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Quasi-static contraction during runaway gas accretion onto giant planets

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Abstract

In this work, we use 3D hydrodynamical simulations, that include radiative transfer, to model the growth of the envelope on planets with different masses in the gas-giant regime. We find that gas accretion is the result of quasi-static contraction of the inner envelope, which can be orders of magnitude smaller than the mass flow through the outer atmosphere. For planets less massive than Saturn, we measure gas accretion rates that are below 1 Jupiter mass per Myr. However, planets in the Jupiter-mass regime accrete up to 10 times faster. Given that the lifetimes of protoplanetary are several Myr long, the reason for the final masses of Saturn and Jupiter remain difficult to understand, unless their completion coincided with the dissipation of the Solar Nebula.

1. Introduction

In the core accretion scenario [5], giant planets emerge after a core of approximately 10 Earth masses is build up through the accretion of solids. This then triggers a phase of so-called runaway gas accretion. In this way, gas-giant planets, like Jupiter and Saturn, acquire massive gaseous envelopes within the approximately 3 Myr-long lifetimes of protoplanetary discs.

The process of runaway gas accretion was initially only studied in 1D time-evolution models, that assume planetary atmospheres are in hydrostatic balance at alltimes [5]. Later, hydrodynamical models in 3D demonstrated that hydrostatic balance is a problematic assumption, because discs easily provide gas to the Hill sphere around accreting cores [1, 6]. Recently, gas flows through atmospheres of low-mass planets, with envelope masses less than the core mass, have been studied in more detail [7, 4, 2, 3], which has inspired us to explore now the high-mass regime towards gas giant planets.

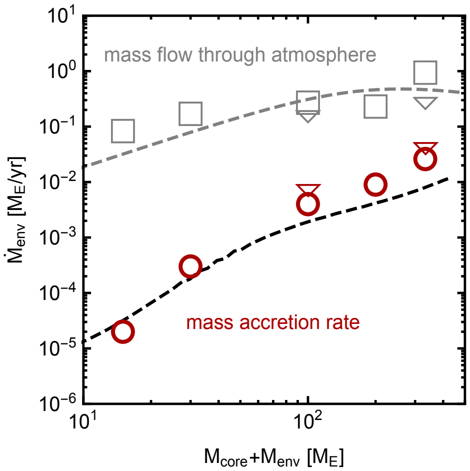

Figure 1: Gas accretion rates as function of planetary mass. Red circles indicate mass accretion rates obtained from the hydrodynamical simulations, for each of the different planetary masses we probed. Gray squares represent the measured mass flux through the outer envelope, measured through the Hill sphere. Gray and red triangles correspond to results from our highest resolution runs. The black dashed curve shows the evolution of the mass accretion rate obtained with a simplified 1D model in order to capture the long-term evolution. The gray dashed line shows the expression by [8] which we found corresponds well with the bulk mass flux through the envelope, but not with the gas accretion rate.

2. Results

We have numerically investigated how giant planets accrete their gaseous envelopes, for different planets between 15 Earth masses and 1 Jupiter mass (Figure 1). The accretion rate of material onto the inner bounded envelope is between 2 to 4 orders of magnitude lower than mass flux of gas through the Hill sphere. Moreover, the effective accretion rate shows a different scaling relation with planetary mass compared to the mass flux through the Hill sphere. Therefore, the complex 3D gas flow in the outer envelope is limited to the advection of gas in and out of the Hill sphere. This flow does not dictate the gas accretion rate onto the planet. Instead, gas accretion is the result of quasi-static contraction of a nearly hydrostatic envelope that is located within the inner $\sim 30\,\%$ of the Hill radius.

By combining snapshot measurements of gas accretion rates onto different planetary masses, we calculate that, after the emergence of an approximately $15\,\mathrm{M_E}$-planet, the formation of a Jupiter-mass planet can occur within approximately 2×10^5 yr at 5 AU. However, these growth rates are dependent on the assumed opacity (here assumed to be ISM-like), viscosity, gas surface density, equation of state (the adiabatic index), and how centrally condensed the deep interior is (the smoothing parameter).

3. Discussion

In the parameter regime explored in this study, we do not identify a strong reduction in the gas accretion rate due to process of disc gap formation. This implies that the final masses of the giant planets are most naturally explained because these planets only had access to a limited gas reservoir. Possibly, this is because of late formation in a depleted disc near the end of the protoplanetary disc lifetime or because planets form in stratified low-viscosity discs where accretion and migration may be slower. This presents a promising avenue for future work.

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