

Visualization of Mercury's Orbital Path Around the Sun Using Matlab for Astronomic Distance Learning

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Abstract: Physical phenomena occurring at both macro and micro scales are often beyond direct observation by the human senses. This study aims to present an alternative astronomical learning activity about the orbital trajectory of the planet Mercury around the Sun using MATLAB assistance. Visualization of the orbital trajectory of Mercury begins by describing the appropriate mathematical equations. Subsequently, these equations are translated into graphical representations using MATLAB for visualization. In this study, students can visualize the orbital trajectory of Mercury around the Sun using MATLAB by varying the components of the coordinate equation. Through this visualization, it is hoped that it can help students understand the movement of Mercury around the Sun in its orbit independently and creatively. Students can also develop mathematical representation skills and visual representations of the orbital trajectory of Mercury around the Sun.

Keywords: Astronomic, Distance Learning, MATLAB, Mercury, Orbit.

Introduction

The demands of technological progress driven by the advent of the fourth industrial revolution are unavoidable for every country. It is characterized by several countries competing in researching and exploring natural resources on Mercury and Mars [1]. While several nations prioritize and schedule research and exploration of planets within the solar system [2], in developing countries, these activities cannot be carried out on a massive scale. Factors such as low income and budget constraints, with priorities allocated to the welfare, education, health, and expanding employment opportunities for their citizens, contribute to these challenges. However, developing countries can still engage in astronomical research, particularly in the study of the planets within the solar system. This

can be achieved through continuous innovation in the fields of education and research [3].

In carrying out innovations in the fields of education and research, every educator and researcher needs to instill an awareness of the importance of cooperation in advancing the field of astronomy. One of the innovative efforts that can be made is to apply the concept of astronomy with the help of technology that is cheap, easy to obtain, accessible, and operated by students [4, 5]. This ensures that the quality of education in developing countries remains competitive with that in developed nations. In addition, this is done so that the results of research in the field of astronomy are not only enjoyed by high-income countries but are accessible to all nations. One effective method of

interpreting astronomical concepts is through visualization, such as simulating rocket motion using MATLAB [6]. However, students need to be given flexibility in constructing the visualization of astronomical concepts.

The visualization of astronomical concepts that exist in most schools is in the form of a set of teaching aids to help visualize basic astronomical concepts such as the concept of the revolutionary movement of the planets in the solar system [7]. However, specific visualizations for astronomy concepts, particularly the orbital paths of planets, are not commonly available in schools. Physical objects are often used for visualizations, but they prove to be inefficient and ineffective when catering to large numbers of students. Additionally, these traditional methods lack integration with technology, limiting their use in schools [8,9]. In contrast, technology-integrated visualization tools like MATLAB can be used anytime and anywhere without an internet network. Thus, with the help of technology such as MATLAB for visualizing astronomical concepts, astronomy education can become more effective and accessible.

Activities that visualize astronomical integrated with MATLAB provide an alternative to distance learning. This assertion is supported by research conducted by Yu *et al.* [10], demonstrating that MATLAB facilitates interactive visualization of astronomical concepts, such as the design and analysis of tertiary mirror systems of thirty-meter telescopes. Furthermore, studies have shown that MATLAB can accurately visualize trajectories of launch vehicles for low-earth orbit applications, aligning with experimental results [11]. MATLAB serves as computational software enabling easy visualization of mathematical equations representing astronomical phenomena, without the need for an internet connection [12].

MATLAB is a graphical computing software used for visualizing mathematical equations, offering two- and three-dimensional graphic visualization results [13]. With MATLAB, users can manipulate matrices, plot mathematical functions and equations, implement algorithms, and create user interfaces. MATLAB serves as a comprehensive computational tool capable of analyzing both simple and complex algebraic equations. MATLAB can be used to support

astronomical research activities, especially in analyzing and visualizing mathematical equations of complex astronomical phenomena [14]. In addition, MATLAB software facilitates distance learning of astronomy.

The integration of MATLAB into astronomy learning simplifies the visual construction of astronomical equations [15]. This application not only enhances students' visual representation skills but also positively impacts their overall proficiency in physics. This is based on the results of research that reveal that learning astronomy that integrates graphic visualization produced from MATLAB can improve students' visual representation abilities [16]. Students' mathematical and graphic representation abilities can also be developed by applying MATLAB-assisted astronomy learning [17]. Once students have good visual representation skills, they can use MATLAB to visualize the mathematical equations of other astronomical phenomena, given its capability to handle both simple and intricate calculations [18,19]. Numerous studies underscore the efficacy of MATLAB in enhancing astronomy education.

MATLAB software has been used to visualize and analyze the gravitational signal from a core-collapse supernovae (CCSNe) [20]. Additionally, it aids in extracting Earth's orbital period from the CO₂ concentration in the atmosphere by using the Fourier transform [21]. Furthermore, MATLAB enables educators and students to visualize and analyze the impact of infrasonic atmospheric noise on gravity detectors [22]. Despite its widespread application in astronomy, there remains a gap in the visualization of Mercury's orbital trajectory using MATLAB. This gap may arise from a predominant focus on discussing Earth's revolution among researchers, educators, and students [23]. Therefore, there is a need to innovate and develop visualization techniques for Mercury's orbital trajectory using MATLAB to enrich astronomical learning and research endeavors.

Theory

The state of each planet's orbit evolves, influencing surface conditions such as seasons, weather, and the duration of day and night [24]. These changes vary across planets, including Mercury. Visualizing Mercury's orbital trajectory around the Sun can greatly aid in understanding

its movement [25]. While many visualization activities focus on Earth's orbit, simulations often overlook other planets, particularly Mercury. Additionally, some visualizations assume circular orbits, which may not accurately describe the actual orbits of the planets [26].

First, let's review the characteristics of Mercury. The planet Mercury has a diameter of about 4 862 000 km and a mass of around 0.055 times that of Earth, with a density of about 5400 kg/m^3 . The distance from the Sun is 0.39 AU.

The revolutionary period for Mercury is 88 days, while the planet's rotation period is 59 days. Mercury's gravitational acceleration is 0.38 times that of Earth's gravity [27]. Mercury has a weak magnetic field and its core contains a lot of iron alloys (iron-nickel) and a thin layer of silicate material [28, 29]. During the day, the surface temperature on Mercury soars to around 700 K, dropping to 425 K at sunset and reaching lows of about 100 K at midnight. This vast temperature range is the largest among all the planets in the solar system [30]. In comparison, on Earth, the temperature variation between day and night rarely exceeds 20 K. Long hot days and a very rapid rate of decline in temperature mean that Mercury has no atmosphere [31]. Mercury reflects only about 6% of the sunlight it receives, and its surface features include a giant valley, evidence of basin formation resulting from the planet's gradual shrinkage [32]. Astronauts have also found evidence that Mercury's crust and upper mantle are tectonically active even though they are not as active as the layers on Earth [33].

For students in high school or early astronomy courses, understanding the fundamental concept of Mercury's orbit around the Sun is crucial. Often, educators primarily focus on explaining the elliptical trajectories of the planets in general, neglecting the specifics of Mercury's orbit [34]. To visualize the orbital trajectory of a planet as it circles the Sun, we start by assuming that the planet has a mass represented by (m), while the Sun's mass is denoted by (M) with ($M \gg m$). According to Newton's law of universal gravity, the gravitational force between the Sun and the planets can be expressed as shown in Eq. (1) below.

$$F = G \frac{Mm}{r^2} \quad (1)$$

Eq. (1) represents the gravitational force between the Sun and a planet or between two planets, where G is the gravitational constant and r is the distance between the Sun and a planet or between the two planets [35]. When the gravitational force components in Eq. (1) are represented in Cartesian coordinates and visualized along the x-axis and y-axis, some components can be represented as shown in Eqs. (2) and (3).

$$F_x = F \frac{x}{r} = \left(G \frac{Mm}{r^2} \right) \left(\frac{x}{r} \right) = G \frac{Mmx}{r^3} \quad (2)$$

$$F_y = F \frac{y}{r} = \left(G \frac{Mm}{r^2} \right) \left(\frac{y}{r} \right) = G \frac{Mmy}{r^3} \quad (3)$$

Equations (2) and (3) can also be written in other forms by substituting them into Newton's second law equation, as shown in Eqs. (4) and (5) below.

$$m \frac{dv_x}{dt} = -G \frac{Mmx}{r^3} \quad (4)$$

$$m \frac{dv_y}{dt} = -G \frac{Mmy}{r^3} \quad (5)$$

Eqs. (4) and (5), derived from the substitution into Newton's second law equation, can be simplified by eliminating the components m on both sides of the equation. This simplification results in the equations shown in Eqs. (6) and (7) below.

$$\frac{dv_x}{dt} = -G \frac{Mx}{r^3} \quad (6)$$

$$\frac{dv_y}{dt} = -G \frac{My}{r^3} \quad (7)$$

Furthermore, because this study will only analyze the orbital trajectories of planets, particularly Mercury, around the Sun, it is determined that $GM = 1$. Besides, it is assumed that Mercury's starting position is at coordinates $(x, y) = (0.5, 0)$, with initial velocities $v_x(0) = 0$ and $v_y(0) = 1.63$ [36]. If it is assumed that $v_x = \dot{x}$ and $v_y = \dot{y}$, the equations for the motion of the planets, particularly Mercury, around the Sun, can be written as in Eqs. (8) and (9) below.

$$\ddot{x} = -\frac{x}{(x^2 + y^2)^{3/2}} \quad (8)$$

$$\ddot{y} = -\frac{y}{(x^2 + y^2)^{3/2}} \quad (9)$$

Eqs. (8) and (9) can be used to visualize the orbits of the planets in the solar system in

general when they circle the Sun [37]. To proceed, they can be formulated as a set of linear ordinary differential equations, as shown in Eq. (10) below.

$$\begin{pmatrix} x_1 = x \\ x_2 = \dot{x} = \dot{x}_1 = v_x \\ x_3 = y \\ x_4 = \dot{y} = \dot{x}_3 = v_y \end{pmatrix} \quad (10)$$

Furthermore, Eq. (10) can be simplified again by substituting it into Eqs. (8) and (9), resulting in Eq. (11) below.

$$\dot{x}_1 = x_2 \quad (11)$$

$$\dot{x}_2 = -\frac{x_1}{(x_1^2 + x_3^2)^{3/2}} \quad (12)$$

$$\dot{x}_4 = -\frac{x_3}{(x_1^2 + x_3^2)^{3/2}} \quad (13)$$

Eqs. (11), (12) and (13) are used to visualize the orbital trajectories of the planets in MATLAB software. Apart from using Eqs. (11), (12) and (13), visualizing the orbital paths of the planets can also be achieved using the wave inference equation as demonstrated in Eqs. (14) and (15) below.

$$x(t) = 2 \cos(1.63 \times t) \quad (14)$$

$$y(t) = 2 \sin(1.63 \times t) \quad (15)$$

To visualize the orbital trajectory of Mercury using MATLAB software, the wave inference equation is also employed, as depicted in Eqs. (16) and (17) below. This approach is adopted because Mercury has a very strange orbit around the Sun [38].

$$x(t) = 93 \cos t + 36 \cos 4.15t \quad (16)$$

$$y(t) = 93 \sin t + 36 \sin 4.15t \quad (17)$$

Materials and Methods

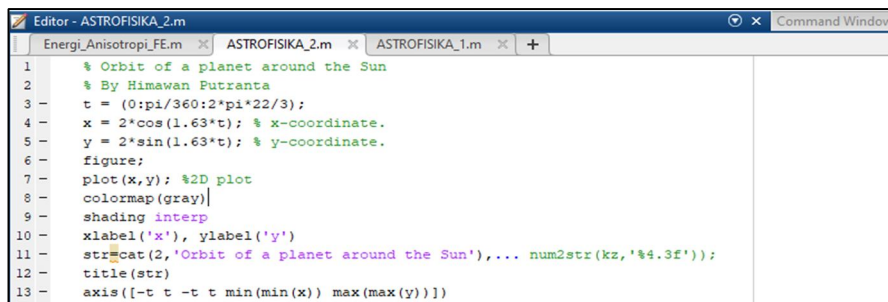
Visualization of the orbital trajectories of the planets in the solar system is carried out in this article using MATLAB software. The purpose is

to determine the visualization of both the general orbital trajectories of the planets around the Sun and the specific orbital trajectory of Mercury around the Sun. MATLAB is chosen for its ability to strengthen mathematical understanding in astronomy and produce smooth visualizations[39]. Besides, MATLAB's features allow for plotting graphs with various shapes, both two-dimensional and three-dimensional, making it suitable for visualizing the orbits of the planets based on Eqs. (14)-(17). Simulating the orbital trajectories of the planets involves several steps.

First, we determine the time interval to be inputted in Eqs. (14)-(17). Next, we input the mathematical equations for the orbital trajectories into the MATLAB workspace. Finally, the equations are processed to produce smooth visualizations. Here is the syntax for visualizing the general orbital paths of the planets around the Sun, which includes Eqs. (14) and (15):

```
% Orbit of a planet around the Sun
% By Himawan Putranta
t = (0:pi/360:2*pi*22/3);
x = 2*cos(1.63*t); % x-coordinate.
y = 2*sin(1.63*t); % y-coordinate.
figure;
plot(x,y); %2D plot
colormap(gray)
shading interp
xlabel('x'), ylabel('y')
str=cat(2,'Orbit of a planet around the Sun'),...
num2str(kz,'%4.3f');
title(str)
axis([-t t -t t min(min(x)) max(max(y))])
```

The displayed workspace of MATLAB with this code inputted can be seen in Fig. 1.



```
Editor - ASTROFISIKA_2.m
Energi_Anisotropi_FE.m ASTROFISIKA_2.m ASTROFISIKA_1.m + Command Window
1 % Orbit of a planet around the Sun
2 % By Himawan Putranta
3 t = (0:pi/360:2*pi*22/3);
4 x = 2*cos(1.63*t); % x-coordinate.
5 y = 2*sin(1.63*t); % y-coordinate.
6 figure;
7 plot(x,y); %2D plot
8 colormap(gray)
9 shading interp
10 xlabel('x'), ylabel('y')
11 str=cat(2,'Orbit of a planet around the Sun'),...
12 num2str(kz,'%4.3f');
13 title(str)
14 axis([-t t -t t min(min(x)) max(max(y))])
```

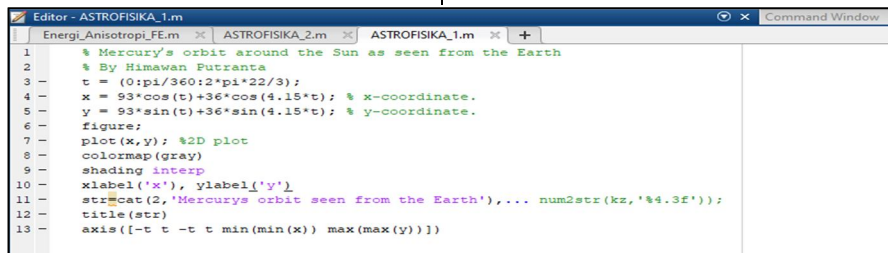
FIG 1. The MATLAB workspace view for visualizing the orbits of the planets around the Sun.

Meanwhile, the following syntax is inputted into the MATLAB workspace to visualize the orbital path of Mercury as it circles the Sun, containing Eqs. (16) and (17):

```
% Mercury's orbit around the Sun as seen from the Earth
% By Himawan Putranta
t = (0:pi/360:2*pi*22/3);
x = 93*cos(t)+36*cos(4.15*t); % x-coordinate.
y = 93*sin(t)+36*sin(4.15*t); % y-coordinate.
figure;
```

```
plot(x,y); %2D plot
colormap(gray)
shading interp
xlabel('x'), ylabel('y')
str=cat(2,'Mercurys orbit seen from the Earth'),... num2str(kz,'%4.3f');
title(str)
axis([-t t -t t min(min(x)) max(max(y))])
```

The workspace display of the MATLAB software, which has been inputted with Eqs. (16) and (17) to visualize the orbital path of Mercury as it circles the Sun, is depicted in Fig. 2.



```
Editor - ASTROFISIKA_1.m
1 % Mercury's orbit around the Sun as seen from the Earth
2 % By Himawan Putranta
3 t = (0:pi/360:2*pi*22/3);
4 x = 93*cos(t)+36*cos(4.15*t); % x-coordinate.
5 y = 93*sin(t)+36*sin(4.15*t); % y-coordinate.
6 figure;
7 plot(x,y); %2D plot
8 colormap(gray)
9 shading interp
10 xlabel('x'), ylabel('y')
11 str=cat(2,'Mercurys orbit seen from the Earth'),... num2str(kz,'%4.3f');
12 title(str)
13 axis([-t t -t t min(min(x)) max(max(y))])
```

FIG 2. MATLAB workspace view for visualizing the orbital trajectory of the Mercury around the Sun.

After inputting Eqs. (14)-(17) necessary to visualize the orbits of the planets, including Mercury, around the sun as shown in Figs. 1 and 2, the next step is to visualize these orbits. Fig. 3

shows the command to be selected for executing the visualization of the orbital paths of the planets. The subsequent step involves analyzing the visualization.

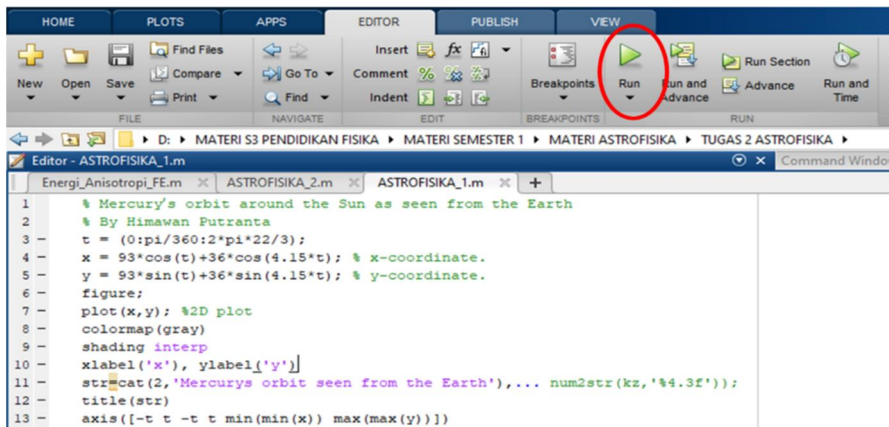


FIG 3. Click the "Run" command on the MATLAB taskbar to display a visualization of the orbits of the planets and Mercury around the Sun.

Results and Discussion

In this article, we demonstrate the process of visualizing the orbits of the planets and Mercury as they circle the Sun using the help of MATLAB. The visualization involves varying the time value from 0 to $\frac{2\pi \times 22}{3}$ with an interval of $\frac{\pi}{360}$. In this study, four equations are used to visualize the orbital trajectories of the planets in

general and the orbital paths of Mercury. Mercury is chosen for this study due to its peculiar orbit around the Sun [40]. The study aims to determine the input and output processes by visualizing these orbits using MATLAB. The results of the visualization are depicted in Fig. 4.

Fig. 4 shows the visualization of the orbits of the planets around the Sun, revealing elliptical paths rather than perfect circles. This observation

is consistent with research demonstrating that the orbital trajectories of the planets in the solar system are elliptical [41]. In Fig. 4 (a), the elliptical blue line represents the orbital path of the eight planets in the solar system, with the Sun positioned at one of the focal points of the ellipse. As per the first Kepler law, the Sun acts as the center of the solar system [42]. The elliptical paths indicate that planets vary in distance from the Sun, with perihelion

representing the closest distance and aphelion the farthest. Planets closer to the Sun exhibit higher orbital speeds [43]. Although in general the orbits of the planets around the Sun are elliptical, each planet exhibits unique trajectory characteristics, influencing surface conditions, seasons, weather patterns, and the length of day and night. The most obvious thing is the difference in rotation and revolution times for each planet in the solar system.

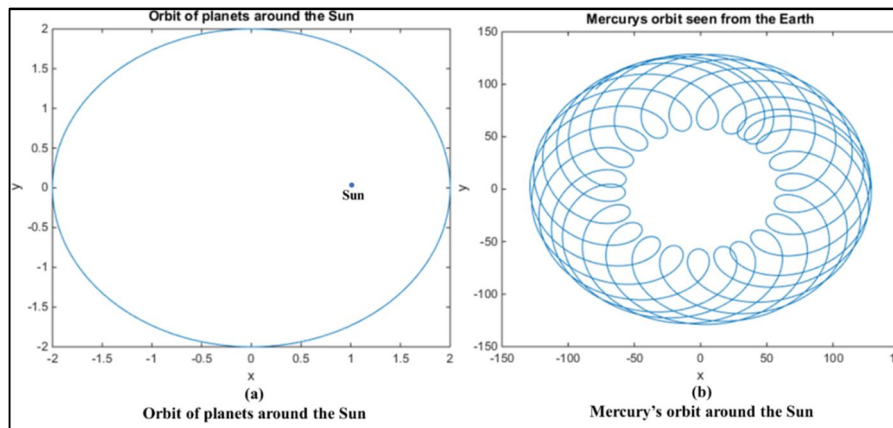


FIG 4. The visualization of orbits: (a) The planets around the Sun and (b) Mercury around the Sun.

Fig. 4 (b) illustrates that the orbits of planets in the solar system, particularly that of Mercury, are elliptical. However, Mercury's orbit exhibits a unique characteristic: it forms a spiral pattern as it circles the Sun. This spiral pattern resembles a coil of wire or a hair tie. As depicted in Fig. 4 (b), Mercury's orbital trajectory when viewed from Earth appears to spiral around the Sun, maintaining a close distance to it. This is consistent with the fact that Mercury is the closest planet to the Sun, with a distance of 57 909 050 km or 0.387 AU [44]. The perihelion distance of Mercury is about 46 001 200 km, while its aphelion distance is 698 169 900 km [45]. Besides, Mercury's orbit, as shown in Fig. 4 (b), exhibits a pattern of adjacent spiral curves, indicating its rapid orbital compared to other planets in the solar system. Mercury certainly moves fastest when it is closest to the Sun and the slowest when it is the farthest from the Sun. The average orbital velocity of Mercury is 47 362 km/s, meaning that Mercury takes approximately 88 days to complete one orbit of the Sun [46]. This swift orbit significantly affects time perception on Earth, as one day on Mercury is equivalent to two years on Earth [47]. Additionally, the spiral pattern of Mercury's orbit, visible as it contracts and expands, reflects the planet's characteristic behavior. At times, Mercury appears to shrink as its core cools,

resulting in a darker appearance [48]. These variations are influenced by Mercury's positions at its closest and farthest distances from the Sun.

This visualization of planetary orbits, including that of Mercury, serves an important purpose in astronomy learning. This activity enables researchers to discern the characteristics and composition of Mercury's natural resources [49]. It also aids in understanding the intricate patterns of Mercury's orbital movements. Given the necessity for technological advancements, especially in the field of astronomy, a comprehensive study of the universe's phenomena and characteristics is essential [50]. This visualization offers researchers a perspective to study the characteristics of the planets neighboring Earth and their responses to the Sun's ultraviolet radiation.

Additionally, it facilitates astronomical learning activities [51] by asking students to analyze Mercury's orbital trajectories and explore the mathematical equations governing planetary orbits, all within the MATLAB software environment. This interactive approach serves as a link between mathematical equations and astronomic phenomena, providing a cost-effective and accessible means for students to engage with complex astronomical concepts [52]. Furthermore, visualizing mathematical

equations of astronomical phenomena supports the implementation of remote astronomy learning activities.

Implementing astronomy learning through visualization activities can significantly enhance student engagement and comprehension. By actively involving students in understanding the mathematical equations of astronomical phenomena and conducting virtual experiments using MATLAB, they can develop skills in mathematical representation and creative visualization. Besides, engaging with the orbital trajectories of planets, particularly Mercury, using MATLAB can enhance students' science process skills and critical thinking abilities. This is because students are required to explore the characteristics and mathematical equations associated with planetary orbits.

Given the ongoing COVID-19 pandemic and the resulting shift towards remote learning, astronomy education that incorporates the visualization process can support distance learning initiatives [53]. This is because astronomical learning is carried out based on

virtual projects and students can be motivated to learn astronomical concepts.

Conclusions

In this research, MATLAB software was employed to visualize the orbital trajectories of planets, with a specific focus on Mercury's orbit around the Sun. MATLAB was chosen for its ease of use, ability to visualize complex astronomical equations, and capacity to generate graphical representations in both two and three dimensions. These features make it accessible and beneficial for high school or college students in the early years of learning, as well as for novice programmers. This visualization activity facilitates a better understanding and implementation of mathematical equations related to astronomical phenomena, particularly concerning planetary orbits and Mercury's path around the Sun. Such visualization aids in remote learning of astronomy at various educational levels. Furthermore, the results of this study can be used as a reference source for researchers or students, offering insights into visualizing planetary orbits beyond our solar system within the Milky Way galaxy.

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