


Figure 1- Sun emitting solar radiation to Earth

### C. Other Prevalent Radiation Factors in Space

Alongside the existence of solar radiation, galactic cosmic radiation (GCR) is also prevalent as it is a result of stellar explosions from outside the solar system, e.g., supernovas. GCR radiation is highly ionized, allowing the particles to be impacted by magnetic fields—however their nature remains relatively consistent [8]. Despite the power GCRs have, Earth's unique atmosphere is able to minimize its effects as the particles either are deflected, spread out, or absorbed. All planets in the solar system have atmospheres, gasses that envelope it, though the strength of the atmospheres can range from thin to dense. Another core contributor in planet protection from radiation are magnetospheres. In the solar system, only Mars and Venus do not have magnetospheres, which refers to the region around a planet where its magnetic field is largely present [9]. While radiation, solar and cosmic, impact planet environments and human survival, there are natural occurrences that planets have that ensure safety.

### D. The Solar System's Orbital Plane

The solar system possesses an orbital plane where the planets that revolve around the Sun form a flat disk shape [10]. The Solar System's planets have a stable orbit, and each planet has its own orbital period. Figure 2 demonstrates the circular paths that each planet takes to complete their orbits around the Sun, forming the plane. Despite all orbits being circular, the orbital periods range in days. For instance, Mercury has the shortest orbital period of 88 days, while Neptune has the longest orbital period of 59,800 days as seen in figure 3.

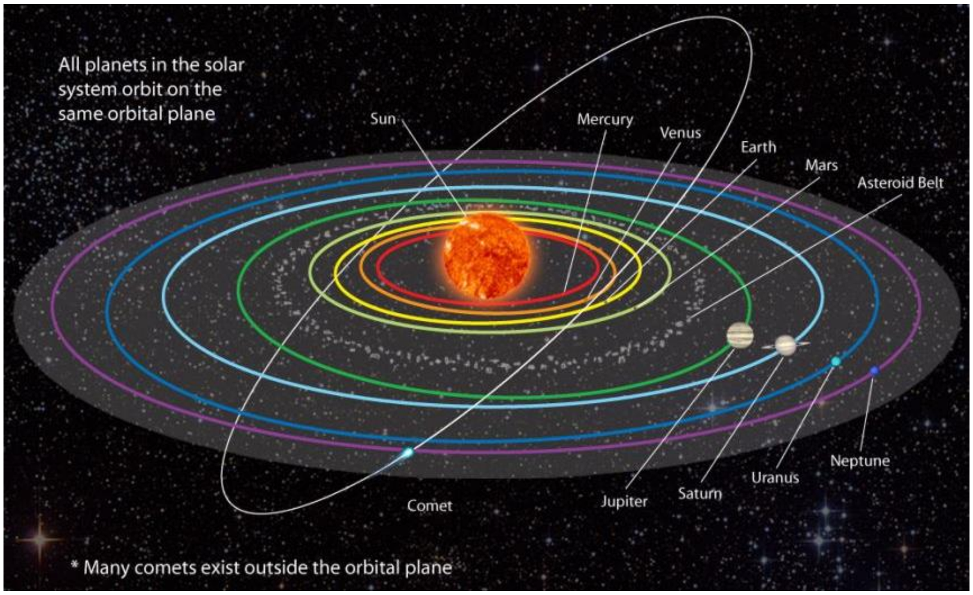
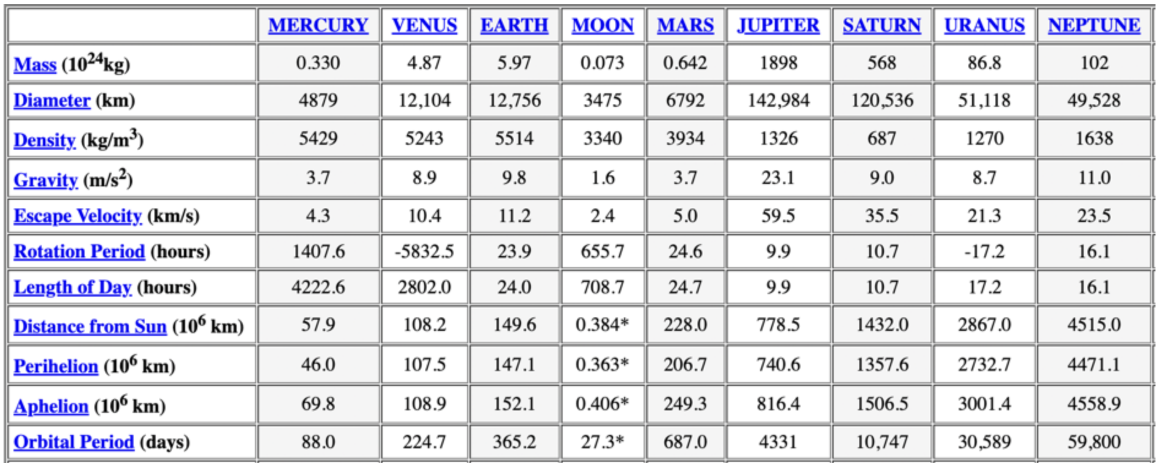


Figure 2- Visual of orbital plane



| | MERCURY | VENUS | EARTH | MOON | MARS | JUPITER | SATURN | URANUS | NEPTUNE |
|---|---|---|---|---|---|---|---|---|---|
| **Mass ($10^{24}$kg)** | 0.330 | 4.87 | 5.97 | 0.073 | 0.642 | 1898 | 568 | 86.8 | 102 |
| **Diameter (km)** | 4879 | 12,104 | 12,756 | 3475 | 6792 | 142,984 | 120,536 | 51,118 | 49,528 |
| **Density (kg/m$^3$)** | 5429 | 5243 | 5514 | 3340 | 3934 | 1326 | 687 | 1270 | 1638 |
| **Gravity (m/s$^2$)** | 3.7 | 8.9 | 9.8 | 1.6 | 3.7 | 23.1 | 9.0 | 8.7 | 11.0 |
| **Escape Velocity (km/s)** | 4.3 | 10.4 | 11.2 | 2.4 | 5.0 | 59.5 | 35.5 | 21.3 | 23.5 |
| **Rotation Period (hours)** | 1407.6 | -5832.5 | 23.9 | 655.7 | 24.6 | 9.9 | 10.7 | -17.2 | 16.1 |
| **Length of Day (hours)** | 4222.6 | 2802.0 | 24.0 | 708.7 | 24.7 | 9.9 | 10.7 | 17.2 | 16.1 |
| **Distance from Sun ($10^6$ km)** | 57.9 | 108.2 | 149.6 | 0.384* | 228.0 | 778.5 | 1432.0 | 2867.0 | 4515.0 |
| **Perihelion ($10^6$ km)** | 46.0 | 107.5 | 147.1 | 0.363* | 206.7 | 740.6 | 1357.6 | 2732.7 | 4471.1 |
| **Aphelion ($10^6$ km)** | 69.8 | 108.9 | 152.1 | 0.406* | 249.3 | 816.4 | 1506.5 | 3001.4 | 4558.9 |
| **Orbital Period (days)** | 88.0 | 224.7 | 365.2 | 27.3* | 687.0 | 4331 | 10,747 | 30,589 | 59,800 |

Figure 3- Table presenting planetary information, including orbital periods

## III. Research

### A. Solar Radiation Intensity Equation

Solar irradiance is related to power, and it is measured in watts per meter squared. Christiana Honsberg, a professor at Arizona State University's School of Engineering, and Stuart Bowden, an associate professor at Arizona State University, presented the solar irradiance equation responsible for calculating the power density the Sun projects onto an object [11]. The equation is written as: $H_0 = \frac{R_{sun}^2}{D^2} H_{sun}$ and is visualized in figure 4. $H_0$ signifies the solar radiation intensity being calculated. $R_{sun}$ is a constant for the radius of the Sun which is $695 \times 10^6\ meters$. $D$ refers to the distance an object is from the sun. $H_{sun}$ is also a constant for the Sun's surface power density which is $64 \times 10^6\ watt/meter^2$. This variable was derived from the Stefan-Boltzmann blackbody equation: $E = \sigma T^4$ which determines the radiant heat emitted over area per unit time. In this equation, $\sigma$ is Stefan's constant of $5.6703 \times 10^{-8}\ watt/meter^2 Kelvin^4$ [12]. Ultimately, the solar radiation intensity equation outlines the ability to establish the solar irradiance through the Sun's known constants and the Stefan Boltzmann equation.

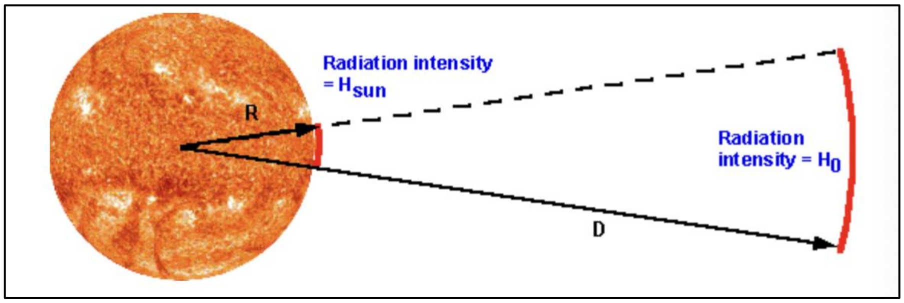
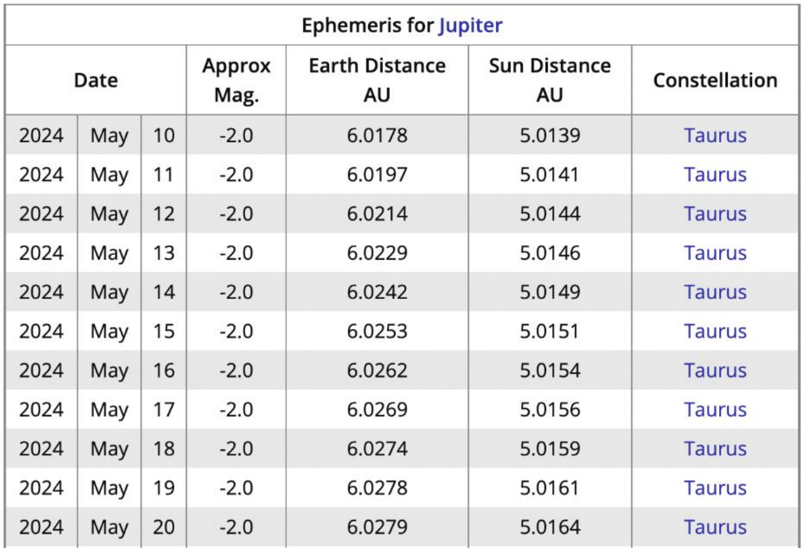


Figure 4- Visual of solar radiation intensity equation

### B. Data

Dr. Dominic Ford is a data scientist at the Institute of Astronomy in Cambridge, and he is currently part of the Planetary Transits and Oscillations of stars (PLATO) mission [13]. Dr. Ford created a searchable catalog of astronomical events with data spanning from 1950 to 2300. A key variable for the SRI equation, distance to the Sun, was provided in the catalog. Figure 5 illustrates dates, approximate magnitudes, distances to Earth, distances to Sun, and constellations provided by Dr. Ford. It should be noted that the planets continuously stay in orbit, however the distance to the Sun was taken as an average for each date.



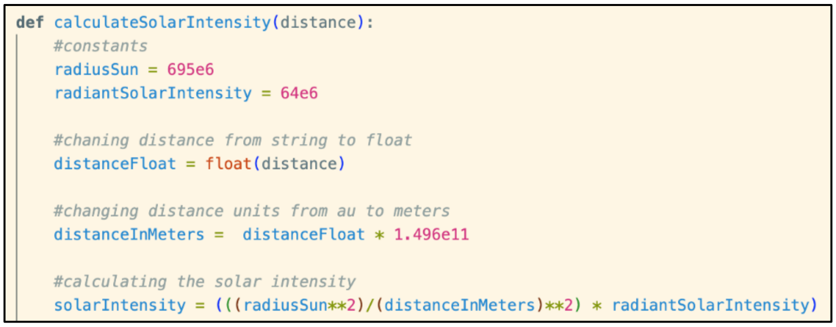
| Ephemeris for Jupiter | | | | | | |
|---|---|---|---|---|---|---|
| Date | | | Approx Mag. | Earth Distance AU | Sun Distance AU | Constellation |
| 2024 | May | 10 | -2.0 | 6.0178 | 5.0139 | Taurus |
| 2024 | May | 11 | -2.0 | 6.0197 | 5.0141 | Taurus |
| 2024 | May | 12 | -2.0 | 6.0214 | 5.0144 | Taurus |
| 2024 | May | 13 | -2.0 | 6.0229 | 5.0146 | Taurus |
| 2024 | May | 14 | -2.0 | 6.0242 | 5.0149 | Taurus |
| 2024 | May | 15 | -2.0 | 6.0253 | 5.0151 | Taurus |
| 2024 | May | 16 | -2.0 | 6.0262 | 5.0154 | Taurus |
| 2024 | May | 17 | -2.0 | 6.0269 | 5.0156 | Taurus |
| 2024 | May | 18 | -2.0 | 6.0274 | 5.0159 | Taurus |
| 2024 | May | 19 | -2.0 | 6.0278 | 5.0161 | Taurus |
| 2024 | May | 20 | -2.0 | 6.0279 | 5.0164 | Taurus |

Figure 5- Chart from Dr. Ford’s catalog

### C. Process

Using the SRI equation and data provided by Dr. Ford, an application to make such calculations was developed. The application was programmed in the Python programming language, utilizing the Tkinter graphical user interface. First, each of the planet’s orbital data was gathered from Dr. Ford’s catalog. This data was downloaded in CSV format to be used in the application, where it was then parsed to specifically obtain the date, distance to Earth, and distance to Sun. The distance values were then converted from astronomical units (au) to meters (m), where one astronomical unit is equivalent to $1.496 \times 10^{11}\ meters$. The distance to Sun values were specifically used for the SRI equation. With this implemented, the solar radiation intensity was then calculated depending on the planets’ distance to Sun on each day. Figure 6 shows the method that is responsible for acting as the SRI equation in the application.

The application can be applied to other solar systems such as the Kepler-186 system. The SRI for the planet Kepler-186f’s was calculated. Kepler-186f’s star is Kepler-186, which almost half the size of the Sun, while Kepler-186f is slightly larger than Earth. These comparisons are seen on figure 7.



```
def calculateSolarIntensity(distance):
    #constants
    radiusSun = 695e6
    radiantSolarIntensity = 64e6

    #chaning distance from string to float
    distanceFloat = float(distance)

    #changing distance units from au to meters
    distanceInMeters =  distanceFloat * 1.496e11

    #calculating the solar intensity
    solarIntensity = (((radiusSun**2)/(distanceInMeters)**2) * radiantSolarIntensity)
```

Figure 6- Method named calculateSolarIntensity() in the Python application

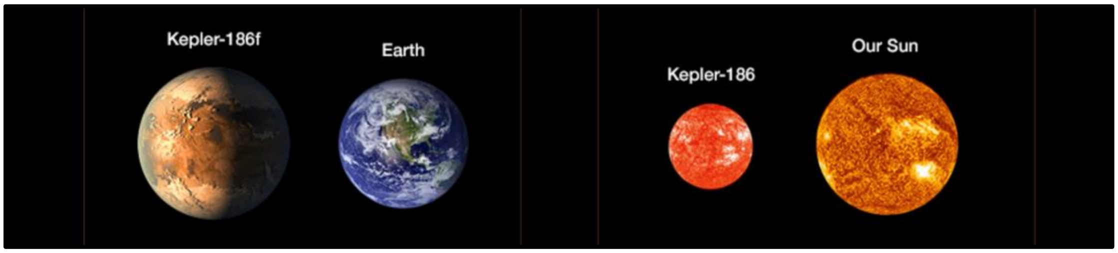


Figure 7- Planet and star comparisons

## D. Limitations

There were also factors present that were not assumed in the SRI equation and the implementation. The factors that were not considered include: the effects of GCRs, atmospheric impact of each planet, solar events, and other astronomical occurrences. The data acquired for distances were also a result of Dr. Ford's work and are estimations. The SRI for Earth was also not calculated because the solar constant, approximately $1370\, watt/meter^2$, is known [14]. Lastly, because the surface power density of Kepler-186 is not known, the Sun's surface power density was used for the value of $H_{sun}$. Therefore, Kepler-186f's SRI is an estimation and may be slightly less because of its star being smaller than the Sun.

## IV. Results

### A. Software Implementation

The software used to program the application was Python, alongside a graphical user interface toolkit named Tkinter. Two screens were developed: one that allows the user to choose a planet and a second where the calculation for SRI is shown with other information, such as average SRI and orbital distances. Figure 6 is the first screen and figure 7 is the second screen.

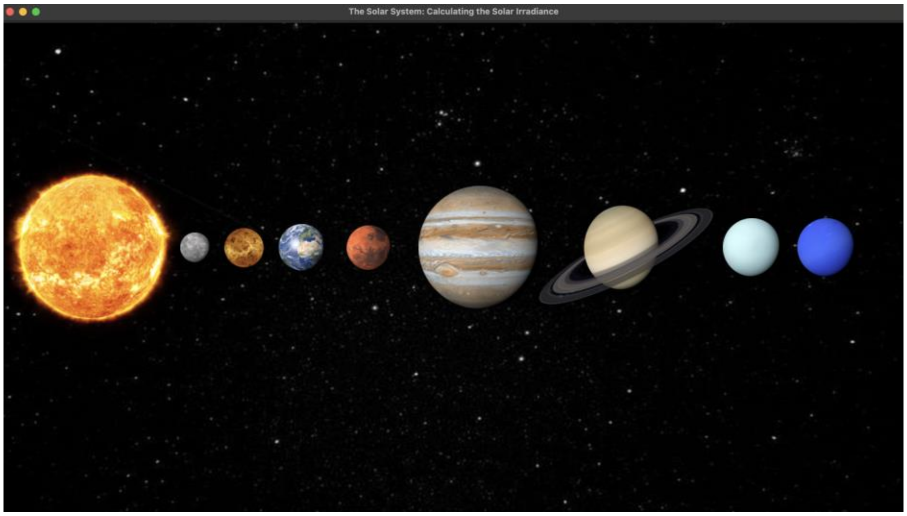
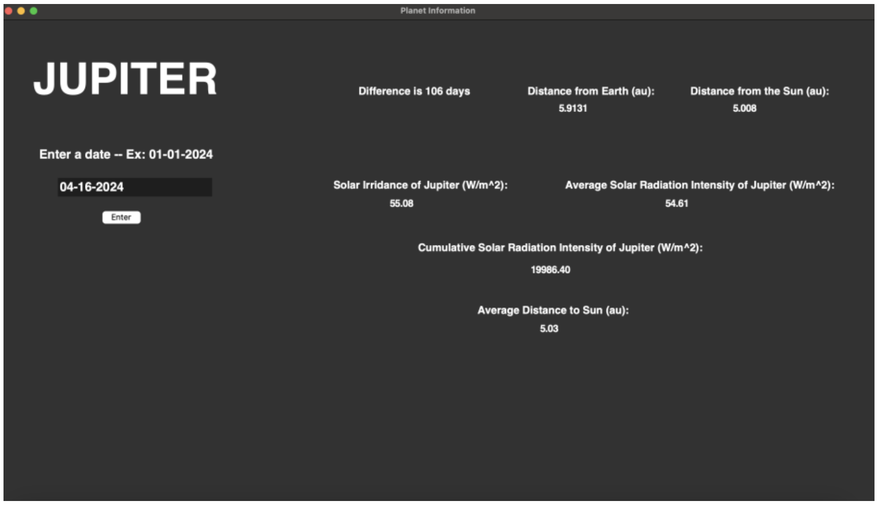


Figure 8- First screen of application



JUPITER

Enter a date -- Ex: 01-01-2024

04-16-2024

Difference is 106 days

Distance from Earth (au):
5.9131

Distance from the Sun (au):
5.008

Solar Irridance of Jupiter (W/m^2):
55.08

Average Solar Radiation Intensity of Jupiter (W/m^2):
54.61

Cumulative Solar Radiation Intensity of Jupiter (W/m^2):
19986.40

Average Distance to Sun (au):
5.03

Figure 9- Second screen of application

## B. Earth's Solar System

The solar system's SRI results were calculated based on each of the planet's average distance to the Sun. Honsberg and Bowden provided their own calculations of the planets' SRI. As seen in Table 1, the SRIs calculated by the application were similar to the SRIs calculated by Honsberg and Bowden [11]. The lowest percentage error pertains to Venus with 0.32%, while the largest percentage error pertains to Mars with 11.35%. Table 2 conveys the correlation between a planet's distance to the Sun and its SRI. Mercury is the closest planet to the Sun and has the shortest orbital period, therefore the SRI is much higher compared to Neptune, the furthest planet from the Sun and longest orbital period.

| Planet | Average Distance to Sun Calculated by Application (au) | Average SRI Calculated by Application ($W/m^2$) | Average SRI Calculated by Honsberg and Bowden ($W/m^2$) | Percentage Error (%) |
|---|---|---|---|---|
| **Mercury** | 0.395 | 9419.63 | 9116.40 | 3.33 |
| **Venus** | 0.723 | 2619.31 | 2611 | 0.32 |
| **Mars** | 1.530 | 655.40 | 588.60 | 11.35 |
| **Jupiter** | 5.030 | 54.61 | 50.5 | 8.14 |
| **Saturn** | 9.685 | 14.73 | 15.04 | 2.06 |
| **Uranus** | 19.584 | 3.60 | 3.72 | 3.23 |
| **Neptune** | 29.899 | 1.55 | 1.51 | 2.65 |

Table 1- Average SRIs calculated by application and Honsberg and Bowden

| Planet | Date | Distance to Sun ($au$) | Solar Radiation Intensity ($W/m^2$) | Orbital Period (days) |
|---|---|---|---|---|
| **Mercury** | 01-01-24 | 0.3479 | 11412.41 | 88 |
| | 12-31-24 | 0.4203 | 7819.30 | |
| **Neptune** | 01-01-24 | 29.9038 | 1.54 | 59800 |
| | 12-31-24 | 29.8944 | 1.55 | |

Table 2- SRI for Mercury and Neptune

### C. Exoplanet

Unlike the solar system implementation of the SRI equation where numerous dates were used, the implementation for the Kepler-186 system utilizes an instance of Kepler-186f's average distance to its sun. The equation's radius variable: $R_{sun}$ is replaced with $R_{Kepler-186}$, referring to Kepler-186's radius of $328417600\ meters$. The distance from Kepler-186f to Kepler-186 is $6.4327 \times 10^{10}\ meters$. As mentioned before, Kepler-186's surface power density is unknown, therefore the Sun's surface power density is used in replace. Hence, the SRI equation is: $H_0 = \frac{(328417600)^2}{(6.4327\times10^{10})^2}(64 \times 10^6) = 1668.19\ W/m^2$. This solar radiation intensity measured for Kepler-186f is like Earth's solar constant.

## V. Future Work

Future work will emphasize the potential for the SRI equation to become more accurate by adding mathematical variables and inputs. For instance, there exist the Earth atmosphere model which considers density, pressure, temperature, and altitude [15]. With this extension, further work can be done for other star systems that have applicable data. Additionally, the impact that different cosmic events can have on the solar irradiance of planets may also be explored, such as solar eclipses or solar fares.

## VI. Conclusion

This research project focused on the solar radiation intensity equation and its application. Solar irradiance can be estimated using the SRI equation. An application that was able to compute SRI was implemented using Python and solar irradiance was calculated for all planets in the solar system from dates between 2024-2026. Overall, the application can be extended to estimate the SRI for other star systems.

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