Gas and Dust Dynamics during Planet Formation in HL Tau

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INTRODUCTION & AIM

The disc planet interaction and planetary formation in accretion discs have become a topic of renewed interest in the last decade, encouraged by the discovery of extra-solar planets, and in particular of hot Jupiters. Recent long-baseline ALMA (Atacama Large Millimeter Array) observations revealed a striking pattern of bright and dark rings in the protoplanetary disc surrounding the young star HL Tau. Our group has provided one of the earliest explanations of this system in terms of the interaction of the disc with three newly born planets (Dipierro et al, 2015).

The aim of this study is to develop a new model for gas and dust distribution within this disc. This work is focused on identifying the mass of the planets able to carve gaps in HL Tau, in the three main ring-like structures observed by ALMA.

STEP 1: FROM OBSERVATIONS TO THE THEORETICAL MODEL

The key to figure out the nature of these substructures is based on the investigation of the spatial distribution of the dust and the gas phases within protoplanetary discs. I therefore derived a new theoretical model to describe the disc surrounding HL Tau, taking into account the most recent observational constraints (Kwon et al, 2011 and 2015; Pinte et al, 2016; Carrasco-Gonzàlez et al, 2016).

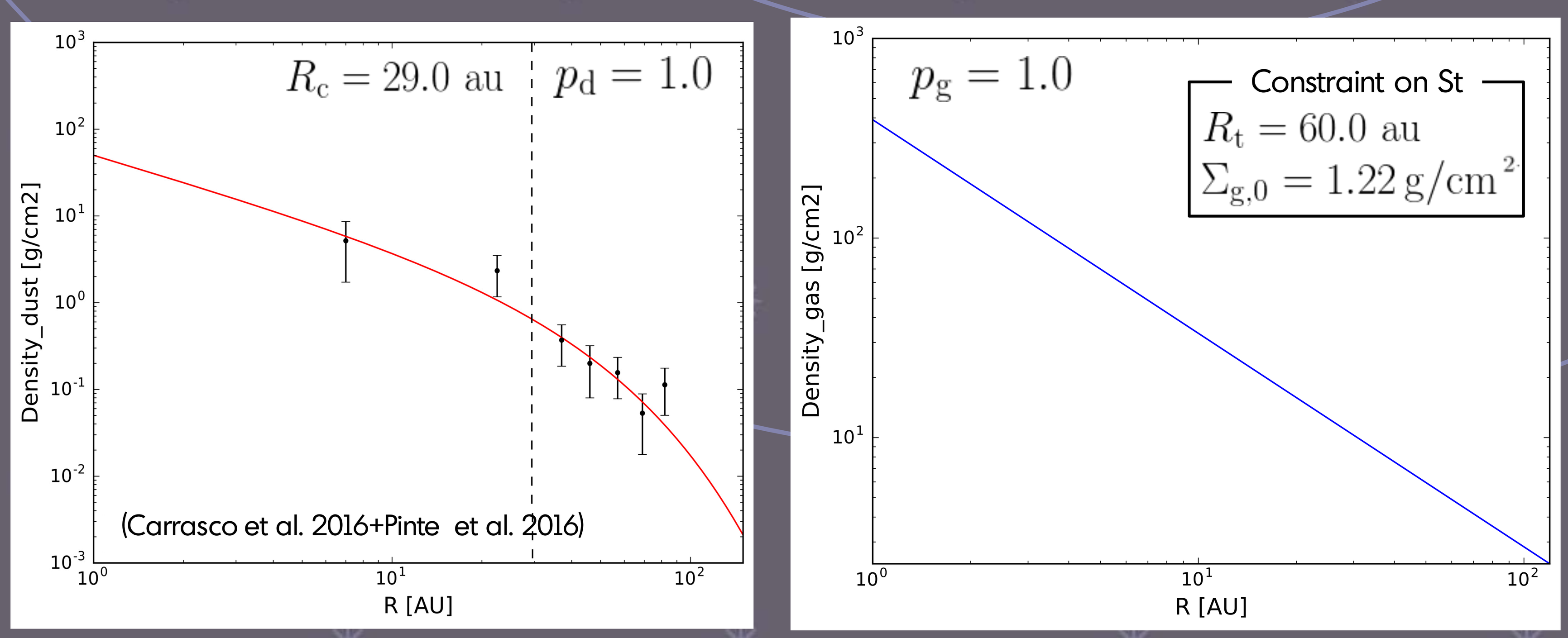

Figure 1: Surface density profile of dust (left) and gas (right) components. Black dots refer to observational data and the fitting red line is a power law tapered by an exponential function.

STEP 2: 3D SPH SIMULATIONS

In order to reproduce the observed structures, I performed global 3D Smoothed Particle Hydrodynamics simulations of both gas and dust (with PHANTOM, Price et al, 2017). The protoplanetary disc hosts one or more embedded planets.

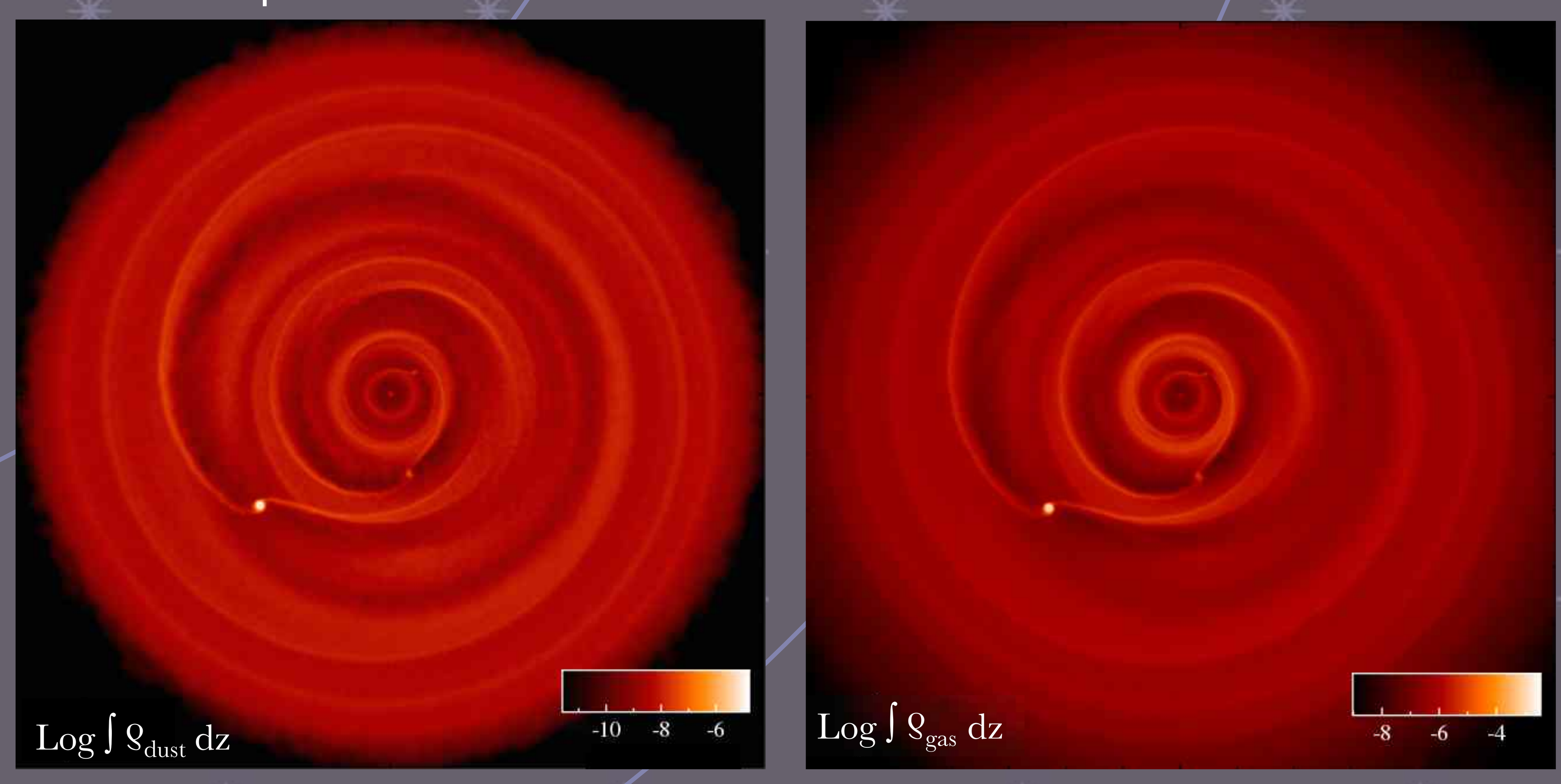

Figure 2: Rendered images of a disc with three embedded planets at orbital radii of 13.2, 32.3 and 68.8 au. The masses estimated for each planet are 0.5, 0.7 and 1.0 M_J. After ~11 orbits of the outer planet, shallow gaps can be observed in the dust phase (left panel). The gas develops similar but smoother structures (right panel).

STEP 3: RADMC3D+CASA

Moreover, I computed the expected emission of the disc model through radiative transfer simulations. I also simulate realistic ALMA observations of the adopted theoretical model in order to compare ALMA predictions with real data.

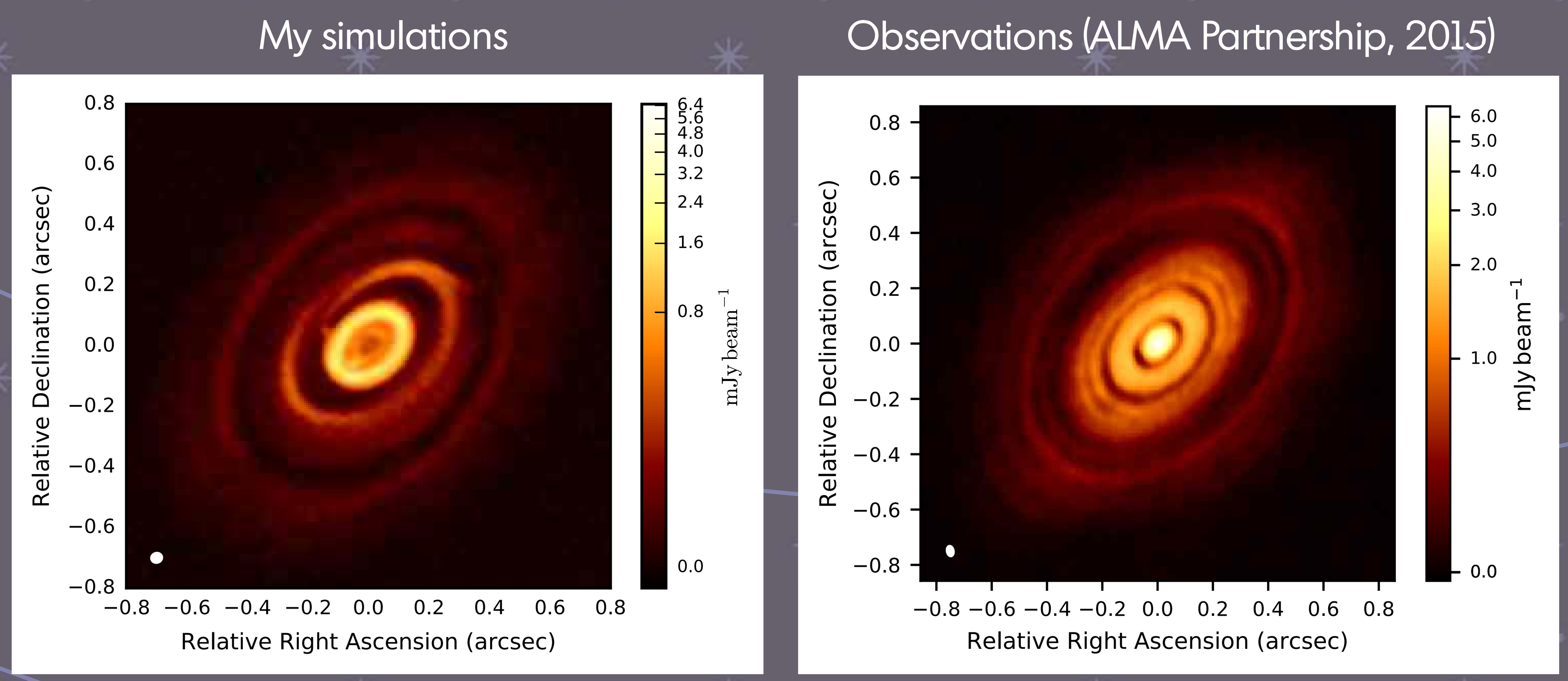

Figure 3: Comparisons between the simulated observations of our disc model at the ALMA Band 6 (left panel) with the ALMA image of HL Tau (right panel). The white colour in the filled ellipse in the lower left corner indicates the size of the half-power contour of the synthesized beam.

VIOLATION OF DUST MASS CONSERVATION + 1D NDSPMHD SIMULATIONS

During my work, I have discovered that my hydrodynamics simulations are affected by the dust mass not being conserved. This unphysical effect is clearly visible at large radii in the upper layers of the disc and it is important to find the cause. I therefore derived new implementations of the variable describing the dust fraction in the code. Then I performed 1D SPH simulations reproducing the dust settling, in order to test these new implementations.

$$\epsilon = \sin^2\theta \qquad\qquad \epsilon = \frac{1}{2}\left[1 + \tanh\left(2x - 1\right)\right]$$

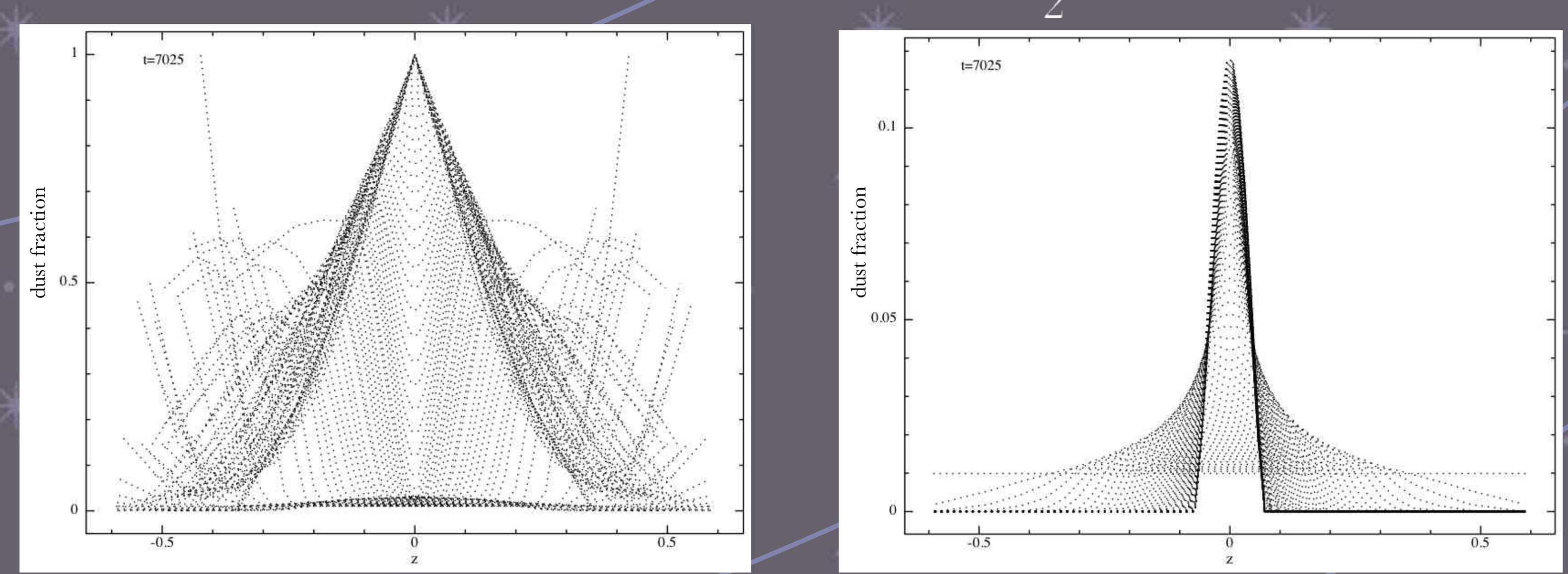

Figure 4: 1D simulations of dust settling performed with NDSPMHD (Price, 2012). Each panel shows the evolution of the dust fraction for two different functions, after 50 orbits. The horizontal axis is the disc scale height z. As we can see in the right panel, dust settles successfully towards the mid-plane.

One of the latest implementations appears to be promising to resolve the numerical issue. It still needs to be computed in the code.

$$\epsilon = \frac{s^2}{\rho + s^2} \qquad \frac{\mathrm{d}s}{\mathrm{d}t} = -\frac{1}{2}\frac{1}{(1-\epsilon)^2}\nabla\cdot\left(\frac{s(1-\epsilon)}{\rho}t_s\nabla P\right) - \frac{t_s}{2\rho}\frac{1}{(1-\epsilon)}\nabla P\cdot\nabla s - \frac{s}{2}\nabla\cdot\mathbf{v}$$

RESULTS

Comparing our results with the real data measured by ALMA, we can notice that there is a good accordance between the intensity scales. This means that our estimate for the dust mass is good. However we are still too far in reproducing the observed cavities in HL Tau, with high precision. We propose this weakness is due to the low value of the Stokes number, currently preventing us from reaching a full and satisfying comprehension of the process of gaps formation in HL Tau.

TO BE CONTINUED...

REFERENCES

ALMA Partnership, 2015, ApJ, 808:L3; Carrasco-Gonzàlez et al, 2016, ApJ, 821:L16; Dipierro et al, 2015, MNRAS, 453:L73–L77; Kwon et al, 2011, ApJ, 741:3; Kwon et al, 2015, ApJ, 808:102; Pinte et al, 2016, ApJ, 816:25; Price, 2012, Journal of Computational Physics, 231:759–794; Price et al, 2017, eprint arXiv.