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THE REFLEX INSTABILITY
OR
ON THE IMPORTANCE OF THE INERTIAL FORCES (INDIRECT TERM)

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Abstract. Gravitational systems in astrophysics often comprise a body that far outweights the others, like stars hosting a circumstellar disc, with or without planet. Such systems are most often studied in a reference frame centred on the primary. However, this is not an inertial frame, and the acceleration of the primary with respect to the centre of mass (often called indirect term) has to be taken into account. In Crida et al. (2022), we had shown that such a situation more rich and exciting as it seems, that the various contributions to the indirect term should be separated, and that which element they apply to should be decided with care (see also Crida et al. 2025b).

In this presentation, we will focus on the contribution of the circumstellar disc to the indirect term, when applied to the disc itself. We show that it leads to a feedback loop, which causes an exponential rise of the amplitude of an $m = 1$ mode in the disc, with the risk of a global destabilisation. The causes and consequences of this *reflex instability* will be discussed (Crida et al. 2025a).

Keywords: accretion, accretion discs — hydrodynamics — methods: numerical — planetary systems: formation — planetary systems: protoplanetary discs

1 Introduction : On the indirect term

What is it? The indirect term (or inertial forces) is a ficticious acceleration applied to all the elements of a system in order to describe correctly their motion in a non-inertial frame. This acceleration is opposite to that of the centre of the frame with respect to an inertial frame.

A classic example is the characters of Tintin's adventure "Explorers on the Moon" who appear to "fall" on the ground of the rocket (in the rocket's frame) when the engine is turned on.

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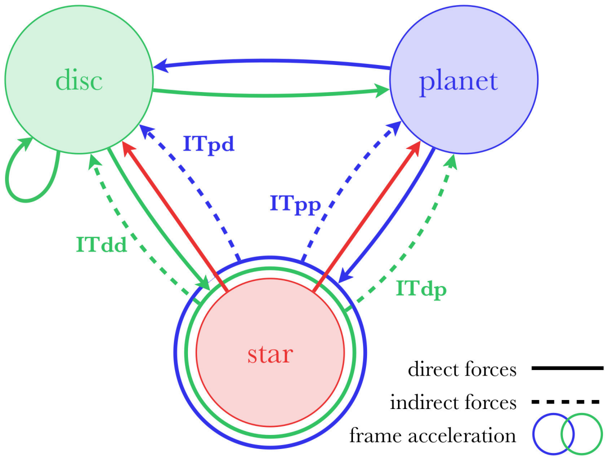

Fig. 1. Summary of all forces applied in a gravitational system comprised of a star, a protoplanetary disc and a planet, in a frame centred on the star. Solid arrows show direct gravitational forces, while dashed arrows show the corresponding indirect forces. Figure from Crida et al. (2025b).

Why do we care? In a numerical simulation of a proto-planetary disc around a star, the star is simply the punctual object of mass 1 at the centre of the frame. But this frame is not inertial since the star is accelerated by the planet(s) and the gas disc itself as soon as it is not axi-symmetric. Hence, an inertial force, often called *the indirect term* is applied.

Fig. 1 shows all the complexity of the situation. The direct gravity of the star (plain red lines) enforces Kepler's laws for the motion of the gas and the planets. The gravity of the planet has a direct effect on the gas disc (top plain blue line) – which creates a wake and/or a gap in the gas distribution – and accelerates the star (as indicated by the blue circle around the star) : this causes the indirect term from the planet, noted **ITp**. The latter can be applied to the planet itself (**ITpp**) or to the disc (**ITpd**, necessary to get the Lagrange equilibrium points) as shown by the dashed arrows. The same thing holds for the gravity of the gas disc (green).

More details on the various effects of each component of the Indirect Term can be found in Crida et al. (2025b), published the day before the SF2A conference and aimed at a pedagogical overview of the problem and a reference with a recipe on how to deal with indirect terms for future star-centred simulations.

2 The reflex instability

In this section, we focus on the role of **ITdd**. We performed many numerical simulations with only a gas disc (no planet), using different codes with various numerical schemes (grid or SPH, Godounov or Van Leer, with different boundary conditions), in a barycentric frame or a stello-centric frame with **ITdd**.

We keep the same physical set-up, though, that is a gloably isothermal disc extending from $0.32R_0$ to $3.125R_0$ (where R_0 is the length unit, while the mass unit is that of the central star, and we set the gravitationnal constant $G = 1$), with an initial surface density $\Sigma_0(r) = 4 \cdot 10^{-3}(r/R_0)^{-3/2}$ and aspect ratio $h(r) = 0.05(r/R_0)^{1/2}$. This corresponds to a uniform Toomre's Q parameter equal to 4, and a disc-to-star mass ratio of 0.06. Such a situation is supposed to be stable. Unless stated otherwise, the self-gravity of the gas is *not* computed.

In all the simulations, we observe an exponential rise of the star – barycentre distance, which is equivalent to the amplitude of an $m = 1$ mode in the gas disc, as illustrated in Fig. 2. The typical growth timescale is of the order of a hundred orbits at R_0, and scales in $\Sigma_0(R_0)^{-1}$. Adding the gas self-gravity does not change the result qualitatively : the instability still develops, but with a shorter timescale. When removing **ITdd**, or fixing the star at the centre of the frame in the barycentric codes, the instabilty disappears – independently of whether or not the self-gravity is computed or not.

This strongly suggests the existence of a positive feedback loop between a mode $m = 1$ in the disc density distribution* and the reflex motion of the star (a.k.a. the indirect term **ITdd**). The amplitude of the latter is proportionnal to Σ_0, and excites the gas motion.

*Modes $m > 1$ exert no acceleration on the star.

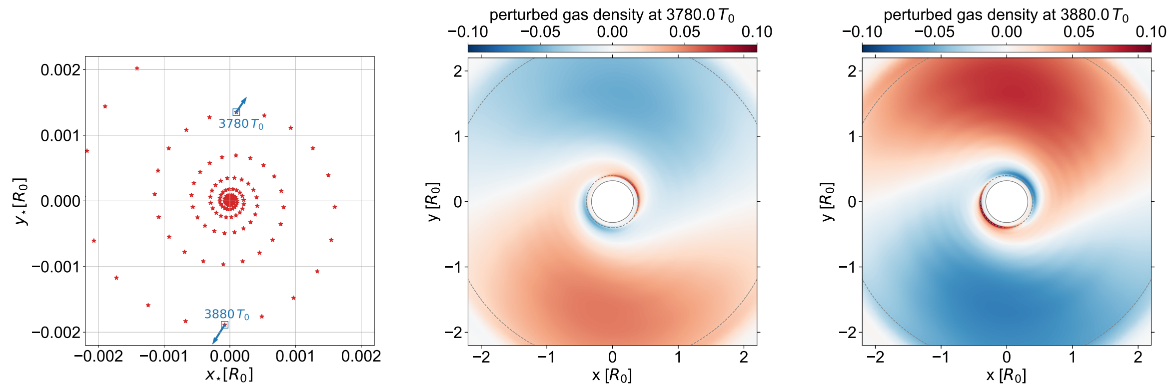

Fig. 2. Left: Position of the star in the barycentric frame at successive times. Centre and right: variations of the surface density with respect to the initial distribution, after 3780 and 3880 orbital periods at R_0 respectively. The acceleration exerted on the star is represented as arrows in the left panel. At each time, the outer mass excess (in red) dominates the position of the centre of mass of the disc, and the star is located opposite to this direction ; in contrast, the inner mass excess imposes the direction of the star acceleration. Figure from Crida et al. (2025a).

3 Conclusions

While we have not yet fuly identified all the ingredients of the feedback loop, we show in the appendix of Crida et al. (2025a, published just after the SF2A conference) how a constant acceleration of the frame linearly excites the eccentricity of a test particle initially on a circular orbit. If the acceleration is set proportionnal to the eccentricity, and in a direction between pericentre and apocentre in the direction of motion, the eccentricity rises exponentially.

Therefore, this reflex instability is probably of physical original and intrisic to discs around a massive primary body. Its timescale may limit the lifetime of massive proto-planetary discs, but even if some physical process limits its growth (e.g. a gap opened by a giant planet), it could still lead to the excitation of the eccentricity of the gas disc. In a future work, we plan to study the missing link in the feedback loop (the response of a gas disc to the acceleration of the star) and provide an analytical model and a linear analysis of the phenomenon.

In any case, this phenomenon seems unavoidable in numerical simulations with **ITdd**, so we warn the community that although the indirect term from the gas disc should be applied onto migrating planets in order to correctly describe their dynamical evolution, one may want to not apply it to the gas disc itself, in order to avoid this perturbation.

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