In the search of Polyphemus

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Abstract - *Planetary migration dynamics emerge in the complex environment that is a planetary system. The features that we observe in our time are the result of a* giants' mischief *in the early evolution of the solar system. The discovery of unusual new systems also lead to a new hypothesis that opened our minds to the possibility of a huge palette of different systems, making the word* unusual *senseless. Can planetary migration create favorable conditions for the existence of Pandora?*

Stranger in a strange land

Since pre-historic astronomic observations that the planets maintained their celestial motions. This lead to the assumption that they were formed in their well-behaved current orbits. This theory was backed up by the fact that inner planets were less massive, since their orbits were smaller than with less accreting material, and with denser compositions - silicates and heavier gases - since lighter elements would not condensate so close to the Sun due to high temperatures. On the other hand, gas and ice giants are in orbits with long orbital periods, i.e. much more accreting volume, and made of primarily light elements - like hydrogen and helium.

This simplified vision of our system remained but the evolution of observational techniques and theoretical modeling came to change this. The demise of Comet *Shoemaker-Levy 9* when it collided with Jupiter in 1994 was striking evidence of the dynamic nature of some objects in the solar system and the highly synchronized orbits of natural satellites were explained by the result of a gradual evolution of their orbits by tidal forces exerted by the planet they are circling [1].

Pluto misfitted the prevailing theories of the solar system's origin: it's rocky and thousands of times less massive than the four gas-giant outer planets, and its orbit is very different from the well-separated, nearly circular, and co-planar orbits of the eight planets. Besides that, its orbit crosses Neptune's in an unstable way — a body in such an orbit will either collide with Neptune or be ejected from the outer solar system in a relatively short time, typically less than 1 percent of the age of the solar system. However, Pluto is protected by a phenomenon called resonance libration in this Neptune-crossing orbit. The planets are in 3:2 resonance so that the distance between them never drops below 17 AU [1].

Pluto raised a lot of questions but it could be a very rare outcome, an outlier in planetary systems. However, the consequent discovery of the Kuiper belt and approximately 100 000 icy trans-Neptunian *minor planets*, ranging between 100 and 1 000 kilometers in diameter, deepened the mystery, and the first theoretical models regarding planetary migration were forged.

Very nice Nice Model

The theory starts in an early Solar System where the main planets are already formed and in circular and much more compact orbits than in the present (Figure 1). A large, dense disk of small rock and ice planetesimals inhabiting among them. The system continues to evolve by the scattering or accretion of these bodies by the major planets so that angular momentum is exchanged. Numerical simulations [2] shows that this exchange lead Saturn, Uranus and Neptune to move outward, while Jupiter drifted inward as it ejected the planetesimals to distant or unbound orbits, probably creating the orbital distribution of trans-Neptunian objects [1].

This inward motion of Jupiter and outward motion of Saturn, representing more than 90% of all planetary mass, during millions of years, makes them cross their mutual 1:2 mean-motion resonance (**MMR**). This resonance quickly excites their orbital eccentricities, destabilizing the entire planetary system. The arrangement of the giant planets alters quickly and dramatically.

Saturn is slingshotted out of its orbit, and due to the *compactness* of the early solar system, gravitational encounters with Neptune and Uranus propel the two ice giants onto much more eccentric orbits, plunging the outer planetesimal disk. The disk is then completely scattered, accelerating planet migration, which stops when the disk is almost completely depleted.

Proving a model of the evolution of the early Solar System is difficult since the evolution cannot be directly observed. However, the success of any dynamical model can be judged by comparing the population predictions from the simulations to astronomical observations of these populations. Two major features strongly support this model - Jupiter's Trojan asteroids and the cataclysmic Late Heavy Bombardment period.

Jupiter's Trojan asteroids were hypothesized to be planetesimals that formed near Jupiter and were captured onto their current orbits while Jupiter was growing [3]. However, this model cannot explain some basic properties of the Trojan population, in particular its broad orbital inclination distribution. Plus, planetary migration would disrupt pre-existing jovian Trojans' orbits, leaving Jupiter's co-orbital region empty [4]. On the other hand, the crossing of Jupiter and Saturn mutual 1:2 reso-

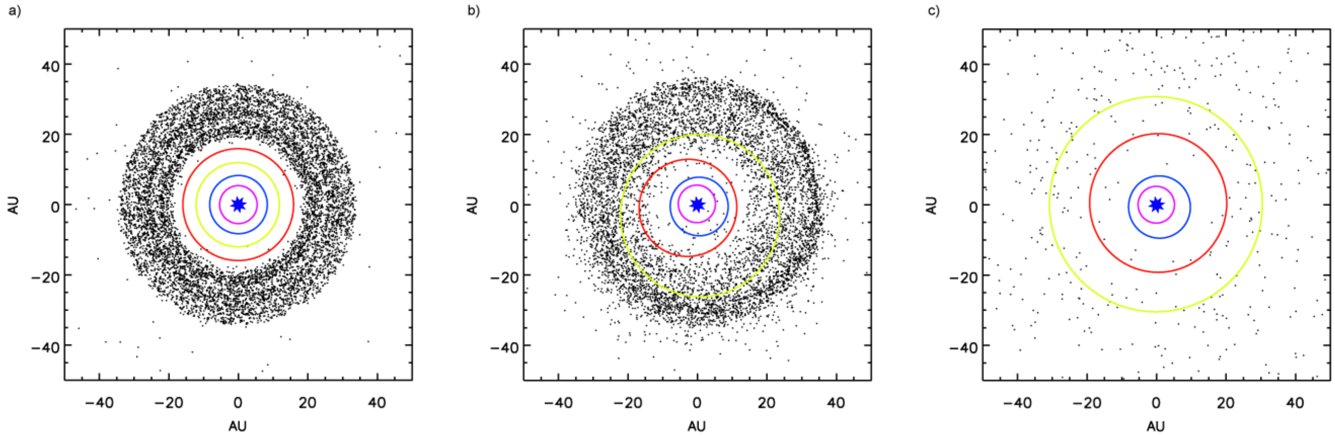

Figure 1. Time evolution of the early solar system as depicted in the Nice model. In the first image, compact planetary orbits and a thick planestesimal disk. After crossing the 1:2 MMR, the major planets' orbits are altered significantly, interacting with the planestesimal disk that is consequently dispersed.

nance creates a time window where the co-orbital region becomes stable and Jupiter could capture and trap the rogue bodies from the outer planetesimal disk until the present time, explaining their range of inclinations, deficient in water and organics (it is hypothesized that they would be devolatilized as they passed near the Sun) and particularly the similarity to cometary nuclei and some Kuiper belt objects. [4]

Late Heavy Bombardment period is evidenced by the petrology record of terrestrial planets, but mainly the Moon. Occurring $\sim$ 700 million years after the planets formed, planetary formation theories cannot naturally account for an intense period of planetesimal bombardment so late in Solar System history. However, the scattering of the outer planetesimal disk by planetary migration would start a late-game bombardment onto the inner planets, creating the record that we can observe to this day. [5]

This model was refined through a series of scientific papers [4][5][6] and was very successful in explaining a lot of solar systems features consistent with planetary evolution. It was named *Nice Model* for the location of the Observatoire de la Côte d'Azur — where it was initially developed in 2005 — in Nice, France.

Galactic Icarus

Until very recently, the only studied planetary system was our own, leaving the option that it could be a rare exception in the universe or even tailor-made by a godly entity. Still, planets could have formed in their observed orbits.

The first detections of exoplanets were made in the '90s, climbing exponentially to almost 5 000 confirmed exoplanets to this date by the huge contribution of Kepler space telescope to the planetary sciences community. Many of the first exoplanets to be detected were then called as *hot Jupiters*, since they are inferred to be physically similar to Jupiter but that have very short orbital periods. They are so close to their parent stars that huge amounts of atmospheric mass are lost due to their stellar activity [7]. So many were found in the early days of exoplanet hunting because this class of exoplanets are the easiest extrasolar planets to detect via the radial-velocity method because the oscillations they induce in their parent stars' motion are relatively large and rapid compared to those of other known types of planets.

Hot Jupiters can't form in their low period orbits. There isn't enough mass in their orbit to form it. Besides that, they are found before the *frost line*, i.e. where the volatile compounds that compose its atmosphere cannot condensate into solid ice grains. Planetary migration could explain hot Jupiters inferring that, similarly to Jupiter's case, they have migrated inward from their original formation orbits, due to the angular momentum exchange with the proto-planetesimal disk. But unlike Jupiter, the planet continued to diminish its semimajor axis to mind-blowingly close orbits. This can happen if the surface density of the planetesimals exceeds a critical value, corresponding to approximately 0.03 solar mass of gas inside the orbit of Jupiter, forcing the planet to migrate inward a large distance [8].

This raises the question - Why Jupiter stoped at the location that it is currently? And could we encounter a gas giant at, for example, Earth-like orbits, in our search for a real-world Polyphemus?

Jove Stream

The Grand Tack model says that Jupiter became so massive and gravitationally influential that it was able

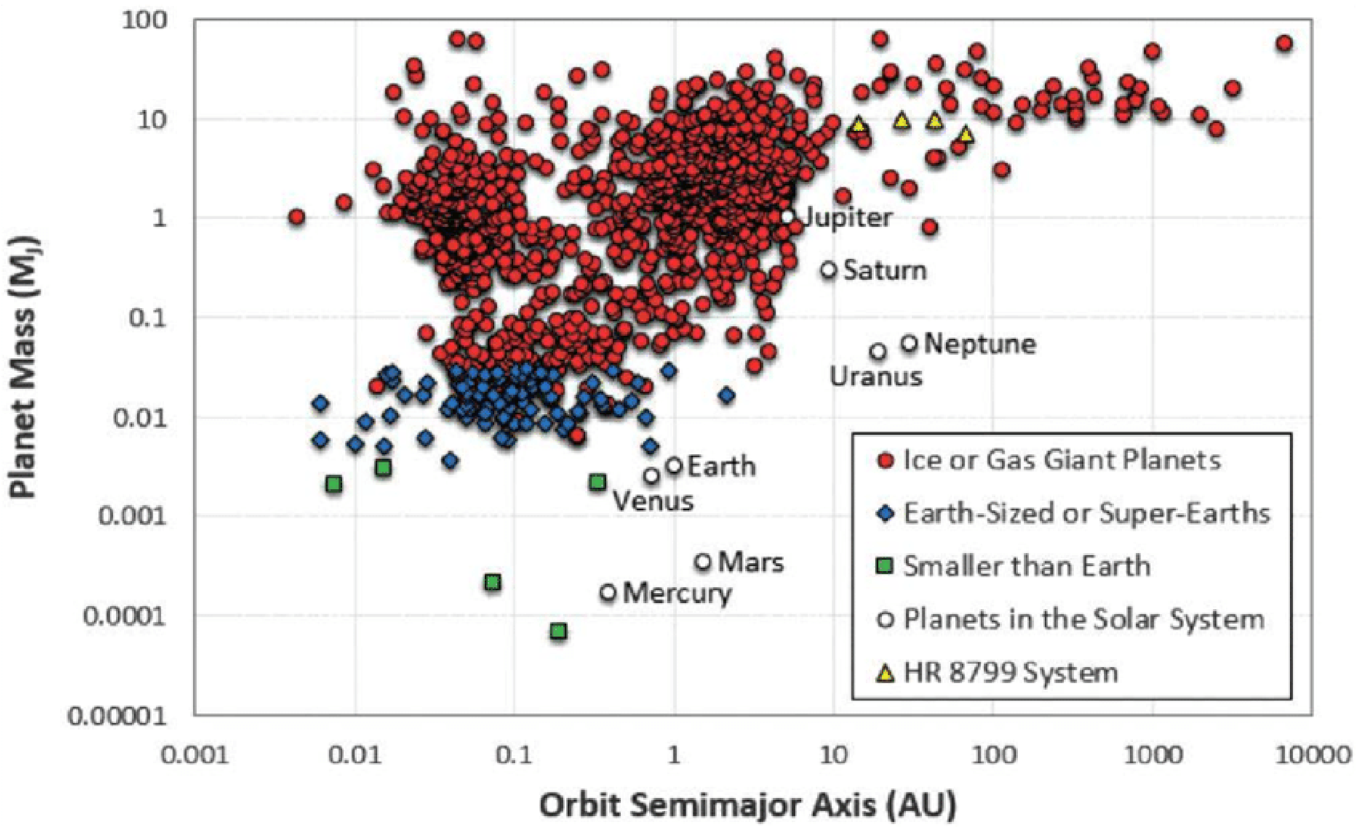

Figure 2. Distribution of different types of confirmed exoplanets semimajor axes and mass.

to clear a gap in the protoplanetary disk. And as the sun pulled the disk's gas in toward itself, Jupiter also began drifting inward, as though carried on a giant conveyor belt. Saturn formed after Jupiter but got pulled toward the sun at a faster rate, allowing it to catch up, getting locked 2:3 MMR. That resonance allowed the two planets to open up a mutual gap in the disk, and they started playing this game where they traded angular momentum and energy with one another. Eventually, that back and forth would have caused all of the gas between the two worlds to be pushed out, a situation that would have reversed the planets' migration direction and sent them back outward in the solar system, something like a boat *tacking* around a buoy. [9]

The hypothesis can be applied to multiple phenomena in the Solar System. The small mass *Mars problem* and asteroid belt could be explained by the dispersal of the material in this region by the inward and outward motion of Jupiter. This could have also sent massive terrestrial planets orbiting near the Sun towards it, explaining why the solar system doesn't have super-earths, a feature that is observed in a lot of exoplanetary systems.

So 3:2 or 2:1 MMR? Grand Track or Nice? Some studies indicate that 2:1 resonance between Jupiter and Saturn results in good Solar Systems analogs [10]. But the answer to this problem is not so straightforward. Planetary systems are very sensitive to initial conditions such as the mass of the disk, the number of formed planets, the distances between them, their distance to the host star, how they dynamically evolve [6]. So it's safe to say that a planetary system can evolve in as many ways as there are planetary systems. Figure 2 illustrates this.

Na'vi nasheed

So what about the title of this essay? Is Avatar's Pandora, or in other words a *surface-inhabited moon* a possibility? Well, Pandora has surface liquid water so it must be found on what's called as circumstellar habitable zone (**CHZ**). This is the range of orbits around a star within which a planetary surface can support liquid water. It is a rather geocentric approach since the bounds of the CHZ are based on Earth's position in the Solar System and the amount of radiant energy it receives from the Sun, however, it'll serve as a good guideline in our search.

Giant planets create good conditions for moons, helping in moon formation by acting almost like a second planetary system, or by capturing already formed bodies. However, they form in larger orbits than CHZ ones, beyond the frost line making surface life unfeasible. But if they migrate inward after their formation, and interact favorably with planetary neighbors, they can end up in CHZ orbits. We can infer that this scenario is likely by analyzing Figure 2, where we see gas giants in a large range of orbits.

The potential planetary systems out there are in near-infinite forms. Top-notch new powerful eyes will set sail in our skies in their finding. Like James Webb Space Telescope that seeks to determine the physical and chemical properties of planetary systems including our own, and investigate the potential for the origins of life in those systems [11]. Or ESA's Atmospheric Remote-sensing Infrared Exoplanet Large-survey (a.k.a. ARIEL) that'll pose a quantum leap in exoplanet characterization by studying deeply its atmospheres [12].

These and other projects will help humanity find the first Solaris or Arrakis, but will we discover a wondrous world like Pandora? We discussed that this is a very real possibility by the sheer number of different worlds that we see in the universe. However, our approach was limited only by the presence of liquid water on the surface of the moon. Are there other conditions necessary for life in moons? What are they? Could we actually find moons with these conditions, or dare we say are they usual? Please don't miss the next long essay where we'll explore this interesting topic!

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Figure 3. Pandora and Polyphemus, home of the Na'vi people