Architectural and chemical insights into the origin of hot Jupiters

Kevin C. Schlaufman\textsuperscript{1,2,3}

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1The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA (kcs@carnegiescience.edu)
2Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
3Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

Abstract

The origin of Jupiter-mass planets with orbital periods of only a few days is still uncertain. This problem has been with us for 20 years, long enough for significant progress to have been made, and also for a great deal of "lore" to have accumulated about the properties of these planets. Among this lore is the widespread belief that hot Jupiters are less likely to be in multiple giant planet systems than longer-period giant planets. I will show that in this case the lore is not supported by the best data available today: hot Jupiters are not lonely. I will also show that stellar sodium abundance is inversely proportional to the probability that a star hosts a short-period giant planet. This observation is best explained by the effect of decreasing sodium abundance on protoplanetary disk structure and reveals that planetesimal-disk or planet-disk interactions are critical for the existence of short-period giant planets.

1 Introduction

Giant planets with mass $M_p > 0.1 \, M_{\text{Jup}}$ and orbital period $P < 10$ days are usually called hot Jupiters. They were the first class of exoplanets discovered orbiting main sequence stars, yet their origin is still debated. While it is formally possible that hot Jupiters could have formed where they are currently observed (e.g., Bodenheimer et al. 2000), most planet formation models suggest that they formed near the water-ice line of their parent protoplanetary disk and subsequently migrated into the close proximity of their host stars. While many migration mechanisms have been proposed, they can be roughly classified as either disk-driven migration or as high-eccentricity migration. In situ formation is also attracting renewed attention.

In disk-driven migration, a giant planet forms near the water-ice line of its parent protoplanetary disk. Its orbital energy and angular momentum are subsequently transferred through dynamical interactions to its parent disk, its orbit shrinks, and it is therefore brought into the close proximity of its host star. Eventually, the inward migration stops because the planet moves inside the inner edge of the disk, the disk is dissipated, or the planet is stalled because of more complex disk structures. Disk migration must be completed within the few Myr available before a disk disappears, and it should depend on the detailed structure of the protoplanetary disk.

In high-eccentricity migration, the giant planet is also thought to form near the water-ice line of its parent protoplanetary disk. The planet loses angular momentum due to scattering with other planets in the system, through secular interactions with another massive body in the system, or through a combination of scattering and secular interactions. Its loss of angular momentum causes its eccentricity to be excited to $e \gtrsim 0.9$. Tidal interactions with its host star near periastron dissipates the orbital energy of the giant planet, and its orbit is subsequently circularized with a much reduced semimajor axis $a \lesssim 0.1$ AU. Because efficient dissipation by a protoplanetary disk almost always prevents the growth of large eccentricities while the disk is still present, high-eccentricity migration must occur after the parent disk disappears. Therefore, it should not depend sensitively on the structure of the protoplanetary disk. At the same time, in an exoplanet system with a hot Jupiter that formed via high-eccentricity
migration, one would not expect to find additional giant planets exterior to the hot Jupiter but interior to the water-ice line. The body that gained the hot Jupiter’s angular momentum must be beyond the water-ice line, while any pre-existing planets interior to the formation site of the hot Jupiter would have been destabilized by orbit crossing during the high-eccentricity phase.

As a result, either the presence inside the water-ice line of long-period giant planet companions to hot Jupiters or a connection between the occurrence of short-period giant planets and the detailed properties of their parent protoplanetary disk would disfavor the high-eccentricity migration scenario.

2 Data

To investigate the occurrence of long-period companions to hot Jupiters, I use the sample of all giant exoplanets with $M \sin i > 0.1 M_{\text{Jup}}$ discovered by the radial velocity technique from exoplanets.org (Wright et al. 2011; Han et al. 2014). I then use Hipparcos parallaxes to select only slightly-evolved main sequence FGK stars. I also use the occurrence rates of giant planets as a function of mass and period in Table 1 of Cumming et al. (2008) and the hot Jupiter occurrence rate calculated in Wright et al. (2012).

To investigate the possible dependence of short-period giant planet occurrence on protoplanetary disk structure, I use the large homogeneous stellar abundance analyses of Valenti & Fischer (2005) and Adibekyan et al. (2012). I further assume that the photospheric abundances observed in planet host stars correspond to the abundances present in the disk during the planet formation epoch. Because the signal I seek may be very small, I need to mitigate the much larger effects of Galactic chemical evolution. For that reason, I use Hipparcos parallaxes and proper motions along with ground-based bulk radial velocities to kinematically isolate thin disk stars and focus my analysis on that subsample.

3 Analysis

Let $P(HJ)$ denote the probability that a star hosts a hot Jupiter and let $P(GP)$ denote the probability that a star hosts a long-period giant planet. Then by Bayes’ Theorem, the conditional probability $P(GP|HJ)$ that a system has a long-period giant planet given that it has a hot Jupiter is

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P(GP|HJ) = \frac{P(HJ|GP)P(GP)}{P(HJ|GP)P(GP) + P(HJ|GP^c)P(GP^c)},
\]

where $P(HJ|GP)$ is the conditional probability that a system with a long-period giant planet has a hot Jupiter, $P(HJ|GP^c)$ is the probability that a system with no long-period giant planet has a hot Jupiter, and $P(GP^c)$ is the probability that a system has no long-period giant planet. Using the data described in Section 2 and Equation (1), the conditional probability that a hot Jupiter has a companion giant planet inside of the water-ice line is plotted in Figure 1.

I use logistic regression and minimize the misclassification cost to identify the combination of elemental abundances that best predicts the occurrence of giant planets. I take a machine learning approach, using a randomly-selected subsample amounting to 70% of the data to fit each possible model. I then use the remaining 30% of the data to evaluate each model. I repeat this process many times. I find that [Fe/H], [Si/Fe], [Ca/Fe], and [Na/Fe] are the best predictors of giant planet occurrence in that they minimize the number giant-planet host stars misclassified as non-giant planet hosts (and vice versa). The coefficients for [Fe/H], [Si/Fe], and [Ca/Fe] are all positive; that is, more iron, silicon, or calcium in a protoplanetary disk leads to more giant planets. Interestingly, the coefficient for [Na/Fe] is negative, so more sodium in a protoplanetary disk leads to fewer giant planets. To explore this more, I split the giant planet sample into short-period and long-period subsamples at $P = 100$ days, roughly the median of the input giant planet sample. I find that the dependence of giant planet occurrence on [Si/Fe], [Ca/Fe], and [Na/Fe] disappears in the long-period subsample. In other words, the inverse relationship between giant planet occurrence and sodium abundance only applies to short-period giant planets.
Figure 1: Conditional probability of the presence of an exterior, long-period giant planet inside the water-ice line with $M\sin i > 0.3\, M_{\text{Jup}}$ and $P < 739$ days given the presence of an interior giant planet with period and minimum mass as indicated. The point between one and ten days gives the companion probability for hot Jupiters, where hot Jupiters are defined as planets with $M\sin i > 0.1\, M_{\text{Jup}}$ and $P < 10$ days. On the hot Jupiter point, the horizontal line gives the extent of the hot Jupiter bin in period, while the vertical line gives 1-$\sigma$ uncertainty in the hot Jupiter companion probability. The light gray regions are the 1-$\sigma$ uncertainties, while the dark gray regions indicate areas where the 1-$\sigma$ uncertainties overlap for $M\sin i > 0.3\, M_{\text{Jup}}$ and $M\sin i > 1.0\, M_{\text{Jup}}$. I assume a water-ice line at $a = 1.6\, \text{AU}$, or $P = 739$ days for a one solar mass star.

4 Discussion and Conclusion

Figure 1 shows that hot Jupiters are just as likely as cooler giant planets to have long-period Jupiter-mass companions – both inside and outside the water-ice line –, which is unexpected in the high-eccentricity migration scenario for the origin of hot Jupiters.
The dependence of short-period giant planet occurrence on sodium abundance is best explained by the dependence of protoplanetary disk structure on sodium abundance. In particular, protoplanetary disks are thought to have a “dead zone” – a region of the disk where the ionization is too low to enable the magnetorotational instability (MRI) to activate and transport angular momentum. The extent of the “dead zone” is difficult to predict from first principles and depends on time, but it is thought to occur in the disk midplane from about 0.1 AU to a few AU. Since sodium and potassium are the two main elements that are both common and can be thermally ionized at the temperatures and densities typical of protoplanetary disks, they are the main sources of free electrons in such a disk. All else being equal, a disk with more sodium will have more free electrons. Therefore, the extent of the viscously-heated MRI-active inner disk will be greater in a disk with more sodium. On the other hand, the extent of the viscously-heated MRI-active inner disk will be smaller in a disk with less sodium.

The boundary between this inner active region and the “dead zone” is a special place for planet formation for three reasons. First, small planetesimals are thought to collect at the boundary, and the accumulation of planetesimals may lead to efficient planetary embryo formation at the boundary. Second, the inward Type I migration of embedded low-mass planets is thought to slow or even stop near this boundary, so planetary embryos may collect at the boundary. Third, the inward Type II migration of gap-opening giant planets is also believed to slow near this boundary, so giant planet may collect near the boundary. The dependence of short-period giant planet occurrence on sodium abundance is therefore naturally explained in the disk-migration or in situ formation scenarios for hot Jupiter formation. In contrast, a dependence of short-period giant planet occurrence on sodium abundance is not expected in the high-eccentricity migration scenario.

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References

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