THE SEPARATION/PERIOD GAP IN THE DISTRIBUTION OF EXTRASOLAR PLANETS AROUND STARS WITH MASSES $M \geq 1.2 M_\odot$

ANDREAS BURKERT$^1$ AND SHIGERU IDA$^2$

Received 2006 August 16; accepted 2007 January 5

ABSTRACT

The evidence for a shortage of exosolar planets with semimajor axes $-1.1 \leq \log (a/\text{AU}) \leq -0.2$ is investigated. It is shown that this valley results from a gap in the radial distribution of planets orbiting stars with masses $M \geq 1.2 M_\odot$ (the high-mass sample, HMS). No underabundance is found for planets orbiting stars with smaller masses. The observational data also indicate that within the HMS population, it is preferentially the more massive planets with $M \sin (i) \geq 0.8 M_\odot$ that are missing. Monte Carlo simulations of planet formation and migration are presented that reproduce the observed shortage of planets in the observed radius regime. A dependence on the disk depletion timescale $\tau_{\text{dep}}$ is found. The gap is more pronounced for $\tau_{\text{dep}} = 10^6 - 10^7$ yr than for $\tau_{\text{dep}} = 3 \times 10^6 - 3 \times 10^7$ yr. This might explain the observed trend with stellar mass if disks around stars with masses $M \geq 1.2 M_\odot$ have shorter depletion timescales than those around less massive stars. Possible reasons for such a dependence are a decrease of disk size and an increase of stellar EUV flux with stellar mass.

Subject heading: planetary systems: formation

1. INTRODUCTION

Within the past decade, nearly 200 extrasolar planets have been detected. Their orbital properties and masses and the relationships between planetary properties and those of the central stars are providing interesting insight into the complexity of planetary system formation and offer important constraints for theoretical models. Recently, extrasolar planets have been found around low-mass stars (M dwarfs) by high-precision radial velocity (Butler et al. 2004; Bonfils et al. 2005) and microlensing surveys (Beaulieu et al. 2006; Gould et al. 2006), with indications that Jupiter-mass planets are rare around M dwarfs (Laughlin et al. 2004; Ida & Lin 2005).

Theoretical models have been developed to explain the statistical properties of exoplanets. Ida & Lin (2005) presented Monte Carlo simulations that predict mass and semimajor axis distributions of extrasolar planets around stars with various masses. Their prescription of planet formation (Ida & Lin 2004a) is based on the core-accretion scenario, in which it is assumed that Jupiter-mass gas-giant planets form through (1) grain condensation into kilometer-sized planetesimals, (2) runaway planetesimal coagulation (Wetherill & Stewart 1989; Kokubo & Ida 1996), (3) oligarchic growth of protoplanetary embryos (Kokubo & Ida 1998, 2000), and finally, (4) gas accretion onto solid cores (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Ida & Lin 2000). The models show that the characteristic mass distribution of planets around M dwarfs should be quite different from that around FGK dwarfs, which agrees well with the results of microlensing surveys (Beaulieu et al. 2006; Gould et al. 2006). The core-accretion model also predicts a strong dependence of the likelihood for finding planets on the stellar metallicity (Ida & Lin 2004b; Kornet et al. 2005), which is in agreement with observations (Santos et al. 2004; Fischer & Valenti 2005).

Like the mass distribution, the semimajor axis distribution of exoplanets needs to be explained by any consistent theoretical model of planet formation. One of the most puzzling questions that had already arisen when the first Jovian planets around main-sequence stars were discovered (Mayor & Queloz 1995) is their wide range of orbital radii, with distances ranging from $2 \times 10^{-2}$ AU to the radial velocity based observational limit of $\sim 5$ AU. According to the core-accretion scenario, preferred formation locations of Jovian planets are the outer regions of protoplanetary disks, where the temperatures are low enough for ice to survive (e.g., Ida & Lin 2004a). However, hot Jupiters have been observed very close to the central star ($\leq 0.1$ AU). It is unlikely that these objects formed in these inner regions, although Jovian planets can form inside the ice boundary in relatively massive disks (Ida & Lin 2004a). Orbital migration due to gravitational interaction between the planet and the gaseous disk (Goldreich & Tremaine 1980; Lin & Papaloizou 1986a, 1986b; Lin et al. 1996) is considered the most promising mechanism for generating hot Jupiters. It starts with relatively fast type I migration (e.g., Ward 1986; Tanaka et al. 2002). As soon as the planet has become massive enough to open a gap in the disk, it enters the phase of type II migration where the infall rate is connected with the viscous evolution of the disk. Numerical simulations have explored the complex migration process in great detail (see, e.g., de Val-Borro et al. 2006 for a recent comparison of different numerical simulations).

The Monte Carlo models of Ida & Lin (2004b) predict that the (differential) distribution for extrasolar planets with radial velocities larger than $10$ m s$^{-1}$ is an increasing linear function in log $a$ from $a \sim 0.1$ AU up to $\sim 1$ AU and decreases with $a$ for $a \gtrsim 1$ AU, independent of disk metallicity, if the disk depletion timescale is comparable to the disk diffusion timescale at the radius where Jovian planets are formed (the diffusion timescale determines the migration speed). Very similar results were found by Armitage et al. (2002) and Trilling et al. (2002). Some planets might survive in the outer regions. Near the inner disk edge ($\lesssim 0.1$ AU), those planets that migrate inwards from the outer regions may pile up (Lin et al. 1996). As a result, a gap (valley) would be created at intermediate semimajor axes (equivalently, intermediate periods) in the distribution. Udry et al. (2003) indeed point out a shortage of planets in the 10–100 day period range in the observed data (see also Zucker & Mazeh 2002), which they interpret as a signature for a transition region between two categories of planets that suffered different migration scenarios.

---

1 University Observatory Munich, D-81679 Munich, Germany.
2 Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8551, Japan.
In this paper, we analyze again the valley in the period and separation distribution of extrasolar planets, taking into account the newest set of observational data. We point out that in the observational data, the valley is much more pronounced around F dwarfs than GK dwarfs, which may reflect a dependence on disk size and/or on the EUV flux from the central star. Section 2 presents the observational evidence for a gap around F dwarfs. Section 3 discusses a series of Monte Carlo simulations that lead to a dependence of the planet semimajor axis distribution on stellar mass. A discussion of the results follows in § 4.

2. A GAP IN SEMIAxis DISTRIBUTION FOR PLANETS AROUND HIGHER MASS STARS

We use the sample of extrasolar planets around normal stars, compiled by the Extrasolar Planets Encyclopedia\(^3\) and include all planets (a total number of 175) with known semimajor axis \(a\) and stellar masses \(M_i\) that have been detected by radial velocity measurements. The stellar masses have been taken from SIMBAD or papers on exoplanets and have been determined by a variety of methods.\(^4\) Figure 1 shows the distribution of orbital semimajor axis \(a\) as a function of stellar mass \(M_i\). Lower mass planets with masses \(M \sin i < 0.8 M_\odot\), with \(M_i \sim 300 M_\odot\), are found preferentially at smaller values of \(\log (a/AU) \leq -0.2\), independent of \(M_i\), for FGK dwarfs, which may be at least partly due to an observational bias of radial velocity surveys. The shortage of planets with semimajor axes \(\log (a/AU) \leq -0.2\) is also clearly visible, but only for systems with stellar masses \(M_i \geq 1.2 M_\odot\).

To investigate this feature in greater detail, we now split the sample into planets (38) orbiting stars with masses \(M_i \geq 1.2 M_\odot\) (the high-mass sample, HMS) and the rest (137), which orbit less massive stars (the low-mass sample, LMS). The right panel of Figure 2 shows the distribution of semimajor axis of the LMS, adopting eight bins, equally spaced in \(\log a\) between \(-1.7 \leq \log (a/AU) \leq 0.7\). The planets are homogeneously distributed for \(-1.7 \leq \log (a/AU) \leq -0.2\), with a larger frequency in the three bins with large semimajor axes, corresponding to \(\log (a/AU) \leq -0.2\). No clear valley is evident for \(\log (a/AU) < -0.2\). The distribution, however, looks very different for the HMS (Fig. 2, left panel), where a clear lack of planets is found in the radius regime of \(-1.1 \leq \log (a/AU) \leq -0.2\).

We tested the assumption that the planets in the five inner logarithmic bins with \(a \leq 0.6\) AU are consistent with a homogenous distribution. The \(\chi^2\) test of the LMS planets leads to a likelihood of 78% that this sample is homogeneously distributed in \(\log a\). In contrast, the \(\chi^2\) statistic of the HMS planets gives a likelihood of only 2% that the gap in the semimajor axis distribution is a result of statistical fluctuations. Although the statistical significance is still marginal due to the low number statistics, there is a good chance that the lack of planets for stars with masses above 1.2 \(M_\odot\) in the semimajor axis regime \(0.1 \leq a \leq 0.65\) AU is real, while the distribution is much more uniform in \(\log a\) for less massive stars.

We also investigated how the difference between the HMS and the LMS depends on the adopted dividing mass. A mass of \(M_i \geq 1.2 M_\odot\) maximizes this difference. For larger dividing masses, the gap in the HMS still remains pronounced. The statistics, however, become worse due to the smaller number of objects in the HMS. For smaller dividing masses, the gap in the HMS is filled by objects with \(M_i \leq 1.2 M_\odot\), and a depression appears in the LMS.

\[ r_{\text{ice}} \approx 2.7 \left( \frac{L_\star}{L_\odot} \right)^{1/2} \text{ AU} \approx 2.7 \left( \frac{M_i}{M_\odot} \right)^2 \text{ AU}, \]

where we assume that the stellar luminosity \(L_\star\) is proportional to \(M_i^3\), although the dependence may be slightly weaker for

\(^3\)See http://exoplanet.eu.

\(^4\)For details, see http://exoplanet.eu./
pre-main-sequence stars. We adopt an (optically thin) disk temperature \( T \) that is regulated by direct stellar irradiation (Hayashi 1981),

\[
T = 280 \left( \frac{r}{1 \text{ AU}} \right)^{-1/2} \left( \frac{M_*}{M_\odot} \right) \text{K}. \tag{2}
\]

Then the viscosity \( \nu = \alpha c_s^2/\Omega \propto \alpha r M_*^{1/2} \), where \( c_s \propto \sqrt{T} \) is the sound velocity, \( \Omega \propto r^{-3/2} \) is the Keplerian frequency, and \( \alpha \) is the parameter of the alpha-viscosity model (Shakura & Sunyaev 1973). With these assumptions for \( r_1 \) and \( \nu \),

\[
\tau_\nu(r_1) \sim \frac{r_1^2}{3 \nu(r_1)} \sim 10^5 \left( \frac{\alpha}{10^{-3}} \right)^{-1} \left( \frac{M_*}{M_\odot} \right)^{3/2} \text{yr}. \tag{3}
\]

To estimate the disk depletion timescale, we adopt the standard similarity solution of viscously evolving disks (e.g., Lynden-Bell & Pringle 1974; Hartmann et al. 1998). The disk depletion time is then

\[
\tau_{\text{dep}} \sim \tau_\nu(r_0) \sim \frac{r_0^2}{3 \nu(r_0)} \sim 3 \times 10^6 \left( \frac{\alpha}{10^{-3}} \right)^{-1} \left( \frac{r_0}{100 \text{ AU}} \right) \left( \frac{M_*}{M_\odot} \right)^{-1/2} \text{yr}, \tag{4}
\]

where the disk size \( r_0 \) corresponds to the radius of the maximum viscous coupling where the radial dependence of the disk gas surface density (\( \Sigma_{\text{gas}} \)) changes from \( r^{-1} \) to \( \exp (-r/r_0) \). For \( t < \tau_\nu(r_0) \), \( r_0 \) is constant with time.

Recently, the dependence of protoplanetary disks on their central stars is being observationally explored. One of the most remarkable dependences that has been found is that the mass accretion rate onto the stars is proportional to the square of the stellar mass \( M_* \) (Muzerolle et al. 2005; Mohanty et al. 2005; Natta et al. 2006). Alexander & Armitage (2006) point out that a decrease in disk size \( r_0 \) with increasing \( M_* \) \( (r_0 \propto M_*^{-1/2}) \) can explain such a strong neglected. In this case, \( \tau_{\text{dep}} \propto M_*^{-1} \) (eq. [4]). From this and equation (3), \( \tau_{\text{dep}}/\tau_\nu(r_1) \propto M_*^{-5/2} \). Therefore, \( \tau_{\text{dep}}/\tau_\nu(r_1) \) may differ by a factor of 3 between disks around stars with \( \sim 0.9 M_\odot \) and those with \( \sim 1.4 M_\odot \).

Motivated by the above arguments, we have carried out Monte Carlo simulations with fixed \( \alpha \) but with various \( \tau_{\text{dep}} \) to determine the semimajor axis distribution of planets with radial velocities larger than 5 m s\(^{-1}\). The details of the calculations of planetesimal accretion, gas accretion onto cores, gap opening, and migration are described in Ida & Lin (2004a, 2004b, 2005). Here, type II migration with \( \alpha = 10^{-3} \) is included, but type I migration is neglected. The effect of type I migration will be presented in a separate paper (Ida & Lin 2007). We assume that the surface density of planetesimals is \( \Sigma_d = f_{\text{disk}} \Sigma_{d, \text{MMSN}} \propto r^{-3/2} \), where \( \Sigma_{d, \text{MMSN}} \) is that of the minimum-mass solar nebula model (Hayashi 1981) and the scaling factor \( f_{\text{disk}} \) takes values of 0.1–10 (see discussion
in Ida & Lin 2004a). On the other hand, the gas surface density is
\[
\Sigma_{\text{gas}} = \frac{f_{\text{disk}} (r/1 \text{ AU})^{1/2} \Sigma_{\text{gas,MMSN}} (1 + t/t_{\text{dep}})^{-3/2} \times r^{-1} (1 + t/t_{\text{dep}})^{-3/2}}{r_{0}},
\]
corresponding to the similarity solution at \( r < r_{0} \).

As long as FGK dwarfs are considered, the formation mechanism of planets is almost independent of \( M_{*}/M_{\odot} \) and stellar (disk) metallicity (Ida & Lin 2004b, 2005). We therefore show results only for \( M_{*}/M_{\odot} = 1 \) and \( \frac{[\text{Fe/H}]}{[\text{Fe/H}]_{\odot}} = 0.2 \), in order to make the discussion simple. With \( M_{*} = 1 M_{\odot} \) and \( \alpha = 10^{-3} \), the viscous timescale in all simulations is \( \tau_{\text{visc}}(r_{1}) \approx 10^{5} \text{ yr} \) (eq. [3]). Since the key parameter to determine the radial variation in the planet semimajor axis distribution is \( \tau_{\text{visc}}(r_{1}) \), we did calculations with \( \tau_{\text{dep}} = 10^{6} - 10^{7} \text{ yr} \), which may correspond to HMS and LMS samples. For other parameters, see text.

The upper panels in Figure 3 show the theoretically predicted mass and semimajor axis distributions. The left panel assumes \( \tau_{\text{dep}} = 10^{6} - 10^{7} \text{ yr} \), while the right one corresponds to \( \tau_{\text{dep}} = 3 \times 10^{6} - 3 \times 10^{7} \text{ yr} \). We identify the former and the latter results with planets forming around HMS and LMS, respectively. The middle panels are histograms of mass distributions of planets with radial velocity larger than \( 5 \text{ m/s} \) (corresponding to currently observable planets). In the right panel, the result with \( 10^{7} - 10^{8} \text{ yr} \) is also plotted with open circles. Lower panels are histograms for planets with \( M \geq 0.8 M_{J} \) (lower left panel) and \( M < 0.8 M_{J} \) (lower right panel) for the \( \tau_{\text{dep}} = 10^{6} - 10^{7} \text{ yr} \) result (middle left panel).

![Figure 3](https://example.com/fig3.png)

**Figure 3.**—Mass distributions of extrasolar planets predicted by the theoretical model. Unit of mass is earth mass \( (M_{\oplus} \approx M_{\odot}/300) \). Upper left and right panels show the mass and semimajor axis distribution with \( \tau_{\text{dep}} = 10^{6} - 10^{7} \text{ yr} \) and \( 3 \times 10^{6} - 3 \times 10^{7} \text{ yr} \), respectively, which may correspond to HMS and LMS samples. For other parameters, see text. Middle panels are histograms of mass distributions of planets with radial velocity larger than \( 5 \text{ m/s} \) (corresponding to currently observable planets). In the right panel, the result with \( 10^{7} - 10^{8} \text{ yr} \) is also plotted with open circles. Lower panels are histograms for planets with \( M \geq 0.8 M_{J} \) (lower left panel) and \( M < 0.8 M_{J} \) (lower right panel) for the \( \tau_{\text{dep}} = 10^{6} - 10^{7} \text{ yr} \) result (middle left panel).
right panel). Because type II migration is slower for more massive planets, the gap is more pronounced for $M \geq 0.8 M_{\odot}$. Thus, if the results with $t_{\text{dep}} = 10^6 - 10^{10}$ yr and $3 \times 10^6 - 3 \times 10^7$ yr represent HMS and LMS, respectively, the theoretical predictions show a trend with stellar and planetary mass that is consistent with the analysis of the observational data in § 2.

Although statistical fluctuations may still be large in the observations presented in Figure 2, the rise of the mass distribution at $\sim 1$ AU appears to be steeper than the theoretical prediction. This might be due to the photoevaporation of disk gas due to EUV radiation from the central star, which is very effective at a few AU and could inhibit type II migration for planets that formed beyond a few AU (Matsuyama et al. 2003). Note, however, that the process of disk gap formation by photoevaporation depends critically on the stellar EUV flux in the pre-main-sequence phase, which is poorly known. The X-ray flux from pre-main-sequence stars, on the other hand, is observed, and the flux may be linearly proportional to $M_*$. (Preibisch et al. 2005). Hence, the EUV flux may also increase with $M_*$. Furthermore, since gas giants form at larger radii due to larger values of $r_{\text{ice}}$ (eq. [1]), the inhibition of the migration may be more efficient for more massive stars. Although the dependence with stellar mass may not be strong enough, photoevaporation effects could make the radial gradient of the planet mass distribution at $\sim 1$ AU steeper for the HMS sample than for the LMS sample. More theoretical work would be required to understand this process in greater detail.

4. DISCUSSION

We should start the discussion with a word of caution. Despite the fact that almost 200 exoplanets are known, the statistics for more advanced correlations like the one discussed here are still poor. In addition, for small numbers, spurious correlations between different variables can always be found. They would appear to have a high statistical significance which is, however, caused by the biased selection of the data. At the moment, we cannot rule out the possibility that the planet shortage in the separation range of $0.08 \leq a \leq 0.6$ AU, first discussed by Udry et al. (2003), is such a case.

However, if this valley in period and separation distribution exists, we argue that it is due to a lack of planets with masses $M \sin i > 0.8 M_J$ orbiting around stars with masses $M_* \geq 1.2 M_\odot$, which provides interesting new insight on the origin of massive planets orbiting close to their parent stars and the dependence on stellar properties. We point out that smaller size protoplanetary disks around more massive stars can account for a deeper valley around these stars. If MRI turbulence is responsible for the disk viscosity, $\alpha$ values for the viscosity would not significantly depend on stellar mass. Adopting a constant $\alpha$, smaller disk sizes around more massive stars would lead to shorter disk depletion timescales, which prevents Jovian planets formed in the outer regions from migrating considerably. Strong EUV radiation from massive (pre-main-sequence) stars may also inhibit the migration across the regions at a few AU. Another possibility is a larger radius of the ice boundary (corresponding to a larger formation radius of gas giants) for massive stars that may also inhibit the smoothing out of the valley. The valley would then be most pronounced for planets around massive stars.

To confirm the existence of the HMS period valley and test the scenario presented here, more detections of extrasolar planets around more massive stars (BA dwarfs) are needed. If our model is correct, the valley in the period/sepARATION distribution of Jovian planets would become even more pronounced for even more massive stars. Because several planets around KG giants, which were BA dwarfs in their main-sequence phase, have been discovered, plenty of planets should also exist around BA dwarfs. Spectroscopic observations are not easy for BA dwarfs because of a smaller number of absorption lines and rapid rotation. However, in spite of the difficulty, relatively massive planets should be detectable. Transit surveys may not have serious problems in searching for planets around BA dwarfs; however, detection is limited to short-period planets. Detailed observations of differences in disk sizes between T Tauri stars and Herbig Ae/Be stars are also needed to test our model.

A. Burkert acknowledges benefits from the activities of the RTN network “PLANETS,” supported by the European Commission under the agreement HPRN-CT-2002-0308. We would like to thank our colleagues at the astronomy department (Lick Observatory) of the University of California, Santa Cruz, for their hospitality.

REFERENCES

Alexander, R. D., & Armitage, P. 2006, ApJ, 639, L83
Armitage, P., Livio, M., Lubow, S. H., & Pringle, J. E. 2002, MNRAS, 334, 248
Beaulieu, J. P., et al. 2006, Nature, 439, 437
Bodenheimer, P., & Pollack, J. B. 1986, Icarus, 67, 391
Bonfils, X., et al. 2005, A&A, 443, L15
Butler, P., Vogt, S., Marcy, G., Fischer, D., Wright, J., Henry, G., Laughlin, G., & Lissauer, J. 2004, ApJ, 617, 580
de Val-Borro, M., et al. 2006, MNRAS, 370, 529
Fischer, F., & Valenti, J. 2005, ApJ, 622, 1102
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Gould, A., et al. 2006, ApJ, 644, L37
Gu, P. G., Lin, D. N. C., & Bodenheimer, P. 2003, ApJ, 588, 509
Hartmann, L., Calvet, N., Gullbring, E., & d’Alessio, P. 1998, ApJ, 495, 385
Hayashi, C. 1981, Prog. Theor. Phys. Suppl., 70, 35
Ida, S., & Lin, D. N. C. 2004a, ApJ, 604, 388
——. 2004b, ApJ, 616, 567
——. 2005, ApJ, 626, 1045
——. 2007, ApJ, submitted
Ikoma, M., Nakazawa, K., & Emori, E. 2000, ApJ, 537, 1013
Kokubo, A., & Ida, S. 1996, Icarus, 123, 180
——. 1998, Icarus, 131, 171
——. 2000, Icarus, 143, 15
Kornet, K., Bodenheimer, P., Różycka, M., & Stepinski, T. F. 2005, A&A, 430, 1133
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73
Lin, D. N. C., Bodenheimer, P., & Richardson, D. 1996, Nature, 380, 606
Lin, D. N. C., & Papaloizou, J. 1986a, ApJ, 307, 395
——. 1986b, ApJ, 309, 846
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
Matsuyama, I., Johnstone, D., & Murray, N. 2003, ApJ, 585, L143
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Mizuno, H. 1980, Prog. Theor. Phys., 64, 544
Mohanty, S., Jayawardhana, R., & Basri, G. 2005, ApJ, 626, 498
Muzerolle, J., Luhman, K. L., Briceño, C., Hartmann, L., & Calvet, N. 2005, ApJ, 625, 906
Natta, A., Testi, L., & Randich, S. 2006, A&A, 452, 245
Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, Icarus, 124, 62
Preibisch, T., et al. 2005, ApJS, 160, 582
Sandqvist, E., Taam, R. E., Lin, D. N. C., & Burkert, A. 1998, ApJ, 506, L65
Santos, N., Israélien, G., & Mayor, M. 2004, A&A, 415, 1153
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Tanaka, H., Takeuchi, T., & Ward, W. 2002, ApJ, 565, 1257
Trilling, D. E., Benz, W., Guillot, T., Lunine, J. I., Hubbard, W. B., & Burrows, A. 1998, ApJ, 500, 428
Trilling, D. E., Lunine, J. I., & Benz, W. 2002, A&A, 394, 241
Udry, S., Mayor, M., & Santos, N. 2003, A&A, 407, 369
Ward, W. 1986, Icarus, 67, 164
Wetherill, G. W., & Stewart, G. R. 1989, Icarus, 77, 330
Zucker, S., & Mazeh, T. 2002, ApJ, 568, L113