

EXTRASOLAR PLANETARY SYSTEM ARCHITECTURES

Joseph Shoer

1. INTRODUCTION

The Solar System appears to have a well-defined architecture in terms of the distribution of planets about the Sun: larger gas and ice giants have larger orbital radii than smaller terrestrial planets. Astronomy is now at a point where dozens of extrasolar planets are discovered per year, over 60 in both 2007 and 2008,¹ so that we can compare the architecture of the Solar System to other stellar systems and perform meaningful statistical analyses. As we uncover more and more extrasolar planets, we can address the question of how common Solar System-like architectures are—a question with implications for constraining formation models of stellar systems and for the number of Earth-like worlds in our stellar neighborhood.

Giant planets are the most easily observed members of stellar systems. Though astronomers cannot yet observe extrasolar terrestrial worlds, the presence and orbital radii of giant planets are used as proxies to classify the architecture of their systems. Numerical models published just before the discovery of 51 Pegasi b suggested a very narrow range of possible architectures, assuming that giant planets would be at least several AU from the parent star and showing varying distributions of terrestrial planets near 1 AU, depending on the gas giant.² However, the discovery of short-period giant planets had a profound effect on formation models of stellar systems from protoplanetary disks. Astronomers now recognize gas giant migration as one of the most important dynamical effects during stellar system formation.

A simple calculation suggests that more massive planets in a stellar system should form in larger orbits than less massive planets. In a disc with surface density Σ , assuming that the accretion cross-section and final mass of planets scale with final planet radius as R and R^3 ,

respectively, the mass of a planet is approximately $m \sim (2\pi a \Sigma)^{3/2}$. If the density depends on semimajor axis by a power law $\Sigma \sim \Sigma_0 a^{-n}$, then more massive planets tend to form in smaller orbits when $n > 1$. $n = 3/2$ is a possible value;³ however, some research indicates that protoplanetary disks may not be well mixed, with decreasing dust-to-gas ratios as orbital radius increases,⁴ suggesting that more of the gas needed to form giant planets orbits at large semimajor axes. There is also a compositional requirement for giant formation: according to current models, giant planets must form outside the “snow line” of a star, typically beyond the 4-5 AU range.³

This model is not supported by observational evidence. The first widely accepted extrasolar planet discovery was that of 51 Pegasi b in 1995, a half-Jupiter-mass (M_J) giant orbiting at $a = 0.05$ AU.⁵ At present, there are over three hundred confirmed extrasolar planets, including multiple-planet systems with up to five members.¹ Many of these are also “hot Jupiters” like 51 Pegasi b, and the majority of the rest are planets greater than Jupiter’s mass in orbits somewhere between the semimajor axes of the Earth and Jupiter. These observations raise the questions of whether the planetary system architecture we see in the Solar System is an outlier among the architectures in our stellar neighborhood, what varieties of architectures form from different protoplanetary disks, and what physical processes govern this variety.

In order to address these questions, astronomers conduct surveys of nearby stars and approach the process of planetary system formation through numerical simulation. Section 2 of this paper provides an overview of observational methods and simulation results. It also discusses some of the statistical data from observing campaigns. Section 3 explores the implications of this data, treating selection effects and physical processes that influence stellar system architectures.

2. METHODS AND DATA

There are several techniques for detecting extrasolar planets. Radial velocity detection involves tracking a stellar spectrum and then correlating Doppler shifts to stellar motions about the star-planet barycenter. Transit detection entails observation of variation in a star's light curve as a planet partially occults the stellar disk. Only a few planets have been discovered by imaging, which relies on instruments capable of resolving a star and planet (perhaps with a coronagraph occulting the star). A few other methods also rely on precise imaging, including observations of gravitational microlensing of a planetary light curve by its parent star and correlation of astrometry to stellar motion about the star-planet barycenter. From these detections, astronomers estimate the mass and orbital parameters of exoplanets, with certain detection methods better able to constrain some parameters than others (for example, radial velocities can constrain an exoplanet's eccentricity better than transits can).^{1,6,7}

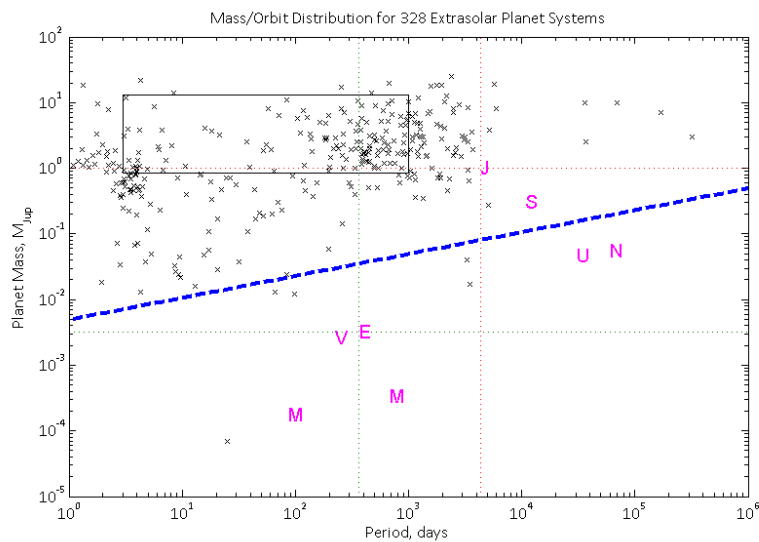


Figure 1. Plot of planet mass versus orbital period for 328 confirmed extrasolar planets and Solar System planets.¹ Dotted lines indicate the orbital periods and masses of Earth and Jupiter for reference. The thick dashed line is the detection limit for > 1 m/s induced stellar velocities.⁷ Planets within the solid boundary form a “less biased” subsample.¹³

With over three hundred known exoplanets, sufficient data exist to perform statistical analyses. Figure 1 shows the masses and orbital periods of most known extrasolar planets, as

well as Solar System planets. If the Solar System possesses a typical architecture, we expect to find two clusters in mass-period space: $\sim 0.1 - 1 M_J$ planets in 5 – 30 AU orbits and $\sim 0.1 - 1 M_{\oplus}$ planets at 0.5 – 2 AU orbital radii. Instead, we find a class of Jovian-mass planets in Earth-like orbits and a class of short-period “hot Jupiters.” Long-period Jovians are conspicuously absent.

Hot Jupiters posed a problem that astronomers have since addressed with planet migration models. Standard disk temperature models show that the temperature of the 51 Pegasi protoplanetary disk, for instance, would have been 2000 K at 0.05 AU, hot enough to vaporize any solid material and prevent core accretion.⁸ However, numerical simulations of gas giant accretion show that giants forming in orbits beyond the snow line interact dynamically with remaining disk material. These interactions cause giants to migrate toward shorter-period orbits.

Planet migration results from exchanges of angular momentum between a giant planet and the protoplanetary disk. Type I migration occurs when a protoplanet excites density waves in the disk, which subsequently exert a torque on the planet. The process tails off as the disk dissipates. Another type of migration results after giant planets have cleared a gap in the disk. As material from the gap edges accretes onto the planet, it contributes positive or negative momentum with a net loss that moves the planet inward. This Type II migration, the dominant mechanism, continues until the planet becomes tidally locked to the star or reaches an orbital radius within which stellar winds have cleared away the disk. Finally, Type III migration is a consequence of angular momentum conservation as material flows into or out of the planet’s orbital radius.⁷

Numerical simulations model the formation of many planets in a stellar disk, capturing the entire architecture of the system. Kokubo and Ida simulated oligarchic growth in the absence of considerable migration for disks with power-law surface density profiles ranging from $n = 1/2$ to $5/2$.⁹ They found that a diverse range of planetary systems result from disks of differing mass

profiles: larger-mass planets accrete for larger Σ_0 values, with the relative distribution of Jovian-, Uranian-, and terrestrial-mass planets governed by the exponent n . These results are consistent with the simple calculation from Section I and include short-period Jovian planets, as well as Solar System-like architectures and systems with only terrestrial planets. Simulations that include migration also turn up a diverse range of architectures. In several cases, these accretion models form terrestrial bodies in the habitable zone of their stars even after a giant has migrated from a several-AU orbit into a hot Jupiter orbit.^{10,11} Still other models of gas accretion onto solid cores by Ida and Lin demonstrate that gas envelope accretion may be a runaway process, suggesting that the most common types of planets will be terrestrial planets or gas giants, with few planets between 10-100 M_{\oplus} mass and < 3 AU orbital radius.¹² In aggregate, these simulations show that the range of planetary system architectures may include a wide variety of Jovian and terrestrial planet distributions, with ice giants restricted to long-period orbits.

3. DISCUSSION

While simulations show a wide range of possible planetary system architectures, astronomers have so far observed only a few distributions of giant planets. The observed giant planet orbits may have some implications for the orbits of smaller planets, as well. For instance, the existence of a Jupiter-sized body in an orbit 1 AU from the central star likely precludes the existence of any terrestrial planets near that orbit. Likewise, the existence of a hot Jupiter around a star may imply that bodies with orbits between the giant planet's formation orbit and its final orbit were scattered away from the star or accreted onto the giant during its migration. As the majority of known planetary systems contain Jovian planets in the < 2 AU range, architectures with terrestrial planets near 1 AU orbits and giant planets at 5 AU and beyond might be rare.

However, there are several selection effects predisposing detections towards short-period, high-mass exoplanet. Radial velocity detections require that the star have a large enough induced velocity to resolve with a spectrometer; a line on Figure 1 indicates this detection lower limit in mass-period space. Likewise, detection of an exoplanet by transit requires that enough starlight be occulted to detect in a light curve; this places a lower limit on the planet radius relative to the star and an upper limit on the planet’s semimajor axis. Furthermore, astronomers must necessarily observe a planet for at least one orbital period to be confident of planet detection by radial velocity, transit, astrometry, or microlensing. Thus, astronomers working since 1995 are unlikely to have detected exoplanets with periods longer than about 13 years—Jupiter itself is only just past the threshold for detection. These selection effects influence any data on extrasolar planetary system architectures.

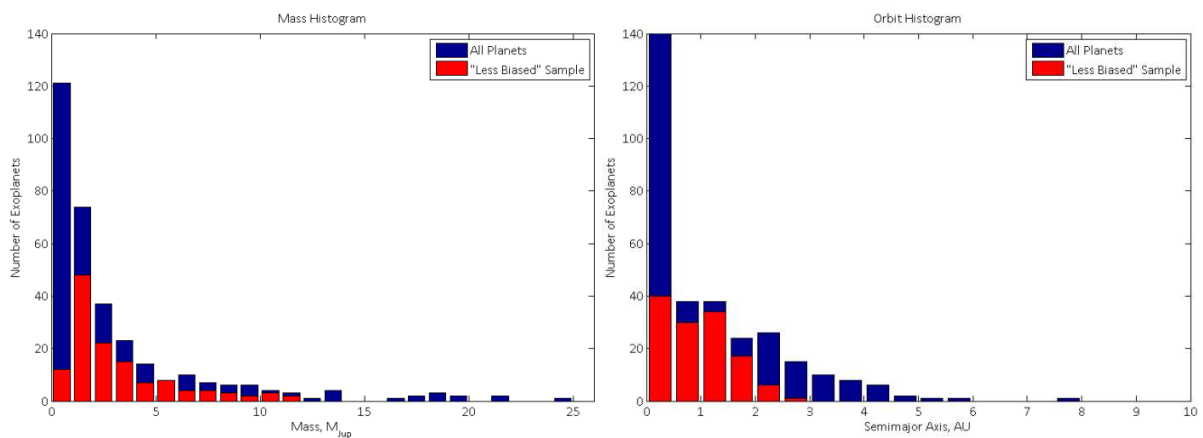


Figure 2 Histograms of the mass (left) and semimajor axis (right) of 328 exoplanets and a “less biased” subsample falling within the window from Ref. 13.

There have been attempts to reduce existing data such that selection effects are less apparent. Lineweaver and Grether identified a “less biased” subsample of 77 known exoplanets in 2002, limiting their sample to a window of periods masses such that planets induce sufficiently large radial velocities in their stars and have been observed sufficiently long to have a high probability of detection (the boxed area in Figure 1).¹³ They found that planets with masses and periods

closer to those of Jupiter are most common, implying that the Solar System has a typical architecture. After five more years of data collection, the mass distribution of planets in the “less biased” window supports this trend (Figure 2); however, the distribution of orbits does not agree. Indeed, using robust statistics techniques to transform this histogram onto a normal distribution, Beer *et al.* found that Jupiter’s semimajor axis (as a representative for the architecture of the Solar System) is still a remote outlier after selection effects have been accounted for.¹⁴

The simulations described in Section 2 suggest some of the physical processes that may contribute to system architectures. If the accretion timescale of a gas giant is much shorter than the lifetime of the protoplanetary disk, then migration is practically assured. Giant planet migration is already the only known formation mechanism of hot Jupiters; it likely plays an important role in moving large planets to orbits between 1 – 5 AU and in the formation of multiplanet systems. However, studies showing significant planet formation after giant migration has occurred indicate the possibility that astronomers should not rule out distributions of terrestrial or Uranian planets in systems with hot Jupiters.¹⁰ Another important effect arises from the differing timescales of solid core accretion and gas envelope accretion: Ida and Lin identified a potential dearth of planets with masses between large terrestrials and small Jovians at orbital radii < 5 AU.¹² The upper limit of this “planet desert” in mass-orbit parameter space is close to the current limits of detection, suggesting that one reason we have not detected many small planets in short-period orbits is that available instrumentation has not yet advanced to the point where the detection threshold crosses the planet desert to locate smaller worlds.

4. CONCLUSION

Most of the known extrasolar planetary systems are unlike the Solar System in their mass and period distributions. Numerical simulations indicate that migration is a nearly ubiquitous effect

driving giant planets into the observed short-period orbits. However, with the current state of the art in planet detection pushing toward a potential “planet desert,” and with the duration of planet-hunting observations just now reaching timescales at which astronomers expect to discover Jovian and Saturnian analogues, it is entirely possible that whole new classes of planets—and architectures—remain to be discovered. It may be that systems with outer gas giants are just as frequent, if not more so, than those containing hot Jupiters. Nonetheless, the most important implication of current statistical and numerical studies is that there is likely a tremendous diversity of system architectures. Some simulations result in planetary systems with terrestrial, ice giant, and gas giant planets arranged in almost any imaginable distribution of orbits. Future exoplanet detection campaigns must push the boundaries of detection to find terrestrial-mass planets and long-period planets to better constrain these models.

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