The Nature of the Radius Valley: Hints from Formation and Evolution Models

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ABSTRACT

Context. The existence of a Radius Valley in the Kepler size distribution stands as one of the most important observational constraints to understand the origin and composition of exoplanets with radii between that of Earth and Neptune.

Aims. The goal of this work is to provide insights into the existence of the Radius Valley from, first, a pure formation point of view, and second, a combined formation-evolution model.

Methods. We run global planet formation simulations including the evolution of dust by coagulation, drift and fragmentation; and the evolution of the gaseous disc by viscous accretion and photoevaporation. A planet grows from a moon-mass embryo by either silicate or icy pebble accretion, depending on its position with respect to the water ice-line. We account for gas accretion and type-I/II migration. We perform an extensive parameter study evaluating a wide range in disc properties and embryo’s initial location. We account for photoevaporation driven mass-loss after formation.

Results. We find that due to the change in dust properties at the water ice-line, rocky cores form typically with $\sim 3 M_\oplus$ and have a maximum mass of $\sim 5 M_\oplus$, while icy cores peak at $\sim 10 M_\oplus$ with masses lower than $5 M_\oplus$ being scarce. When neglecting the gaseous envelope, rocky and icy cores account naturally for the two peaks of the Kepler size distribution. The presence of massive envelopes for cores more massive than $\sim 10 M_\oplus$ inflates the radii of those planets above $4 R_\oplus$. Still, lower core masses with thin atmospheres can populate the second peak of the size distribution after evaporation occurs.

Conclusions. While the first peak of the Kepler size distribution is undoubtedly populated by bare rocky cores, as shown by previous studies, the second peak can host water-rich planets with thin H-He atmospheres. Some envelope-loss mechanism should operate efficiently at short orbital periods to explain the presence of $\sim 10-40 M_\oplus$ planets falling in the second peak of the size distribution.

Key words. planets and satellites: formation; planets and satellites: composition; planets and satellites: interiors

1. Introduction

Re-analysis of the Kepler data using precise stellar radii from Gaia, led Fulton et al. (2017) to find that exoplanets within a 100-day orbital period present a bimodal size distribution, with peaks at $\sim 1.3$ and $\sim 2.4 R_\oplus$. More recent analysis of better characterised sub-samples revealed the peaks at $\sim 1.5$ and $\sim 2.7 R_\oplus$, and the valley or gap at $\sim 1.9-2 R_\oplus$ (Van Eylen et al. 2018, Martinez et al. 2019, Petigura 2020).

The valley can be explained by atmospheric mass-loss mechanisms, such as photoevaporation (e.g. Owen & Wu 2017, Jin & Mordasini 2018) or core-powered mass-loss (e.g. Ginzburg et al. 2018, Gupta & Schlichting 2019). Both models are able to reproduce the correct position of the valley only if the naked-cores resulting from the mass-loss are rocky in composition. This has led to the interpretation that most Kepler planets with radii between Earth and Neptune accreted only dry condensates and were therefore formed within the water ice-line (Owen & Wu 2017, Gupta & Schlichting 2019).

From a formation point of view, it is hard to envision scenarios where planets with masses below $20 M_\oplus$ are devoid of water.

Indeed, accretion beyond the ice-line is usually prominent, and type-I migration tends to move planets in the mass range of $\sim 20 M_\oplus$ inwards in a very effective way (e.g. Mordasini 2018). Hence, a pure dry core composition for most short period exoplanets is not really expected from formation models (Raymond et al. 2018, Izidoro et al. 2019, Bitsch et al. 2019, Brügger et al. 2020). A possible way out is to invoke migration traps due to the existence of dead zones in the disc (Alessi et al. 2020). However, even if the super-Earths produced by those models are dry, they cannot account for the Kepler size bimodality.

Recent studies, based on Mass-Radius relations, suggest, on the other hand, that only the first peak of the radius distribution corresponds to rocky planets, while the second are water-rich objects (Zeng et al. 2019). The problem with associating the second peak to water-rich planets is that it cannot explain why such planets do not fill the valley. Indeed, cores containing 50% rock-50% ice by mass would fall in the radius valley if they had a mass of $\sim 3$ to $6 M_\oplus$ (Sotin et al. 2007, Zeng et al. 2019, Haldemann et al. 2020, Owen & Wu 2017, Gupta & Schlichting 2019). Zeng et al. (2019) showed that the Kepler size distribution can be matched if the icy planets are assumed to follow the mass distribution suggested by RV measurements, which encompass masses in the range of $\sim 0.5$ to $15 M_\oplus$, with a peak at $\sim 9$
M\textsubscript{\oplus}. However, no explanation for the origin of such mass distribution is offered.

In an accompanying paper (Paper I) we show that when pebble accretion is computed self-consistently from dust growth and evolution models, pure rocky planets are typically less massive than 5 M\textsubscript{\oplus}. In that work, we also show that the change of dust properties at the ice-line affects dramatically the growth mode of planets, which was originally proposed by\cite{morbidelli2015} to explain the dichotomy of gaseous versus terrestrial planets in the Solar System. In this letter, we show that a bimodality in core mass/composition from birth naturally renders a radius valley at \( \sim 1.5 - 2 \) R\textsubscript{\oplus}. We additionally discuss the effect of gaseous envelopes and their photoevaporation on the Kepler size bimodality.

2. Methodology in brief

Our physical model is the same as in Paper I, except that planets are always allowed to migrate. We recall it here briefly. An embryo grows from lunar-mass by pebble and gas accretion, embedded in an \( \alpha \)-disc that undergoes X-ray photoevaporation from the central star. The pebble surface density is computed self-consistently from dust coagulation, fragmentation, drift and ice sublimation at the water-ice-line\cite{brunstiel2011,drzazkowska2016},\cite{guller2020}. We consider the growth of one embryo per disc. Gas accretion is computed, both in the attached and detached phases. To reduce computational time in the detached phase, the interior structure of the planets is calculated using the method presented in\cite{albert2019}, which uses deep neural networks, trained on pre-computed structure models. Before the core reaches the pebble isolation mass (when \( M_{\text{core}} = 0.9 M_{\text{iso}} \)), we switch to solve the internal structure equations to capture the increase of gas accretion resulting from the halt of pebble accretion (see Paper I). Type-I migration prescriptions correspond to those of\cite{jimenez2017} and\cite{masset2017}, which account for the possibility of outwards migration due to corotation and thermal torques. Planets switch to type-II migration once a partial gap opens in the disc\cite{crida2006}. We perform in total 665 planet formation simulations, spanning a wide range in initial conditions and disc properties, as detailed in Appendix A.

We also account for atmospheric mass-loss via photoevaporation during 5 Gyr after disc dissipation. The details of the model are described in Paper I. In this work, we consider not only the photoevaporation of H-He as in Paper I (hereafter called model A), but also the mass-loss of H\textsubscript{2}O, which is assumed uniformly mixed within the H-He envelope (model B, see details in Sect.2.1.2 of\cite{mordasini2020}).

3. Results

The water ice-line splits a protoplanetary disc into two distinct growth environments. This is because fragmentation renders silicate pebbles considerably smaller than icy ones (see Paper I), resulting in an increase in Stokes number at the water-ice-line\cite{morbidelli2015}. In Fig. 1 we illustrate this effect, showing the growth tracks of seven planetary embryos that form in the same disc (one at a time). Three embryos start their growth within the ice-line and four beyond. The color-bar indicates the ice mass fraction of the core. The planets that start forming beyond the ice-line remain always water-rich (\( f_{\text{ice}} \approx 0.5 \)), because they attain the pebble isolation mass beyond \( r_{\text{ice}} \). This is a typical feature in pebble accretion simulations\cite{bruegger2020}.

We note that all the cores that start beyond the ice-line and reach \( a \leq 0.43 \) au (or \( P < 100 \) days for a Sun-mass star) are considerably more massive than the ones forming inside it. This is due to the two-order-of-magnitude jump in Stokes number\cite{orme2010,lambrechts2012}.

Figure 2 shows the final core and envelope mass of all the simulated planets that end their formation with \( P \leq 100 \) days. Again, the color-bar indicates the water mass fraction of the core. The effect of the ice-line in the core growth is noticeable: icy cores (blue) tend to be more massive than rocky ones (red). This is more clear when we plot a histogram of the core masses (Fig. 3, left panel). We note that the distribution of rocky core masses (\( f_{\text{ice}} = 0 \), red bars) is pretty narrow, with a peak at \( \sim 3 \) M\textsubscript{\oplus} and maximum core mass of \( \sim 5 \) M\textsubscript{\oplus}, in agreement with Paper I. On the contrary, the distribution of icy cores is more spread, with \( 1 \leq M_{\text{core}} \leq 36 \). However, the peak occurs clearly for larger core masses (\( \sim 10 \) M\textsubscript{\oplus}) compared to the rocky case. Indeed, the median for those planets occurs at \( M_{\text{core}} = 10.9 \) M\textsubscript{\oplus}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Top panel: formation tracks corresponding to disc 1, \( Z_0 = 0.0144 \), and \( \alpha = 10^{-4} \). The green-colored circles indicate the times 0.012 Myr, 0.25 Myr, and 2 Myr. \( M_{\text{iso}} \) is reached in each simulation when \( M_{\text{core}} \) stops growing. Bottom panel: evolution of the Stokes number at the planet location for the 7 cases shown in the top panel (the labels indicate initial semi-major axis). The grey circles show the time when planets enter in the region \( r < r_{\text{ice}} \).}
\end{figure}
Fig. 2. Core mass vs. envelope mass for all the cases with final orbital period within 100 days.

and only 25% of the icy cores have $M_{\text{core}} < 8.1 M_{\oplus}$. Hence, the effect of the change of composition with the corresponding transition in the Stokes number at the water ice-line is inherited in the overall population.

The right panel of Fig. 3 shows the histogram of the core radii for the same cases as the left panel. The radius was calculated following the simple mass-radius relation of Zeng et al. (2019). Interestingly, the two peaks of the Kepler size distribution are very well reproduced, with a clear paucity of core radii at $R_{\text{valley}} \approx 1.6 - 2 R_{\oplus}$.

However, big cores tend to accrete large amounts of gas, as Fig. 2 shows. How does the size distribution look like when the gaseous envelopes are not neglected and atmospheric mass-loss is accounted for? We show this in Fig. 4. The left panels correspond to Evaporation Model A, where only the loss of H-He is considered. The right panels correspond to Evaporation model B, where the water is assumed to be homogeneous mixed with the primordial H-He envelope and can also be removed. We note in this figure that the second peak (of originally icy cores) gets considerably wiped out. Indeed, most cores of 10 $M_{\oplus}$ have envelopes of equal mass just after formation (Fig. 5), and evaporation cannot remove much gas for such massive cores. Then, part of the second peak moves to $R_{\oplus} \approx 8 R_{\oplus}$. Planets concentrated at this radius correspond to discs of low viscosity ($\alpha = 10^{-4}$). This can be noted by comparing the solid-black and grey-dashed lines in the histograms of Fig. 4. Such low viscosity is necessary to form rocky planets (see Paper 1), but creates an over-density of icy/gas-rich planets at $R_{\oplus} \approx 8 R_{\oplus}$. This could suggest a viscosity transition at the water ice-line, although $\alpha$ is expected to decrease with radial distance. Kretke & Lin (2007) and Lyra & Umurhan (2019) have shown that the planets form in a mixed layer, where the water is mixed with the primordial H-He envelope. Alternatively, an efficient envelope mass-loss might operate. Nevertheless, the right panels suggest that the second peak of Fig. 3 remains for both evaporation models. Furthermore, model B, a valley and small second peak appear at the position reported by Fulton et al. (2017) (Fig. 4 right lower panel).

Next, we analyse the resulting planet mass. We plot the three cases described above (bare cores after formation, and evaporation models A and B) in a Mass-Radius diagram in Fig. 5.

The bare cores are shown color-coded with the core water mass fraction. Planets run under evaporation model A are depicted as magenta triangles and as green diamonds under evaporation model B. The grey dots represent real exoplanets from the NASA Exoplanet Archive. Yellow shaded areas highlight the two-modes of the Kepler size distribution, with darker tones towards the peaks. The gap is marked with grey lines for $1.82 \leq R_{\oplus} \leq 1.96$ following Martinez et al. (2019).

It is interesting to note that the three models overlap with existing exoplanets, and actually bracket the observed population fairly well. Regarding evaporation model A, we note that it can strip out H-He envelopes completely for $M_{\text{core}} \leq 8 M_{\oplus}$. Larger cores retain sufficient H-He to be kicked out of the second peak. Evaporation model B retains more planets in the second peak, but leaves all planets with $R_{\oplus} < 4 R_{\oplus}$ with $M_{\text{He}} < 6 M_{\oplus}$. We discuss the implications of this in Sect. 5.

4. Composition of super-Earths/sub-Neptunes

While the composition of first-peak exoplanets is undoubtedly rocky (Owen & Wu 2017; Jin & Mordasini 2018; Gupta & Schlichting 2019), planets with radius in the second peak have an intrinsic degenerate composition, with rocky planets with thin H-He atmospheres yielding the same radius as icy-dominated objects (e.g. Born et al. 2017; Zeng et al. 2019). Atmospheric mass-loss models tend to suggest that second-peak planets correspond to the first type. What do our combined formation and evolution models show?

We do not form rocky planets with masses above ~ 5 $M_{\oplus}$, and evaporation model A strips the envelopes of those completely for cases with orbital periods concentrated at 10 days. (At larger orbital periods some H-He can survive, see Appendix B and Paper 1). Since water is not removed in model A, the few planets falling in the valley/second peak of that case are half-rock/half-water (Fig. 5).

To understand the composition of second-peak planets coming from evaporation model B, we plot in Fig. 6 the mass of water, rock, and the planet H-He mass fraction ($f_{\text{HHe}}$) just after formation (left panel) and after atmospheric mass-loss by evaporation (right panel). The only quantity that remains invariant between the two panels is the mass of rocks. The color of the circles’ border distinguishes between cases that end up in the first (yellow) or second peak (black). We analyse first the case after evaporation. First-peak planets are basically devoid of water and H-He. Regarding the second peak, most planets have water in similar amounts than rocks. These planets are not completely depleted of H-He, and have $f_{\text{HHe}}$ spanning 0.2% and 10%. Nevertheless, a few second-peak objects are basically dry and have a H-He mass fraction below 10%, as found by pure evaporation models.

It is also interesting to know if first/second-peak planets accreted from inside or outside the ice-line. The left panel of Fig. 6 shows the same quantities as the right one, but just after formation, before mass-loss takes place. The circles’ borders still indicate the posterior belonging to the first/second peak. We note that in this case where the semi-major axis is typically $a \approx 0.1$ au (see Appendix B), all second-peak objects were born water-rich (also clear from the lower-right panel of Fig. 5) that is, they migrated from beyond the ice-line. Interestingly, even though most first-peak planets were born dry (i.e., within the ice-line), a few also started with water that was then lost. This means that bare rocky cores could also originate beyond the ice-line and lose all their water.

The data was downloaded the 14th of July 2020.
volatile content (H-He and water) due to the stellar irradiation.
The amount of first-peak objects with this origin should decrease with increasing orbital period.

5. Discussion

We found that for the Radius Valley to exist, it is not mandatory that all planets are dry, as pure evolution models suggest. From a planet formation perspective, many of the existing super-Earths/sub-Neptunes are expected to form beyond the water ice-line, as shown in this work and many others (e.g. Alibert et al. 2013; Izidoro et al. 2019; Bitsch et al. 2019; Schlecker et al. 2020). Our results indicate that second-peak planets can be often half-water/half-rock with ~0.01-10% H-He by mass (Fig. 6).

In addition, planets in the first peak with periods within 10 days could actually have lost all their H-He and water, and remain as bare rocky cores. Thus, planets starting their formation beyond the ice-line can end up as purely rocky as well. Our study suggest that interpreting the origin of super-Earths/sub-Neptunes can be more cumbersome than previously thought.

When analysing the final mass-radius in Fig. 5, we note that the results of our models encompass the short-period exoplanet population. When combining formation and evaporation models, it seems difficult to obtain planets with mass of ~10-40 M⊕ and radius below Neptune. Nevertheless, such objects could be bare cores of half-water/half-rock if some missing mechanism could remove the gas during or after the formation. A process proposed to remove atmospheres completely during formation at short orbital periods is the ‘atmospheric recycling’ (Ormel et al. 2015; Lambrechts & Lega 2017; Cimerman et al. 2017), although recent work reports it not to occur in non-isothermal discs (Kurokawa & Tanigawa 2018). Another possibility is the accretion of planetesimals in addition to pebbles (Alibert et al. 2018; Venturini & Helled 2020). In such ‘hybrid scenario’ the heat released by planetesimals delays the accretion of gas once pebble accretion stops at isolation mass (Guilera et al. 2020). We show, in Appendix B, that such effect could reduce the mass of the envelope by a factor of ~2. Finally, we have neglected the effect of collisions, which can also remove gas, especially once the disc dissipates. We estimate the magnitude of collisions on the envelope-loss in Appendix D. We find that collisions could reduce the mass of the envelope by a factor of ~2.5 and that the Mass-Radius of the observed exoplanets is better reproduced when one giant impact takes place after disc dispersal. Too many collisions would promote compositional mixing, smearing out the Radius Valley (Schlecker et al. 2020; Van Eylen et al. 2018).

6. Conclusions

By studying pebble-based planet formation we found that the change of dust properties at the water ice-line renders two distinct populations of planetary cores, one rocky peaked at ~3 M⊕ with all masses below ~5 M⊕, and another icy, more spread and peaked at ~10 M⊕. Remarkably, when neglecting the presence of the gaseous envelopes, such mass-bimodality accounts naturally for the bimodal size distribution of the Kepler exoplanets.

When considering the formed planets with their envelopes, by computing the photoevaporation of the accreted atmospheres, we corroborate that such process can by itself render the correct radius gap. Nevertheless, contrary to pure evaporation studies, we find that the gap separates (typically) dry from wet planets, provided that water mixes in the gaseous envelope. Future atmospheric characterisation with JWST and ARIEL will be crucial to learn how water-rich/poor second-peak exoplanets are, and will provide precious constraints for planet formation and evolution models.

By considering extreme-case scenarios with and without gaseous envelope, we find that the exoplanet population is fairly well bracketed by these end-members (Figure 5). This suggest, on one hand, that reality might be in between, and on the other, that much more effective gas-loss mechanisms might be at operation to explain planets with masses ranging ~10-40 M⊕ and falling on the second peak. The combination of different processes such as hybrid pebble-planetesimal accretion, collisions, photoevaporation and core-powered mass-loss into a single framework might be an important venue to bridge the gap between theory and observations.

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Fig. 4. Radius histogram of the synthetic planets with $P \leq 100$ days, after computing mass-loss by evaporation. Top panels: all population. Lower panels: zoom on radius between that of Earth and Neptune. Left panels: model A (evaporation of H-He envelopes). Right panels: model B (evaporation of H-He-H$_2$O envelopes). Red, blue and green indicate different initial water core fractions as in Fig. 3, and black lines the overall distributions. The grey dashed-line in the upper panels shows water-rich planets born in discs of $\alpha = 10^{-3}$.

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**Fig. 5.** Mass-radius of all the planets with final orbital period within 100 days. Filled circles with color (indicating the water mass fraction of the core after formation) correspond to the mass-radius of the cores of the planets (i.e., the envelope is neglected). The radius is calculated following Zeng et al. (2019) for this case. Magenta triangles show the results of evaporation of H-He after formation. Green diamonds show the same but assuming mass-loss of H, He and H$_2$O. Grey small circles are true exoplanets with orbital periods within 100 days, planet radius below 12 R$_{\oplus}$, error in radius of less than 20% and error in mass of less than 75% (taken from the NASA Exoplanet Archive, July, 14th, 2020).

**Fig. 6.** Water versus rock content after formation (left) and after evolution (right). The color-bar indicates the planet H-He mass fraction at each corresponding epoch. Yellow-line circles represent cases that end up in the first peak ($1 < R_p \leq 1.7$) and black-line circles cases that finish in the second peak ($1.7 < R_p < 4$).
observations of Andrews et al. (2010): We adopt the initial gas surface density profile inferred from the Appendix A: Disc parameters and initial conditions

\[ \Sigma_g = \frac{\Sigma_0}{r_c} - \frac{\gamma}{r_c^\gamma} e^{-\frac{r}{r_c}} \]

where \( \Sigma_g \) is a normalisation parameter determined by the disc initial mass \( (M_{d,0}) \), \( \gamma \) is the exponent that represents the surface density gradient and \( R_c \) is the characteristic radius of the disc. All the disc parameters are taken from Andrews et al. (2010) and are shown in Table A.1 with their corresponding lifetime \( (\tau) \) and initial ice-line position \( (r_{icel}) \). For the viscosity we consider \( \alpha = 10^{-3} \) and \( \alpha = 10^{-1} \). Only the low-alpha case produces pure rocky planets, as shown in Paper I.

We run simulations for all the discs with lifetimes between 1 and 12 Myr (19 discs), for which we consider the initial dust-to-gas ratios shown in Table A.2. Such wide range in dust-to-gas ratios or metallicities spans the metallicities of planet-host stars (Petigura et al. 2018). We launch 7 embryos per disc (one embryo at a time), with initial semi-major axes of \( a_{ini} = 0.5, 1, 3 \), \( r_{icel} = 0.1, r_{icel} + 0.1, 4, 8 \) and 16 au.

Appendix B: Dependence on the disc inner edge

The inner border of the disc determines the minimum semi-major axis that planets can attain by inward migration. When planets migrate in resonant chains, the innermost planet tends to stop its migration at or near the edge of the protoplanetary disc (Cossou et al. 2014), although outwards migration can also occur due to the expansion of the inner cavity during disc dispersal (Liu & Ormel 2017). Since we do not include N-body interactions nor the effect of the magnetic cavity in our calculations, most planets tend to park near the disc inner edge, assumed as \( r_{ini} = 0.1 \) au in our nominal set-up (all figures of main text). The final planet’s position affects mainly the photoevaporation rate and hence the final mass of a planet’s atmosphere.

Despite that the innermost exoplanet of planetary systems is typically found at \( a \approx 0.1 \) au (Mulders et al. 2018), the mean orbital period of second-peak exoplanets is \( \approx 38 \) days (Martinez et al. 2019), which corresponds to \( a \approx 0.22 \) au for Solar-type star. We therefore repeat the simulations with \( r_{ini} = 0.2 \) au, together with the histograms of Fig 4 for Model B. Both histograms (nominal set-up and \( r_{ini} = 0.2 \) au) are shown in Fig B.1. We note that for \( r_{ini} = 0.2 \) au some planets that formed inside the water ice line (and are therefore devoid of water, the red bars) end up in the second peak, meaning that they retain some H-He atmosphere. The longer the orbital period, the larger the amount of rocky-to-icy objects that should contribute to the second peak. Future work with population synthesis will be able to quantify this precisely and give quantitative predictions.

Appendix C: Planet formation by the hybrid accretion of pebbles and planetesimals

When the planet reaches the pebble isolation mass and pebble accretion is halted, the accretion of gas onto the planet is triggered (Koma et al. 2000, Guidera et al. 2020). However, if planetesimals form in the same disc, the heat released by their accretion can significantly reduce the planet’s gas accretion (e.g. Allibert et al. 2018, Venturini & Helled 2020, Guidera et al. 2020). Moreover, if a non negligible amount of pebbles is transformed into planetesimals, the growth of the planet’s core could also be affected.

In order to quantify how the hybrid accretion of pebbles and planetesimals can reduce the gas accretion by the planet, or modify the core growth, we implement, following Voelkel et al. (2020), the planetesimal formation model based in the flux of pebbles along the disc (Lenz et al. 2019). Thus, we compute now the hybrid accretion of pebbles and planetesimals (the details of such implementation will be shown in a forthcoming paper). As in Voelkel et al. (2020), we find that the formed planetesimals distribute in a very steep profile in the inner regions of the disc. This is depicted in Fig C.1 where we plot the evolution of the radial profiles of the surface density of dust/pebbles (the solid lines) and planetesimals (the dashed lines) for disc 1 of Table A.1 using \( \alpha = 10^{-3} \) and \( Z_0 = 0.0144 \) (same disc as in Fig 1).

Next, we compare the growth of a planet by pure pebble versus hybrid pebble-planetesimal accretion, for the planet of Fig 4 starting its formation at \( a_{ini} = 4 \) au. The top of Fig C.2 shows the growth of the core (solid lines) and envelope (dashed lines). The black lines correspond to the case where the core grows by pure pebble accretion. The red lines represent the new case where planetesimal formation and the hybrid accretion of pebbles and planetesimals are considered. We note that in both cases the growth and migration pathways are similar. However, for the hybrid case, solid accretion continues beyond pebble isolation mass, due to planetesimal accretion. Despite of reaching similar final core masses, in the pure pebble case the final envelope mass is approximately 11 M_\oplus, whereas for the hybrid case M_{env} = 5 M_\oplus.

Appendix D: Envelope mass-loss by giant impacts

Giant collisions, which may be important at the time of disc dispersal (Ogihara et al. 2020), represent, in addition to photoevaporation, a possible mechanism that could help removing a planet’s atmosphere. Although we did not consider collisions in our simulations since we formed only one planet per simulation,
Table A.1. Observed discs from Andrews et al. (2010) with their parameters and corresponding lifetimes and initial ice-line positions.

| Disc number | $\gamma$ | $M_{d,0}$ [M$_{\odot}$] | $r_c$ [au] | $\alpha = 10^{-3}$ $\tau$ [Myr] $r_{\text{ice}}$ [au] | $\alpha = 10^{-4}$ $\tau$ [Myr] $r_{\text{ice}}$ [au] |
|-------------|----------|--------------------------|------------|----------------------------|----------------------------|
| 1           | 0.9      | 0.029                    | 46.0       | 1.73 2.47                  | 3.54 1.74                  |
| 2           | 0.9      | 0.117                    | 127.0      | 7.24 2.79                  | 8.84 1.87                  |
| 3           | 0.7      | 0.143                    | 198.0      | 9.08 1.89                  | 11.07 1.53                 |
| 4           | 0.4      | 0.028                    | 126.0      | 2.03 1.38                  | 3.16 1.37                  |
| 5           | 0.9      | 0.136                    | 80.0       | 7.62 3.79                  | 9.63 2.30                  |
| 6           | 1.0      | 0.077                    | 153.0      | 4.93 2.47                  | 6.47 1.75                  |
| 7           | 0.8      | 0.029                    | 33.0       | 1.61 2.68                  | 3.65 1.81                  |
| 8           | 0.8      | 0.004                    | 20.0       | 0.39 1.66                  | 1.75 1.47                  |
| 9           | 1.0      | 0.012                    | 26.0       | 0.80 2.30                  | 3.25 1.69                  |
| 10          | 1.1      | 0.007                    | 26.0       | 0.59 2.01                  | 3.00 1.59                  |
| 11          | 1.1      | 0.007                    | 38.0       | 0.56 1.84                  | 2.87 1.53                  |
| 12          | 0.8      | 0.011                    | 14.0       | 0.78 2.65                  | 3.51 1.81                  |

Fig. B.1. Same as bottom-right panel of Fig. 4, but comparing the nominal case ($r_{\text{in}} = 0.1$ au, left panel) with the case where $r_{\text{in}} = 0.2$ au (right).

Table A.2. Adopted initial dust-to-gas ratio or disc metallicity ($Z_0$) and the corresponding [Fe/H].

| $Z_0$      | [Fe/H] |
|------------|--------|
| 0.0008     | -0.350 |
| 0.0099     | -0.185 |
| 0.0144     | -0.025 |
| 0.0210     | 0.138  |
| 0.0305     | 0.300  |

we can estimate in a simple way, the fraction of envelope mass-loss a planet could suffer if we allowed it to collide with another, less-massive planet, formed isolated in the same disc. These "hypothetical" collisions could happen within the first million years of evolution after gas dissipation and before substantial photoevaporation takes place (Izidoro et al. 2017, 2019). The goal is to compute the envelope mass-loss of a planet due to a possible collision plus the subsequent atmospheric-loss due to evaporation, to explore how Fig. 5 could be affected.

Following the same procedure as in Ronco et al. (2017) (see their Sec. 2.2.3), we compute the core mass of the collision remnant as the sum of the core masses of the target and the impactor. The final gaseous envelope is computed following Inamdar & Schlichting (2015), who calculated the global atmospheric mass-loss fraction for planets with masses in the range of the SuperEarths and Mini-Neptunes. Although this study does not provide mass-loss fractions for collisions with gas giant planets with extended atmospheres, we use the same results due to lack of works in the area.

For simplicity and following the results of Oghiara & Hori (2020), who report only one or two giant impacts when accounting for N-body interactions, we allow only one collision per planet, but compute all the possible results of that collision considering that all the less-massive planets in the same disc (with final periods < 100 days), can be the impactor.

We compute mean values for the core mass, envelope mass and core ice fraction for each "family of impacts". The percentage of the envelope mass-loss due to impacts ranges between 12% to 98% with a mean of 62%. If, for each family of impacts we consider the most destructive one, this is the one that generates the maximum envelope mass-loss, the percentage of the envelope mass-loss ranges between 15% to 100%, with a mean value of 80% for this latter case.

After computing collisions, we compute the mass-loss due to photoevaporation (only with Model B) for the mean and maximum values of each family of impacts. In Fig. D.1 which is sim-
Fig. C.1. Evolution of the radial profiles of the surface density of dust/pebbles (solid lines) and planetesimals (dashed lines) of disc 1 (see Table A.1), with $\alpha = 10^{-4}$ and $Z_0 = 0.0144$. Initially, all the solid mass of the disc is in the form of dust (the black line). As dust grows into pebbles, the flux of pebbles drifting inward forms planetesimals very efficiently in the inner region of the disc, generating a steep planetesimal surface density profile in such region. From $5.0 \times 10^5$ yr, the resulting planetesimal surface density is of about one order of magnitude higher than the initial solid surface density. After $5.0 \times 10^5$ yr, the planetesimal surface density remains almost constant. For simplicity, this simulation does not consider planet formation.

Fig. C.2. Top: evolution of the core mass (solid lines) and envelope mass (dashed lines) for the growth of a planet initially located at 4 au in the disc corresponding to Fig. C.1. Black lines: pure pebble accretion. Red lines: hybrid accretion of pebbles and planetesimals. The black and red circles represent the pebble isolation mass. Bottom: evolution of the planet’s semi-major axis. The black and red squares represent the time and the planet’s semi-major axis when the planets open a gap in the gaseous disc.
Fig. D.1. Same as Fig. 5 but showing only model B from that figure (green diamonds), plus the results of hypothetical giant impacts followed by photoevaporation. The violet diamonds represent the planets that suffered the maximum envelope mass-loss due to a collision, and the lilac ones represent the mean values of envelope mass-loss for each family of collisions. The colored squares are the planets that lost their entire envelope after a collision, and the colored circles are those that lost their entire envelope after collision plus photoevaporation. The color scale represents the ice mass fraction in the naked cores of only the cases where we considered collisions (circles and squares). The grey dots represent the observed exoplanet population as in Fig. 5.