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Modeling circumstellar disc fragmentation and episodic protostellar accretion with smoothed particle hydrodynamics in cell

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ABSTRACT

We discuss the ability of the smoothed particle hydrodynamics (SPH) method combined with a grid-based solver for the Poisson equation to model mass accretion onto protostars in gravitationally unstable protostellar discs. We scrutinize important features of coupling the SPH with grid-based solvers and numerical issues associated with (1) large number of SPH neighbors and (2) relation between gravitational softening and hydrodynamic smoothing length.

We report results of our simulations of razor-thin disc prone to fragmentation and demonstrate that the algorithm being simple and homogeneous captures the target physical processes — disc gravitational fragmentation and accretion of gas onto the protostar caused by inward migration of dense clumps.

In particular, we obtain two types of accretion bursts: a short-duration one caused by a quick inward migration of the clump, previously reported in the literature, and the prolonged one caused by the clump lingering at radial distances on the order of 15–25 au. The latter is culminated with a sharp accretion surge caused by the clump ultimately falling on the protostar.

1. Introduction

Dynamical processes in accretion discs of young stellar objects has recently gained much attention. Among them are short-lived episodes of high-rate accretion of FU-Orionis-type stars (FUors). While there exist many theoretical models that can explain FUors (see e.g. a review by Audard et al., 2014), the disc fragmentation model proposed by Vorobyov and Basu (2006, 2010, 2015), has a certain appeal because it suggests a causal link between episodic accretion in young protostars and the initial stages of planet formation in gravitationally unstable discs. In this model, accretion and luminosity bursts are the result of massive fragments forming in the outer parts of gravitationally unstable discs and spiraling onto the star owing to the loss of angular momentum via gravitational interaction with spiral arms and other fragments. If fragments have enough time to accumulate solid protoplanetary cores deep in their interiors, this mechanism can propose an alternative gateway to the formation of planets via the so-called tidal downsizing hypothesis (Nayakshin, 2010; Boley et al., 2010).

Mathematical models of gravitational fragmentation of razor-thin and thick discs were applied to investigate episodic protostellar accretion e.g. by Vorobyov and Basu (2006) and Machida et al. (2011). Numerical simulations of protostellar discs prone to fragmentation require a high numerical resolution to resolve the minimum perturbation unstable to growth under self-gravity (e.g. Truelove et al., 1997). That is why Lagrangian methods, such as the smoothed particle hydrodynamics (Lucy, 1977; Gingold and Monaghan, 1977) where resolution naturally follows mass are often adopted for such simulations.

For SPH simulations of self-gravitating gaseous disc calculation of short-term and long-term forces is optimized to avoid looping over all particle pairs. In particular, to compute short-range hydrodynamic forces near-neighbor particles are determined. To compute long-range gravitational force the gravity of a distant group of particles is substituted by the gravity of one particle of the total mass. It means that for efficient forces calculation in SPH we organize kind of Euler decomposition for particles. Moreover, for simulation of self-gravitating gas with SPH it is natural to perform the decomposition once, and than to adopt it twice for short-range and long-range force calculation. During last several decades an approach when tree-code is used to determine nearest neighbors and to calculate disc self-gravity in SPH proved to be the optimal choice for serial and high-performance computing e.g. Springel (2010).

On the other hand, due to fast development of supercomputer architecture workstations with different power and number of

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processors become available for numerical simulations. This diversity of available supercomputers promotes interest to the algorithms that could be easily transferred from small clusters with several computational nodes to large-scale machines with thousand nodes. This work was motivated by the idea that logically simple algorithms can be transferred to large-scale supercomputers more efficiently than complex branching algorithms, albeit they could demonstrate inferior performance on serial and medium-sized supercomputers. For this reason we searched a logical simplification of a standard approach to organize SPH simulations of self-gravitating gaseous discs.

It is well known, that after substitution of arbitrarily spaced masses with equigravitating set of masses located on uniform Cartesian grid the gravitational potential could be found faster due to convolution theorem. It allows us to propose an algorithm that combines the SPH technique and a grid-based method for calculating gravitational forces to solve numerically the Euler equations for the gas dynamics. This modification to the standard SPH approach, wherein the gravity force is calculated using a tree-code, increases simplicity and homogeneity of the numerical scheme, but features one of two inevitable negative aspects: inequality between gravitational softening and hydrodynamic smoothing length (Nelson, 2006) or – in case when the smoothing length is kept fixed and equal to gravitational softening length – usage of smaller or larger than optimal number of neighbors in SPH (Price, 2012; Dehnen and Aly, 2012).

As a first step we investigate the scheme when the gravitational softening and hydrodynamics smoothing length are kept equal. A feature of usage SPH instead of grid-based gas dynamics on uniform mesh is higher actual resolution of hydrodynamic parameters of formed clumps that are small-scaled anticyclone vortices with high velocity, density and pressure gradient. We aim to demonstrate that our scheme (1) provides results that are independent on numerical resolution when the dynamics of fragmenting disc is simulated, (2) allows to capture different regimes of accretion of gas onto the protostar in dense discs. We report our preliminary results in detail focusing on (a) confirmation of already described scenarios for accretion bursts using numerical methods that differ from those used in the previous studies by Vorobyov and Basu (2015) and Machida et al. (2011) and (b) finding new modes of episodic accretion.

The paper is organized as follows. In Section 2 we presented the model of self-gravitating accretion disc used for the simulations. In Section 3 we described the numerical model focusing on the way of coupling SPH and mesh. In Section 4 we focused on problematic numerical issues of protostellar accretion simulation using SPH and presented results of simulations, where we test specially designed by Thomas and Couchman (1992) and Dehnen and Aly (2012) measures to suppress clumping instability for the case when more than optimal number of neighbors in SPH should be used. In Section 5 we compared numerical results obtained for our disc model with different numerical resolution, especially focusing on the ratio between hydrodynamic smoothing length and gravitational softening length, which is known as a possible source of numerical artifacts in the solution e.g. Nelson (2006). In Section 6 we presented results of modeling accretion for the fragmenting and non-fragmenting discs.

2. Basic equations

The computational experiments reported in this paper were carried out within a razor-thin model of the disc. This means that we neglected the vertical motion of matter and considered the dynamics of the disc where its entire mass was concentrated inside the equatorial plane of the system.

Since we do not focus on the thermal dynamics of fragments, we treat cooling via simple assumption about the equation of state. We used adiabatic evolution where specific entropy is held fixed and entropy generation in shocks is ignored (also used e.g. by Pickett et al., 1998, 2000). More details on classification of cooling models of the discs can be found in Durisen et al. (2007). We note, that this approach allows to mimic the temperature of migrating clumps (see Appendix A obtained from simulations of other authors (Zhu et al., 2012; Nayakshin and Cha, 2013; Vorobyov, 2013).

The gas component was described by the following gas dynamics equations:

$$\frac{\partial \Sigma}{\partial t} + div(\Sigma \boldsymbol{v}) = 0, \tag{1}$$

$$\Sigma \frac{\partial \boldsymbol{v}}{\partial t} + \Sigma(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\nabla p^* - \Sigma \nabla \Phi_{sum}, \tag{2}$$

$$\frac{\partial S^*}{\partial t} + (\boldsymbol{v}\cdot\nabla)S^* = 0, \quad p^* = T^*\Sigma. \tag{3}$$

These gas dynamics equations include surface quantities that were obtained from volume quantities by integration with respect to the vertical coordinate z:

$$\Sigma = \int_{-\infty}^{+\infty} \rho dz; \quad p^* = \int_{-\infty}^{+\infty} p dz.$$

Here, $\boldsymbol{v} = (v_x, v_y)$ is the two-component gas velocity, and p^* is the surface gas pressure. $T^* = \frac{p^*}{\Sigma}$, $S^* = \ln \frac{T^*}{\Sigma^{\gamma^*-1}}$ are the quantities similar to gas temperature and entropy. γ^* is a 2D version of γ (Fridman et al., 1984), which is related to the constant ratio of specific heats as $\gamma^* = 3 - \frac{2}{\gamma}$.

Φ_{sum} is the gravitational potential in which the motion occurs, defined as the sum of central body potential and disc potential:

$$\Phi_{sum} = \Phi_c + \Phi, \Phi_c = -\frac{M_c G}{r},$$

where M_c is the mass of central body. Φ is the potential of self-consistent gravitational field, which satisfies Poisson equation:

$$\Delta\Phi = 4\pi G\Sigma, \quad \Phi \longrightarrow_{r\to\infty} 0.$$

2.1. Notions of gravitational instability theory used in the paper

The dispersion relation for the considered model of razor-thin disc is introduced in several works (see e.g. Binney and Tremaine, 2008; Nelson, 2006)

$$\omega^2 = c_s^2 k^2 + \kappa^2 - 2\pi G\Sigma|k|,$$

where κ is the epicyclic frequency, and c_s is the sound speed. For Keplerian discs $\kappa = \Omega$.

For an extended hypothetical sheet of gas $\kappa = 0$ and $\omega^2 = c_s^2 k^2 - 2\pi G\Sigma|k|$, from which one can obtain the critical Jeans length λ_J:

$$k_J = \frac{2\pi}{\lambda_J} = \frac{2\pi G\Sigma}{c_s^2}, \quad \lambda_J = \frac{c_s^2}{G\Sigma}.$$

For the rotating disc, one can obtain the Toomre condition of marginal stability from the equations $\frac{d\omega^2}{dk} = 0$, $\omega^2 = 0$:

$$k_T = \frac{\pi G\Sigma}{c_s^2}; \quad \lambda_T = \frac{2\pi}{k_T} = 2\lambda_J.$$

By substitution of the found value k_T into $\omega^2 = 0$ we derive the critical value of Toomre parameter $Q = \frac{\Omega c_s}{\pi G\Sigma} = 1$. For $Q > 1$ the razor-thin disc is stable against growth of radial perturbations, for $Q < 1$ the disc is unstable against growth of radial perturbations.