Binary Star System With a Non-circumbinary Planet

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1 Introduction

A binary star system occurs when two gravitationally bound stars orbit around each other. Binary stars are quite common in our galactic neighborhood [3], and there is reason to believe that the number of binary star planets may surpass that of single-star systems [1]. Planets within these systems can be categorized as follows:

i Planets that orbit the center of mass of both stars are said to have a P-type orbit [3] and are called circumbinary planets.

ii Planets that orbit only one of the stars are said to have an S-type orbit [3] and are called non-circumbinary planets.

iii Finally, planets can orbit near triangular Lagrange points [1].

The question of the orbital stability of planets within binary star systems is intriguing, considering factors such as the masses of the three bodies, their distances, and the eccentricity of their orbit. This project seeks to explore how non-circumbinary planets behave within a binary star system.

To understand this behavior, we will provide a basic idea of the forces at play within a binary star system and how they change with the presence of a planet.

In short, binary star systems function because each star exerts force on the other, resulting in their mutual orbit. It's crucial to note that while there is a center of mass, the stars are not orbiting around it. Figure 1 shows a diagram of a binary star system in an elliptical orbit both without a non-circumbinary (left) and with a non-circumbinary (right). Note how, in this diagram, the stars are placed opposite each other due to the nature of their orbit. Since binary stars orbit due to the force they exert on each other, they remain opposite each other in their orbits.

When a non-circumbinary planet is introduced, it orbits around one of the stars as that star orbits. This functions very similarly to the way a moon orbits around the Earth as it orbits around the Sun. However, there is one crucial difference: both stars are exerting force onto the planet, and thus we must consider the force that the non-primary star exerts on the planet as well.

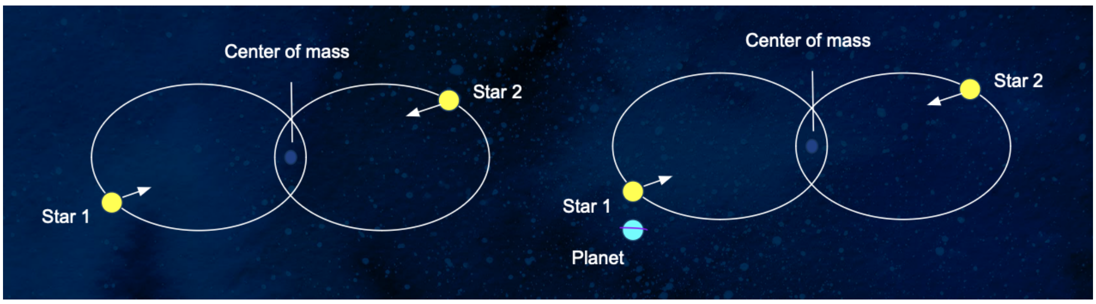


Figure 1: **Binary star system in an elliptical orbit with (right) and without (left) a non-circumbinary planet**.

2 Equations

2.1 *Modeling the binary star system*

Let $\vec{X}_1$ denote the position of the first star and $\vec{X}_2$ denote the position of the second star. Similarly, let $\vec{U}_1$ and $\vec{U}_2$ denote the velocity of the first and second star, respectively. Finally, let m_1 refer to the mass of the first star and m_2 refer to the mass of the second star.

The governing equations for a binary star system are largely based on Newton's second law of motion, $f = ma$, and the equation for gravitational force between two bodies with masses m_1 and m_1, and radius r between them[2],

$$\frac{-Gm_1m_2}{r^2} \tag{1}$$

Note that G is the gravitational constant.

We can rewrite Newton's second law of motion using the definition of acceleration (i.e. acceleration is the rate of change of the position) and combine it with the formula for gravitational force to produce the equations of motion for the binary star system:

$$m_1\frac{d\vec{U}_1}{dt} = \frac{Gm_1m_2}{r^2}\frac{\vec{X}_2 - \vec{X}_1}{r} \tag{2}$$

$$m_2\frac{d\vec{U}_2}{dt} = \frac{Gm_1m_2}{r^2}\frac{\vec{X}_1 - \vec{X}_2}{r} \tag{3}$$

The terms, $\frac{\vec{X}_2 - \vec{X}_1}{r}$ and $\frac{\vec{X}_1 - \vec{X}_2}{r}$, added to the equation of gravitational force, are both unit vectors specifying which body is exerting the force. In other words, these quantities do not alter the magnitude of the gravitational force but ensure that the direction aligns with the force direction.

It is important to realize that m_1 cancels out of Equation 2 and m_2 cancels out of Equation 3.

Using the definition of velocity (i.e. velocity is the rate of change of the position) we can say:

$$\frac{d\vec{X}_1}{dt} = \vec{U}_1 \tag{4}$$

$$\frac{d\vec{X}_2}{dt} = \vec{U}_2 \tag{5}$$

Finally, we can define the radius between the two stars, r, to be the distance between them:

$$r = ||\vec{X}_2 - \vec{X}_1|| \tag{6}$$

Presently, the binary star-system is represented as a two body problem. However, we will ultimately represent it as a one body problem by using the center of mass and defining new quantities.

We define the position and velocity of the center of mass position in Equations 7 and 8, respectively. In essence, these equations simply state that the center of mass will lie between the positions of the two stars, weighted by their masses, and its velocity will depend on the velocity of the two stars, also weighted by their masses.

$$\vec{X}_{com} = \frac{m_1\vec{X}_1 + m_2\vec{X}_2}{m_1 + m_2} \tag{7}$$

$$\vec{U}_{com} = \frac{m_1\vec{U}_1 + m_2\vec{U}_2}{m_1 + m_2} \tag{8}$$

In order to make our calculations easier, we will choose a frame of reference so that $\vec{U}_{com} = 0$, in other words, we will make $\vec{X}_{com}$ constant. We can also devise coordinates for our system so that that the center of mass is at the origin.

Once we have made these choices, it follows from equations 7 and 8 that:

$$m_1\vec{X}_1 + m_2\vec{X}_2 = 0 \tag{9}$$

$$m_1\vec{U}_1 + m_2\vec{U}_2 = 0 \tag{10}$$

We now define $\vec{X}$ and $\vec{U}$ such that

$$\vec{X} = \vec{X}_2 - \vec{X}_1 \tag{11}$$

$$\vec{U} = \vec{U}_2 - \vec{U}_1 \tag{12}$$

Once we cancel out the redundant masses in equations 2 and 3, we can subtract 2 from 3 to obtain:

$$\frac{d\vec{U}}{dt} = \frac{-G(m_1 + m_2)}{r^2}\frac{\vec{X}}{r} \tag{13}$$

Likewise, from Equations 4, 5, and 6 we obtain

$$\frac{d\vec{X}}{dt} = \vec{U} \tag{14}$$

$$r = ||\vec{X}|| \tag{15}$$

We now have expressed the binary star system in terms of a single-body problem. However, we must still able to obtain the original $\vec{X}_1$, $\vec{X}_2$, $\vec{U}_1$ and $\vec{U}_2$ from equations 13, 14, and 15. We can do so by solving the following equations:

$$m_1\vec{X}_1(t) + m_2\vec{X}_2(t) = 0 \tag{16}$$

$$\vec{X}_2(t) - \vec{X}_1(t) = X(t) \tag{17}$$

These equations are derived from Equations 9 and 11.
The solution to 16 and 17 yields

$$\vec{X}_1(t) = -\frac{m_2}{m_1 + m_2}\vec{X}(t) \tag{18}$$

$$\vec{X}_2(t) = \frac{m_1}{m_1 + m_2}\vec{X}(t) \tag{19}$$

Which can be differentiated to find $\vec{U}_1$ and $\vec{U}_2$:

$$\vec{U}_1(t) = -\frac{m_2}{m_1 + m_2}\vec{U}(t) \tag{20}$$

$$\vec{U}_2(t) = \frac{m_1}{m_1 + m_2}\vec{U}(t) \tag{21}$$

2.2 *Designing the orbit*

We have established that, given the masses of two stars and their positions, we can define a binary star system. Now, we will describe how to design specific orbits using those equations. To design an orbit, we need to know the masses of the bodies in that orbit, as well as the furthest and closest distances between them (also called the apogee and perigee). Let us denote the masses of stars 1 and 2 as m_1 and m_2, respectively. Define a to be the apogee and b to be the perigee.

To devise the orbit, we will position the stars initially on the axis $y = 0$, with their x-coordinates chosen to maximize the separation between them. Mathematically, this can be expressed as:

$$\vec{X} = \vec{X}_2 - \vec{X}_1 = (a, 0, 0) \tag{22}$$

The initial velocity vector of such a system can be obtained by

$$\vec{U} = \vec{U}_2 - \vec{U}_1 = (0, v_a, 0) \tag{23}$$

where v_a is the velocity at point a given by:

$$v_a = \sqrt{\frac{b}{a}\frac{2G(m_1 + m_2)}{a + b}} \tag{24}$$

Equation 24 stems from a combination of the equations for conservation of angular momentum and conservation of energy [2].

Using equations 18, 19, 20, and 21, we can obtain the ideal initial positions and velocities for stars 1 and 2 from 22 and 23:

$$\vec{X}_{1(0)} = -\frac{m_2}{m_1 + m_2}(a, 0, 0) \tag{25}$$

$$\vec{U}_{1(0)} = -\frac{m_2}{m_1 + m_2}(0, v_a, 0) \tag{26}$$

$$\vec{X}_{2(0)} = \frac{m_1}{m_1 + m_2}(a, 0, 0) \tag{27}$$

$$\vec{U}_{2(0)} = \frac{m_1}{m_1 + m_2}(a, v_a, 0) \tag{28}$$

2.3 *Incorporating a non-circumbinary planet*

When incorporating a non-circumbinary planet, much of the previous work remains intact if we can consider the mass of the planet to be negligible. When conceptualizing the orbit of a non-circumbinary planet around a star in a binary star system, we only need to consider the orbital velocity at which it orbits the primary star and then its relative velocity to the orbit. In other words, if the planet is orbiting around star 1, then:

$$U_{planet} = \sqrt{\frac{GM_{star_1}}{r_{planet,star_1}}} + U_{planet,star_1} + U_{planet,star_2} \tag{29}$$

Let $\vec{U}_p$ refer to the velocity of the planet, $\vec{X}_p$ be the position of the planet, and $\vec{X}_1$ and $\vec{X}_2$ continue to be the positions of the stars. We can then compute $\vec{r}_{ps1} = ||\vec{X}_P - \vec{X}_1||$ and $\vec{r}_{ps2} = ||\vec{X}_P - \vec{X}_2||$ as the distances between the planet and each star.

Using the same technique we did in equations 2 and 3, we define $\frac{d\vec{U}_{ps1}}{dt}$ and $\frac{d\vec{U}_{ps2}}{dt}$, the acceleration of the planet due to stars 1 and 2, as:

$$\frac{d\vec{U}_{ps1}}{dt} = \frac{Gm_1}{r_{ps1}^2}\frac{\vec{X_P} - \vec{X_1}}{r_{ps1}} \tag{30}$$

$$\frac{d\vec{U}_{ps2}}{dt} = \frac{Gm_2}{r_{ps2}^2}\frac{\vec{X_P} - \vec{X_2}}{r_{ps2}} \tag{31}$$

We can obtain the velocities, U_{ps1} and U_{ps2} using various mathematical methods, but we will refrain from doing so as these values are calculated by the simulation using Euler's method (see Section 3).

As star 1 is the primary star the planet, we set the initial position of the planet to be

$$\vec{X}_{p(0)} = \vec{X}_1 + (r_{ps1}, 0, 0) \tag{32}$$

The initial velocity of the planet, $\vec{U}_{p(0)}$, is the velocity which it is orbiting the primary star added to the initial velocity of the primary star. Mathematically,

$$\vec{U}_{p(0)} = \vec{U}_1 + (0, \sqrt{\frac{GM_{star_1}}{r_{planet,star_1}}}, 0) \tag{33}$$

And with this, we have established all of the equations and conditions to set up a binary star system with a non-circumbinary planet.

2.4 *Summary*

In conjunction, these three concepts allow us to design a binary star system with a non-circumbinary planet when given:

1. The masses of the stars,
2. The maximum and minimum distance between the stars,
3. The mass of the planet, and finally,
4. The distance from the planet to the star which it is orbiting.

3 Numerical Method

To discretize the values, we utilized a modified Euler's method. Applying this method to equation 13, it becomes:

$$\frac{\vec{U}(t+\Delta t) - \vec{U}(t)}{\Delta t} = \frac{-G(m_1+m_2)}{r^2(t)}\frac{\vec{X(t)}}{r(t)} \tag{34}$$

Equation 14 becomes

$$\frac{\vec{X}(t+\Delta t) - \vec{X}(t)}{\Delta t} = \vec{U}(t+\Delta t) \tag{35}$$

Equation 30 becomes:

$$\frac{\vec{U}_{ps1}(t+\Delta t) - \vec{U}_{ps1}(t)}{\Delta t} = \frac{Gm_1}{r_{ps1}^2(t)}\frac{\vec{X_P} - \vec{X_1(t)}}{r_{ps1}(t)} \tag{36}$$

and finally, equation 31 becomes:

$$\frac{\vec{U}_{ps2}(t+\Delta t) - \vec{U}_{ps2}(t)}{\Delta t} = \frac{Gm_2}{r_{ps2}^2(t)}\frac{\vec{X_P} - \vec{X_2(t)}}{r_{ps2}(t)} \tag{37}$$

It is important to note that each value is evaluated at $t + \Delta t$.

4 The code:

To facilitate the parametric study of the system's behavior which will be provided in Section 6, we created a function that computes and plots the orbit when given the following parameters:

1. `m1` - The mass of the primary star.
2. `m2` - The mass of the secondary star.
3. `a` - The maximum distance between the primary star and the secondary star.
4. `b` - The minimum distance between the primary star and the secondary star.
5. `rp` - The distance between the primary star and the planet.
6. `clockmax` - The total number of timesteps.
7. `tmax` - The total time for the program to run.
8. `c1,c2,c3,c4` - Custom colors for plotting the stars' trajectory, planet, and planet's trajectory.

Note that the timestep for this program is calculated as: `dt = tmax/clockmax`.

The function is included below. For succinctness, star1, star2 and planet will be abbreviated to s1, s2, and p:

```
G  = 6.67e-11;                            % Gravitational constant

function binstar(m1, m2, a,b,rp, clockmax, tmax, c1,c2,c3,c4)
   M     = m1 + m2;                       % Combined mass of stars
   va    = sqrt(b/a * (2*G*M)/(a+b));     % Initial velocity of stars
   U     = [0, va, 0];                    % Initial velocity vector
   s1pos = -m2/M * [a, 0, 0];             % Position of s1
   U1    = -m2/M * U;                     % Velocity of s1
   s2pos =  m1/M * [a, 0, 0];             % Position of s2
   U2    =  m1/M * U;                     % Velocity of s2
   vpi   = sqrt(G*m1/rp);                 % Initial orbital velocity of p
   ppos  = s1pos + [rp, 0, 0];            % Initial position of p
   UP    = U1 + [0, vpi, 0];              % Initial velocity of p in system
   X = s2pos - s1pos;                     % Distance btwn s1 and s2
   com = (m1*s1pos + m2*s2pos)/(M);       % Center of mass

   % Create handles for stars, planet & trajectory:
   hc = plot(com(1), com(2), 'co', 'linewidth', 2);% plot center of mass
   hold on
   title(['Orbit with ','rp = ', num2str(rp)],...
   'Color','black');
   hp1 = plot(s1pos(1), s1pos(2), 'b*','linewidth', 5); % s1
   ht1 = plot(s1pos(1), s1pos(2),  c1 ,'linewidth', 2); % s1 trajectory
   hp2 = plot(s2pos(1), s2pos(2), 'r*','linewidth', 5); % s1
   ht2 = plot(s2pos(1), s2pos(2),  c2 ,'linewidth', 2); % s2 trajectory
   hpp = plot(ppos(1), ppos(2)  ,  c4 ,'linewidth', 1); % p
   hpt = plot(ppos(1), ppos(2)  ,  c3 ,'linewidth', 1); % p trajectory
   scaled_a = 1.05 * a;
   axis equal                                          % ensure same axis scales
   axis([-scaled_a, scaled_a, -scaled_a, scaled_a])    % set axis limits
   axis manual                                         % freeze axes

   % Initializing arrays to hold values
   tsave   = zeros(1, clockmax);
   s1xsave = zeros(1, clockmax); %Star 1
   s1ysave = zeros(1, clockmax);
   s2xsave = zeros(1, clockmax); %Star 2
   s2ysave = zeros(1, clockmax);
```

```
    pxsave  = zeros(1, clockmax); %Planet
    pysave  = zeros(1, clockmax);
    dt = tmax/clockmax;
    for clock = 1:clockmax
        r = norm(X);                           % Distance between two stars
        t = clock*dt;                          % Updating time
        U = U - dt*G*M*X/r^3;                  % Updating velocity for s1 and s2
        X = X + dt*U;                          % Updating X

        % Calculate individual positions and velocities from X and U
        s1pos = -m2/M*X;
        s2pos =  m1/M*X;

        % Update planet position and velocity due to the stars
        rp1          = ppos - s1pos;                     % Vector from p to s1
        rp1norm      = norm(rp1);                        % Distance btwn p and s1
        rp2          = ppos -s2pos;                      % Vector from p to s2
        rp2norm      = norm(rp2);                        % Distance btwn p and s2
        vPS1         = G*m1*rp1/rp1norm^3;               % Velocity due to s1
        vPS2         = G*m2*rp2/rp2norm^3;               % Velocity due to s2
        UP           = UP - dt*vPS1 - dt*vPS2;           % Update p's velocity
                                                           due to s1 and s2
        ppos         = ppos + dt*UP;                     % Update p's position

        % Save positions for plotting
        tsave(clock)   = t;
        s1xsave(clock) = s1pos(1);
        s1ysave(clock) = s1pos(2);
        s2xsave(clock) = s2pos(1);
        s2ysave(clock) = s2pos(2);
        pxsave(clock)  = ppos(1);
        pysave(clock)  = ppos(2);

        if mod(clock, 100) == 0
            ht1.XData = s1xsave(1:clock);
            ht1.YData = s1ysave(1:clock);
            ht2.XData = s2xsave(1:clock);
            ht2.YData = s2ysave(1:clock);
            hpt.XData = pxsave(1:clock);
            hpt.YData = pysave(1:clock);
            hp1.XData = s1pos(1);
            hp1.YData = s1pos(2);
            hp2.XData = s2pos(1);
            hp2.YData = s2pos(2);
            hpp.XData = ppos(1);
            hpp.YData = ppos(2);
            disp(t/tmax * 100)          % Print percentage until completion
            drawnow
        end
        hold on         % Be able to plot consecutive functions on same graph
    end
end
```

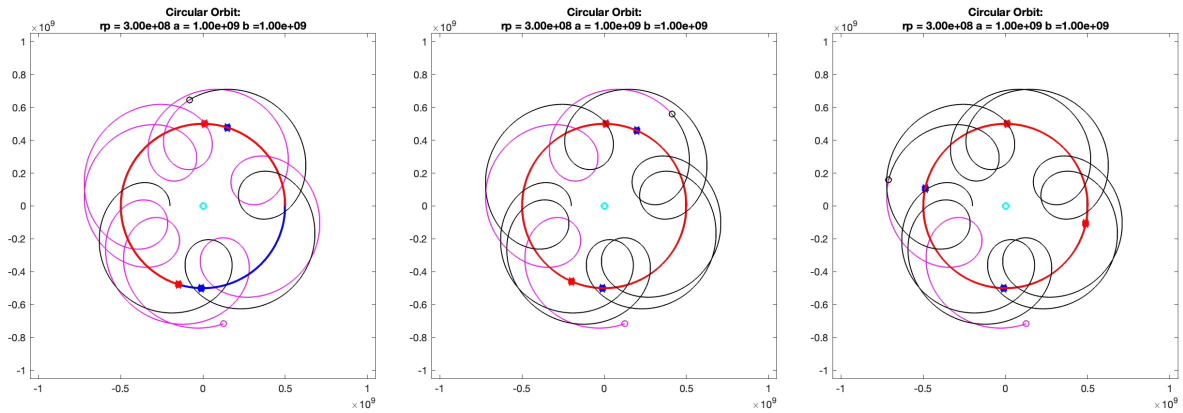
An example call to this function would be:

```
binstar(6.0e24, 6.0e24, 10e8, 10e8, 9e7, 180000, earth_year/4, 'b', 'r', 'm', 'mo')
```

This function will automatically plot consecutive function calls on the same graph–this was done to make validation (Section 5) and analysis easier. If the user would like to plot multiple function calls in different graphs, they should either delete the `hold on` on the third to last line, or add `hold off` between function calls.

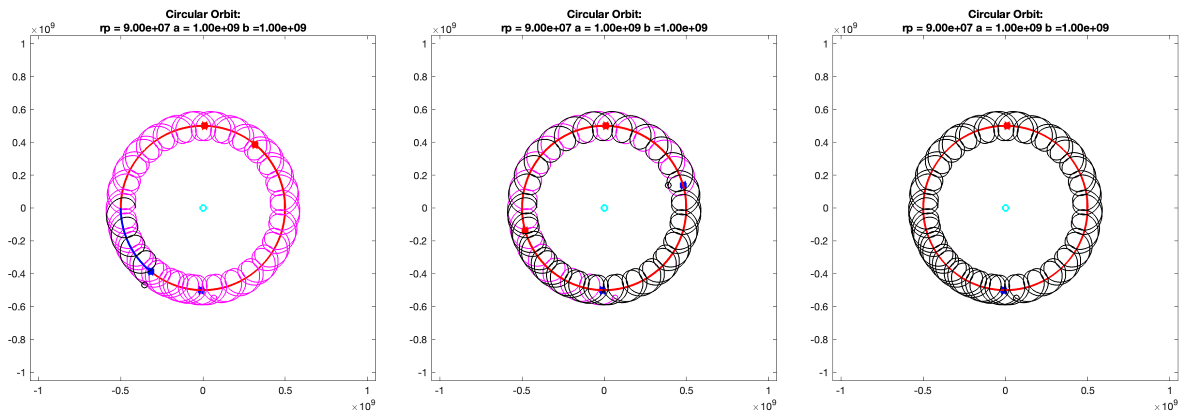
5 Validation

Each graph presented in this paper underwent a dual computation: once with a regular timestep (`dt`) and then with a halved timestep (`dt/2`). The outcomes of both timesteps were overlaid on the same graph, with the planet depicted in magenta for the normal timestep and in black for the halved timestep. In terms of the code, this adjustment was accomplished by modifying the `clockmax` parameter to `2*clockmax`, given that `dt = tmax/clockmax`. The validated results are illustrated in the graphs below:



(a) (b) (c)

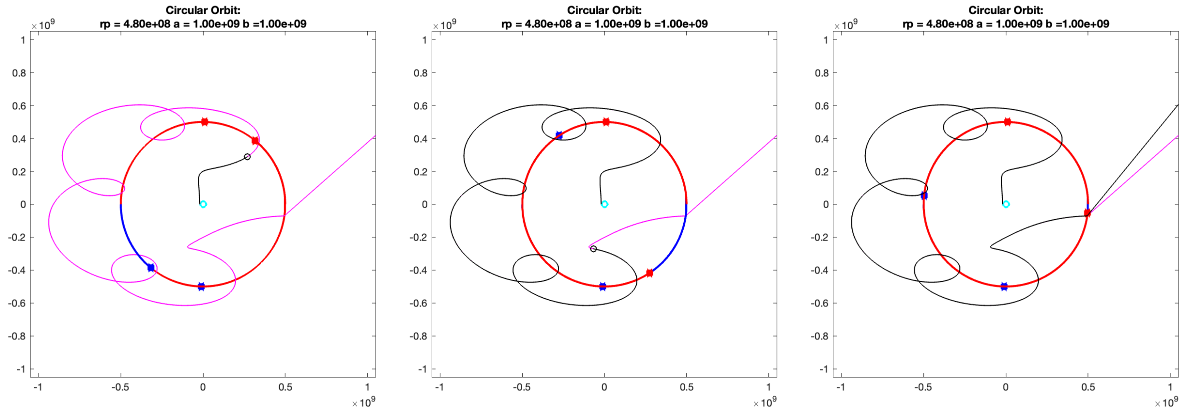
Figure 2: Circular orbit with rp = 3e8, 3 frames of correction



(a) (b) (c)

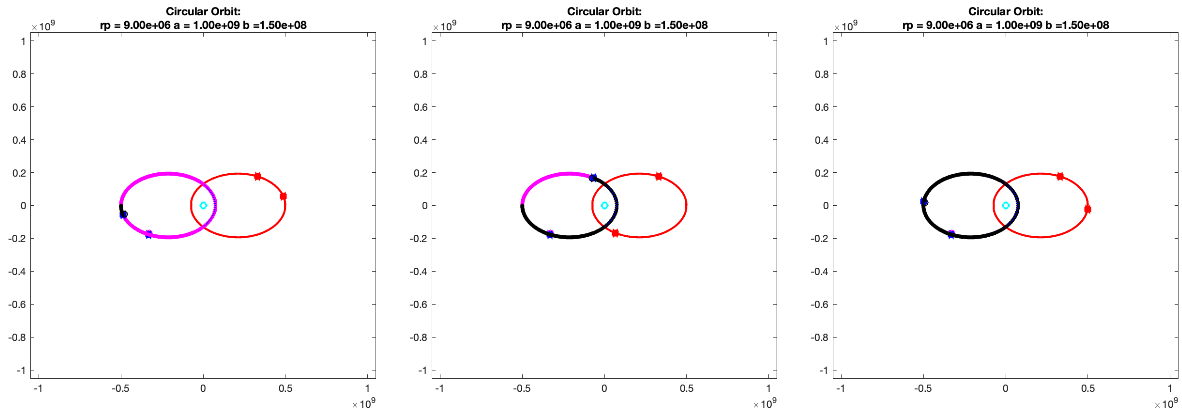
Figure 3: Circular orbit with rp = 9e7, 3 frames of correction

As we can see, in all of the figures, the red and blue lines never leave the circular orbit; this indicates that regardless of the timestep, we can consider the circular orbit of the stars to be correct. Likewise, since the black line covers the magenta one in all of the figures, the results are independent of the time step. It is important to note, though, that in Figure 4, frame (c), the very final behavior of the planet is not the same. Therefore, for the purposes of our study, we will disregard the behavior of the planet once it shoots off.



(a) (b) (c)

Figure 4: Circular orbit with rp = 48e7, 3 frames of correction



(a) (b) (c)

Figure 5: Elliptical orbit with rp = 9e6, 3 frames of correction

6 Results and Discussion:

To investigate the behavior of a non-circumbinary planet in a binary star system, it is useful to manipulate the distance between the planet and its primary star, as alterations in this distance cause changes in the planet's orbit. For this study, the masses of the primary and secondary stars remain constant and equal, both set to 6.0e24.

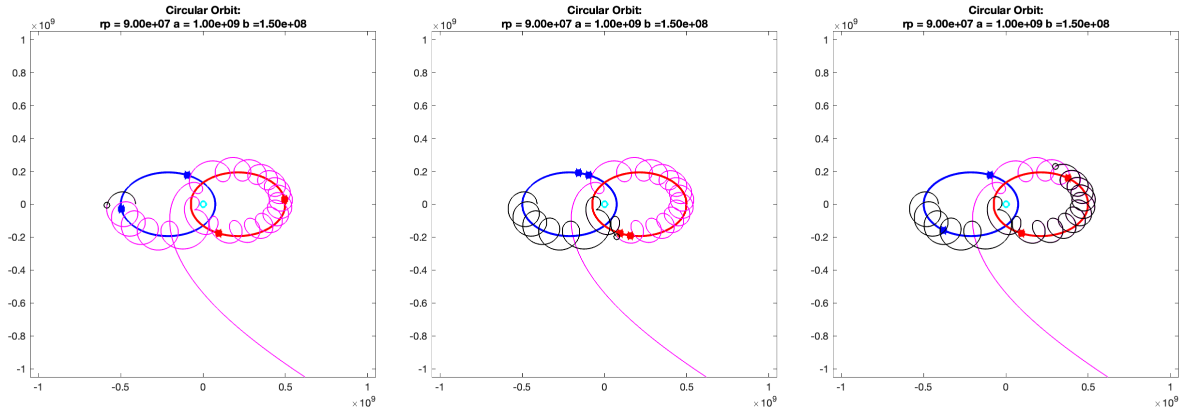
Additionally, it is beneficial to categorize the system's behavior into two primary cases: when the stars are in a perfectly circular orbit (Subsection 6.1) and when they are in an elliptical orbit (Subsection 6.2).

6.1 *Perfectly Circular orbit*

To investigate the behavior of a non-circumbinary planet orbiting a star in a perfectly circular orbit, we examined three different values for the distance between the planet and its primary star, denoted as rp: 3e8 (Figure 8), 9e7 (Figure 9), and 48e7 (Figure 10).

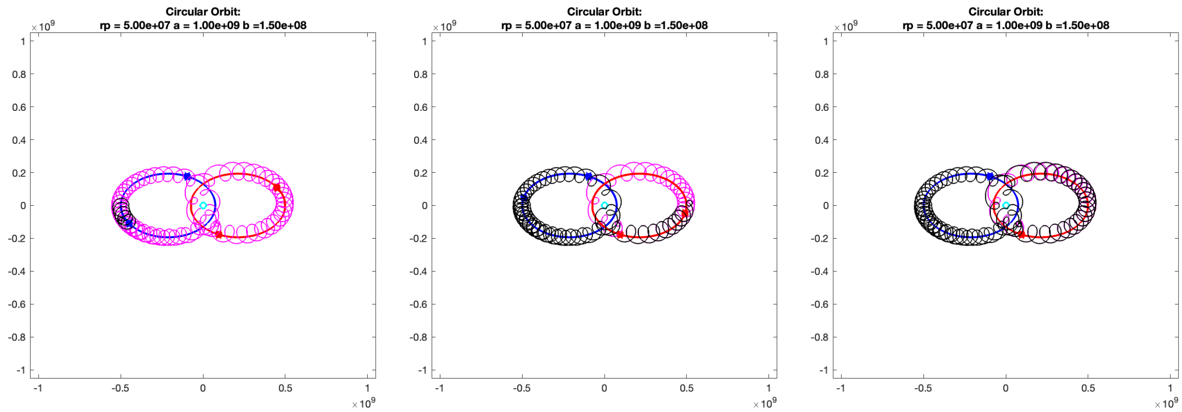
The remaining parameters were set as follows:

1. Since the orbit is circular, the maximum and minimum distances between the stars are identical and were both set to 10e8.
2. The clockmax and tmax parameters were set to 360000 and earth_year/2.



(a) (b) (c)

Figure 6: Elliptical orbit with rp = 9e7, 3 frames of correction



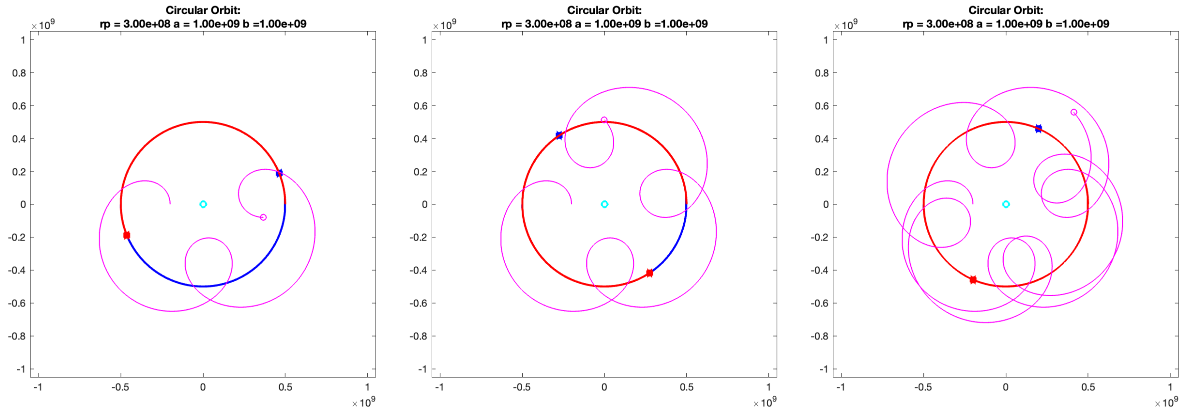
(a) (b) (c)

Figure 7: Elliptical orbit with rp = 50e6, 3 frames of correction

Remember that, since the mass of the planet is considered negligible, it is not included in our parameters.

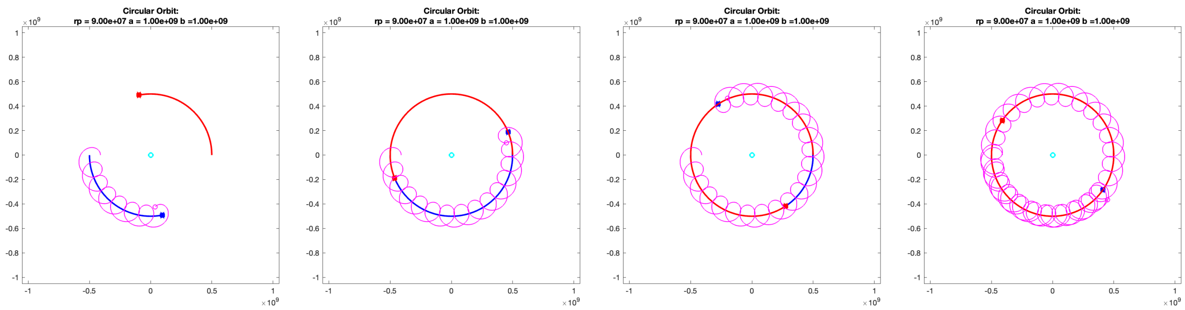
In Figures 8 and 9, it is observed that the planet maintains a stable orbit around its primary star (the blue star). There is no evidence of the planet being stripped away by the secondary star (the red star). This stability is likely attributed to the planet never approaching the secondary star closely enough for the gravitational force exerted by the secondary star to surpass that of the primary star. It is interesting to note that despite the apparent stability of the planet's orbit in these cases, there is a gradual shift in its orbit over time. The reason for this phenomenon is not currently understood.

An interesting phenomenon occurs when the distance between the planet and its primary star is set to 48e7 (as depicted in Figure 10). When the planet begins its orbit near the center of mass, it is stripped away by the secondary star before completing a revolution around the primary star. This can possibly be attributed to the planet approaching the secondary star at the beginning of its orbit around the primary star. The secondary star exerts a stronger gravitational force due to the reduced distance between them. The trajectory of the planet around the secondary star appears unstable, as indicated by its path. However, no definitive conclusions can be drawn regarding the planet's final destination, as observed in frame (d), due to the lack of proper validation for that portion of the orbit (refer to Figure 4).



(a) (b) (c)

Figure 8: Circular orbit with rp = 3e8, 3 frames



(a) (b) (c) (d)

Figure 9: Circular orbit with rp = 9e7, 4 frames

6.2 *Elliptical orbit*

To observe the behavior of a non-circumbinary planet orbiting a star in an elliptical orbit, we considered three different values for rp: 9e7 (Figure 12), 9e6 (Figure 11), and 50e6 (Figure 13).

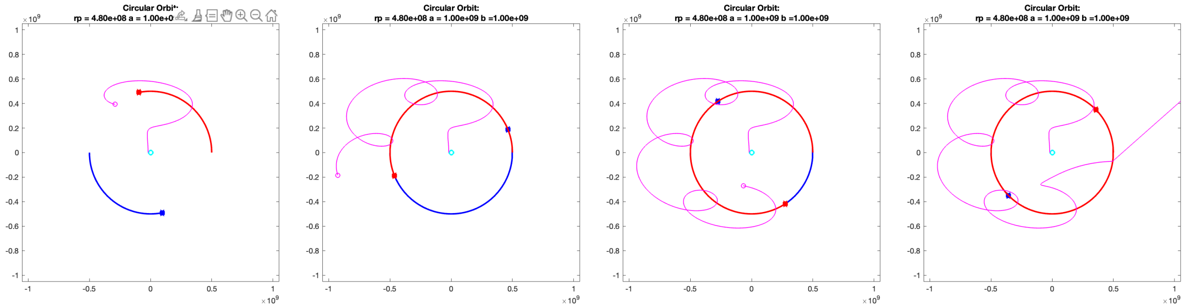
In contrast to the circular orbit setup where the maximum and minimum distances were the same, for the elliptical orbit, we set the maximum distance to 10e8 and the minimum distance to 1.5e8. Varying timesteps were employed to ensure greater precision, particularly when the two stars are in close proximity to each other at the perigee.

In general, elliptical orbits appear to be more prone to instability compared to circular orbits, as seen in how the planet tends to be stripped away by the secondary star. This behavior can be seen in Figure 12 and Figure 13, where the planet gets stripped away as the stars approach the perigee. The explanation lies in the nature of elliptical orbits: the reduced distance between the stars which occurs as they come closer together gives the secondary star a chance to exert a stronger force on the planet than the primary star.

As seen in Figure 11, when the distance between the planet and its primary star is smaller, the planet does not get stripped away by the secondary star. Similar to circular orbits, the planet's orbit in Figure 11 exhibits a gradual shift over time.

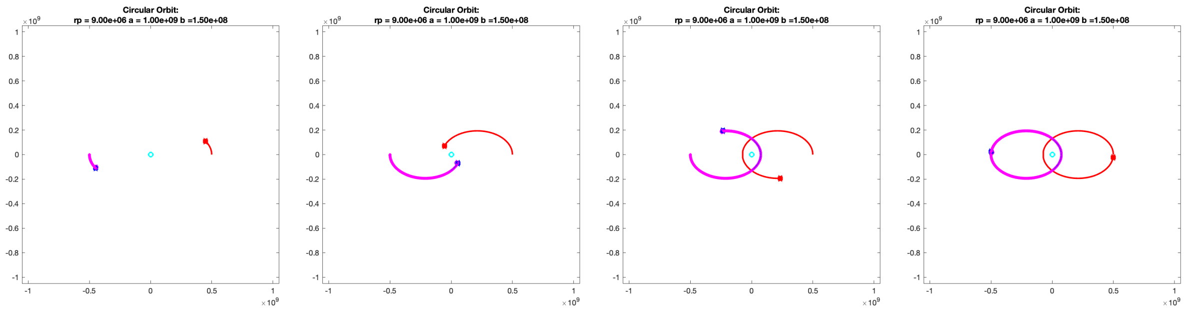
In the case depicted in Figure 12, the stripping away of the planet may also be attributed to the faster movement of the primary star near its perigee. As the primary star moves away from the planet at a faster rate than the planet approaches it, the gravitational pull of the star becomes insufficient to keep the planet in its orbit. Thus, the planet is stripped away by the secondary star.

A notable aspect of the case presented in Figure 13 is that the planet is not being stripped



(a) (b) (c) (d)

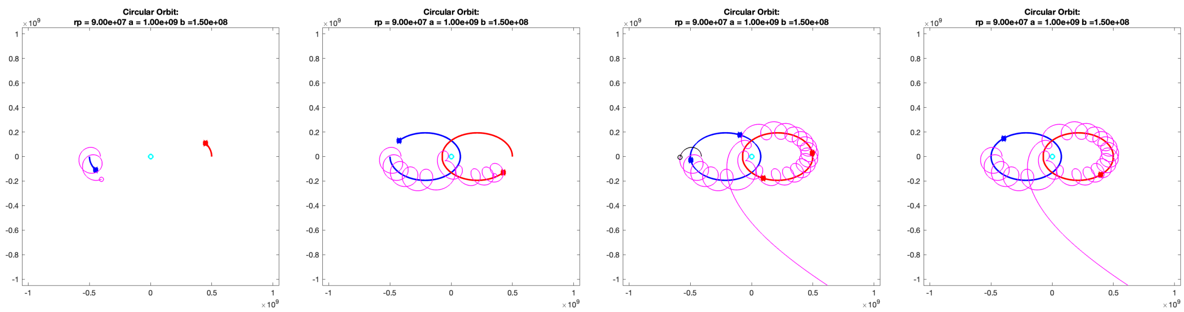
Figure 10: Circular orbit with rp = 48e7, 4 frames



(a) (b) (c) (d)

Figure 11: Elliptical orbit with rp = 9e6, 4 frames

away on its initial orbit. This is evident in frame (d) where the planet continues on its original path with a slightly shifted orbit. However, on its second approach to the perigee, it gets stripped away by the secondary star and remains in that orbit for a full revolution. The exact reason for this occurrence is not fully understood, but it might be associated with the shifted orbit bringing the planet closer to the secondary star during its second approach to the perigee.

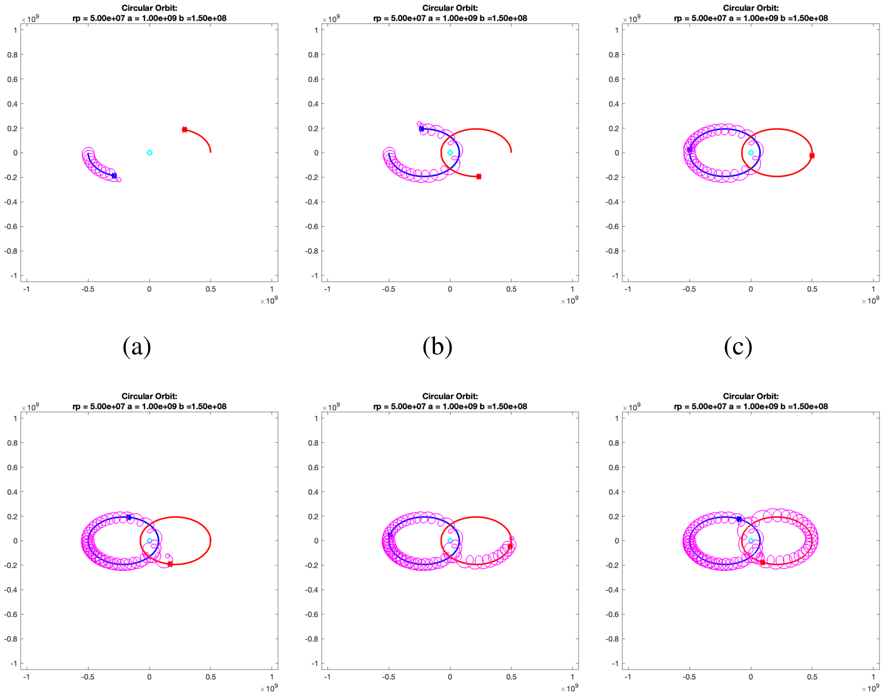


(a) (b) (c) (d)

Figure 12: Elliptical orbit with rp = 9e7, 4 frames

7 Conclusions

This project was centered around exploring the behavior of non-circumbinary planets in binary star systems. Throughout this study we learned that, unsurprisingly, the smaller the distance between the planet and its primary star, the more stable its orbit. However, we were surprised to see that the orbits of the planet shifted over time, even when stable and orbiting around a star



(a) (b) (c)

(d) (e) (f)

Figure 13: Elliptical orbit with rp = 50e6, 6 frames

in a perfectly-circular orbit. It was also interesting to see how, in elliptical orbits, planets were stripped and returned to their primary star (Figure 13. Finally, we observed that in elliptical orbits, even when the distance between the planet and its primary star is small, the orbit widens. Ultimately, this study has confirmed the lack of stability of non-circumbinary planets in binary star systems.

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