The Possible Ejection of a 5th Giant Planet in the Early Solar System and the Presence of a Large Free Floating Planet Population

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INTRODUCTION

The origin of the solar system's current architecture has long been an item of interest for astronomers. Only in the last few decades has technology allowed the computationally-expensive dynamical investigation that must be employed to account for the planet migration and scattering events that must have occurred in the early solar system. The Solar System's planets are believed to have formed according to a process called core accretion, which is described in more detail below. However, quantitative evaluation of the core accretion model posed a seemingly insurmountable problem: how to explain the existence of Uranus and Neptune when the accretion time scale to form those planets was on order the age of the Solar System (and much longer than the putative 10 million year lifespan of the gas disk).

What is widely referred to as the Nice Model (Tsiganis et al. 2005) has attempted to explain this by considering a case where the outer planets scattered to their current semi-major axes and eccentricities from a much more compact configuration. The planets would have been born in the protoplanetary disk and migrated to resonant orbits within ~15 AU of the Sun. Sometime after the dispersal of the protoplanetary disk, Jupiter and Saturn come into 3:2 (or 2:1) resonance and scatter Uranus and Neptune outward and a large fraction of the protoplanetary population throughout the disk, the remnant of which now reside in the Kuiper Belt. The scattering of the small bodies is invoked to explain the Late Heavy Bombardment of the inner solar system ~3.9 Gya inferred from the cratering statistics of the inner solar system and radiometric dating of Lunar samples taken during the Apollo missions (Tera et al. 1974).

Of course, there is an inherent bias in our efforts to reconstruct the history of the early Solar System in that we naturally gravitate towards initial conditions that appear will most likely result in the planetary configuration we see in the Solar System today. *A priori*, however, there is no reason to suggest that the dynamical processes that occurred early on *had* to result in solutions the same or similar to the Solar

System. In fact, without reference to information gleaned from planetary systems outside our own, we have no idea whether the result in our Solar System is a particularly likely or unlikely one. We must both consider a wide variety of initial conditions and utilize empirical data of exoplanets provide to assess the success of dynamical models and the likelihood of any given end result.

Nesvorny (2011) expanded plausible initial conditions to include the possibility of a 5th giant planet in the early solar system that was later ejected from the system during the planet scattering event that led to the migration of the Uranus and Neptune and the LHB. Using an ensemble of N-body simulations, Nesvorny finds that the inclusion of a 5th planet that was later ejected substantially increases the likelihood of producing a final solar system with four giant planets with similar orbital characteristics to our giant planets. In contrast, the simulations starting with a resonant system of four giant planets have a much lower success rate in matching the imposed constraints (e.g., the solar system ends up with four giant planets, the terrestrial planets survive, etc.). Conveniently, this model also helps to explain the prevalence of free-floating giant planets untethered from any host star, which recent microlensing surveys (Sumi et al. 2011) have suggested outnumber the stars in our galaxy.

This latter subject is in itself very interesting for a variety of reasons. The observations of rogue planets are another observational couple into physics of planet formation. However, recent studies have even suggested that planet-planet scattering alone is not enough to explain the number of free-floating planets, perhaps muting their usefulness for this purpose (Veras & Raymond 2012). Finally, some have suggested that these interstellar wonderers might be habitable abodes for life, tiny oases in a cold, dark cosmic desert (Abbot & Switzer 2011).

In this paper we will briefly discuss, in order, 1) a basic summary of the core accretion model, 2) the methods and assumptions of Nesvorny (2011) and similarities to the Nice model, 3) the constraints placed on the Nesvorny simulations that judge the 'success' of a simulation, 4) the specific results of the Nesvorny simulation ensemble, 5) the method of microlensing as applied to detecting planets, 6) the results of Sumi et al. (2011) that demonstrate a prevalence of free-floating planets, 7) some additional notes on free-floating planets, and finally a small discussion of the future work that may be done to falsify or strengthen the results presented here.

THE CORE ACCRETION MODEL

The core accretion model is a mechanism invoked to explain the formation of the gas giant planets from the protoplanetary disk. We will not discuss the competing model, gravitational instability, as evidence has shown that planets formed in this manner would originate at large distances from the central star (Boley 2009). Core accretion involves the amalgamation of solid particles to form a ~10 Earth mass core when gas is still present in the disk. The core then has the gravitational influence to accrete a large atmosphere of hydrogen and helium from the disk and grow to large size (Pollack et al., 1996; see review in Morbidelli 2011). There are two stages to core accretion, runaway growth and oligarchic growth.

The planetesimals in the disk begin with low eccentricities and inclinations ('dynamically cold') and the escape velocities of the planetesimals may be larger than the dispersion velocities of the planetesimals, allowing easy capture and coagulation. As the planetesimals grow larger their own gravity starts to play a role, affecting the trajectories of passing debris and effectively increasing their collisional cross section by an enhancement factor $(1+\frac{V_{esc}^2}{V^2})$. In the early stages the dispersion velocity is not ruled by the largest bodies. In this runaway growth phase the relative mass growth of the planetesimals is a function of its own mass (Morbidelli 2011) so that $\dot{M} \propto m^{4/3}$ (Wetherill & Stewart 1980).

When the relative velocity of the planetesimals becomes comparable to the escape velocity from the most massive objects, it is the end of the runaway growth phase and the beginning of the oligarchic growth phase. Now the velocities are ruled by the largest bodies and $\frac{V_{esc}^2}{V^2}$ is constant so $\dot{M} \propto m^{2/3}$

Once the planet has captured or scattered most of the mass within its gravitational reach, its growth stops at what is called its isolation mass (Lissauer & Stewart 1993):

$$M_{iso} = \frac{(8\pi\sqrt{3}\sigma)^{3/2} a^{3/2}}{(3M_{sol})^{1/2}}$$

Where σ is the cross-section and a is the semi-major axis.

Though, of course, there are nuances to this and still some problems in getting a core from 1 to 10 Earth masses (Morbidelli 2011).

NESVORNY (2011) METHODS AND ASSUMPTIONS

The paper begins with the assumption that the outer solar system began with a compact configuration of gas and ice giant planets in a resonant configuration in the disk. After the disappearance of the gas disk, the planets orbits evolved until they underwent a violent phase where the planets scattered of one another and acquired eccentric orbits (Thommes et al. 1999, Tisganis et al. 2005). The planets regained low eccentricity orbits by damping excess orbital energy into the disk. Planets radially migrated to their present orbits by interacting with planetesimals (Levison et al. 2008).

Nesvorny first used hydrodynamic (Fargo code) and N-body simulations (SyMBA code) to identify likely resonant orbital configurations in the early solar system. Planets with identical masses to those of Jupiter, Saturn, and the ice giants were placed in initial orbits that had slightly larger periods than those required for the selected resonances. He considered cases with four and five planets, the additional planet present in half the cases was placed into a resonant orbit between the Saturn and Uranus analog and had a mass between 1/3 and 3 times the mass of Uranus.

Starting positions of the planets, rates of semi-major axis and eccentricity evolution, and the time scale for disk dispersal were all varied in the ensemble of simulations. Resonances between Jupiter and Saturn were restricted to 3:2 and 2:1, though 3:2 is strongly preferred from previous work. Only configurations that were stable for ~10^9 years were considered since the LHB occurred ~600 Myr after planet formation.

The transplanetary disk was modeled by 1000 equal-mass bodies that were set with small initial eccentricities and inclinations in radial distances between $r_{in} < r < r_{out}$. The value r_{in} was varied with the cases r_{in}=0.5, 1, and 3.5 AU explored while r_{out} was set to be 30 AU to park Neptune at its current location. The surface density of the disk decreased as 1/r. Six different masses of the planetesimals disk were considered ranging from 10 M_{Earth} to 100 M_{earth}. The simulations began just before the scattering phase. Overall, 6000 scattering simulations were completed and each system was followed for 100 Myr.

NESVORNY (2011) SUCCESS CRITERIA/CONSTRAINTS

The successes of the simulations were judged based on the following factors:

Criterion A – The final planetary system must have four giant planets.

Criterion B – The orbits of the final planets must resemble the present SS planets.

Criterion C – All planets must participate in encounters with planetesimals such that the e_{55} mode > 0.22 for Jupiter in the final systems (half its current value).

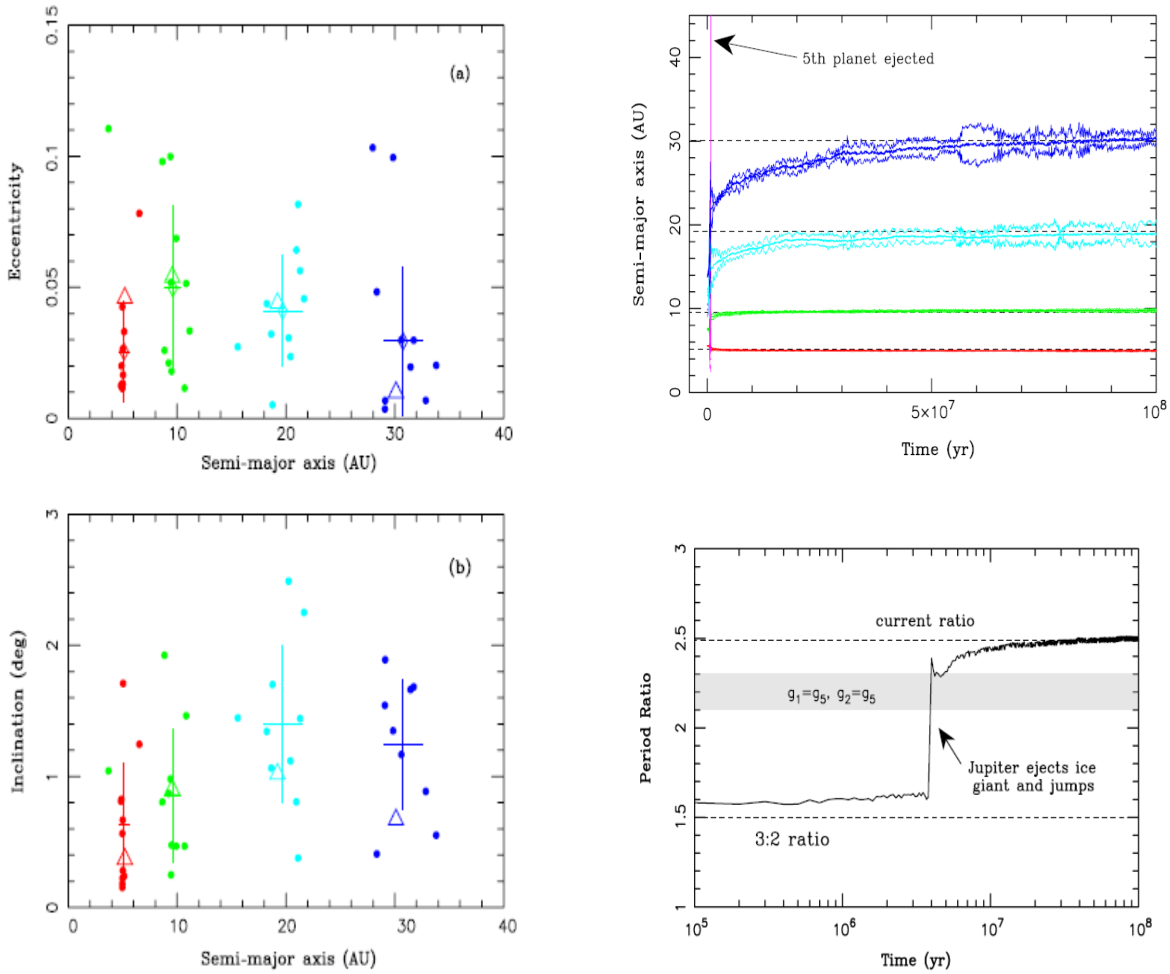
Criterion D – The evolution of the secular modes provides a constraint, because if g_1=g_5 or g_2=g_5, the resonances can excite instabilities in the terrestrial planet system (Brasser et al. 2009), so they must not have these values for very long in the simulation to produce a planetary system likes ours with inner terrestrial planets. These modes are mainly a function of the separation between Jupiter and Saturn, so Nesvorny parameterizes this constraint in terms of $P_{Saturn}/P_{Jupiter}$. The ratio must change from 2.1 to 2.3 in < 1 Myr. This occurs if the ice giant encounters with the gas giants scatter Saturn outward and Jupiter inward.

NESVORNY (2011) RESULTS – 5th GIANT PLANET LIKELY?

Nesvorny first considers the four planet results. How often are criteria A-D achieved and is that a function of the disk mass? The best results are obtained for disk masses of 35 M_{Earth} and 50 M_{Earth}. The fraction of the simulations with these two disk masses fulfilling criterion A are 10% and 13%, respectively. Only three out of 120 simulations results in planets with similar orbital parameters to the Solar System Planets (~2%). Less massive disks result in solutions with fewer than four planets while heavier disks do a poor job meeting the other criteria.

In contrast, in the case of M_{disk}=50 M_{Earth} the fraction of five-planet cases matching criteria A and B rise to 37% and 23% respectively. Figure 1 shows the final orbits resulting from the five-planet simulations with planets starting in the (3:2,3:2,4:3,5:4) resonances, M_{disk}=50 M_{Earth} and r_{in}=15 AU. Only the systems that result in four planets are shown in this figure. Figure 2 displays the orbital histories of the giant planets in a single simulation with five starting planets. Figure 3 shows the evolution of the period ratio for a single selected five planet case. This plot shows that the region where 2.1 < P_{Saturn}/P_{Jupite}r < 2.3 is mostly avoided, which is necessary for the survival of the terrestrial planets.

According to these simulations then, a five-planet initial condition is ten times more likely to produce a solar system like our own than a four-planet initial condition! Of course, even this addition to the initial conditions doesn't change the fact that the majority of the simulations result in a Solar System that doesn't look like ours, either because the final system has less than four giant planets or their orbital elements don't match up to our planets. This result provides insight into why so many of the planetary systems we observe do not look like our own and of course reinforces planet-planet scattering as a plausible source for the free-floating planet population.



Figures from Nesvorny (2011) – 1) Left: final orbits of five-planet simulations that resulted in a four-planet system. Error bars are the average rms of the semi-major axes and inclinations. Jupiter, Saturn, Uranus and Neptune are denoted by the red, green, turquoise, and blue triangles, respectively. 2) Upper right: Orbital histories of the giant planets in one of the simulations. Very early the 5th planet was ejected and the remaining planets were stabilized by the planetesimals disk and migrated to orbits that closely match those of the SS planets. 3) Lower right: evolution of the period ratio $P_{Saturn}/P_{Jupiter}$. The fifth planet was ejected at 3.5 Myr causing a jump from 1.5 to 2.4.

PLANET DETECTION VIA MICROLENSING

Gravitational lensing is observed as the perturbation of light from a straight-line path from the source to the observer due to an intervening mass distribution. This perturbation can produce varying numbers of images, varying angular offsets on the sky from the apparent image positions and the true source position, and varying magnification of those images depending on the characteristics of the intervening lensing mass distribution. For planets we are only concerned with the point-mass case. Surveys look for the increased flux caused by the magnification of a source star by an intervening lensing mass. The deflection angle is $\alpha = \frac{4GM}{c^2 b}$ and is usually so small for lensing stars or planets that the lensed images remain in the same PSF with the lens itself.

Figure 4 demonstrates the lensing geometry for the deflection of light by a point source.

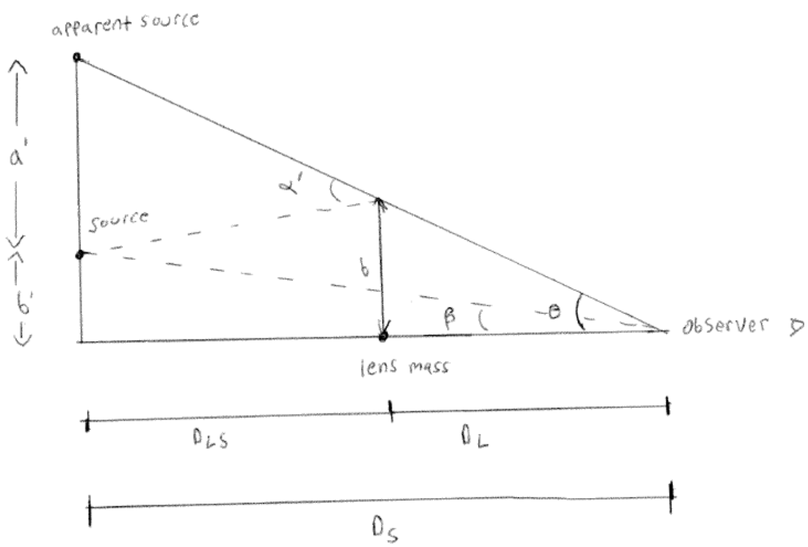


Fig. 4 *– Basic geometry of a lensing system. Note that only one of two apparent sources is shown.*

The relevant parameters are:

θ – The apparent angular distance between the image and the lens on the image plane.

β - The angular distance between the lens and the source on the image plane.

α' – The deflection angle of the lens.

b – The impact parameter of the deflected/undeflected light ray.

D_L – The angular-diameter distance from the observer to the lens mass.

D_S – The angular-diameter distance from the observer to the source

D_{LS} – The angular-diameter distance from the lens to the source.

a' – Real space distance between the source and the image in the source plane.

b' – Real space distance between the source and lens mapped back to the source plane.

We can define a 'crossing time' for the lens to pass in front of the source, i.e. the timescale of the increase in the signal. This is called the Einstein crossing time and it's a function of the tranverse velocity of the lens and the 'Einstein radius' itself a function of D_l, D_s, and D_{LS}:

$$t_{\mathrm{E}} = \frac{R_{\mathrm{E}}(M, D_{\mathrm{l}}, D_{\mathrm{s}})}{v_{\mathrm{t}}}, \text{ where } R_{\mathrm{E}} = \sqrt{\frac{4GM}{c^2}\frac{D_{\mathrm{l}}(D_{\mathrm{s}} - D_{\mathrm{l}})}{D_{\mathrm{s}}}}$$

The magnification is given by:

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad \text{where} \quad u(t) = \sqrt{u_{min}^2 + \left(\frac{t - t_0}{t_E}\right)^2}$$

It is important to note the magnification is inversely proportional to the radius of the lens, so that smaller lenses produce larger (but briefer) magnification events. Figure 5 is a cartoon illustrating the lensing process for planets bound to stars, which is similar for unbound planets (just take out the gentle rise and fall from the lensing due to the star).

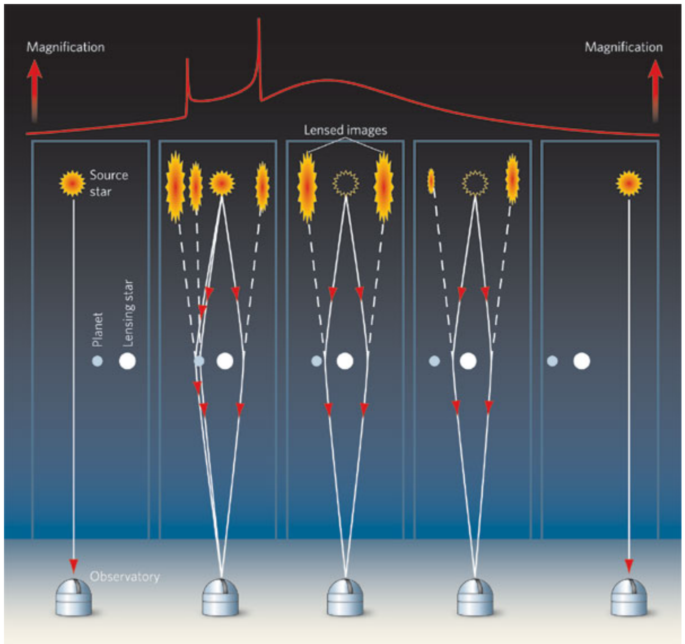


Fig. 5 – Lensing due to a star-planet system

DETECTION OF LARGE ROGUE PLANET POPULATION VIA MICROLENSING

Sumi et al. (2011) describe the results from the MOA microlensing survey that indicate a substantial free floating planet population. The survey was directed towards the galactic bulge where a large density of field sources and possible lenses were available. High-cadence photometry was employed to detected events with $t_E < 2$ days. Conservative cuts were applied to their data to rule out data artifacts, resulting in 474 events that passed their criteria out of thousands of initial detections.

They fit their t_E distribution (the length of each lensing event) to two mass models – one a broken power law model and one a log-normal distribution- to fit the stellar mass function of possible lensing objects. These models predicted 1.5 to 2.5 events with $t_E < 2$ days, but ten where detected. The excess is the inferred free-floating planet population. (Seven of those ten detections were also verified with the OGLE survey).

Figure 6 is an example MOA/OGLE light curve of a lensing event with $t_E < 2$ days. Figure 7 is a plot showing distribution function for t_E observed and modeled for each mass function. The excess at low t_E is modeled as a free-floating mass planet population with a median mass of about a Jupiter mass.

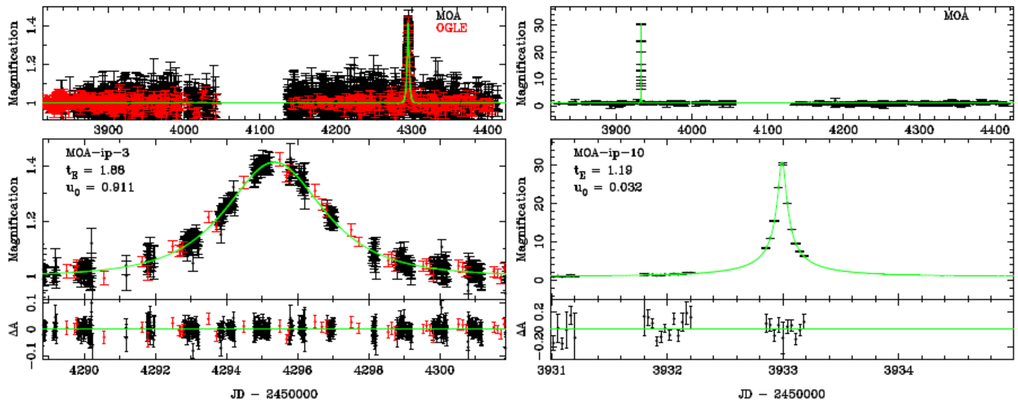


Fig. 6 – MOA/OGLE light curve of a sub-two day lensing event

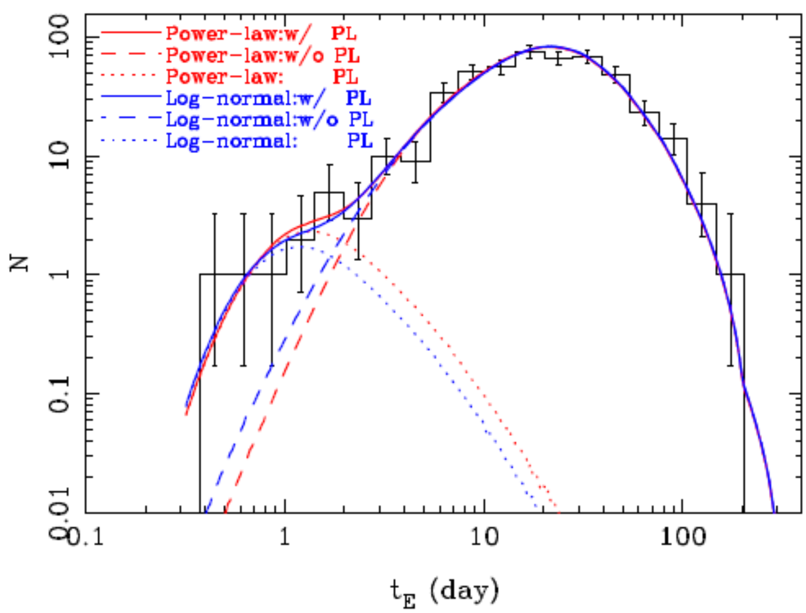


Fig 7 - $\varphi(t_E)_{obs}$ (black) and $\varphi(t_E)_{model}$ (red and blue). PL=planet

From the measured excess of tE < 2 day events, Sumi et al. (2011) infer a total lensing population of ~1.8 unbound planets per star. Of course one must consider the cases where the source star is simply passes outside the Einstein radius of a lensing star-planet system and only the planet contributes to the lensing effect. Sumi et al. The star would have to be more than ~10 AU away from the lensing planet in this case, which is not that implausible (Saturn is at about 10 AU). Using upper limits for the number of planets outside of 10 AU for a typical star derived from the Gemini Planet Imager survey, they find that only 0.4 of the 1.8 planets per star could actually be distantly bound planets. One wonders about the rigor of those upper limits, however!

CONCLUDING DISCUSSION AND IMPLICATIONS OF ROGUE PLANET POPULATION

The Nesvorny and Sumi papers seem to dovetail nicely together. The Sumi paper illustrates the pervasiveness of unbound planet sized bodies in interstellar space. The results from the Nesvorny analysis provide a mechanism to create a rogue planet population from planet-planet scattering in addition to a change in the initial conditions of the early solar system that seems to drive simulations closer to resulting in solar systems like our own. It seems to fit together very nicely.

Veras and Raymon (2012), however, find that planet-planet scattering alone cannot produce the observed population of free-floating planets unless an implausible number of planets are ejected per solar system. This point either to a systematic error in the Sumi results or additional sources of planet-sized objects other than ejection of planets from dynamically unstable systems.

It is interesting to briefly mention the astrobiological implication of free-floating planets. Large geologically active Super-Earths with an insulating ice sheet could produce enough geothermal flux to retain a subsurface ocean even without the energy input of a host star (Abbot & Switzer 2011). Large H_2 atmospheres of several bars have also been shown to considerably increase the zone of habitability around cool stars and perhaps may extend into interstellar space (Pierrehumbert & Gaidos 2011). We can also consider Titan-like worlds that may persist with liquid ethane oceans due only to geothermal fluxes without the contribution from a parent sun (Gilliam & McKay 2011). The ability of non-polar solvents like liquid methane and ethane to substitute for liquid water in living processes has not been completely ruled out.

There is definitely more work that can be done in the future to falsify or strengthen the arguments in Nesvorny 2011. Higher fidelity, more costly simulations that can take a model solar system from t=0 to beyond 600 Myr with a widening set of initial parameters can better inform us of the strengths and weaknesses of current models. Varying the mass ratio of Jupiter and Saturn could change the final configuration of the solar system and it would be fascinating to explore the tolerance of this parameter to alteration while still producing a Solar System analog.

Further data from microlensing surveys would achieve higher signal-to-noise and would give us a stronger idea of what the true mass distribution of planets are in the rogue planet population. Another possibility is that further study would uncover and unknown systematic in Sumi et al.'s analysis perhaps reducing the number of inferred rogue planets and providing a solution to the problem found in Veras and Raymond (2012).

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