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# 3D Radiation Hydrodynamics simulations of gas accretion onto Saturn mass planets

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## Abstract

In order to clarify the dependency of gas accretion rates onto protoplanetary cores on three different important parameters, we present a set of 3D radiation hydrodynamics simulations. We first present a resolution study from which a resolution criterion for reliable gas accretion rate measurment emerges. We then discuss the changing physics of envelope structures as envelope opacities are varied. In agreement with earlier work, our resulting accretion rate measurments indicate rapid gas accretion at the stage when a protoplanet reaches a Saturn mass, indicating this stage is short-lived.

## Introduction

Gas accretion rates onto protoplanets are an important ingredient in the theory of the evolution of solar systems, and are also relevant for the interpretation of luminosities of observed protoplanetary growth candidates. Therefore a thorough physical understanding of how simulations generate both those quantities, gas accretion rates $\dot{M}$ and luminosities $L$, needs to be established, as simulation frameworks grow more and more sophisticated.

## Methods

To this end, we present a set of grid-based, global 3D radiation hydrodynamics simulations with FARGOCA (see [1]), which compute $\dot{M}$ and $L$ in a self-consistent manner through establishing heating-cooling equilibria. Important free parameters are the opacity $\kappa$, resolution of the Hill-sphere $N_{\rm c}$ and the gravitational smoothing length $r_{\rm s}$, the latter gives the potential depth of the planetary potential. The focus of this work lies on a detailed understanding of the impact of those parameters on $\dot{M}$ and $L$. We measure both those quantities independently by following the accumulation of mass in the planetary envelope with time for $\dot{M}$, and computing the optically thin-thick transition surface for $L$.

## Results

We find it to be critical to resolve the Hill-sphere, and particularly the smoothing length sufficiently well, otherwise gas accretion rates are underestimated, or even stalled.

We find the physics that need to be resolved inside the smoothing length to be related to the properties of the accretion flow. Once it reaches the smoothing length region near the planet, the infalling gas settles into a slow overturning circulation. This motion exhibits a finite amount of shear that, together with the physical viscosity of the simulation, heats the envelope. If underresolved, the amount of viscous heating from this region can be drastically overestimated, leading to an envelope structure that is close to hydrostatic. This can prevent further gas accretion, as the radiated luminosity is then provided artificially by the viscous heat instead of compressional work.

Our results for the numerical parameters $N_{\rm c}$ and $r_{\rm s}$ are summarized in fig. 1 and those results indicate there exists a common resolution criterion when using viscosity in radiation hydrodynamics settings, which we specify as 10 cells per smoothing length.

Our results show a weak dependency of the gas accretion rates on the used opacities, which behave according to $\dot{m} \propto \kappa^{0.25}$. This trend is in agreement with earlier work by [2] for Saturn-mass planets and is an intermediate result between $\dot{m} \propto \kappa^{0.5}$ for $20 m_{\oplus}$ planets and $\dot{M} \propto const.$ for Jovian masses, as found by [2]. We find that the simple relation

$$\dot{M} = \frac{r_s L}{G M_p} \quad (1)$$

with $M_p$ being the planetary mass, holds. Typical values of $\dot{M} \approx 0.01 m_{\oplus} yr^{-1}$ for Saturn-mass planets and an opacity of $\kappa = 0.01 cm^2 g^{-1}$. For well-resolved simulations, deepening the gravitational potential $r_s$ decreases the accretion rates by non-negligible amounts (see the red and blue line fig.1), so that we estimate realistic accretion rates to be one order of magnitude lower. This can be explained as $L$, as a result of the temperature gradients in the envelope, is increasing less than the internal energy content of the envelope when deepening the planetary potential.

Flow structures into and through the planetary Hill-sphere in a radiation hydrodynamics setting differ from traditional isothermal computations (see also the comparison in [3]), as the surfaces of constant temperatures can become inclined to the surfaces of constant density. We find that in general, the planets accrete 90% of the mass through the midplane, while only 10% come in through the vertical direction, with a slight dependency on the opacities. Circulations inside the envelope can differ significantly when going from an opacity of $\kappa = 1.0 cm^2 g^{-1}$ to $\kappa = 0.01 cm^2 g^{-1}$.

# Implications for planet formation

In order to form a Jupiter-mass planet in 3 Myrs time, a uniform mass accretion rate of $\dot{M} \approx 10^{-4} m_{\oplus} yr^{-1}$ is required. Our results indicate very rapid formation of gas planets once the conditions for rapid gas accretion are given, thus the bottle neck for the formation of gas giants is the formation of planetary cores capable to transition into rapid gas accretion.

The changing flow structures at varying opacities might lead to interesting circulation phenomena in circumplanetary discs, which needs to be explored in further work.

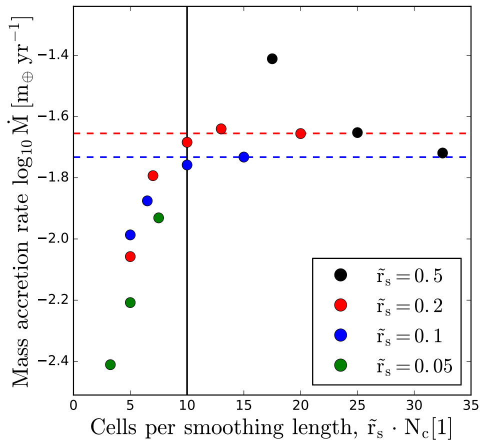


Figure 1: Plot of cells per smoothing length vs. the gas accretion rates. Different smoothing lengths are used as colour parameter. From the data it becomes clear that one needs to resolve the planetary smoothing length with at least 10 cells (black vertical line) to reach numerically convergent results. Red and blue dashed lines indicate the values towards which the accretion rates settle at sufficient resolution, which differ significantly from each other. Values for $\tilde{r}_s = 0.5$ are shown but excluded from the interpretation due to anomalous injection of shear into the planetary envelope.

# Acknowledgements

# References


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