EPSC Abstracts
Vol. 12, EPSC2018-59, 2018
European Planetary Science Congress 2018

Metalicity effect and planet mass function in pebble-based planet formation models

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Abstract

Adopting the Bitsch et al. 2015 disc model we use a population synthesis approach to compare the formed planets with observations. We find that keeping the same parameters as in Bitsch et al. 2015 leads to no planet growth. Indeed a large fraction of the heavy elements should be put into pebbles in order to form massive planets using this approach. The resulting mass functions show a huge amount of giants and a lack of Neptune mass planets, which are abundant according to observations. To overcome this issue we include the computation of the internal structure for the planetary atmosphere to our model. This leads to the formation of Neptune mass planets but no observable giants. Reducing the opacity of the planetary envelope finally matches observations better. Using this model we observe a metalicity impact.

1. Introduction

One of the main scenarios of planet formation is the core accretion model where first a massive core forms accreting solids, either planetesimals or pebbles, and then accretes a gaseous envelope. Classical planetesimal accretion scenario predicts that the time needed to form a giant planet's core is much longer than expected disc lifetimes. This leads to the development of another scenario, in which cores grow by accreting pebbles, which are much smaller and thus more easily trapped by the planets gravity before being accreted, leading to more rapid formation of the core.

2. Bitsch et al. 2015 model

We initially use the disc model given by Bitsch et al. 2015 (B15). To test our implementation we aimed to reproduce their results and, getting encouraging results by recreating their gas disc model, we compared the planet growth (Fig. 1). The outcomes are completely different: no planets grow. The issue comes from the computation of the pebble flux , which should be evaluated at the pebble growth radius r_g and not at the location of the planet:

$$\dot{M}_{\mathrm{pebbles}}(r) = 2\pi r_{\mathrm{g}} \frac{dr_{\mathrm{g}}}{dt} Z_{\mathrm{peb}}(r_{\mathrm{g}}) \Sigma_{\mathrm{gas}}(r_{\mathrm{g}}) \qquad (1)$$

Applying the wrong flux equation (taking $\Sigma_{\mathrm{gas}}(r)$ instead of $\Sigma_{\mathrm{gas}}(r_{\mathrm{g}})$) in our model allows us to reproduce B15 results (the thin and thick lines in Fig. 1 overlap).

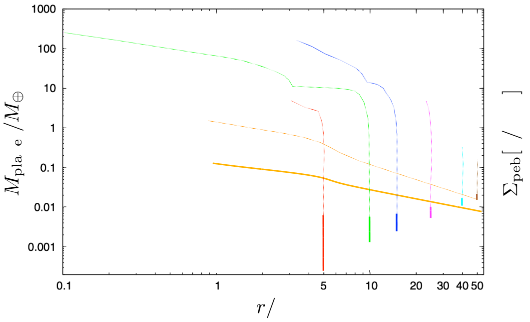

Figure 1: Planet growth comparison for the results of B15 (thin lines) and our results (thick lines).

3. Increasing the amount of pebbles

With a view of forming planets and using the correct equation for the flux of pebbles, we increase the amount of solids that form pebbles. We decide to put 90% of the total amount of solids into pebbles and 10% into dust. This ratio allows the formation of giant planets and prevent the migration from being too efficient. However, comparison with observations shows a lack of Neptune mass planets.

4. Solving the internal structure of the planet

In the B15 model the internal structure is very simple: once the planet has reached the pebble isolation mass, a rapid gas accretion phase starts. In reality, if the isolation mass is small, once it is reached, the envelope contracts. We thus compute the internal structure of the planet. The resulting mass function yields a significant amount of Neptune mass planets, in agreement with observations, but also a total absence of giant planets.

5. Decreasing opacity

An alternative to form giants is the reduction of the opacity of the planet's atmosphere. There are observational hints that this opacity is much smaller than the full interstellar one (Mordasini et al. 2014), which is used in our nominal case. We therefore apply a reduction factor ($f_{\rm opa} = 0.01$). Figure 2 gives the mass functions of the formed planets using the full interstellar opacity and the reduced one. Applying a detection probability given by Mayor et al. 2011 we see that the fraction of planets with masses higher than 20 $M_\oplus$ is significant and a high amount of giant planets are observable.

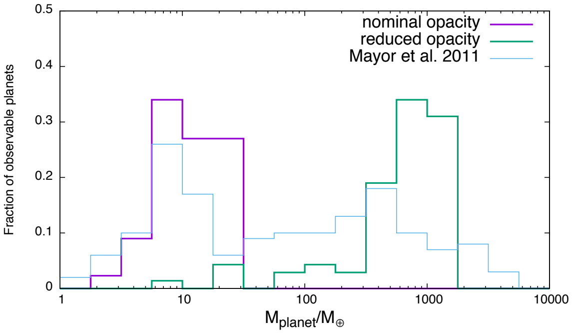

Figure 2: Fraction of observable planets solving the internal structure and using a reduced opacity.

6. Metallicity effect

We then discuss the well established metallicity effect for our internal structure model with a reduced opacity. We see in Fig. 3 that the amount of giant planets increases with metallicity. For metallicities up to $[\mathrm{Fe/H}] = 0,3$, no planet is observable. Comparing the red and blue curves, we see that a fraction of formed planets (red curve) may be lost in the star (difference between red and blue).

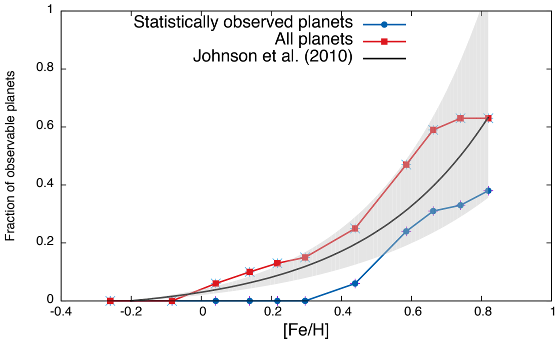

Figure 3: Fraction of planets with radial velocity higher than 20 m/s as a function of the metallicity.

7. Summary and Conclusions

Using the B15 model, the amount of pebbles in the disc should be increased in order to form planets. This model forms mainly giant planets and no Neptune-mass planets. Solving the internal structure equations settles the lack of Neptunes but no giants are created anymore. By reducing the opacity in the model solving the internal structure equations it favours the formation of planets with masses above 20 $M_\oplus$ as well as giant planets. We thus use this last model to discuss the metallicity effect and show that the amount of giant planets increases with the metallicity.

Acknowledgements

This work has been carried out within the frame of the National Centre for Competence in Research PlanetS supported by the Swiss National Science Foundation. The authors acknowledge the financial support of the SNSF.

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