ON THE AGES OF PLANETARY SYSTEMS WITH MEAN-MOTION RESONANCES

SHUKI KORISKI and SHAY ZUCKER
Department of Geophysics & Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel; jehoshu1@post.tau.ac.il, shayz@post.tau.ac.il

ABSTRACT

We present preliminary though statistically significant evidence that shows that multiplanetary systems that exhibit a 2/1 period commensurability are in general younger than multiplanetary systems without commensurabilities, or even systems with other commensurabilities. An immediate possible conclusion is that the 2/1 mean-motion resonance in planetary systems tends to be disrupted after typically a few Gyrs.

Key words: celestial mechanics – methods: statistical – planetary systems – planets and satellites: dynamical evolution and stability – stars: statistics

1. INTRODUCTION

The number of known extrasolar multiplanetary systems is constantly growing. A significant fraction of these systems exhibit what seems to be couples of planets that are locked in mean-motion resonances (MMRs). The question whether a specific system is indeed in a state of MMR is usually hard to answer conclusively. Period commensurability (PC) is a necessary condition for MMR, but not sufficient. Full diagnosis of an MMR requires long-term monitoring of the resonant argument, which is impractical in many cases. Nevertheless, Wright et al. (2011b) used PC as a proxy indicator for MMR and showed, in a brilliantly simple statistical test, that planetary systems exhibit PCs much more than expected in random. Since PC is not known to relate to any other physical phenomenon, except for MMR, the simple conclusion is that MMR is a preferred state of planetary systems (e.g., Beaugé et al. 2008).

Models show that planets can get trapped in a state of MMR through convergent orbital migration (e.g., Papaloizou & Szuszkiewicz 2010; Ketchum et al. 2011) or planet-planet scattering (e.g., Raymond et al. 2008). The long-term survivability of MMR is also the focus of several studies. Chaotic diffusion may lead eventually to disruption of the resonance (e.g., Tiscareno & Malhotra 2009; Goździewski & Migaszewski 2009). Thommes et al. (2008) claim that the presence of a remnant planetesimal disk may be a common reason for the disruption of such resonances.

It seems that the most prominent MMR is the 2/1 resonance. Pierens & Nelson (2008) show that the 2/1 resonance is a preferred outcome of the orbital evolution of two planets embedded in a protoplanetary disk. Michtchenko et al. (2008a, 2008b) draw a detailed portrait of the phase space of the 2/1 resonance, while Voyatzis et al. (2009) provide a detailed analysis of the families of solutions to the general dynamical problem of three bodies in 2/1 MMR, addressing specifically the issue of stability.

If indeed most MMRs are destined to get destabilized and disrupted, as Thommes et al. (2008) claim, we would expect to see a shortage of MMRs around older stars. This is the phenomenological claim we set out to examine in this short study. The results we obtained were a little different—we found out that only stars hosting planets in a 2/1 PC were statistically significantly younger. All other PCs do not seem to show such an age relation.

In the next section, we describe the way we built the sample on which we tested our hypothesis, Section 3 details the statistical tests we applied on this sample to test our claims, and we conclude in Section 4.

2. THE SAMPLE

We first built a sample of stars hosting known multiplanet systems, using the publicly available exoplanet orbit database that Wright et al. (2011a) have put up online. In order to make our sample as homogeneous as possible, we considered only planets that were detected by radial velocities, around stars of spectral types F, G, or K. Thus, we excluded most of the known transiting planets (except those detected first through radial velocities), pulsar planets, planets detected in direct imaging, planets around M stars, and the solar system planets.

Next, we identified those systems that exhibited PCs. We included in our definition of commensurabilities integer ratios larger than 1, with a denominator less than 6, i.e., the ratios 2/1, 3/1, 3/2, 4/1, 4/3, 5/1, 5/2, 5/3, and 5/4. In order to tag two periods as commensurate, we defined a “normalized commensurability proximity” (NCP) score defined by

\[
\delta = 2 \frac{|r - r_c|}{r + r_c},
\]

where \( r \) is the actually measured period ratio and \( r_c \) is the commensurability ratio against which we compare \( r \). We chose to tag systems with at least one NCP value of \( \delta < 0.1 \) as commensurate.

Next we had to introduce an age estimate for the stars in our sample. Stellar ages are notoriously difficult to estimate. Soderblom (2010) reviewed and compared several age estimation approaches. There are two approaches that dominate the literature. The first uses the stellar activity, as estimated by the H and K lines of singly ionized calcium in the stellar spectrum. The second places a star on model isochrones on the Hertzsprung–Russell diagram. Both methods, as well as the less frequently used methods, are strongly model dependent and suffer many drawbacks and pitfalls.

For the sake of sample homogeneity, we decided to focus purely on one approach. Furthermore, Figure 8 in the paper by Soderblom (2010) shows that besides a prevailing systematic shift between isochrone ages and chromospheric activity ages, it seems that isochrone ages might lose their sensitivity for stars younger than about 2 Gyr. Thus, we decided to use in our study only chromospheric activity ages based on the calcium H and K emission lines. To avoid non-uniformities in the interpretation of observations, we extracted the chromospheric activity ages...
only from large surveys we found in the literature, and not from papers that presented analysis of individual stars. Our use of chromospheric activity ages is also another reason for excluding M stars from our sample, as M stars are notorious for having variable activity (Soderblom 2010).

Table 1 presents the resulting sample of commensurate planetary systems, including the relevant commensurability ratios and the NCP values. The table also lists the chromospheric activity ages we found in the literature and the average age we computed from these values. Table 2 lists the systems that did not pass our criterion for PC (δ < 0.1) and their relevant ages. In both tables, we also included systems for which we did not find any chromospheric activity age in any large published survey. In total, our sample conveniently includes 15 age estimates for commensurate systems and 15 for non-commensurate systems.

3. STATISTICAL TESTS

The mean chromospheric activity age of the commensurate systems in our sample is 5.213 Gyr, while that of the non-commensurate systems is 6.577 Gyr. This difference of 1.36 Gyr hints that resonant systems tend to be younger on average. In order to test this hypothesis, we adopted the most simple approach of the permutation test (Good 1994). Thus, we
repeatedly drew a random assignment of the ages to the two samples, effectively ruining any correlation that may exist between age and commensurability. For each such random assignment we recalculated the mean age difference. We used $10^6$ random assignments, among which 20,650 yielded an age difference larger than 1.36 Gyr. This implies a statistical significance of $p = 0.021$.

The main advantage of the permutation test approach is in avoiding the need to assume any special assumptions about the distribution of the samples. However, one may still argue that using the mean values is prone to strong influence by the extreme values in each sample. An alternative is to use the median instead, which is more robust to extreme values. The median age of the resonant systems is 5.59 Gyr and that of the non-resonant systems is 7.17 Gyr, with a difference of 1.58 Gyr. We repeated the permutation test, this time obtaining 17,178 out of $10^6$ values larger than the actual value. Thus, the permutation test for the medians leads to a somewhat more significant result, with a significance of $p = 0.017$.

The results we have presented above are only marginally significant. They do seem to point to a tendency of the commensurate systems to be younger than the non-commensurate ones, but their statistical significance is not that high. Further examination of the sample shows that the tendency we see may be attributed only to the 2/1 PC systems. Close examination of Table 1 hints that the subset of the 2/1 PC systems (HD 37124, HD 73526, HD 82943, HD 128311, and $\mu$ Ara) seem to possess lower ages. The additional two 2/1 PC systems HD 40307 and 24 Sex do not have an age estimate and thus do not contribute to the statistical significance. Since the number of 2/1 PC systems is much smaller than the total number of PC systems, it is not immediately obvious that this result is statistically significant. We repeated the tests we performed earlier, this time dividing the sample into 2/1 PC systems, and all the rest. This new division clearly enhances the statistical significance: the “difference in means” test now yields $p = 0.007$ (6745 out of $10^6$) and the “difference in medians” test gives $p = 0.004$ (4178 out of $10^6$). The actual age difference is 2.40 Gyr for the difference of the means and 2.15 Gyr for the difference of the medians.

Further tests we have performed showed that the rest of the commensurate systems did not exhibit any significant age difference compared to the non-commensurate systems.

4. CONCLUSION

The results we presented in this short Letter support the claim that the phenomenon of MMR, which manifests itself as PC, is not generally ever lasting. The actual numbers we obtained suggest that a typical life expectancy of a 2/1 MMR is around 4 Gyr. For the other families of resonances we cannot assert at this stage any statistically significant claim, probably because no other category is as populated yet as the 2/1 category.

The above conclusion is extremely simplistic. It does not take into account the details of the orbits involved in the resonance, such as mass ratios or eccentricities. It is also prone to large and significant uncertainties, which are known to plague stellar age estimates. However, the scarcity of the current data set does not allow for a more detailed and refined analysis.

Our results suggest that the 2/1 resonance stands out among all the resonances. This may very well be the case, as Pierens & Nelson (2008) have claimed. It might be that the orbital evolutionary history of the 2/1 resonance is unique and different from that of all the other resonances. In fact, Pierens & Nelson (2008) also singled out the 3/2 resonance as another preferred outcome of the resonance trapping scenario. Our analysis may support this, as the only 3/2 PC system in the sample (HD 45364) is indeed younger than average (4.87 Gyr).

Since there is currently only one system in this category, we chose not to include this claim in our tests, even though it would have surely improved the statistical significance.

In order to explain the scarcity of 2/1 PC among the older systems, one needs to invoke some mechanism to disrupt them. Thus, our results agree with the claim by Thommes et al. (2008) that breakup (maybe violent) of resonantly locked planets is a common evolutionary step of planetary systems. The fact that non-2/1 resonances seem to survive may hint that their formation is an outcome of a much later stage in the evolution of planetary systems. In order to test this possibility, it is essential to perform much more long-term dynamical studies of resonant systems, lasting a few Gyrs and more.

In order to further explore the issue of survivability of MMRs, we need also to refine our knowledge of multiplanetary systems. Specifically, we should compile a more comprehensive data set of stellar ages for the multiplanetary systems. Hopefully, with the advent of the recent planet finding missions, such data will become more abundant.

The results we presented in this Letter are only a preliminary attempt to test whether the issue of survival of MMRs is worth exploring with the tools of stellar age estimates. Apparently, the existing data partly corroborate the hypothesis we presented in Section 1, and the 2/1 PC indeed tends to be found in younger systems. This may very well be another window into the understanding of planetary orbital evolution.

This research was supported by the Israel Science Foundation—The Adler Foundation for Space Research (grant no. 119/07). This research has made use of the Exoplanet Orbit Database and the Exoplanet Data Explorer at http://exoplanets.org.

REFERENCES

Arriagada, P. 2011, ApJ, 734, 70
Beaugé, C., Ferraz-Mello, S., Michtchenko, T. A., & Giuppone, C. A. 2008, in IAU Symp. 249, Exoplanets: Detection, Formation and Dynamics, ed. Y.-S. Sun, S. Ferraz-Mello, & J.-L. Zhou (Cambridge: Cambridge Univ. Press), 427
Good, P. 1994, Permutation Tests: A Practical Guide to Resampling Methods for Testing Hypotheses (New York: Springer)
Goździewski, K., & Migaszewski, C. 2009, MNRAS, 397, L16
Isaacson, H., & Fischer, D. 2010, ApJ, 725, 875
Keichumian, J. A., Adams, F. C., & Bloch, A. M. 2011, ApJ, 726, 53
Maldonado, J., Martínez-Arnáz, R. M., Eiroa, C., & Montesinos, B. 2010, A&AS, 521, A12
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Michtchenko, T. A., Beaugé, C., & Ferraz-Mello, S. 2008a, MNRAS, 387, 747
Michtchenko, T. A., Beaugé, C., & Ferraz-Mello, S. 2008b, MNRAS, 391, 215
Papaloizou, J. C. B., & Szuszkiewicz, E. 2010, in Extrasolar Planets in Multi-body Systems: Theory and Observations, ed. K. Goździewski, A. Niedzielski, & J. Schneider (EAS Publication Series Vol. 42; Les Ulis: EDP Sciences), 333
Pierens, A., & Nelson, R. P. 2008, A&A, 482, 333
Raymond, S. N., Barnes, R., Armitage, P. J., & Gorelick, N. 2008, ApJ, 687, L107
Rocha-Pinto, H. J., & Maciel, W. J. 1998, MNRAS, 298, 332
Saffe, C., Gómez, M., & Chavero, C. 2005, A&A, 443, 609
Soderblom, D. R. 2010, ARA&A, 48, 581
Thommes, E. W., Bryden, G., Wu, Y., & Rasio, F. A. 2008, ApJ, 675, 1538
Tiscareno, M. S., & Malhotra, R. 2009, ApJ, 138, 827
Voyatzis, G., Kotoulas, T., & Hadjidemetriou, J. D. 2009, MNRAS, 395, 2147
Wright, J. T., Fakhouri, O., Marcy, G. W., et al. 2011a, PASP, 123, 412
Wright, J. T., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2004, ApJS, 152, 261
Wright, J. T., Veras, D., Ford, E. B., et al. 2011b, ApJ, 730, 93

3