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BACK-REACTION OF DUST ON GAS IN PROTOPLANETARY DISCS: CRUCIAL, YET OFTEN OVERLOOKED

J.-F. Gonzalez[1], G. Laibe[1] and S. T. Maddison[2]

Abstract. We show that the back-reacting drag of dust on gas in protoplanetary discs has strong effects on the dynamics of both phases and should therefore not be neglected as is too often the case.

Keywords: hydrodynamics, methods: numerical, protoplanetary discs

1 Introduction

Protoplanetary discs around young stars, the birthplaces of planets, are made of gas and dust. The gas mass is usually considered to be 100 times larger than that of the dust, as is the case in the interstellar medium. As such, most studies of gas and dust dynamics in discs have taken into account the drag of gas on dust only and neglected its back-reaction, the drag of dust on gas (Weidenschilling 1977; Birnstiel et al. 2010). It is only in recent works that back-reaction has been included more systematically (Gonzalez et al. 2017; Kanagawa et al. 2017; Dipierro et al. 2018). Here, we stress the importance of back-reaction on the dynamics of both gas and dust as well as in the interpretation of disc observations.

2 Gas and dust radial velocities

The velocities of gas and dust in a protoplanetary disc, under the influence of the star's gravity and aerodynamic drag, were derived for an inviscid disc by Nakagawa et al. (1986) and for a viscous disc by Kanagawa et al. (2017); Dipierro & Laibe (2017). In the latter case, the radial velocities of gas and dust are:

$$v_{\mathrm{g},r} = -\frac{\epsilon\,\mathrm{St}}{(1+\epsilon)^2+\mathrm{St}^2}\,v_{\mathrm{drift}} + \frac{1+\epsilon+\mathrm{St}^2}{(1+\epsilon)^2+\mathrm{St}^2}\,v_{\mathrm{visc}} \text{ and } v_{\mathrm{d},r} = \frac{\mathrm{St}}{(1+\epsilon)^2+\mathrm{St}^2}\,v_{\mathrm{drift}} + \frac{1+\epsilon}{(1+\epsilon)^2+\mathrm{St}^2}\,v_{\mathrm{visc}}. \quad (2.1)$$

$\epsilon = \rho_\mathrm{d}/\rho_\mathrm{g}$ is the dust-to-gas ratio, where ρ_d and ρ_g are the volume densities of the dust and gas fluids, respectively. St is the Stokes number, i.e. the ratio of the drag stopping time to the Keplerian orbital period, and is proportional to the dust grain size s in the Epstein regime. v_{drift} is the optimal drift velocity obtained by Nakagawa et al. (1986) and v_{visc} is the viscous velocity derived by Lynden-Bell & Pringle (1974), with $v_{\mathrm{drift}}/v_{\mathrm{visc}} \sim 1/\alpha$ (Gonzalez et al. 2017), α being the Shakura & Sunyaev (1973) viscosity parameter. When $\epsilon \to 0$, the equations without back-reaction are recovered. When $\epsilon \neq 0$, back-reaction slows down the dust radial drift and modifies the gas motion. Its consequences include the streaming instability (Youdin & Goodman 2005; Johansen et al. 2007), or self-induced dust traps (Gonzalez et al. 2017).

Figure 1 displays maps of $v_{\mathrm{g},r}/|v_{\mathrm{visc}}|$ and $v_{\mathrm{d},r}/|v_{\mathrm{visc}}|$ in the (St, ϵ) plane for $\alpha = 10^{-2}$. The limit $\epsilon \to 0$ shows the well-know behaviour when back-reaction is neglected: both gas and dust flow inwards, with a maximum dust velocity for St ~ 1. However, as soon as ϵ reaches a few %, as seems to be the case in some discs (Williams & Best 2014), back-reaction completely changes the picture, making the gas flow outwards for $0.1 \lesssim \mathrm{St} \lesssim 10$, with larger velocities for increasing ϵ.

[1] Univ Lyon, Univ Lyon1, Ens de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, 69230, St-Genis-Laval, France
[2] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia

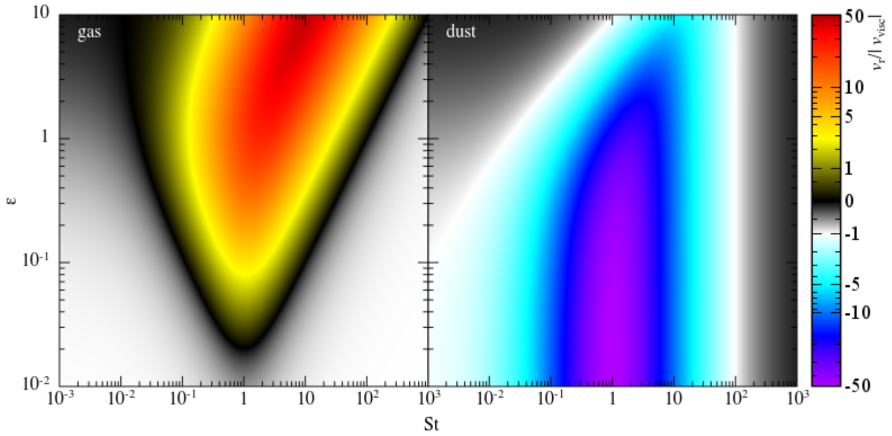

Fig. 1. Maps of the radial velocities of gas (**left**) and dust (**right**) relative to the absolute value of the viscous velocity in the (St, ϵ) plane for $\alpha = 10^{-2}$. The colorbar shows the values in a logarithmic-like scale preserving the sign: $\mathrm{sign}(x) \log(1 + |x|)$.

3 A practical case: a disc in a binary star system

In order to assess the back-reaction's influence on the interpretation of disc observations, we simulated a 0.003 $M_\odot$ disc around a 1.7 $M_\odot$ star in a system with a 0.3 $M_\odot$ companion star with the 3D SPH code Phantom (Price et al. 2017, 2018). We ran simulations with 5×10^5 gas particles and 5×10^4 dust particles representing 1 mm grains (for which $\mathrm{St} \sim 1$ in most of the disc) for 10 binary orbits, without back-reaction for $\epsilon = 1$ % and with back-reaction for $\epsilon = 1$, 3 and 5 %. Maps of the final gas and dust column densities are show in Fig. 2. While the gas is little affected, apart from a slight change in the contrast of the spiral arms, notable differences are seen in the dust. Whithout back-reaction, the dust ends up in a compact disc with dense (bright) rings at its edges whereas with back-reaction, the dust disc is more extended (all the more so as ϵ increases) and contains faint spiral arms. This practial case highlights the need to use the proper ingredients, in this case back-reaction, in simulations aiming at interpreting observations.

4 Conclusion

While most studies of gas and dust dynamics in protoplanetary discs, and their application to the interpretation of observations, neglect the back-reacting drag of dust on gas, we have shown that it is in fact very important. It changes drastically the location of dust grains in discs and, for dust-to-gas ratios of a few %, can alter the gas motion. Back-reaction should therefore be taken into account in studies of protoplanetary discs.

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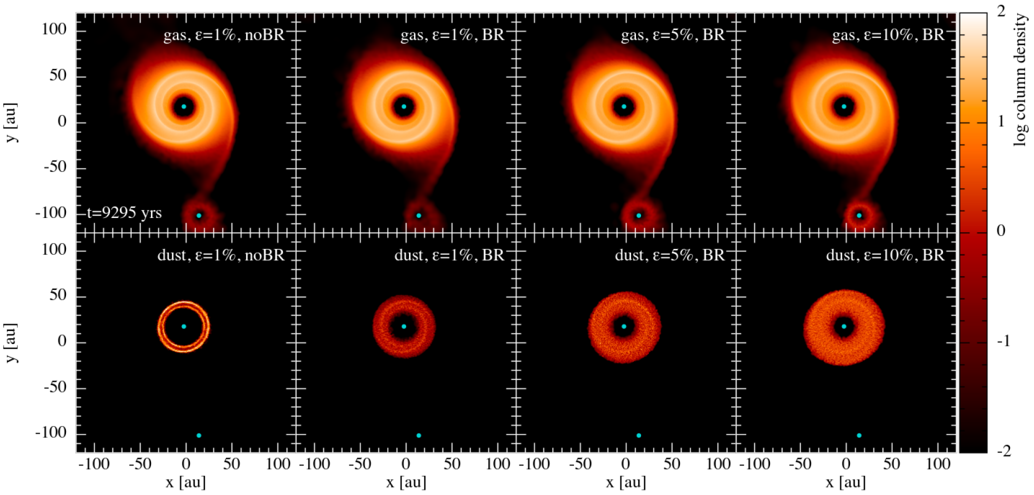

Fig. 2. Gas (**top**) and dust (**bottom**) column density maps in our simulations after 9295 yr (10 orbits) for simulations without back-reaction and $\epsilon = 0.01$, and with back-reaction for $\epsilon = 0.01$, 0.05 and 0.1 (**from left to right**).

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