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The diverse origin of exoplanets' eccentricities & inclinations

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Abstract. Radial velocity surveys have discovered over 400 exoplanets. While measuring eccentricities of low-mass planets remains a challenge, giant exoplanets display a broad range of orbital eccentricities. Recently, spectroscopic measurements during transit have demonstrated that the short-period giant planets ("hot-Jupiters") also display a broad range of orbital inclinations (relative to the rotation axis of the host star). Both properties pose a challenge for simple disk migration models and suggest that late-stage orbital evolution can play an important role in determining the final architecture of planetary systems. One possible formation mechanism for the inclined hot-Jupiters is some form of eccentricity excitation (e.g., planet scattering, secular perturbations due to a distant planet or wide binary) followed tidal circularization. The planet scattering hypothesis also makes predictions for the population of planets at large separations. Recent discoveries of planets on wide orbits via direct imaging and highly anticipated results from upcoming direct imaging campaigns are poised to provide a new type of constraint on planet formation. This proceedings describes recent progress in understanding the formation of giant exoplanets.

Keywords. planets and satellites: formation

1. Introduction

Radial velocity surveys have discovered dozens of systems with multiple giant planets (Wright *et al.* 2011 and references therein). These can be roughly assigned into the following categories: 1) systems in or near a mean motion resonance (MMR), 2) systems with significant secular interaction (but not near a strong MMR), and 3) hierarchical systems where no significant interactions are expected based on the known planets (and assuming inclinations are not extreme). Early results from HARPS (Mayor & Udry 2008) and NASA's *Kepler* mission (Borucki *et al.* 2011) suggest that systems of multiple low-mass (i.e., less than Neptune) planets may differ from those of giant planets. In particular, there appears to be a population of systems with multiple low-mass planets that are closely-spaced, but non-resonant (Lissauer *et al.* 2011a, 201b).

Of course, many (most?) stars with only a single known exoplanet may harbor additional planets that have yet to be detected, perhaps due to their low mass and/or long orbital period (for RV surveys) or their orbital inclination (for transit surveys). Even if future observations exclude additional planets today, there may have once been additional planets that have been ejected, collided with with other planets or been swallowed by the host star. Thus, we interpret the hundreds of systems with a single known planet in the context of the formation and orbital evolution models developed for explaining multiple-planet systems.

2. Eccentricity Distribution

The distribution of orbital eccentricities provides an important constraint for planet formation models (Ford & Rasio 2008). The precision of eccentricity measurements varies widely, depending primarily on the ratio of the Doppler amplitude to the measurement precision and the number of Doppler observations. Precision can also be adversely affected by the presence of multiple planets and/or poor phase coverage, particularly in cases where the orbital period is comparable to or greater than the timespan of precise Doppler observations.

Unfortunately, characterizing the eccentricity distribution of a population of exoplanets is further complicated by measurement biases (Shen & Turner 2008; Zakamska *et al.* 2011). Population analyses suggest that Doppler-detected giant planets can be modeled by two populations: 1) a set of low-eccentricity planets (∼20-30%) and a second population with a broad eccentricity distribution (e.g., Rayleigh(0.3), ∼70-80%; Wang & Ford 2011).

Complications due to large measurement uncertainties and biases for "small" eccentricities become more significant as one pushes towards Neptune-mass and smaller planets. Transit durations are proportional to $e \sin \omega$ and occultations durations to $e \cos \omega$. When the occultation can be well-measured (e.g., Spitzer, ground, Kepler), the combination provides an accurate eccentricity that is robust to the effects of additional planets (Colón *et al.* 2009). For planets where occultation observations are not practical, it is still possible to characterize the eccentricity distribution of a population of transiting planets, provided accurate stellar properties (Ford *et al.* 2008; Moorhead *et al.* 2011).

3. Eccentricity & Inclination Excitation

Several mechanisms have been proposed to explain the broad range of eccentricities among giant exoplanets. In most cases, these mechanisms have implications for the orbital inclinations. For example, planets formed via disk instability would be expected to have significant primordial eccentricities. The most promising location for disk instabilities for form planets is at large distances from the host star. If the protoplanetary disk is sufficiently warped, then these planets could also have significant inclinations relative to interior planets (and presumably the stellar rotation).

Planet-disk interactions during migration have also been proposed to excite the eccentricities. For isolated planets, this disk perturbations could excite the eccentricity and inclination of the most massive planets (greater than $\sim 10 M_{\rm Jup}$ for solar-mass host). However, most planets are not sufficiently massive. In cases, where there are multiple giant planets, disk migration leading to trapping (or passing through) MMRs can excite eccentricities and inclinations (Lee & Thommes 2009).

For a system of multiple planets, the current eccentricities represent just a snapshot of the range of values visited over a secular timescale (Veras & Ford 2009a; Veras & Ford 2010). Secular perturbations lead to the exchange of angular momentum between bodies in a bound hierarchical system. If all bodies start on circular and coplanar orbits, then there is no angular momentum deficit to be exchanged. Thus, secular evolution of planetary systems can sculpt systems, but does not provide a mechanism for exciting eccentricities in the first place. For sufficiently widely separated binary stars, protoplanetary disks are rarely aligned, suggesting that a substantial fraction of planets around one star in a wide binary could have their eccentricities excited by the "Kozai effect." While this inevitably affects some systems, Monte Carlo simulations show that this mechanism under-predicts the abundance of planets with intermediate eccentricities relative to nearly circular or highly eccentric orbits (Takeda *et al.* 2008). Thus, perturbations from binary stars are not sufficient to explain the whole population of exoplanet eccentricities. For planetary systems with a distant and massive planet, angular momentum conservation implies that a small change in the eccentricity of the outer planet can lead to large eccentricities of interior and less-massive planets (Wu & Lithwick 2011).

Finally, densely packed planetary systems can lead to planet-planet scattering in systems with multiple massive planets. Large eccentricities are generated when one planet scatters a comparable mass planets so that it is effectively removed from the system, either due to being ejected from the system, falling into the host star, or being perturbed by another body (e.g., Rasio & Ford 1996; Weidenschilling & Marzari 1996). N-body simulations show that this mechanism produces a broad distribution of both eccentricities and inclinations (Chatterjee *et al.* 2008; Nagasawa *et al.* 2008; Juric & Tremaine 2008). However, the correlation is statistical and individual system may have a significant eccentricity but low inclinations, or vice versa. Similar interactions in systems with more disparate mass ratios can produce smaller eccentricities. For low-mass planets and small separations, interactions typically result in collisions rather than ejections (Ford & Rasio 2008). In these cases, the final orbits typically have small eccentricities and inclinations, unless at least one planet had already acquired a large eccentricity or pericenter. Of course, the situation is complicated if the planet scattering occurs while there is still significant gas present (Matsumura *et al.* 2010).

4. Implications of Inclined Transiting Planets

The planet scattering model makes several predictions that have been discussed previously (e.g., Ford & Rasio 2008; Juric & Tremaine 2008). Recently, spectroscopic observations during transit (i.e., Rossitter-McLaughlin measurements) provide evidence for a substantial population of hot-Jupiters on highly-inclined, nearly-polar or even retrograde orbits (measured relative to the current stellar spis axis; Fabrycky & Winn 2009; Morton & Johnson 2011; Triaud *et al.* 2010; Winn *et al.* 2010). The highly-inclined population includes some planets that remain highly eccentric (e.g., HD 80606; Winn *et al.* 2009) and some that are nearly circular today. Eccentricity damping is expected to proceed more rapidly than inclination damping (e.g., Hut 1982). Thus, these observations strongly suggest that many hot-Jupiters were formed by eccentricity and inclination excitation followed by tidal damping (Rasio & Ford 1996). The eccentricity and inclination excitation could be due to either planet scattering or secular evolution by a distant massive body (either a star, i.e., "Kozai-effect" or one or more massive planets with significant initial angular momentum deficit; Chatterjee *et al.* this volume, Naoz *et al.* this volume; Wu & Lithwick 2011).

While these mechanisms appear the most natural candidates, researchers are also considering alternative mechanisms, including perturbations due to stellar encounters (e.g., Malmberg *et al.* 2011; Payne *et al.* 2011; Boley *et al.* this volume) or torques on the star (Lai *et al.* 2011). Future observations of Rossiter effect in planets at large separations (e.g., Borucki *et al.* 2011) and the relative inclinations among multiple planet systems (Payne *et al.* 2010; Ragozzine & Holman 2010; Ford *et al.* 2011; Lissauer *et al.* 2011b) can be expected to help determine the significance of each mechanism.

5. Implications of Planet at Wide Separations

The planet scattering model also makes predictions for the frequency of planets in very-long period orbits around young stars and even an abundance of free floating planets

(Scharf & Menou 2009; Veras *et al.* 2009b). As researchers refine these models, they can be tested by upcoming observations from direct imaging campaigns (e.g. Bonavita *et al.*, this volume) and microlensing results (Beaulieu *et al.* this volume).

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