Why Wide Jupiter-Mass Binary-Objects Cannot Form

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The discovery of $N_{\rm pp} = 40$ Jupiter-mass binary objects (JuMBOs) alongside $N_{\rm p} = 500$ free-floating Jupiter-mass objects (JMOs) in the Trapezium cluster's central portion raises questions about their origin [1]. Wang et al. [2] argue that the rate at which two planets orbiting the same star are stripped by a close encounter can explain about half the observed JuMBOs in the Trapezium cluster. Although, their cross-section calculations agree with our own [3], one cannot extrapolate their results into clustered environments because it ignores the dissociation of JuMBOs due to subsequent encounters in the clustered environment. The inability of forming JuMBOs via the proposed scenario either calls for another formation mechanism, or the observed JuMBOs require thorough confirmation.

1 Introduction

Particularly puzzling about the observed Jupiter-Mass Binary Objects (JuMBOs) in the Trapezium cluster, are their wide (28 au to 400 au) orbits[1]. This makes them soft pairs in the local environment. Wang et al. [2] explored the possibility of two Jupiter-mass planets in wide orbits around the same host star getting knocked off their orbits after a close encounter with a passing star. As a consequence, these stripped JMOs may form a pair of weakly bound free-floating planets (scenario SPP for Star-Planet-Planet, [3]). The results of [2] seem to indicate that this scenario can explain roughly half the observed JuMBOs. Although, their cross-section calculations agree with our own, one cannot extrapolate their results into clustered environments because it ignores the softness of these systems. Integrating the SPP scenario in a clustered environment to account for their formation as well as ionization, we show that at best $\mathcal{O}(1)$ JuMBO is expected to be present at any time in the Trapezium cluster.

Assuming identical Jupiter-mass objects (JMO, $m = 0.001\,M_\odot \simeq 1$ $\mathrm{M_{Jup}}$) and stars ($m_\star = 1$ $\mathrm{M_\odot}$), Wang et al. [2] conducted 4-body scattering experiments to determine the JuMBO formation rate. Although their cross-sections are consistent with other calculations [3, 4], the extrapolation of their results to a clustered environment lacks sustenance.

2 Accounting for JuMBO ionisation

For a Trapezium-like cluster environment, Wang et al. [2] find a peak 4% JuMBO formation rate per star when two Jupiter-mass planets in planar circular orbits at 400 au and 500 au (their figure 6). For any other configuration, the JuMBO production rate drops rapidly. A 4% formation rate can produce 40 JuMBOs if the cluster contains 1000 stars, and therewith explain the observed population if they remain bound. However, this idealised scenario, even if all other stars would be barren, such a population would overproduce the number of free-floating JMOs.

Assuming a broken power-law initial mass function (IMF) [5], the kinetic energy of a typical ($\langle m_\star \rangle \sim 0.35\,M_\odot$) star in the Trapezium cluster (with a velocity dispersion of $v_{\rm disp} = 2\,\mathrm{km/s}$, [6]) $> 10^4$ times larger than the binding energy of the tightest observed JuMBO. Even free-floating JMOs in the Trapezium cluster carry $\gtrsim 100$ times more kinetic energy than needed to dissociate or ionise the tightest observed JuMBOs, making any dynamical origin improbable and their long-term survivability questionable.

Quantifying this, the ionisation cross-section of a JuMBO with component masses 1 $M_{\rm Jup}$ and semi-major axis $a \gtrsim 35$ au is $\sigma_{\rm ion} \gtrsim 2 \cdot 10^7$ au^2 (see eq. 5.1 of [7], and [2] derive an ionisation cross section of $5.5 \times 10^5\,\mathrm{au}^2$, but fail to explain on how this is obtained.). The resulting ionisation timescale in the Trapezium cluster (stellar number-density $n_\star \approx 5 \times 10^4$ pc^{-3} and $v_{\rm disp} \simeq 2\,\mathrm{km/s}$, [8]) is $\tau_{\rm ion} = 1/(n_\star \sigma_{\rm ion} v_{\rm disp}) \approx 20\,\mathrm{kyr}$. With a cluster age of ~ 1 Myr [6] the formation timescale is $\tau_{\rm form} \gtrsim (1\ \mathrm{Myr})/40 = 25\,\mathrm{kyr}$, roughly comparable to the ionisation timescale. We would then expect ~ 1 JuMBOs to be present in a Trapezium-like cluster at any instant, and a substantially lower JuMBO to free-floating JMO ratio than observed.

To emphasise the improbability of JuMBO-formation through the SPP model, we note that only $\sim 2\%$ of young stellar objects in the Trapezium cluster host disks with sizes $r_d \geq 500\,\mathrm{au}$ [9]. Given that JuMBO ionisation occurs at a similar timescale as JuMBO formation, $\tau_{\rm ion}/\tau_{\rm form} \sim 1$, and adopting the peak $f_{\rm peak} = 4\,\%$ production rate [2], then for 42 JuMBOs to be present simultaneously, one requires a cluster with $N_\star \sim 42/(0.04 \times 0.02) \gtrsim 50000$ stars; about a factor 20 larger than the observed $N_\star \approx 2500$ for the Trapezium cluster.

3 Extrapolating to the Trapezium Cluster

Wang et al. [2] find through scattering experiments of isolated encounters that $f_{\rm peak} \equiv N_{\rm pp}/N_\star \sim 4\%$ occurs when the outer-most JMO has orbital velocity 10 % of the encountering stars' velocity ($v_{\rm out} = 0.1 v_{\rm enc}$) and if both JMO's are on circular, co-planar orbits with an inner-to-outer semi-major axis ratio of $a_{\rm in}/a_{\rm out} > 0.8$, and satisfies $a_{\rm out} > a_{\rm in}$.

For the Trapezium cluster, these conditions translate to $a_{\rm out} \simeq 2.2 \times 10^4$ au, and $a_{\rm in} \sim 1.8 \times 10^4$ au. These adopted orbits are much wider than observed circumstellar disk sizes [10] and known planetary orbits [11]. In addition, two planets with such orbits are typically separated by < 2.3 mutual Hill radii, making the system dynamically unstable. Alternatively, we can assume the planetary system to be stable (separated by 5 mutual Hill radii, or somewhat less when in mean-motion resonance) and the two planets' orbits separated by 100 au (to reproduce the observed JuMBOs observed projected distances). The resulting velocity dispersion when fixing $v_{\rm out} = 0.1 v_{\rm enc}$, to correspond with the highest JuMBO formation rate, leads to a density of $\sim 10^9\,$stars/pc^3, much larger than what is observed (For $v_{\rm out}(a = 500{\rm au}, M_\star = 1.0\,M_\odot) = 1.33 km/s$ then leads to cluster velocity dispersion of $v_{\rm disp} = 13.3\,$km/s, which for a $1000\,M_\odot$ Plummer sphere leads to a Plummer radius of about 0.004,pc.). In such an environment, the formation rate of JuMBOs is virtually zero, and their destruction rate several orders of magnitude higher (survival timescale is less than an orbital period).

Shifting our focus to more realistic initial conditions (between the red-dotted and blue-dashed lines of [2]'s fig. 3c), they find that one JuMBO forms for every 10^4 free-floating JMOs. Although consistent with the SPP model in Portegies Zwart and Hochart [3], this does not agree with observations as it can then only explain $\sim 0.13\,\%$ of the observed population. Here we assume that the identified population of 40 JuMBOs is confirmed. Considering complications of the spectroscopic identification of extremely red and low-luminosity Jupiter-mass objects in the Trapezium cluster we expect this number to drop substantially, in which case the discrepancy with the SPP model becomes even worse.

Ignoring the system's intrinsic instability and allowing the JMOs to orbit nearer one another, the JuMBO-to-free-floating JMO rate increases, yet still falls short of the observed rate: fig 3c of [2] shows one JuMBO forming for every 200 free-floating JMOs: similar to the SPM rate (for Star-Planet-Moon) of Portegies Zwart and Hochart [3] (with which they unfortunately compare their SPP rates while claiming consistency). The SPM model, however, will produce mugh tigher $\lesssim 1\,$au orbits, and rather unequal masses.

4 Numerical Support

To further support the arguments against the SPP model, we conduct new simulations using a unsoftened 4-th order Hermite direct N-body code coupled with stellar evolution through the AMUSE framework [12]. We explore both a virialised Plummer and fractal (with fractal dimension 1.6) distribution and evolve the system until 1 Myr. Fig 1 (for JuMBOs) and Fig. 2 (for JMOs) show the Plummer models' results, as the more realistic fractal models do not produce any JuMBOs.

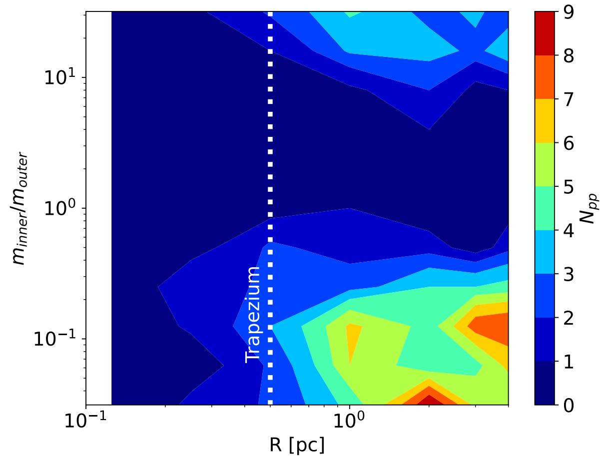

Fig. 1 JuMBO and free-floating JMO population at an age of 1 Myr. The number of JuMBOs as a function of the cluster virial radius (R) and the inner-to-outer planet mass ratio. All clusters are initialised with 2500 stars from a broken power-law mass-function between 0.08 $M_\odot$ and 30 $M_\odot$ [5] distributed in a virialised Plummer sphere [13]. We randomly select 300 stars and supply them with two planets, the inner planet with $m_{\rm in} = 0.001\, M_\odot$, and the outer planet $m_{\rm out}$ (see vertical axis). The orbital separations are selected to ensure that $a_{\rm out} - a_{\rm in} = 100\,$au with the additional requirement that five mutual Hill-radii separate the two planets.

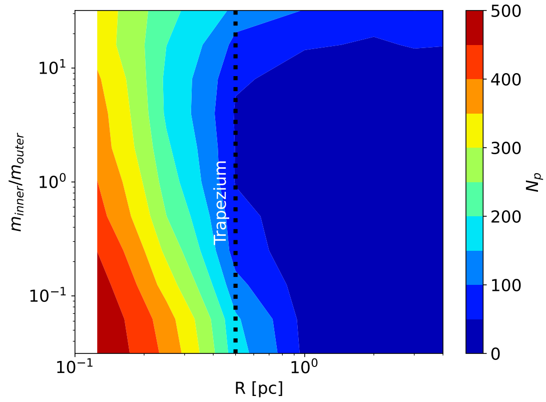

Fig. 2 JuMBO and free-floating JMO population at an age of 1 Myr. The number of free-floating Jupiter-mass objects as a function of the cluster virial radius (R) and the inner-to-outer planet mass ratio. Simulation parameters are identical to those presented in Fig. 1.

For Trapezium cluster's conditions Wang et al. [2] find typically $\lesssim 1$ JuMBO for some $\gtrsim 100$ JMOs, or $\lesssim 1\%$ JuMBOs among the JMOs, consistent with our finding Fig. 1 and Fig. 2.

Decreasing $m_{\rm inner}/m_{\rm outer}$ also increases the JuMBO formation rate. Indeed, given the right conditions where the outer JMO is ejected, the gravitational force exerted by the outer JMO onto the inner JMO can tip the outcome in favour of also ejecting the inner JMO. This behaviour is more pronounced for massive outer JMOs because of their greater gravitational influence, and leads to the increase in JuMBOs for sparser clusters but with massive outer planets $m_m \gtrsim 10\,{\rm M_{Jup}}$. Figure 2 shows the number of rogue JMOs liberated through dynamical encounters. The increase in rogue planets for denser clusters is consistent with the results of [3] (see their table 1).

5 Verdict

The observed number of JMO's in the Trapezium cluster could be explained by disrupted planetary systems if half the stars had a wide ($a_{\rm out} \gtrsim 330$ au) planet, but the tail of the stellar mass function provides a more plausible explanation for the isolated sub brown-dwarf-mass objects [14].

We expect that at most 1 JuMBO could originate from the SPP model, but then its mass ratio is probably rather small ($\lesssim 0.1$). However, the SPP model requires very wide ($a_{\rm out} \gtrsim 330$ au) planetary systems to be present in the cluster. The absence of these in the observed planetary systems does not necessary excludes those, as such wide orbits are hard to identify in the observations. On the other hand, only a few circum-stellar disks in the Trapezium cluster appear to extend beyond 300 au [9], and also in the Taurus association disks appear smaller [15]. Because of the inefficiency of the SPP model, the lack of large disks, and the absence of wide planetary orbits make us render the SPP model ineffective for producing JuMBOs.

We consider the SPM scenario more promising by about an order of magnitude, but their orbits are expected to be much tighter ($\lesssim 1$ au); which makes them still short lived (i.e., soft) at a velocity dispersion of $\gtrsim 0.7$ km/s. Overall, explaining the number of JuMBOs and their orbital separations, either with SPP, SPM, or even primordially, remains problematic. We can imagine that one or two coincidence alignments appear in the data, but those systems would be transient.

If the existence of JuMBOs is confirmed, we expect them to be either primordial or produced by ejecting a planet-moon pair from a parent star. In either case, they must be rare ($\lesssim 10^{-3}$ per stars), with tight ($\lesssim 1$ au) orbits, and unequal in mass.

6 Competing interests

The authors declare no competing interests.

7 Data availability

The code for this manuscript is available at
StarLab: https://github.com/amusecode/Starlab
The Astrophysics Multipurpose Software Environment: http://amusecode.org
The specific script for reproducing the runs this manuscript: https://gitlab.strw.leidenuniv.nl/spz/jumboformation.

8 Author contributions

Simon Portegies Zwart: initiated the topic, wrote the run scripts, perform the simulations, analyzed the data, discussed the science, wrote the first version of the manuscript, and dealt with the refereeing and editorial contacts.
Erwan Hochart: initiated the topic, checked run scripts, performed independent validation runs, discussed the science, wrote the second and the version of the manuscript that eventually led to the submitted version.

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10 Energy consumption

Calculations are performed on a 13th Gen Intel Core i7-1370P (20-core x86 64-bit Little Endian) processor, which consumes 64 Watt. We performed a total of 77 simulations covering cluster radius and mass ratio. Each calculation was performed 5 times for Plummer and fractal initial distribution functions, totaling 770 calculations of about 1 hour each. The 50 kWh used in these calculations was produced from solar power.

11 Software used

This work was made possible because of the following public software packages, for which we are grateful to the authors: AMUSE [16] (see http://amusecode.org); Fractal-model generator [17]; Numpy [18]; ph4 [19]; pyplot [20]; python [21]; SeBa [22]; Scipy [23]; Starlab [24] (see https://github.com/amusecode/Starlab).

12 Source Data

The scripts for generating initial conditions, performing the calculations and analyzing the data are available at Git: https://gitlab.strw.leidenuniv.nl/spz/jumboformation.

These scripts are based on the Astrophyiscs Multipurpose Software Environment [16], which is an open source package available at http://amusecode.org.

Further data on JuMBOs is available at zenodo 10.5281/zenodo.10149241, which is produced with the source code on github https://github.com/spzwart/JuMBOs.

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