Effect of Strong Stellar Interactions on Planetary Systems and the Formation of Hot Jupiters

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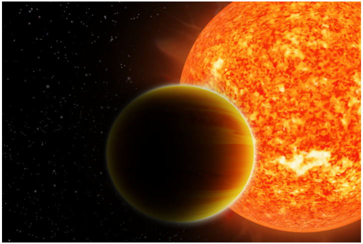
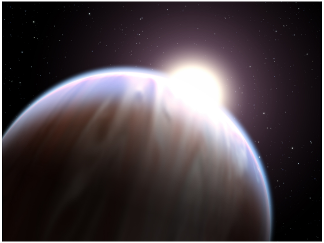


Overview

Hot Jupiters

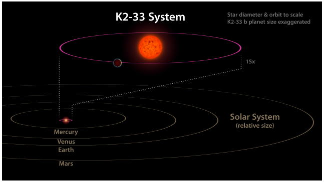
- Jupiter-mass planets orbiting very close (< 0.5 AU) to their host star.
- Jupiters are believed to form far out in the solar system.
  - How do they become so close?
  - What causes their migration?
- An estimated 1% of planetary systems contain a Hot Jupiter (A. Brucalassi et al. 2016)[1].



[1] James B. Pollack, Olenka Hubickyj, Peter Bodenheimer, Jack J. Lissauer, Morris Podolak, Yuval Greenzweig, Formation of the Giant Planets by Concurrent Accretion of Solids and Gas, Icarus, Volume 124, Issue 1, 1996, Pages 62-85, ISSN 0019-1035, http://dx.doi.org/10.1006/icar.1996.0190. (http://www.sciencedirect.com/science/article/pii/S0019103596901906)

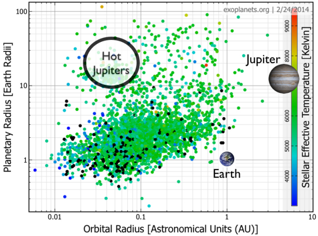
Background

- Explore formation scenarios for Hot Jupiters (HJs) in planetary systems.
- Understand the side-effects of HJ formation.
  - Does the migration of the HJ affect other planetary orbits?
  - Are terrestrial planets in highly eccentric orbit a possible indicator of Hot Jupiter formation?



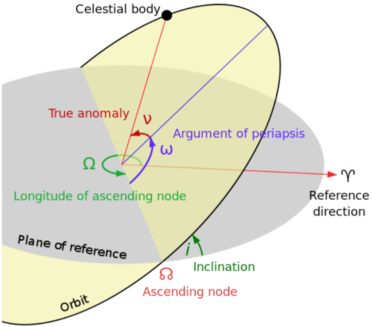
Theory

- Scattering Effects
  - HJs start like normal gas planets, but are perturbed inward.
  - Perturbation may come from stellar interactions within a star cluster.
  - This could cause other planets in the system to be knocked into eccentric orbits by the HJ.
    - If we understand what this might look like, we can look for it in the universe.
- We will use computational simulations to explore this scenario.



Orbital Elements

- Allow us to compute the closest approach analytically.
- Characterize planetary orbits.
- Allow numerical categorization of orbit changes.



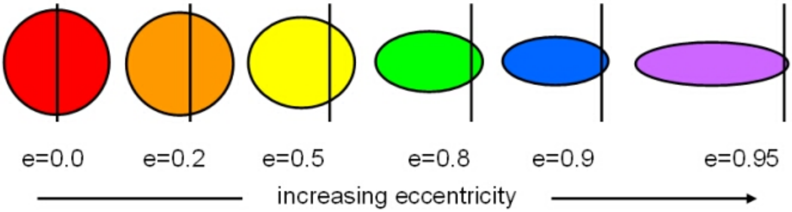
Orbital Elements

e – Eccentricity - How oblong the orbit is.

- $e = 0.0$ is a circular orbit.
- $e < 1.0$ is an elliptical orbit.
- $e > 1.0$ is a hyperbolic escape trajectory.

a – Semimajor Axis - The longest orbital axis length.

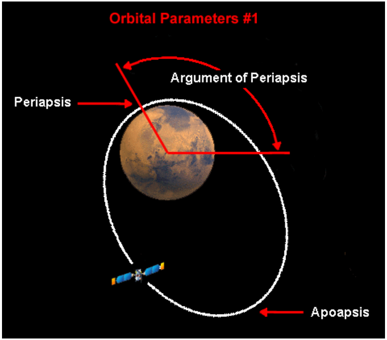
i – Inclination - Vertical tilt from horizontal.



Periapsis

- Periapsis – The point of closest approach of two orbiting bodies.
- Distance at periapsis is distance of closest approach.
- Easily computed from orbital elements:

$$r_{per} = (1 - e)a \tag{1}$$



Environment & Code

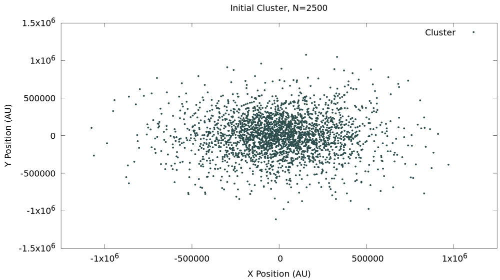
- Simulations are built atop the AMUSE astrophysics library.
- Run on Drexel's Draco computing cluster.
- 24 node shared between all users.
  - Three to six GPUs on each node
  - 12 core CPUs

Simulation Framework

- AMUSE does the gravitational dynamics in highly efficient code.
- Our python code sits on top
  - Setup the simulation initial state
  - Send the full setup to AMUSE
  - Let AMUSE run the simulation
  - Periodically pause the simulation to observe the state
    - AMUSE may also send us notifications about close encounters as it runs.

Star Cluster Simulation

- Jupiter-mass planets are only affected by very close ($\leq$30 AU) encounters.
- Time scale between these interactions is long.
  - About 1 encounter per 0.1 Myr
  - Not all of these are interesting for planetary interactions.
- Time scale for planetary orbits are short.
  - Earth orbits the sun in 0.001 Myr.
- Simulating planets in the cluster would require much more computation than just stars.



Star Cluster Simulation

Idea: Simulate only stars and add planets later in isolation.

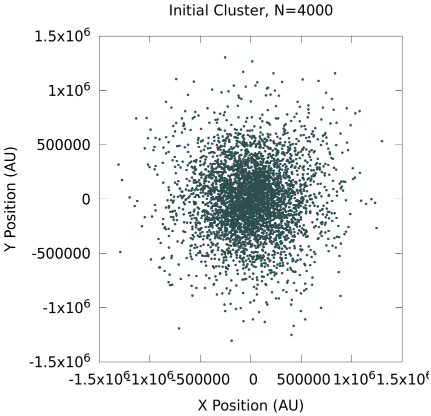
- Record exact parameters of star encounters.
- Don't waste resources simulating stable planet orbits.
- Allows much more detailed simulation for strong encounters without slowing everything down.
- The data can be reused with different configurations of planets.

Data Pipeline

1. Star Cluster N-Body simulations
   - Catalog close encounters for later simulation
2. Planetary system simulations of two interacting systems.
   - Use encounters found in star cluster simulations.
   - Observe how these encounters affect planets.
   - Save planetary system end-states for analysis.
3. Analysis
   - Observe patterns over many different encounters.
   - Look for Hot Jupiter formation or other interesting events.

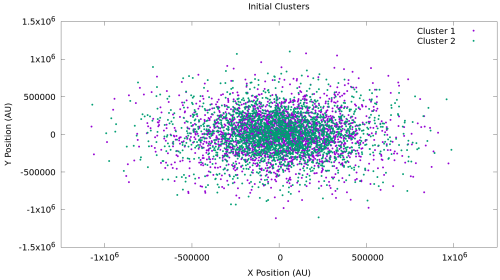
Star Cluster Simulation Approach

- Run many gravitational simulations of star clusters.
  - Each cluster has the same set of parameters.
    - Number of Stars
    - Mass distribution
- Catalog encounter parameters of all close star-star encounters.



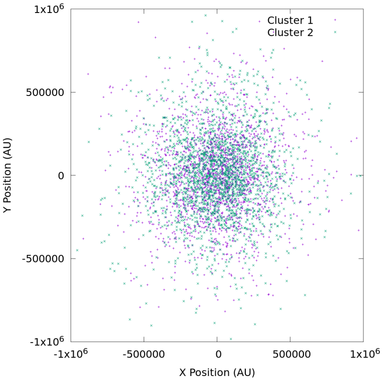
Star Cluster Setup

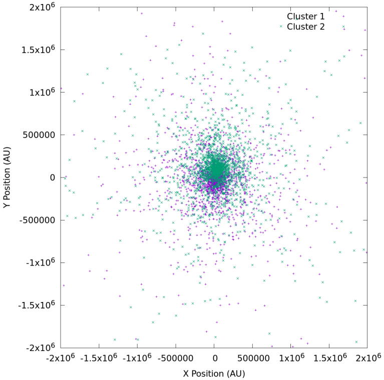
- King Model with $W_0 = 3.0$.
  - Sampled randomly to create a cluster.
- Clusters of 1000, 2000 and 4000 stars.
- Run for 250, 500, 1000 Myr, respectively.
- Each star has fixed $M = 1M_\odot$.



Star Cluster Simulation

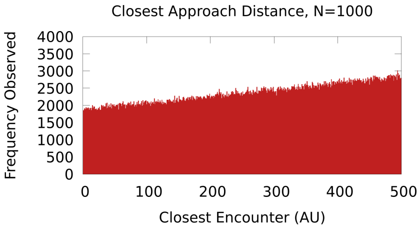
- Let AMUSE simulate a cluster, call back into user code for close stellar encounters.
- Compute and record:
  - Dynamical parameters of each star.
  - Orbital parameters (a, e, r)
  - Distance of closest encounter





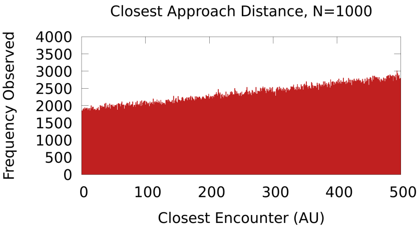
Encounters

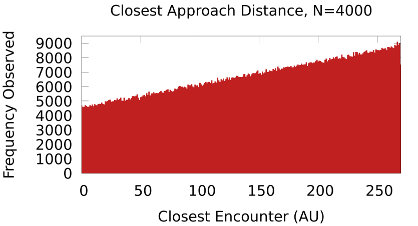
- For 1000 star clusters...
  - 1,000 total clusters simulated.
  - 250 Myr each.
  - 1,831,075 encounters returned between 0 and 500 AU periastron.
  - 57,351 encounters at 30 AU or less.
    - This is the most distant approach considered for Jupiters.



Encounters

- For clusters with more stars, close encounters were more frequent.



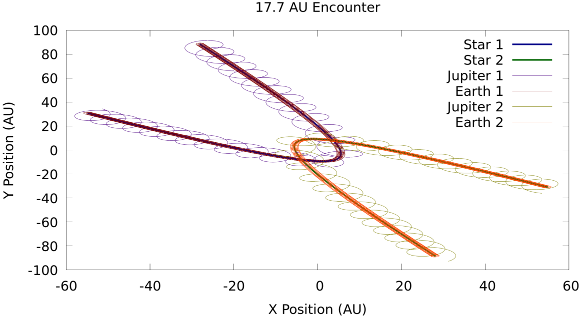


Phase 2: Planetary Simulations

- Take the star encounter data and run detailed simulations.
- Each simulation has 2 stars and 4 planets:
  - Earth, Jupiter
- Stop the simulation when the stars are far apart.

Planetary Simulations

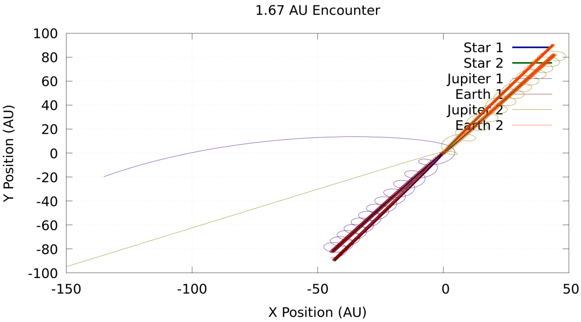
- Initialize stars from observed encounters.
- Filter out distant encounters.
- Add desired planets.
- Let the simulation run until the encounter is over.
- Store final state of both planetary systems.



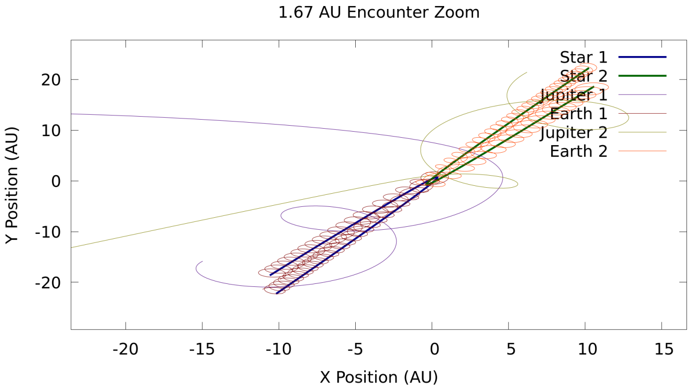
Simulation Example

```
Perihelion: 1.67705799622 AU
Initial Distance: 362.606167516 AU
```

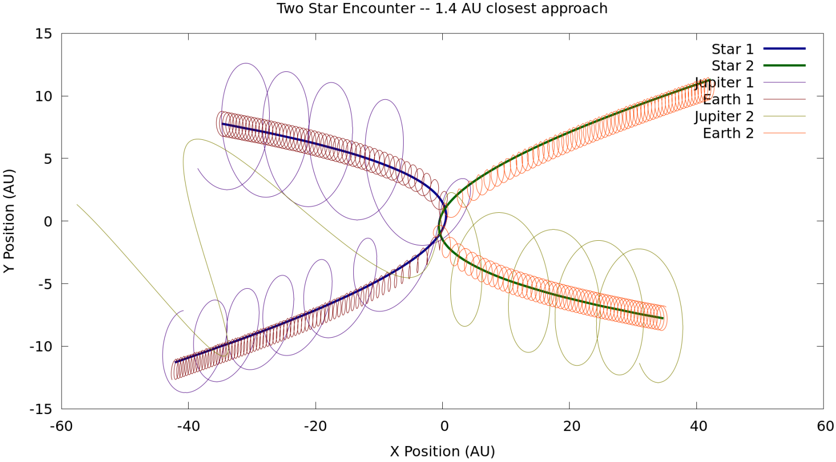
key	id	mass	name	radius	vx	vy	vz	x	y	z
-	none	MSun	none	km	kms	kms	kms	AU	AU	AU
14229468552050989204	0	1.000e+00	Star 0	2.766e+10	7.823e-01	1.485e+00	4.474e-01	-8.076e+01	-1.520e+02	-5.693e+01
11825874699291785002	1	1.000e+00	Star 1	2.766e+10	-7.823e-01	-1.511e+00	-4.474e-01	8.075e+01	1.520e+02	5.693e+01
6999041658655030245	0	9.546e-04	Jupiter 0	6.991e+04	7.823e-01	1.455e+01	4.474e-01	-7.556e+01	-1.520e+02	-5.693e+01
343256044450290936	0	3.003e-06	Earth 0	6.371e+03	7.823e-01	3.127e+01	4.474e-01	-7.976e+01	-1.520e+02	-5.693e+01
15051051450329116899	0	9.546e-04	Jupiter 1	6.991e+04	-7.823e-01	1.156e+01	-4.474e-01	8.595e+01	1.520e+02	5.693e+01
6442959288518190323	0	3.003e-06	Earth 1	6.371e+03	-7.823e-01	2.828e+01	-4.474e-01	8.175e+01	1.520e+02	5.693e+01



Simulation Example



Simulation Example



Planetary Simulations

- These simulations generate a lot of data.
  - Prohibitively slow to analyze by hand.
  - If anything needs changed, everything would have to be repeated.
- Develop a way to analyze data computationally.
  - The orbital elements help us here.
- Store the data in a way to facilitate easy computational analysis.
- Store all data needed to interpret simulations without rerunning them.

Cluster Simulation Performance

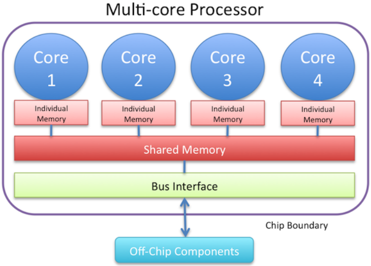
- Need a few hundred thousand stars * Myr for each configuration.
- Simulating a single 4,000 star cluster for 1000 Myr requires up to 4 hours to run.
- Ran about 200 of these clusters to get enough encounters.
- A naive approach would require around 800 hours to complete just the 4,000 star clusters!

Planet Simulation Performance

- Require about 30 seconds each.
- Far more numerous – 55,000 total simulations.
- In series, this would require approximately 400 hours.

Parallelism

- Each simulation is independent of all others.
- Each node of Draco has many processing "cores".
- Running many simulations in parallel can reduce time required dramatically.



Parallelism Results

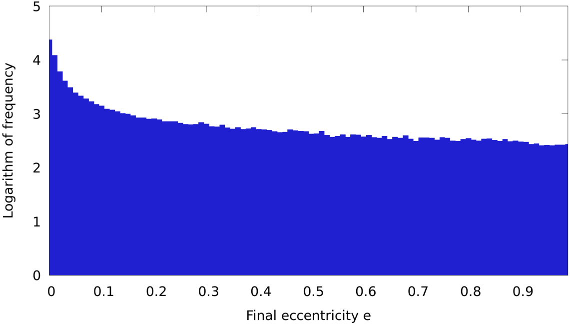
- Cluster Simulations
  - 3-6 per node.
  - Run over 6 nodes.
  - About 25 simultaneous simulations.
  - Time reduced to $\approxeq$ 3 days for largest clusters.
- Planetary Simulations
  - 8 per node.
  - Run over 6 nodes.
  - About 50 simultaneous simulations.
  - Time reduced to $\approxeq$ 24 hours.

Analysis

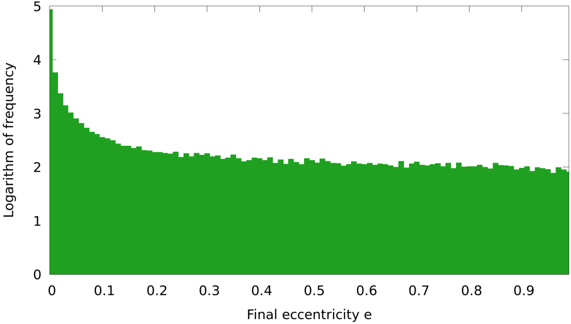
- We want to analyze the results of many simulations.
- Using numerical categorization such the orbital elements, we can try to answer questions about the simulation results.
- Develop analyses that can be used on any data set.

Results: Eccentricity, Jupiter

- All planets are initialized to have zero eccentricity.
- Higher eccentricities correlate to larger changes.
- Eccentricities ≥ 1.0 imply a planet escaped from its original system.
  - These aren't included on the plot.



Results: Eccentricity, Earth

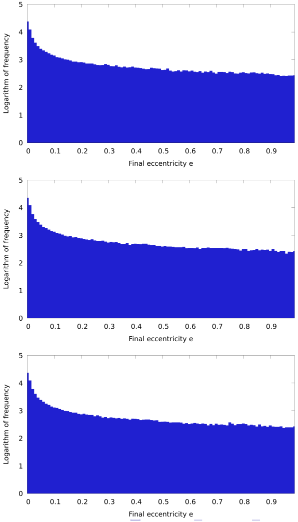


- Most planets are relatively unaffected by the encounter.
- As eccentricity gets more extreme, frequency decreases.
- Some planets are thrown into highly eccentric orbits.
- Jupiters are much more affected than Earths.

Results: Eccentricity

- Cluster size does not significantly affect eccentricity distribution

Jupiter eccentricity spectrum for 1000, 2000 and 4000 star clusters.



Planet Ejection and Capture

Final states of Jupiter planets.

Cluster Size	Remaining Planets	Ejected Planets	Captured Planets
1000	46,935	6,472	1,593
2000	46,925	6,528	1,548
4000	47,146	6,343	1,511

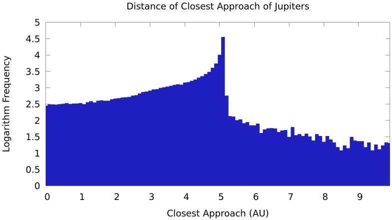
Final states of Earth planets.

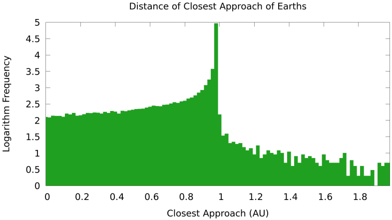
Cluster Size	Remaining Planets	Ejected Planets	Captured Planets
1000	53,427	1,245	328
2000	53,489	1,229	282
4000	53,413	1,299	288

Results: Periastron

- Jupiter gets close to its star $\approx$ 3 times more frequently than Earth.

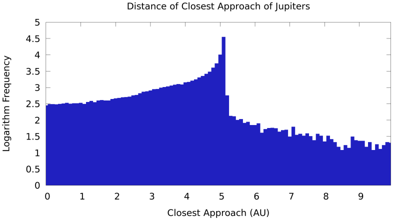
Jupiter vs Earth, N=1000

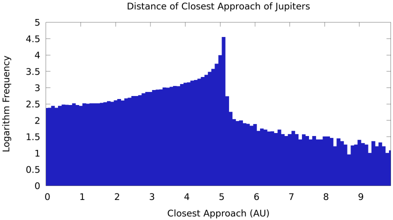




Results: Periastron, Jupiter

- Larger clusters have fewer close planets.

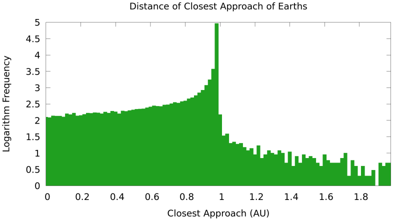


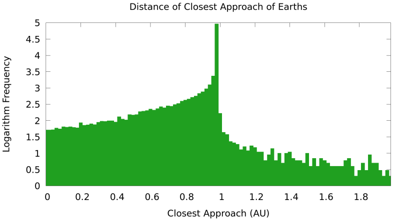


Results: Periastron, Earth

- The effect is more dramatic for Earths.

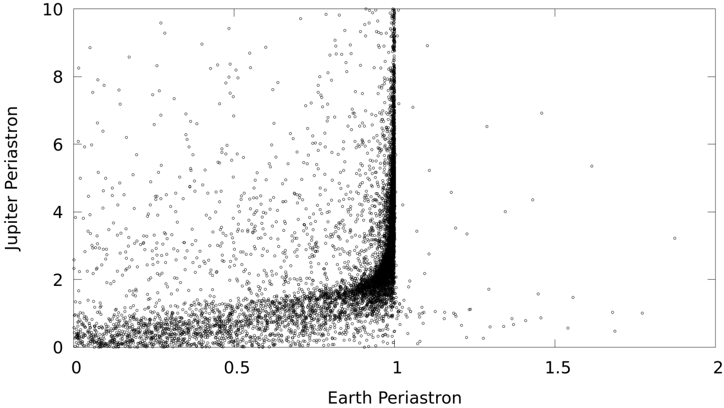
N=1000 vs N=4000





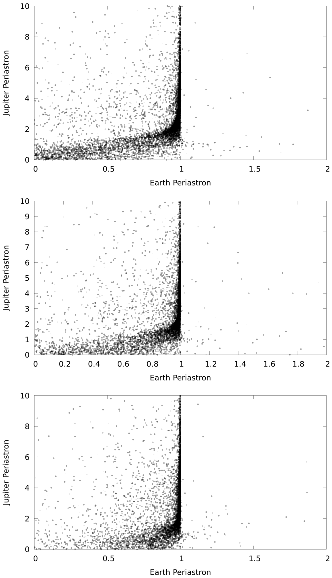
Pair Planets

- A close Jupiter greatly increases the chance of the Earth also being moved close.



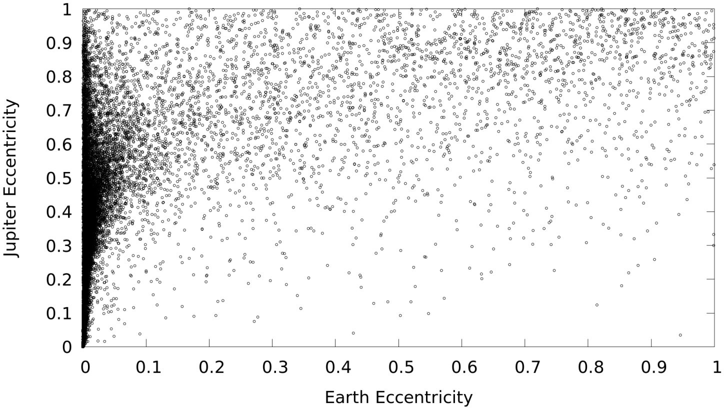
Pair Planets

- This effect diminishes somewhat as the cluster size increases.



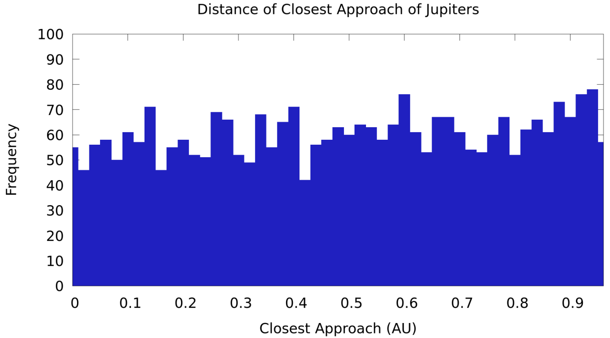
Pair Planets

- An eccentric Jupiter highly increases the likelihood of Earth being eccentric.



Conclusion: Hot Jupiter Formation

- Several hundred Jupiter planets are under 0.25 AU at closest approach.
- As we started with 110,000 Jupiters, the rate of occurance is between 0.1% and 1.0%.
- These Jupiters are highly eccentric.



Conclusion: Circularization?

- Most Hot Jupiters are mostly circular orbits.
- Our simulations output eccentric Jupiters.
- Tidal effects on the Jupiter may "circularize" the orbit.
  - This process occurs over thousands of years.
  - Our simulation only simulates about 1,000 years for each encounter.
- Further simulations need performed to determine if this can make our results match observation.

Questions?