On the various origins of close-in extrasolar planets

S. Marchi\textsuperscript{1}*\thanks{\textsuperscript{*}E-mail: simone.marchi@unipd.it}, S. Ortolani\textsuperscript{1} M. Nagasawa\textsuperscript{2} and S. Ida\textsuperscript{2}

\textsuperscript{1}Department of Astronomy, Padova University, 34122 Padova, Italy
\textsuperscript{2}Tokyo Institute of Technology, Tokyo 152-8550, Japan

Accepted ...

ABSTRACT

The extrasolar planets (EPs) so far detected are very different to the planets in our own Solar System. Many of them have Jupiter-like masses and close-in orbits (the so-called hot planets, HPs), with orbital periods of only a few days. In this paper, we present a new statistical analysis of the observed EPs, focusing on the origin of the HPs. Among the several HP formation mechanisms proposed so far, the two main formation mechanisms are type II migration and scattering. In both cases, planets form beyond the so-called snow-line of the protoplanetary disk and then migrate inward due to angular momentum and energy exchange with either the protoplanetary disk or with companion planets. Although theoretical studies produce a range of observed features, no firm correspondence between the observed EPs and models has yet been established. In our analysis, by means of principal component analysis and hierarchical cluster analysis, we find convincing indications for the existence of two types of HPs, whose parameters reflect physical mechanisms of type II migration and scattering.

Key words: planets and satellites: formation – planetary systems: formation – planetary systems: protoplanetary discs.

1 TAXONOMY OF HOT PLANETS

The present EPs database consists of a rather heterogeneous sample of planets, showing great variety in all the measured quantities. Statistical analysis provides a necessary means to find correlations among various physical parameters involved in planetary formation and evolution. Nevertheless, we caution that statistical analysis may not be able to disclose important relationships due to the complex and mostly unknown interplay of the involved parameters. In order to overcome such problems, we performed a global statistical analysis of the EPs, using a novel approach. The underlying idea is to find groups of similar EPs and to distinguish different EP groups on the basis of their diversity. In this work, the concept of similarity and diversity among EPs is quantified by means of a distance measure in the multifold space of physical parameters. This goal has been achieved with the aid of principal component analysis and hierarchical cluster analysis. In the present analysis we followed the procedure used by Marchi (2007), and updated in Marchi & Ortolani (2008). The database used in this paper is updated to July 9\textsuperscript{th}, 2008. We restricted our analysis to those EPs having measurements for five input variables, that is: planetary mass ($M_p$), semimajor axis ($a$), eccentricity ($e$), stellar mass ($M_s$) and metallicity ([Fe/H]). Of 308 EPs (including Jupiter), 252 were finally selected for the analysis. The purpose of our analysis is to identify planets which are similar with respect to the 5-fold space of the input variables. As a result, 6 robust EP clusters have been identified. Before focusing on HPs, we briefly outline the general nature of the clusters.

Cluster C1 is characterized by sub- to jovian-like $M_p$, $a < 1$ AU, and super-solar [Fe/H]. Cluster C2 has sub-jovian $M_p$, $a < 1$ AU, sub-solar $M_s$ and sub-solar [Fe/H]. Both clusters C1 and C2 also have low mean eccentricity. Cluster C3 is the least populated cluster (14 EPs) and probably has no strong significance except the fact that it contains many peculiar EPs that for different reasons have been rejected by the other clusters. They are mostly jovian mass planets, having a remarkably super-solar [Fe/H]. Cluster C4 has mostly jovian mass planets, a relatively large $a$, orbiting solar mass stars with a widespread [Fe/H] distribution characterized by sub-solar values (Jupiter belongs to this cluster). Cluster C5 has super-jovian mass, $a > 1$ AU, super-solar $M_s$ and sub-solar [Fe/H]. The same holds for cluster C6, except for its super-solar [Fe/H] and its higher average eccentricity. All the input variables have an important role in defining the clusters, in particular $a$ and [Fe/H]. Beyond the general traits of the solutions, which will be described in more detail elsewhere, we focus in this paper on the HPs defined as...
those having a period less than 12 days (see later for further comments on this selection). According to the adopted definition, 69 HPs are present in the database. The main results of the taxonomy is that HPs have been split into two main groups, belonging to clusters C1 and C2. In addition, there are a few outliers placed in other clusters.

1.1 Two types of HPs

One of the most interesting features about the HPs, is the shape of their mass distribution (see fig. 1). It has two peaks. These peaks are thought to be real, even if the shape of the present distribution is severely affected by observational biases that make the discovery of low mass HPs difficult. In the literature, the bodies belonging to the lower mass peak are referred to as hot neptunes (HNs) while those belonging to the higher mass peak as hot jupiters (HJs). Theoretical models also predict a double peaked distribution (Mordasini et al. 2007; Ida & Lin 2008), where HNs are expected to be much more abundant than HJs. It is interesting that our taxonomy splits the majority of HPs into two different clusters (except for a few outliers). Most of the HPs belonging to the peak at $\log(M_p) \sim 0$ are placed in cluster C1 (fig. 1). HPs of the cluster C2 have a broad and flatter mass distribution, and it contains most of the HNs. Concerning the semimajor axis distribution, similar considerations hold. HPs of cluster C1 are strongly clustered at $\log(a) \sim −1.35$ (a $\sim 0.045$ AU); while those of cluster C2 have a flatter a distribution (fig. 1). The two groups of HPs have also quite distinct traits in terms of properties of stellar metallicity and - to a lesser extent- to stellar mass. These variables are important because they account for the environment where the planets formed. Figure 2 shows a remarkable result: HPs of cluster C1 have super-solar [Fe/H], while those of C2 have a sub-solar [Fe/H]. Notice that this result is also valid for the whole of C1 and C2, and not only for their HPs. A similar, but less pronounced, result also holds for the stellar mass: HPs of C1 have mostly super-solar $M_*$; while those of C2 have mostly sub-solar $M_*$ (fig. 2). The HPs of cluster C1 and C2 also have other distinctive traits. We found some significant intracluster correlations which hold for one cluster but not for the other. These are the correlations $a − e$, $M_p − [Fe/H]$, $M_p − M_*$ (see fig. 3). The semimajor axis of the HPs of cluster C1 strongly correlate with $e$, while this correlation is absent for cluster C2. On the other hand, HPs of cluster C2 exhibit a strong correlation of $M_p − [Fe/H]$ and $M_p − M_*$, while cluster C1 does not (fig. 3). These two plots in turn clearly show that HNs of cluster C1 are very different from the few belonging to cluster C2. The latter have remarkable sub-solar [Fe/H] and sub-solar $M_*$. Another important point is why some HPs have been placed in clusters other than C1 and C2. They are: HD73256b, HD68988b, HAT-P-7b and HD118203b (C3); XO-4b, HAT-P-6b and HD162020b (C4); WASP-14b, CoRoT-Exo-3b and XO-3b (C5); HAT-P-2b (C6). It is not clear if they are real outliers or if they are misplaced by the clustering algorithm. However, a close look at their properties shows that the main characteristic of these HPs is that they have high $M_p$ and high $M_*$. Among the outliers, the most massive ($M_p \sim 10 M_J$) HPs are present, namely HAT-P-2b, WASP-14b, CoRoT-Exo-3b, XO-3b and HD162020b (see fig. 2 left panel). Notice that the massive HD41004Bb is placed instead in C2, due to the very low stellar mass. In the present database, the combination of high $M_p$ and high $M_*$ is rather unusual, and this suggests that these HPs may be real outliers. Of course, if more HPs having such characteristics are discovered, it is possible that they may be grouped into a third class of HPs. Finally, it is also important to note that previous results are robust to changes in the selection of HP periods, at least in the range from 10 d to 30 d.

2 PHYSICAL INTERPRETATION

Our present theoretical understanding of the formation of HPs is based on two models: planetary migration within a protoplanetary disk (Lin & Papaloizou 1983) and planet-planet scattering followed by tidal circularization (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Lin & Ida 1997). Planetary migration has been shown to be an efficient mechanism to produce HPs. Migration can occur when planetary embryos are still embedded within the disk (type I), or when they are large enough to open a gap in the disk (type II). According to the present state of the art, the migration seems the best candidate for HP formation. On the other hand, early works on planet-planet scattering showed that the probability for the scattering model to produce HPs was very low. However, Nagasawa et al. (2008) found that the Kozai mechanism enhances the probability significantly. Therefore, it is possible that the scattering contributes to the formation of hot planets as well as type II migration, although the latter may be a main channel. Type II migration is more efficient for moderate mass planets since the planets have to be massive enough to clear a gap in the disk, but not too massive to efficiently exchange angular momentum and energy with the disk itself. Previous simulations have shown that the formation of HPs via gravitational scattering among planets and the subsequent Kozai mechanism combined with tidal dissipation is more likely for dynamically active systems of multiple planets, typically containing three or more gas giants (e.g. Marzari & Weidenschilling 2002). The formation of many giant planets is preferred in high dust surface density disks (Ida & Lin 2008). Dust surface density scales as $\rho_{dust}^{0.5}$, where $M_d$ is the total disk mass. The latter scales, according to theoretical models, as $\sim M_*^k$, where $0.7 < k < 2.2$ (Vorobyov 2005). Therefore high stellar masses and high-metallicity disks favor the onset of a scattering phase. It must also be noted that smaller planets tend to be scattered inward during the scattering phase and that the tidal circularization is more efficient for planets with small mass and large physical radius. The detailed final orbital configuration of the HPs may vary according to several parameters. However, there are a number of general features that can be outlined.

In the case of type II migration, the HPs final position is close to the location of the disk’s inner edge. This is placed near the corotation radius (namely the distance where the keplerian period matches the star spin period), where disk material accretes onto the stellar poles following the magnetic field lines. The spin period for young stars having $0.4 M_\odot < M_* < 1.5 M_\odot$ may vary considerably, from 1 d up to 20 d or more (Herbst et al. 2007). Therefore, taking also into account a wide variety of disk parameters, the fi-
nal location of HPs formed by type II migration tends to be spread, in the range from 0.01 to 0.1 AU. Concerning the eccentricity, at the end of the migration phase low $e$ values are expected. Recent simulations [Rice et al. 2008] suggest that, when HPs reach the stellar magnetosphere cavities, they may further evolve to smaller $a$. For moderate-to-high $M_p$, the $e$ also increases. On the other hand, the location of HPs formed by scattering is determined by the location where the tidal force is effective. The tidal force depends on several parameters (planetary radius, planetary mass, etc) but the final location tends to be in the range $0.03$-$0.08$ AU, for typical parameter values. The eccentricity of the inner planet is excited to values close to unity by close scattering and via the subsequent Kozai mechanism. The resultant small pericenter distance enables the planet’s eccentricity and semi-major axis to be decreased by the tidal dissipation and moderate eccentricities can remain in some cases (Nagasawa et al. 2008). We show this in fig. 1

The outcome of the simulations vary according to tide efficiency. For the simulations shown here, we followed the tidal evolution of test planets, according to Ivanov & Papaloizou (2007), for a time span of $10^7$ – $10^9$ yr. A large number of planetary radii, planetary masses and stellar masses have been considered, chosen at random within the following intervals: $0.4 R_J < R_p < 2.8 R_J$, $0.5 M_J < M_p < 3 M_J$, $0.5 M_\odot < M_s < 1.5 M_\odot$. The initial eccentricity is randomly chosen from the distribution obtained by Nagasawa et al. (2008). Figure 1 (left panel) shows that at the end of the scattering and tidal evolution phases the eccentricity and semimajor axes are correlated (compared to the observed distribution in fig. 3), while the right panel shows that the resulting semimajor axis distribution is peaked. The value of the peak depends on the strength of the tide, and for the values used here it is peaked at $a \approx 0.05$ AU, as observed in cluster C1 (compare with the observed distribution in fig. 1).

3 DISCUSSION AND CONCLUSION

The two main processes of HP formation produce different orbital distributions. On the basis of our taxonomic analysis, we identify two types of HPs, which may retain the footprints of these different formation processes. In this respect, HPs of cluster C2 and C1 may have been formed by migration and scattering, respectively. This scenario is supported by a number of facts. First of all the $a$ distribution and the strong $a$–$e$ relationship for cluster C1, which do not hold for cluster C2. Moreover, also the $M_p$ distribution of the two clusters support this conclusion: higher mass bodies are located in cluster C1, indicating more massive protoplanetary disks, which in turn is confirmed by high [Fe/H] and high $M_\odot$. In this case, the detected HPs are expected to be the least massive for each system, since in a multibody scattering the least massive planets are more effectively pushed inward. The orbits of the most massive planets are, however, only slightly affected by the scattering phase, therefore they tend to stay close to their formation regions and therefore on relatively large $a$. Although HJs originated via the scattering process are expected to be accompanied by outer companions, the latter would be beyond the detectable limit by present surveys. We find no significant difference between C1 and C2 about the multiplicity of planets, but we caution that this result is affected by low number statistics. Some Jupiter-like mass HPs are also present in cluster C2, but in this case they may be the most massive bodies formed in these systems, given also the moderate-to-low $M_\odot$ and low [Fe/H]. Another interesting point is that most of the HNs belong to cluster C2.

Therefore, if we extrapolate directly the percentage of HPs belonging to C1 and C2 into the efficiency of formation of the two processes, we end up with 50% of HPs formed via scattering and 30% via migration. The remaining 20% are outliers and may be formed either way. These numbers, however, have to be taken with caution, since some degree of mixing between the two clusters is expected. On the other hand, from a theoretical point of view (see discussion in previous sections) type II is expected to be more efficient in producing close-in EPs. This fact is not in contradiction with our findings since it is possible that planets migrating inward by type II may stop before becoming HPs. This would be the case, for instance, if the gas in the disk dissipates before the planet reaches the magnetospheric cavity. In this respect, it is interesting that many giant EPs exist in the range 0.1–3 AU and that their semimajor axis distribution is well explained by the type II migration model (Schlaufman et al. 2009).

An alternative scenario is that the two groups of HPs were formed by the same process, and the cluster analysis splits them on the basis of their diversity in the input variables. In this case, the most distinctive variable would be the metallicity. Formation in low metallicity, moderate-to-low $M_\odot$, environments would have produced the HPs of cluster C2. On the other hand, high [Fe/H] and moderate-to-high $M_\odot$ would have produced the HPs of cluster C1. The combinations of these diversities would have also produced the observed differences in the $M_p$ and $a$ distribution of the two groups. Although this is a possibility, we think the peculiar traits of cluster C1 and C2 clearly shown the influences of the two formation mechanisms.

REFERENCES

Herbst, W., Eisloffel, J., Mundt, R., & Scholz, A. 2007, Protostars and Planets V, 297
Ida, S., & Lin, D. N. C. 2008, ApJ, 673, 487
Ida, S., & Lin, D. N. C. 2008, ApJ, 685, 584
Ivanov, P. B., & Papaloizou, J. C. B. 2007, MNRAS, 376, 682
Lin, D. N. C., & Ida, S. 1997, ApJ, 477, 781
Lin, D. N. C., & Papaloizou, J. 1985, Protostars and Planets II, 981
Marchi, S., & Ortolani, S. 2008, IAU Symposium, 249, 123
Marchi, S. 2007, ApJ, 666, 475
Marzari, F., & Weidenschilling, S. J. 2002, Icarus, 156, 570
Mordasini, C., Alibert, Y., Benz, W., & Naef, D. 2007, arXiv:0710.5667
Nagasawa, M., Ida, S., & Bessho, T. 2008, ApJ, 678, 498
Rasio, F. A., & Ford, E. B. 1996, Science, 274, 954
Rice, W. K. M., Armitage, P. J., & Hogg, D. F. 2008, MNRAS, 384, 1242
Schlaufman, K. C., Lin, D. N. C., & Ida, S. 2009, ApJ in press
Vorobyov, E. I. 2008, arXiv:0810.1393
Marchi et al.

Weidenschilling, S. J., & Marzari, F. 1996, Nature, 384, 619

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
Figure 1. Left panel: Hot planet mass distributions. The current distribution of all HPs shows two peaks (indicated by arrows). Right panel: HP semimajor axis distributions. Hot planets of clusters C1 and C2 differ considerably in terms of their semimajor axis distributions. HPs of C2 have quite a flat semimajor axis distribution, while those of C1 seem to be narrowly peaked at $\log(a) \sim -1.35$ ($a \sim 0.045$ AU).

Figure 2. Left panel: HP metallicity distributions. HPs of cluster C1 have super-solar [Fe/H], while those of C2 have a sub-solar [Fe/H]. Right panel: HP stellar mass distributions. HPs of C1 have mostly super-solar $M_*$; while many HPs in C2 have sub-solar $M_*$. 
Figure 3. Significant intracluster correlations. Left panel: $a - e$ distribution for cluster C1 and C2. The two groups of HPs show a remarkable difference: C1 shows a very strong, statistically significant, correlation between $a$ and $e$ (2-tailed probability of 0.01%), while C2 has no correlation. Moreover, cluster C2 exhibits two statistically significant correlations. They are the $M_p - [Fe/H]$ correlation (middle panel) and $M_p - M_s$ correlation (right panel), respectively with a 2-tailed probability of 1% and 4%. Such correlations do not hold for cluster C1.

Figure 4. Details of the final orbital configuration obtained in the scattering model. As for the initial conditions, we adopted an uniform distribution (in linear scale) of $M_p$, an uniform distribution in planetary radius, and a gaussian $M_s$ distribution, peaked at 1 $M_\odot$. Initial semimajor axes were choosen at $\sim 1.35 M_\odot^2$ AU (half of the snow-line distance). The $e$ distribution has been taken according to fig. 9 of Nagasawa et al. 2008, where only $e > 0.9$ is interesting for the tidal evolution (see text for more details).