The Fate of Planetary Systems Without Gas Giants

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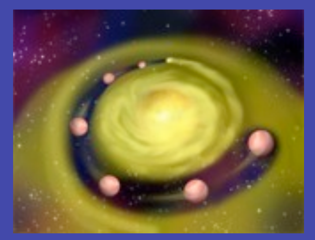


Abstract:

Recent studies show that for a large subset of circumstellar disks, the gas disk will dissipate before the planetary embryos are able to grow into gas giants. In spite of the fact that this may be a common scenario, little work has been done to study these systems because they are virtually invisible to traditional planet hunting techniques. We present the results of simulations of planetary systems investigating this scenario. Each simulation begins after the nebular gas has disappeared and oligarchic protoplanets have begun to grow from a disk of planetesimals with a mass concentration at a hypothetical "ice line" at 5-6 AU. We investigate systems with different (i) mass fractions in oligarchs, (ii) spacing of oligarchs in the ice line (degree of over packing), (iii) number of oligarchs in the ice line, (iv) size of the ice line, (v) and total mass in the ice line. Simulations show high levels of chaos at early times, but eventually settle into stable configurations. We find that the degree of over packing and the total mass in the ice line play the largest roles in the final configuration, while the other variables have less significant but measurable effects. Further, we investigate the feasibility of detecting such bodies by microlensing, through new telescopes like the Space Interferometry Mission, and through direct detection of oligarch-oligarch collisions. We find that oligarchs that reach stable orbits at 2-6 AU are the most likely to be detected by microlensing and SIM, and that oligarch-oligarch collisions are rare, but detectible provided the oligarch is thrown out to at least 20 AU for nearby stars.

Introduction/Motivation

Under core accretion theory, the cores of giant planets form from small bodies of rock and ice that collide and accrete into larger bodies. If they gain enough mass then they can accrete and hold a massive hydrogen envelope. This process is augmented in the area where water vapor turns to solid ice, commonly called the ice line,[10]. How often does this process happen? Current observations indicate that only 17-20% of solar type stars have gas giants within 20 AU[4] in spite of the fact that more than 80% have disks[6]. Additionally, gas disks disappear on timescales of less than ~6 Myrs and half disappear by 3 Mys[6]. Under core-accretion, Jupiter can take more than 5 Myrs to produce[7]. Planetary systems with a large number of oligarchs but no gas giants are likely more common than those with gas giants.

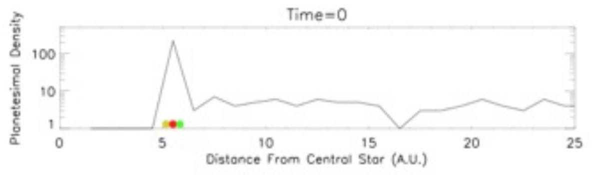
Since these bodies cannot be detected by the most popular planet hunting methods, little work has been done so study them in detail. What is final configuration of these systems? What variables play the largest role in their evolution? Can they be detected and if so, how? Once detected, what can we say about how they evolved?

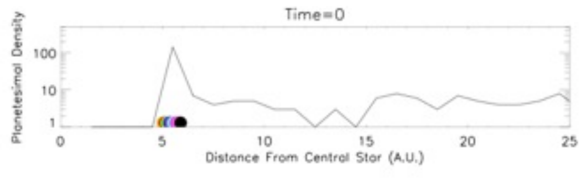
How to Build a Realistic System:

The simulations were run with the Mercury6 hybrid integrator, which combines a symplectic integrator with a conventional integrator for close encounters[1]. Simulations start right after the disappearance of the gas and run to 5 billion years. We assume a solar type star, including approximate disk mass and chemical abundances[9]. The basic parameters of each set are shown in the table below. Each set contains 10 simulations of nearly identical initial conditions..

Set #	# of Oligarchs in Ice Line	Fraction of Ice Line Mass in Oligarchs	Ice Line Width in AU	Number of Planetesimals	Mass in Ice Line In Earth Masses	# of planets In Inner System	Spacing in Hill Radii (b)	Time step in days
1	7	0.750	1	500	35	0	2	100
2	9	0.500	1	500	35	0	2	100
3	12	0.250	1	500	35	0	2	100
4	2	0.025	0.67	500	35	0	8	50
5	3	0.038	1	500	35	0	8	50
6	4	0.050	1.33	500	35	0	8	50
7	2	0.088	0.67	500	10	0	8	50
8	3	0.130	1	500	10	0	8	50
9	4	0.173	1.33	500	10	0	8	50
10	3	0.025	1	1000	35	0	8	50
11	3	0.038	1	500	35	2	8	10
12	3	0.088	1	500	35	4	8	10

Below are two sample simulations at time=0 (right after the disappearance of the gas) representing two extremes in initial conditions. Each data point represents an oligarch's semi-major axis and scaled in size by mass. This is plotted over the planetesimal density. The upper plot represents a highly packed, evolved (higher mass fraction in oligarchs) oligarchy while the lower is a younger, more distributed system. This corresponds to set 1 and 5 respectively (see table above).

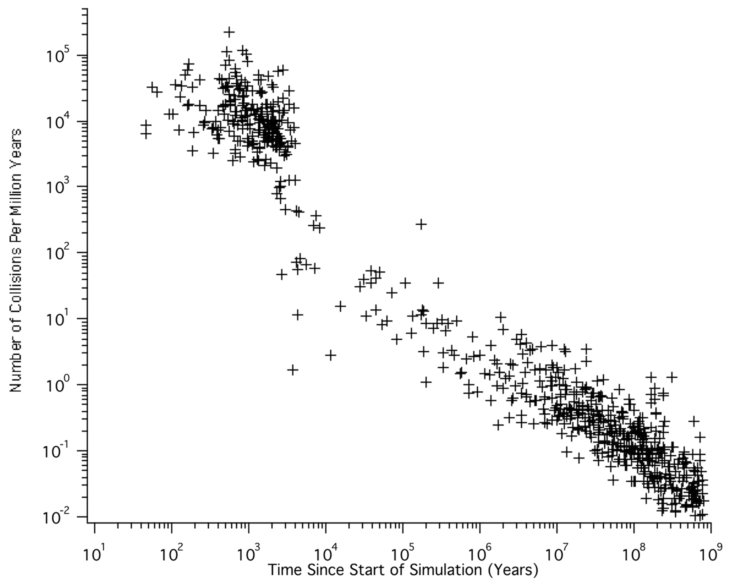


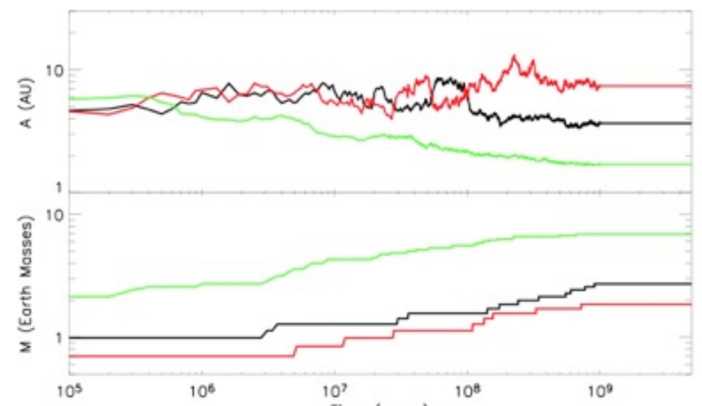


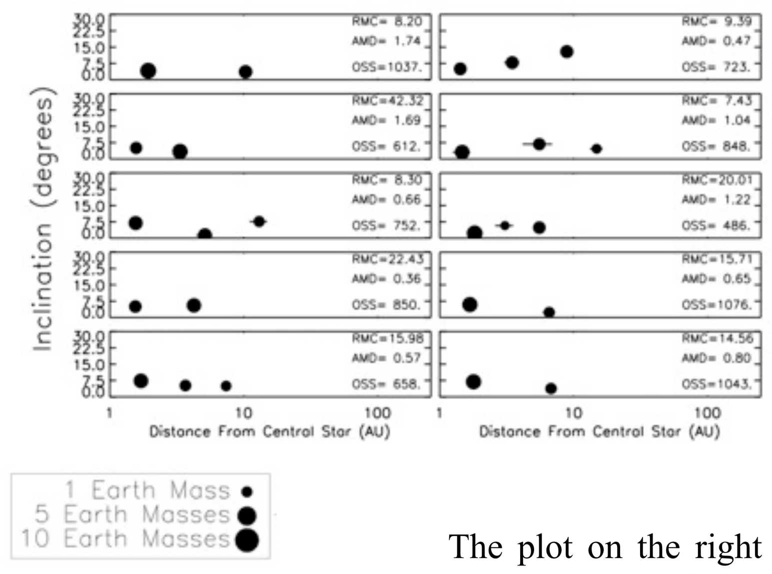
The Results:

Evolution and final configuration

Set #5





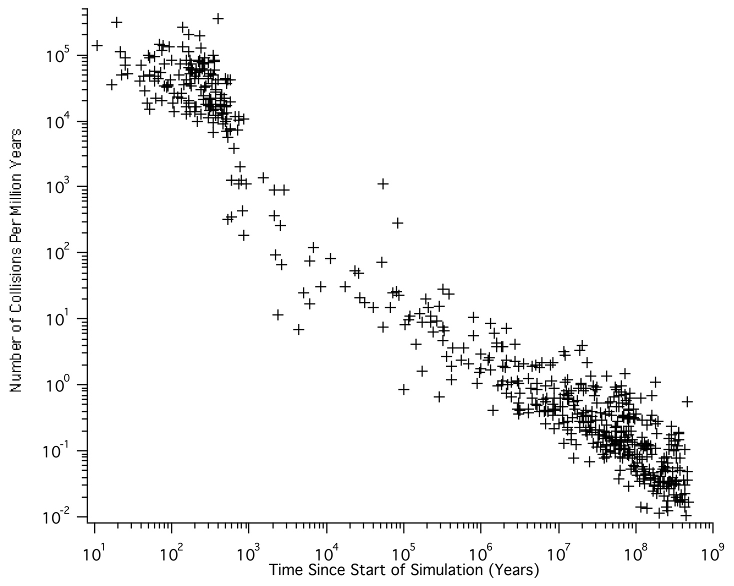


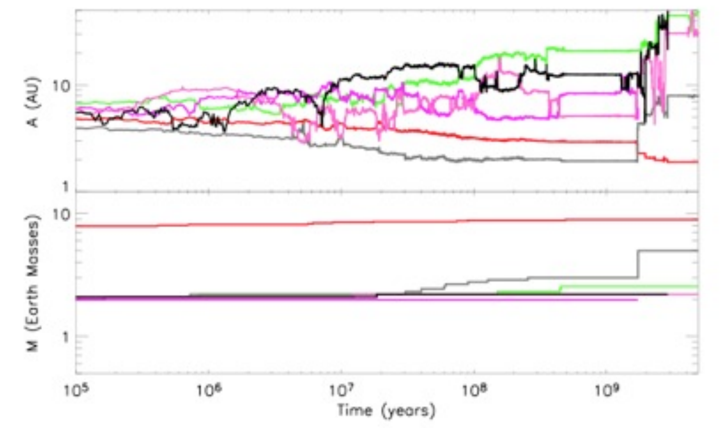
The columns to the left and right represent 2 different simulations sets. The left side representing set 5 and the left side representing set 1. These are chosen because they have very different evolutionary paths from each other. The top plot is a measure of collision frequency for each set. The center plot shows mass and semi-major axis evolution for a sample simulation within each set. The bottom plots show the final configurations of each set, Each data point represents a single oligarch, plotted based on it's semi-major axis and inclination, scaled in size by mass, and with a line through each point indicating the span of the orbit of a given oligarch.

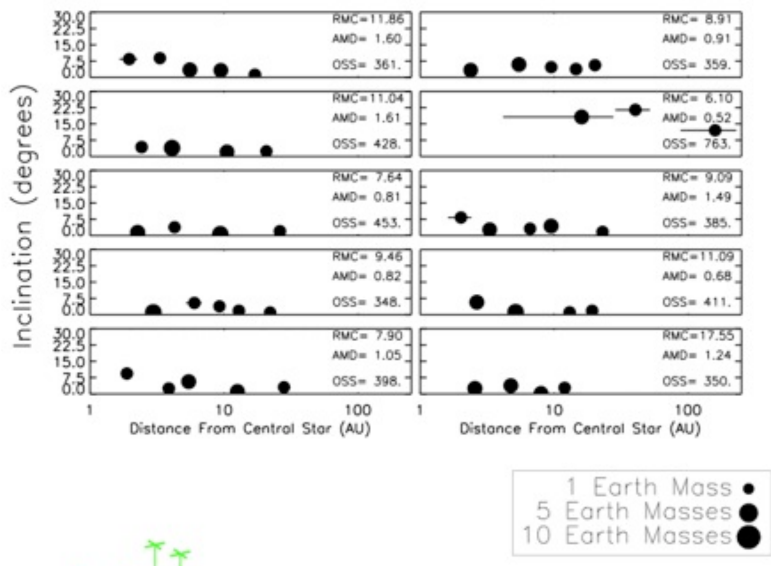
Both sets show an early 'chaotic' stage followed by a 'quiescent' stage. For set 1 the chaotic stage is more rapid and aggressive compared to set 5 (see top plots). After this, the oligarchs accrete very little mass from the planetesimals in set 1, whereas in set 5 they accrete most of their mass after 10^5 years (see center plots). Both simulation sets show oligarchs swapping positions at various times. This is especially true for the red and black bodies in the left plot and the red and grey bodies in the right plot. In set 1, interactions between oligarchs are strong enough to push other oligarchs completely out of the system, as happens to the oligarch shown in black in the right plot.

The final configurations can vary, even for nearly identical initial conditions. However, there are clear common trends. For example, all the simulations on the left have a high mass oligarch at ~1.5 AU (see bottom plots).

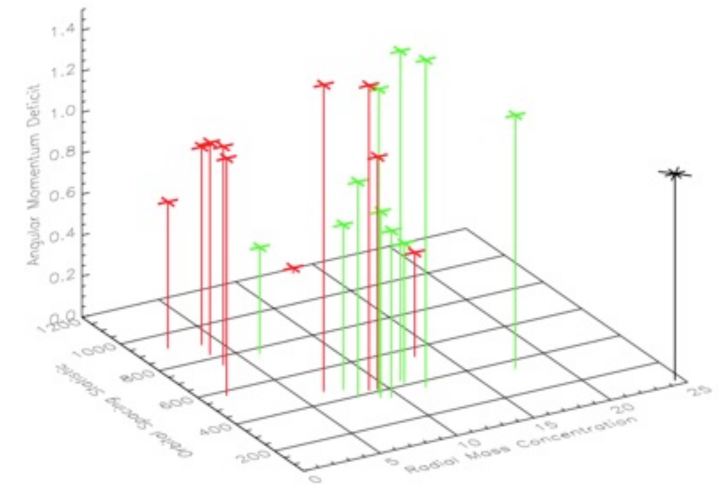
Set #1







The plot on the right shows the values for radial mass concentration, orbital spacing statistic, and angular mass deficit[2] plotted for the 2 sets of simulations shown above (numbers for individual system are given in the plots above). Set 1 is done in red, set 5 in green. The black point is the solar system values for comparison. These dimensionless numbers can be used to quantify the level of chaos in a given set of simulations (how spread the points are) as well as to compare different sets of simulations to each other.

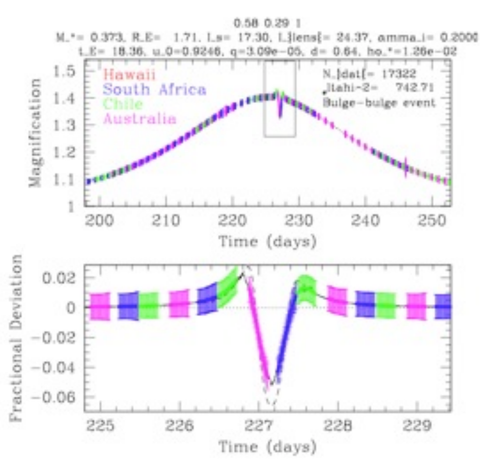


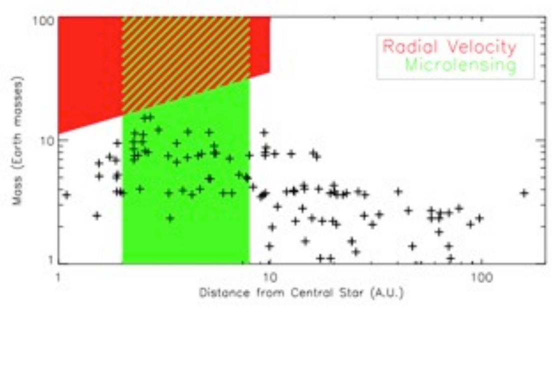
Detection:

Finding a mouse hiding behind an elephant while standing 500 meters away

Compared to most discovered exosolar planets, these oligarchs are small and light. This makes them difficult targets to observe, as the most popular techniques of planet hunting (radial velocity and transiting) favor more massive planets closer to their parent star.

Microlensing:

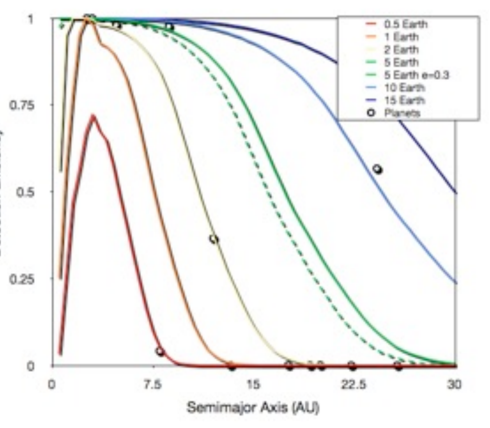




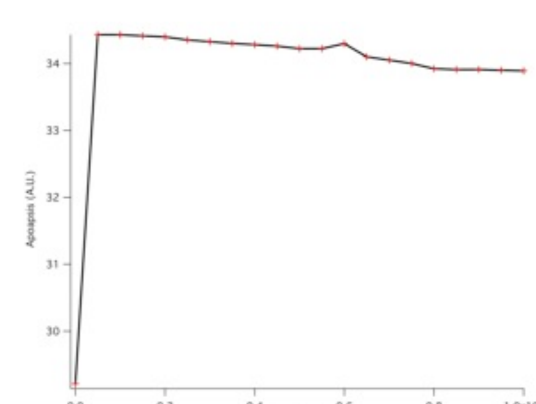
Although our planets land outside the range of radial velocity, many of them land in the sensitive zone for gravitational microlensing (see right plot)[5]. Shown above (left) is a simulated light curve for a microlensing event containing one of our planets. Bodies similar to ours have likely already been found this way.

Space Interferometry Mission:

To the right is the detection efficiency for the Space Interferometry Mission (SIM). A random sample of our simulated planets are shown. Assuming SIM searches systems containing these planets, for many of these bodies SIM has nearly 100% chance of detecting them.



Hot Collisional Afterglow



To the left is the apoapsis of an oligarch for 10^6 years following a collision with another oligarch. During this time, it will be hot (several thousand Kelvin), and radiate heavily in the infrared. In the case that the collision also throws the body to a high enough semi-major axis, the object could be directly observable.

Conclusions/Future Work:

We find that systems of oligarchs formed at the ice line evolve into planets from 2 to 12 Earth masses and can migrate as far in as 1 AU. The spacing of bodies (b) and the total mass in the ice line are the most important parameters in determining the final configuration. Other parameters most often change the final configuration in a trivial or predictable way. Adding another oligarch to the simulation, for example, typically results in a system with an additional planet, and slightly more total mass. The average RMC, OSS, and AMD values are changed by less than the standard deviation of these numbers within a simulation set. Further, we find that ~31% of planets across all simulations are detectible through microlensing and ~86% of simulated systems have at least one planet detectible through microlensing. Although SIM is still in hypothetical stages, it also can provide a powerful tool to detect and characterize these planets. Hot oligarch collisions offer a method of directly detecting a planet, however these collisions are rare, making them difficult to find on realistic timescales. Additionally, a close young star at ~50pc with a collision at ~20 AU will have an apparent separation of 4" from its parent star. This is only barely resolvable by future powerful telescopes, and requires ideal conditions. Once a planet has been detected and characterized, these results can be used to inform us about how a given system has evolved. This is particularly true for orbital spacing and ice line mass, since these parameters produced the most easily distinguished final configurations.

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