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Dynamical origin of JuMBOs (Jupiter Mass Binary Objects) in Orion Nuclear Cluster

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Abstract

This work investigates a theory that the Jupiter Mass Binary Objects (JuMBOs) initially form as planets in protoplanetary discs but are later ejected by close stellar flybys. A direct summation N-body code was used to simulate the flyby events in the ONC (Orion Nuclear Cluster) during the period of JuMBO formation. The simulations assumed the cluster was about five times smaller than the current observations. The results suggest each planetary system produces, on average, at least one free-floating planet (FFP). However, the ratio of produced JuMBOs to FFPs was found to be at most 1%, with radial separations in the range 6 to 140 AU which does not match the observations by Pearson & McCaughrean (2023).

1 Introduction

1.1 Review of the discovery

The questions of stellar and planetary formations have occupied the minds of astrophysicists of multiple generations. The creation of the Hubble Space Telescope (HST) allowed scientists to see beyond the limits of their eyesight. It had made significant discoveries in the field of stellar and protoplanetary formation. Specifically, HST discovered the evidence of the protoplanetary discs in the Orion Nebula (HubbleSite.org 1994)[2], proving the theories and settling the questions about planetary formation. After thirty years, Hubble's successor, the James Webb Space Telescope (JWST), was able to provide further evidence of these phenomena. However, not long ago, JWST made a discovery that put the question again in the air. Using its Near Infrared Camera as part of Cycle 1 GTO programme 1256, it covered $11' \times 7.5'$ area focused on the inner region of Trapezium Cluster (Pearson & McCaughrean 2023)[1]. It conducted 34.9 hours of observations between September 26th and October 2nd, 2022. As a result of these observations, Pearson & McCaughrean identified 540 candidate Planetary Mass Objects (PMOs) in the Trapezium Cluster, which fit the masses of $13M_{Jup}$ or lower[1]. Unlike the standard planets, these PMOs are not found within the planetary systems; on the contrary, they are "free-floaters" – planets not bound gravitationally to a central star. Unexpectedly, in their paper on the observational discovery, Pearson & McCaughrean[1] state that 9% of these PMOs are found in binaries, thus called Jupiter Mass Binary Objects, or JuMBOs.

1.2 Motivation

Why is this discovery important? Our current theories state that the multiplicity fraction of celestial bodies decreases with decreasing mass. For massive stars and stars of solar type, this fraction is $>$ 50% (Duquennoy& Mayor 1991)[3], while this decreases to 15% for high-mass brown dwarfs [50-80 M_{Jup}] and falls to 8% for lower-mass brown dwarfs [20-60 M_{Jup}]. (Fontanive et al. 2018)[4]. The masses of JuMBOs range from $13M_{Jup}$ to $0.7M_{Jup}$. Subsequently, the multiplicity fraction of the newly discovered PMOs would need to be $\approx$ 0%, which it is not. Furthermore, JuMBOs have evenly distributed separations between $\sim 25 - 390$ AU, much wider than the average separation between brown dwarf- brown dwarf pairs. Therefore, this discovery poses a new question that challenges our current theories: "How do these PMOs form, and why do so many form JuMBOs?"

1.3 Current theories

Pearson and McCaughrean propose two possible formation scenarios in their paper (Pearson & McCaughrean 2023)[1]. The first theory states that the JuMBOs are produced in a "star-like" mechanism. This means that they form simultaneously with large stars during the collapse of molecular clouds and turbulent separation. However, this theory questions our current understanding and observations of star formation. The issue is that JuMBOs cover a wide range of masses, with a minimum of $0.7M_{Jup}$, which is way below the minimum mass that is thought to be produced through the fragmentation or shocks (see Low & Lynden-Bell, 1976 and Boyd & Whitworth 2005)[5 6]

Another more plausible theory to the scientists proposes that the JuMBOs are formed in a "planet-like" mechanism. The theory states that these objects initially form around the central stars in the circumstellar disks and then, through close stellar encounters (Bonnell et al. 2001)[7], are ejected from the system to become a PMO. This is a common process in dense star-forming regions like the Trapezium Cluster, and so, as of now, this theory is centrally used to explain the origin of JuMBOs. However, the question is, " How can pairs of young planets be ejected simultaneously and remain gravitationally bound at wide separations?"

The paper by Wang Y., Perna R., and Zhu Z., published in 2024 (Wang et al. 2024)[8] demonstrates that "in direct few-body simulations JuMBOs could arise from the ejection of two giant planets following a close encounter with a passing star if the two planets are nearly aligned at closest approach". Unfortunately, they do not demonstrate the desired multiplicity fraction that the JWST observed. However, they provide a good estimate of the rates of JuMBO production per planetary system in typical and densely populated clusters.

Another paper by Zwart and Hochart (Zwart & Hochart 2023)[9] uses a somewhat different approach. Using a direct N-body integration of the stars and planets in the Trapezium cluster, starting with a wide variety of planets in various configurations. They tested four models: first, some selected stars had two outer orbiting Jupiter-mass planets; second, stars are orbited by Jupiter-mass planet-moon pairs; three, JuMBOs are formed together with the stars; four, introduced a population of free-floating single Jupiter-mass objects, but no initialized binaries. As a result, the first and the fourth methods did not produce a sufficient amount of JuMBOs. Overall, they concluded that "JuMBOs and free-floaters are best produced if they formed in pairs and as free-floaters together with the other stars in a smooth density profile with a virial radius of $\sim 0.5pc$".

Our research focuses on the "planet-like" formation of JuMBOs. We investigate their potential creation through close stellar encounters involving planetary systems that contain Jupiter-mass planets undergoing fast flybys. By adjusting the parameters of the initial setup, we aim to achieve the desired multiplicity fraction and test the theories presented in the previously mentioned papers. Additionally, we do not limit ourselves to using the observed separations and masses outlined by Pearson and McCaughrean. This decision was made because their paper was rejected from publication, and we suspect that the masses they described may differ from the observed values.

2 Method

2.1 Procedure

To test the theory of the dynamical origin of JuMBOs, we investigate whether the observed number of free-floating planets (FFPs) with the observed multiplicity fraction could be recreated by simulating the close stellar encounters. This work combined the ideas proposed in both papers: by Wang et al. (2024) and by Zwart et al. (2023). The simulations were performed using a direct N-body code. A planetary system of a varied radius r_u [AU] was set up. A variable number of planets with masses normally distributed around a mean mass was used. Then, the perturber was sent to the hyperbolic orbit with a random impact parameter that satisfied the desired pericenter distance. This distance was chosen randomly between the minimum and maximum values, where the minimum value corresponds to the perturber going straight through the system and the maximum - with little to no planetary perturbation. In addition, the code was also adjusted to consider the perturbation by the binary system rather than by a single star. This was considered, given that most stars in the population of the Trapezium cluster have masses $\sim 1M_{\odot}$ and based on the current theory (Duquennoy & Mayor 1991)[3] more than 50% of the stars of this type are found in the binary pairs. Lastly, we checked the pairwise energy between the planets and the stars to determine whether they were bound together or if a planet was ejected and became a free-floater. Then, we checked whether any FFPs were gravitationally bound so we could call them JuMBOs.

The distinction from the method proposed by both papers is that this research considered the tightly packed system (with a number of planets ~ 10) and much denser cluster, taking into account that the JuMBOs were formed in the early stages of the Trapezium cluster when it was ~ 5 times smaller than today. Before describing the procedures, it is necessary to mention that this and the results sections are fully described in the code units, where we use $G = 1$ (in the description of the formulas, we leave G at its place for consistency), $M = 1M_{\odot}$ and the unit of length is parametrized by a factor r_u with 1 code unit of length $= 1r_u$. The parameter r_u was a variable used to study the behaviour of the systems for various sizes and speeds. However, we return to the physical units in the Discussion section to see how well the results align with the observations.

2.2 Setup of a Planetary system

The setup of the planetary system is done sequentially for each planet. In order to set up stable initial orbits with low eccentricities, we use the formulas for the Keplerian orbit and the angular momentum in polar coordinates:

$$\begin{cases} l = r^2\dot{\theta} = \sqrt{GM_{\text{tot}}a(1-e^2)} \implies \dot{\theta} = \sqrt{\frac{GM_{\text{tot}}}{a^3}} \left(\frac{-esin\theta}{\sqrt{1-e^2}}\right) \\ r = \left(\frac{a(1-e^2)}{1+ecos\theta}\right) \implies \dot{r} = \sqrt{\frac{GM_{\text{tot}}}{a}} \frac{(1+ecos\theta)^2}{(1-e^2)^{3/2}} \end{cases} \tag{1}$$

Where M_{tot} is the total mass (in this case, a sum of the mass of a planet we want to set and a central star), r, θ and $\dot{r}$, $\dot{\theta}$ are radial and angular positions and velocities respectively. In our case, a-semi-major axis and e-eccentricity are random parameters chosen in the following way.

The first planet (the outermost one) has a semi-major axis of $a_1 = 1$ (Figure 1a.), with a focus located at the position of the central star ((0,0,0) initially). Then, the eccentricity is randomly chosen from the uniform distribution in the $[0, 0.05]$ range (Figure 1b.), corresponding to orbits varying from circular to slightly eccentric, similar to the Solar System (NASA)[11]

The initial angular position is also uniformly random in the range $\theta \in [0, 2\pi]$ to assure that the system is genuinely random and no two planets are located along a single radial line. Lastly, we choose an inclination in the range $\phi \in [0, 0.05]$rad, as seen in Figure 1c.) to ensure that the planetary system is approximately planar, to corresponding to the observations of the planetary systems in young and dense stellar clusters (van Elteren et al. 2019)[10]. The planets' masses were determined using a random number generator from the Gaussian distribution with a median of 1 and a variance of 0.2. The formula for the masses is

$$m = C \cdot 10^{-4}(1 + 0.666 R_N) \qquad (2)$$

(this is the mass of a planet in units of solar mass), where C is a varied parameter, and R_N is a random number. This formula ensures that we get a Jupiter mass planet for $C = 7$, and by varying that mass, we investigated how the production rates for FFPs and JuMBOs varied. We want the mass of a planetary system to be 1 in code units, so the mass of a central star is then $M_\star = 1 - \sum_i^N m_i$, where N- is the number of planets in the system.

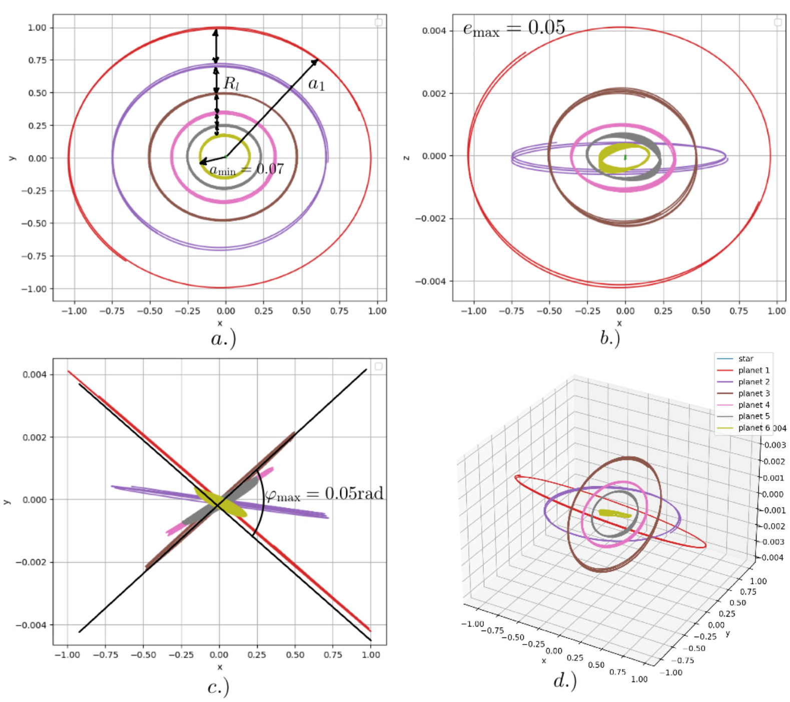


Figure 1: *Planetary system used in the simulation with random parameters: a) - x-y plane projection; b) - x-z plane projection; c) - y-z plane projection; d) 3D plot; (Note the difference in the axes scales)*

After the parameters were determined, the equations 1 were used to determine the initial conditions and set the first planet in its orbit. The generation of all the subsequent planets is performed using the same procedure, with each following planet (i) being separated from the previous (j) by:

$$a_j - a_i = \Delta a = 3.5 R_{ij} = 3.5 \left(\frac{m_i + m_j}{3M_{\text{tot}}} \right)^{1/3} a_j \qquad (3)$$

With aj - a semi-major axis of the previous planet, m_i, m_j are the masses of the planet we wish to set and already set planet respectively (see Figure 1a.)), and M_{tot} is, as before $M_{\text{tot}} = m_i + M_\star$. R_{ij} is the mutual Roche-lobe radius of the two adjacent planets, and it is used in this case to ensure the system's stability and prevent it from "disassembling" due to planet-planet interactions. The factor of 3.5 is used according to the paper by P. Artymowicz (1987)[12]

These procedures are repeated until the next planet's semi-major axis is expected to be smaller than 0.07. This limit ensures that there are no close star-planet interactions within the system, thereby preserving the numerical conservation of energy.

2.3 Setup of a Perturber

The setup of a close encounter is done similarly to a classical gravitational scattering problem where the perturber moves on the hyperbolic orbit with respect to the planetary system. The main parameters we controlled were r_{pmin}, r_{pmax} and r_0. These parameters determined the minimum and maximum pericenter distances and the initial distance from the planetary system we wanted to use in the simulations, respectively. The setup of the encounter is controlled by initial positions and velocities, meaning we had to derive the impact parameter used by a particular system, namely, b_{sim}, eccentricity of the perturber e and the initial velocity $\vec{v}_0 = (v_{r0}, v_{\phi 0})$.

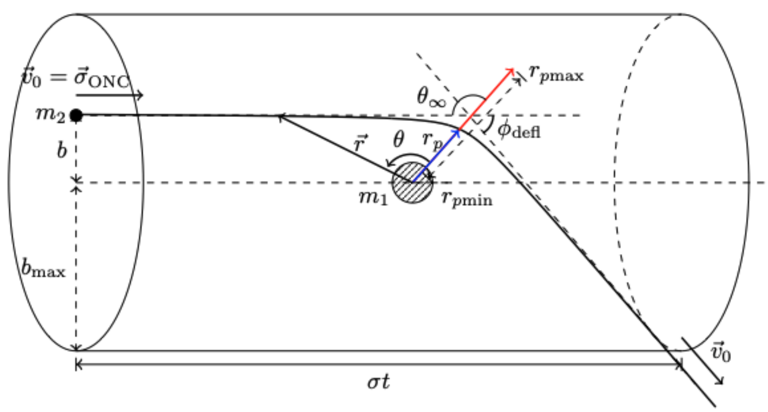


Figure 2: *Scheme of a setup of a close flyby of mass m_2 on an eccentric hyperbolic orbit with initial velocity $\vec{\sigma}_{ONC}$ and the impact parameter b with the planetary system of mass m_1.*

To set up a perturber with mass m_2, we chose the random impact parameter b_{sim}, which depended on r_{pmax}. To derive $b_{max}(r_{max})$, we start by considering the gravitational focusing of the flyby. The conservation of energy and angular momentum in Figure 2 give

$$\begin{cases} l = v_0 b = v_{coll} r_p \\ E = \frac{v_0^2}{2} - \frac{GM_{tot}}{r_\infty} = \frac{v_{coll}^2}{2} - \frac{GM_{tot}}{r_p} \end{cases} \tag{4}$$

where l is the angular momentum, E is the energy, v_0 is the initial velocity of the perturber, and it is equal to σ_{ONC}, which is the average velocity in the Orion Nuclear Cluster. r_p, v_{coll} can be read directly from Figure 2 as the pericenter distance of the perturber and the collision velocity (velocity at r_p). $M_{tot} = m_1 + m_2$, with m_1 and m_2 being the masses of the planetary system and the perturber, respectively. In single-perturber systems, m_2 was set to 1 and m_1 was the mass of a central star, the procedure for determining which was described in section 2.2. From equations 4, we find that

$$b = \sqrt{r_p(r_p + r_B)}; \tag{5}$$

where $r_B = \frac{2GM_{tot}}{v_0^2}$. Having found the dependence of the impact parameter on the pericenter distance, we then used a random number generator to pick two numbers, $R1$ and $R2$, from the uniform distribution to obtain the value of b_{sim} for a given system:

$$b_{sim} = b(r_{pmax})\sqrt{R_1^2 + R_2^2} = \sqrt{R_1^2 + R_2^2}\sqrt{r_{pmax}(r_{pmax} + r_B)} \tag{6}$$

Using equations 5 and 6 we determine

$$r_p = \sqrt{b_{sim}^2 + \frac{r_B^2}{4}} - \frac{r_B}{2} > r_{pmin} \tag{7}$$

From equations 7 and $r_p = a(1-e)$ we determine that

$$e = 1 + 2\frac{r_p}{r_B} \tag{8}$$

Finally, using the conservation of energy and the fact that $v_0^2 = v_{r0}^2 + v_{\phi 0}^2$, we arrive at the expressions for the initial velocities:

$$\begin{cases} v_{\phi 0} = \frac{r_p}{r_0}\sqrt{\frac{GM_{tot}}{r_p}}\sqrt{1+e}; \\ v_{r0} = -\sqrt{\frac{GM_{tot}}{r_p}}\sqrt{[e - 1 + 2\frac{r_p}{r_0} - \frac{r_p}{r_0}^2(1+e)]} \end{cases} \tag{9}$$

Using equations 9 and the initial distance r_0, we determine the initial positions and velocities of the planetary system and the perturber, using a random angle θ to orient them in space with respect to each other.

2.3.1 Binary Perturber

Some simulations were set up using a binary perturber. The procedure of setting up a planetary system is unchanged, while the setup of a perturber on a hyperbolic orbit is changed only by using a binary mass instead of an m_2 in M_{tot}. In addition, instead of a perturber's position, the center of mass of a binary system was used. The binary setup was done using equations 1 with random semi-major axis, eccentricity and inclination. The inclination and the eccentricity were determined using the same procedure as described in section 2.2. At the same time, the semi-major axis was set using $a = 0.5 + R$ ($R \in (0,1)$), producing a wide, what is called a 'soft' binary. The masses of the stars in the binary were randomly chosen using $m_i = 0.5 + R_i$, where $R_i \in (0,1)$ for both primary and secondary stars.

2.4 Lauching the system

Once the setup is done, we launch the simulation using the direct summation N-body force calculation and the numerical integrator with a variable timestep. The N-body force calculation was performed using the formula

$$m_i\left(\frac{d\vec{v}_i}{dt}\right) = \sum_{j=1}^{N}\left[\frac{-Gm_im_j(\vec{r}_i - \vec{r}_j)}{r_{ij}^3}\right] \tag{10}$$

Where r_{ij} is the softened distance (softening length was chosen to be 10^{-7}) between the i-th and the j-th planets. The integrators that were tested and used to perform the simulations of the systems were based on the Runge-Kutta-Fehlberg 7(8) order formula (Fehlberg, E. (1968))[13] and the symplectic 4-th order integrator. The integrators were modified to have a variable time step error-correction routine to decrease the numerical errors during the close encounters. The routines evaluated positional and energy errors and decreased the timestep to satisfy the tolerance requirements. Ultimately, the symplectic integrator was chosen, which showed better energy conservation and faster performance. The comparison of RK78 and symplectic 4th order can be seen in Figure 3. Note that the final energy error obtained using the symplectic integrator is ~ 9 orders of magnitude lower than that of the RK78.

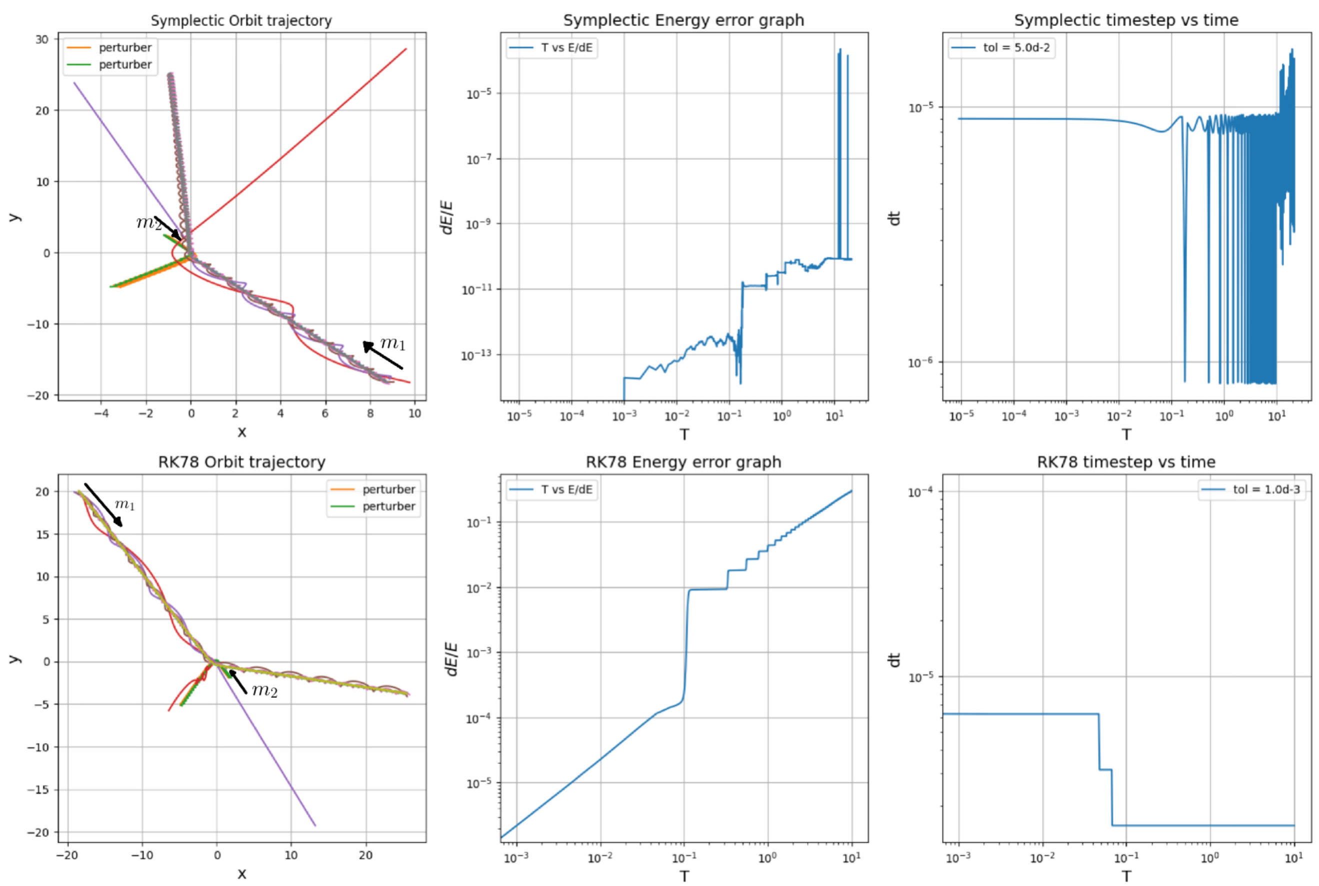


Figure 3: *Comparison of the performance of RK78 (bottom row) vs symplectic 4th order (top row) integrators; The first column shows the simulations of a planetary system perturbed by a binary perturber projected on the x-y plane using $r_u = 150$ and $m_{pl} \approx 0.4 \cdot 10^{-3} M_\odot$ the arrows on the plot identify the direction of initial velocities of the planetary system (denoted with m_1 and of the CM of the perturbers (denoted m_2; the second column shows the Energy error vs time graphs and the third column shows the timestep as a function of time*

2.5 Finding ejecta and JuMBOs

After the simulation had run for the time it takes a flyby (or a binary) to approach the system and depart again at a distance $\approx r_0$ from the planetary system, the simulation stopped, and the ejecta and JuMBO-checking procedure started. The logic map of this subroutine is shown in Figure 4. For each of the data sets produced, there were 1200 simulated systems. Ten tests were performed in total - six with a single perturber and four with binary perturbers. As described before, the study was performed by varying parameters r_u, and fixing a factor $C = 5$ in equation 2

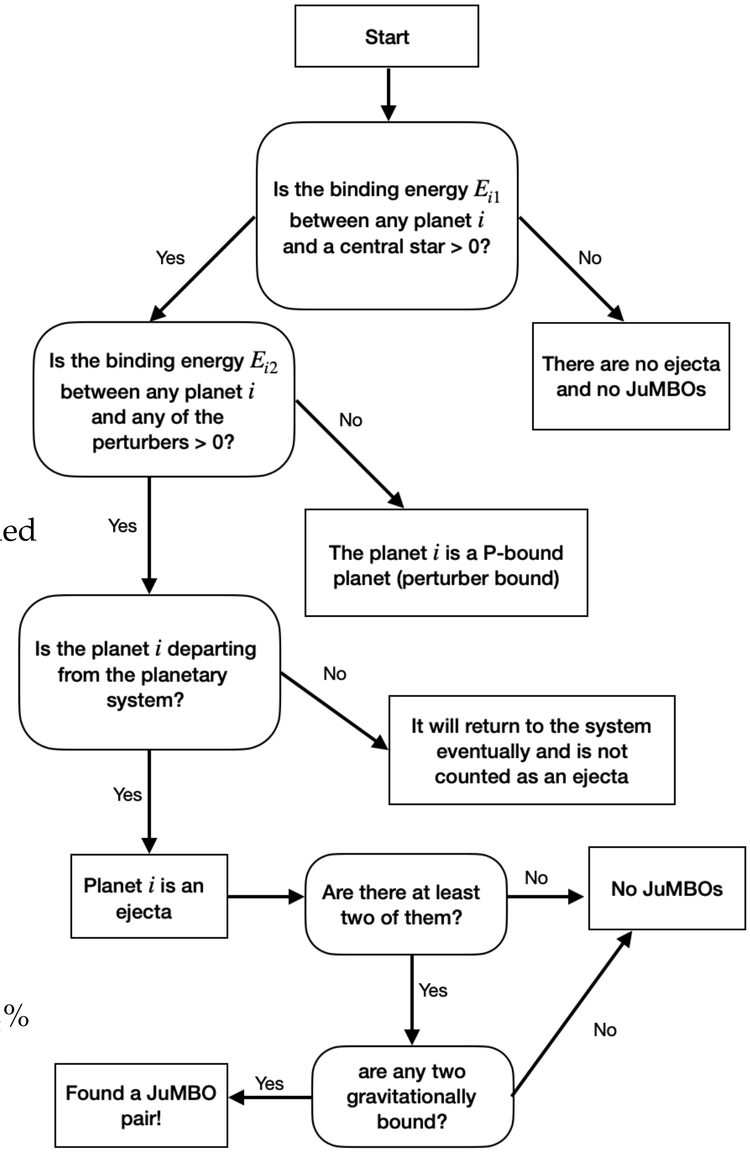


Figure 4: *Flowchart showing the procedure of finding the ejecta and JuMBOs*

3 Results

The ten simulations performed were done with different values of r_u, and other parameters fixed: $C = 5$, $r_{pmax} = 1$; namely, for a single perturber. The data obtained is presented in table 1

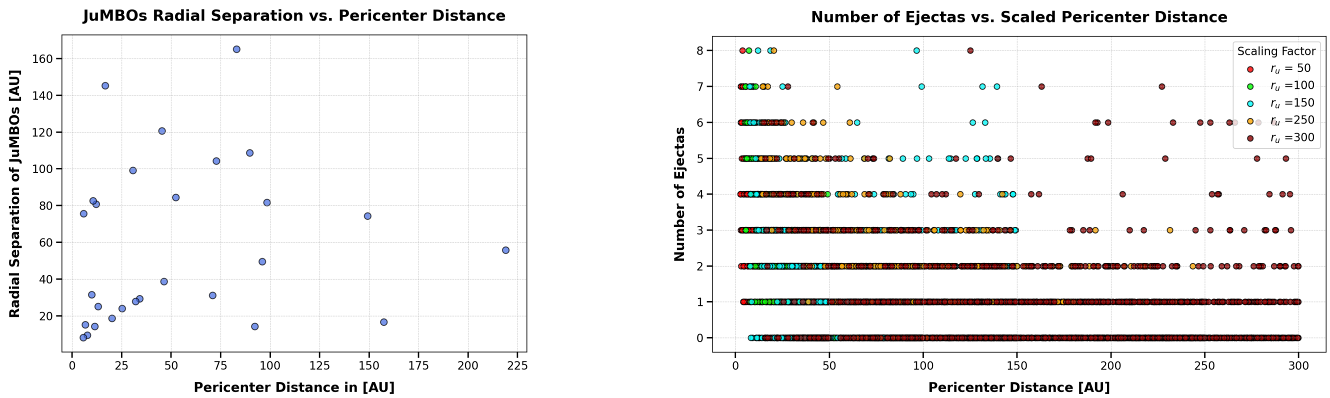
r_u [AU]	N_{ejecta}	N_{JuMBOs}	N_{JuMBOs}/N_{ejecta}%
50	1701	4	0.235%
100	1461	8	0.548%
150	1370	7	0.511%
200	1461	4	0.274%
250	1190	4	0.336%
300	1106	1	0.09%

Table 1: *Results obtained for simulation of the systems with single perturbers and varied radius of the planetary system r_u*

In the tests with the binary perturbers, where the semi-major axis was varied to test the difference between the results produced by the 'soft' and 'hard' binaries. The data found is presented in table 2. Overall, we can see that the ratio of the

a	r_u [AU]	N_{ejecta}	N_{JuMBOs}	N_{JuMBOs}/N_{ejecta}
$a = 0.1 + 1.5R$	50	1039	3	0.289%
$a = 0.1 + R$	100	1647	1	0.061%
$a = 0.1 + R$	100	1537	3	0.195%
$a = 0.5 + R$	150	1452	7	0.482%

Table 2: *Results obtained for simulation of the systems with binary perturbers, varied scaling parameter r_u and variable semi-major axis a of a binary ($R \in (0, 1)$, uniform). Models in lines 1, 2 and 4 had $C = 5$ and in line 3, $C = 3$ respectively.*



(a) (b)

Figure 5: *a.) The radial separation of JuMBOs formed during the close encounter with a single perturber vs the pericenter distance of the perturber; Both axes are scaled to AU by multiplying the data obtained in the simulation by r_u for that system; b.) Number of ejecta vs Pericener distance for $r_u \in (50, 300)$.*

number of JuMBOs simulated in the
given work is far from the observed value of 9% proposed by Pearson & McCaughrean (2023)[1]. Figure 5a demonstrates JuMBOs separation distance as a function of the pericenter distance of a single perturber during an encounter that produced these pairs. It is necessary to outline a few important observations from this figure. First, note that most of the points are located in the left half of a figure. This result implies that the JuMBOs form mainly during the close encounters of a perturber with a planetary system. More precisely, since all of the planetary systems were set with radius 1 in code units and r_u was varied from 50 to 300, this suggests that JuMBOs are formed mainly when a flyby flies straight through the planetary system. Second, the radial separations of JuMBOs simulated are in the range $(0, 140)$ AU, on average, $\sim 60AU$. This separation is smaller than the average value observed by Pearson & McCaughrean (2023)[1]. However, some particular JuMBOs do align well with the observations. Unfortunately, the data presented in Figure 5a is inconclusive as it contains only 28 data points, which is insufficient to describe any statistical data.

On the other hand, Figure 5b demonstrates a number of ejecta per a given system in a simulation with varied r_u vs the pericenter distance. This data demonstrates that the ejecta mainly form when the perturber passes directly through a planetary system, and the closer it is to the star - the more bodies are ejected. In addition, note that for the higher size of a planetary system, more planets are ejected, which can also be explained by the longer time it takes a perturber to exit a system.

Overall, the study showed that, on average, at least one ejecta is produced per close encounter of a planetary system with a flyby, while the appearance of JuMBOs is a rare event, and their number was not observed to exceed 1% of the ejecta produced.

4 Discussion

4.1 Validity of the approach

To understand how valid the approach is, the approximation of close flyby events in the Orion Nuclear Cluster needs to be made. Assume a cylinder, as shown in Figure 2 with radius b_{max} and length σt. the volume of that cylinder is then $V = \sigma t \pi b_{max}^2$. The number density of stars in a cluster is $n = \frac{3}{4}\frac{N_\star}{\pi r_c^3}$, where r_c is a radius of a cluster as it was when JuMBOs were produced. We require that

$$1 = \pi b_{max}^2 v t_{coll} n \tag{11}$$

where t_{coll} is the time in which a star has a flyby within b_{max}. The number of flyby events in the ONC is then the number of stars in a cluster times the ratio of the period of time through which JuMBOs were produced and t_{coll}:

$$N = N_\star \frac{\Delta t}{t_{coll}} \tag{12}$$

Combining equations 11 and 12 we arrive at the expression:

$$N = \frac{3}{4} N_\star^2 \Delta t \left(\frac{b_{max}}{r_c}\right)^2 \left(\frac{\sigma}{r_c}\right) \tag{13}$$

using equation 6 with $M_{tot} = 2M_\odot$ and $r_{pmax} = 1r_u \approx 200\ AU$, we get that $b_{max} \approx 247\ AU$ Our assumption states that the JuMBOs were produced in a period when ONC was ~ 5 times smaller, meaning that $r_c \approx 0.16pc = 4,937 \times 10^{12}\ km = 33000\ AU$ (the value of the modern-time $r_c = 0.64$ was found in (Morales-Calderón et al. 2011))[14]. In addition, we take $\sigma \approx 9\ km/s$. The number of stars $N_\star$ and the timescale of JuMBO creation can be taken to be $N_\star \approx 2000$, and $\Delta t \approx 0.2 \times 10^6 yr$ (Kroupa et al. 2001)[15]. Therefore, we can estimate that there were ≈ 1930 close flybys, which aligns with the number of simulated numbers planetary systems.

4.2 Problems and future research

In the results section, it was demonstrated that we get ≈ 1 ejecta per encounter and considering our estimate above, we can say that the number of observed FFPs is satisfied and can be explained through the dynamical origin. However, the origin of JuMBOs is still a mystery, as this work showed that only $\approx 0.5\%$ of all the FFPs are JuMBOs, while in the paper describing the discovery, this number is $\approx 9\%$. There might be a number of reasons that our results were so far from the observed values. First, this might not be a mechanism through which the JuMBOs form. The results explain how a fraction of them could have been formed, while the formation mechanism for the majority of them is still a mystery. Recent work by Diamond, J. & Parker, R. (2024)[16] suggests that JuMBOs might be formed by the process of photoerosion of massive stars. Another paper by Huang et al. (2024)[17] suggests that the JuMBOs could have formed through the dynamical interaction with the close flyby; however, the pair initially has a minor semi-major, which then is increased through its evolution within a stellar cluster. Another reason for the inconsistency of the result is the lack of statistics. Due to a large number of numerical problems, the initial steps took much longer than expected, and, as a result, the obtained data does not fully cover the whole parameter space.

In order to increase the statistics and see any dependencies, future research might be focused on exploring the wide range of parameter space. Determining the conditions for producing this ratio and comparing it to the observational data might be a fruitful approach. Another approach that can be taken is adding the moons to the planets and predicting the gas accretion rates on the satellite, since during the period of JuMBO formation, ONC had a large mass of gas $500M_\odot$ (Kroupa, Aarseth & Hurley 2001)[15]. Overall, research in this area is fruitful, with new ideas and theories coming up every day.

5 Conclusion

The process of JuMBO formation is still a big and open question, with various proposed theories appearing every month. This work explored a process in which the JuMBOs form as planets in a stable planetary system but are later ejected by the close flyby that disrupts the system and ejects planets and, in the process, forms JuMBOs. The theory was tested using a direct summation N-body code to simulate the approximate number of flybys that were occurring inside the ONC during the period of JuMBO formation. The number of FFPs satisfies the observational data and proposes an idea that, on average, each planetary system produces at least one free-floating planet. The simulation was set up assuming the cluster was ~ 4 times smaller than current observations. The ratio of the produced JuMBOs to the number of FFPs was found to be 1% at most. In addition, the separation distances between the simulated JuMBOs was $\approx 60AU$. These two results do not align with the observations described by Pearson, & McCaughrean (2023)[1]. Future research might be directed towards the exploration of the parameter space to produce more data to determine the conditions in which the desired ratio is achieved, or the ideas might be shifted towards the JuMBO production by accretion of gas or to other processes.

After the first version of this report was produced, we discovered a new paper published in the New York Times (23 Oct. 2024)[18] which discusses a new perspective on the JuMBOs and their numbers. This article quotes McCaughrean, who states that based on the spectral analysis of the JWST results, they reduced the number of observed JuMBOs from 42 to about 20 pairs, making the binarity ratio $\approx$ 3.7%. This result is much closer to the binarity ratio found within our simulations

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