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The inner parsecs of our Galaxy: star formation and its environment

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Abstract. We aim to investigate the formation of young stars in the inner parsecs of the Milky Way by means of adaptive mesh refinement (AMR) hydrodynamical simulations. Observations show the presence of young massive stars and possible on-going star formation in the vicinity of the central supermassive black hole (SMBH).Though star formation is expected to be inhibited by the strong tidal field of the SMBH, several studies show that stars could be born out of molecular gas reaching the center from tens of parsecs distance. Compared to previous studies, we will study star formation in the innermost parsecs through treatment of heating/cooling processes, non-equilibrium chemistry and radiation effects.

1. Introduction

The project INA17_C1A05 - The inner parsecs of our Galaxy: star formation and its environment - got 2500000 computational core-hours, of which 1500000 hours on Marconi A1 (Broadwell) and 1000000 hours on Marconi A2 (Knights Landing). The project consisted in running a set of high-resolution simulations (Figure 1) of molecular clouds orbiting a supermassive black hole (SMBH) with mass equal to the estimated mass of SgrA*, $M_{SMBH} = 4.3 \times 10^6 M_\odot$ (e.g. Gillessen et al. 2017), to study the impact of initial conditions on the formation and distribution of stars at the center of our Galaxy. The simulations were performed with the hydrodynamical adaptive-mesh-refinement (AMR) code RAMSES (Teyssier 2002). More specifically, the goal was to understand whether the observed young stars in the Galactic Center could be born in streamers of gas reaching SgrA* from tens of parsec distances or, later on, from a gravitationally unstable disk, formed by molecular gas accumulating in the proximity of the SMBH.

The initial conditions for the set of simulations consist of 16 (2x2x2x2) turbulent molecular clouuds, with masses equal to 10^4 and $10^5 M_\odot$, radius equal to 5 and 10 pc, distance from the SMBH equal to 30 and 60 pc and tangential velocity equal to 10 and 100 km/s. For this parametric study, the gas thermodynamics has been treated with a simple isothermal equation of state. The AMR was pushed for all simulations up to level 14, corresponding to a maximum spatial resolution of 0.0061 pc. The scalability of RAMSES on Marconi A1

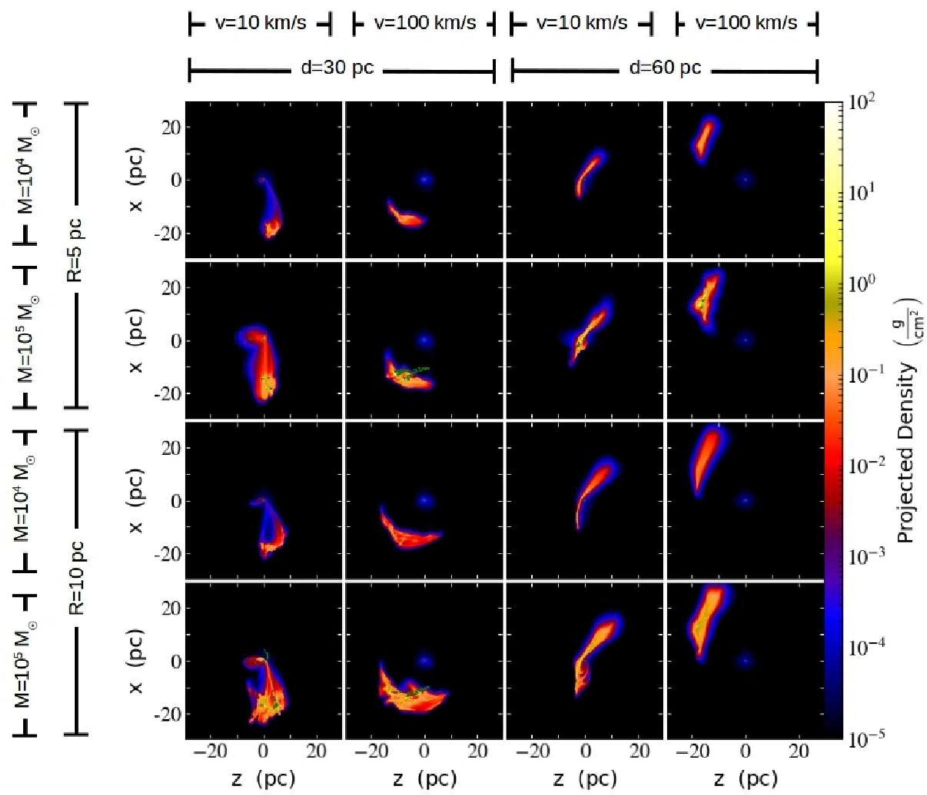

Fig. 1. Set of simulations of molecular clouds in the Galactic Center

and Marconi A2 turned out to be much worse than what we expected from our preliminary tests, mostly due to the sink formation algorithm, needed to model the star formation. This significantly slowed down each run and forced us to reduce the maximum AMR resolution by one level of refinement, compared to what we estimated in the project proposal.

We are currently analysing the output of the set of simulations and the first results show that the star formation can indeed happen in different episodes: some stars form at the first pericenter passage of the cloud, where the compression due to the SMBH induced tides is maximal, with the cloud getting stretched along the orbital direction and getting thin in the perpendicular direction (see panels (a) and (b) in Figure 2); a second population of stars forms instead in a more continuous way at later times, in the density peaks induced by the initial turbulence (panel (c) in Figure 2). The presence of different stellar populations is also reflected in different orbital properties: in fact, the orbital plane of the first population is essentially the same as the cloud's one, while the second population shows a spread in their orbital inclination. Our best model is able to reproduce some of the observed properties of the molecular gas in the inner parsecs of our Galaxy (Ballone 2019). In particular, when the cloud reaches the SMBH for its second pericenter passage, it reminds of the current configuration of the +20 km/s cloud and of the circumnuclear ring (CNR) of molecular gas sitting at a distance of 1-2 pc from the SMBH. In particular, the +20 km/s cloud is currently

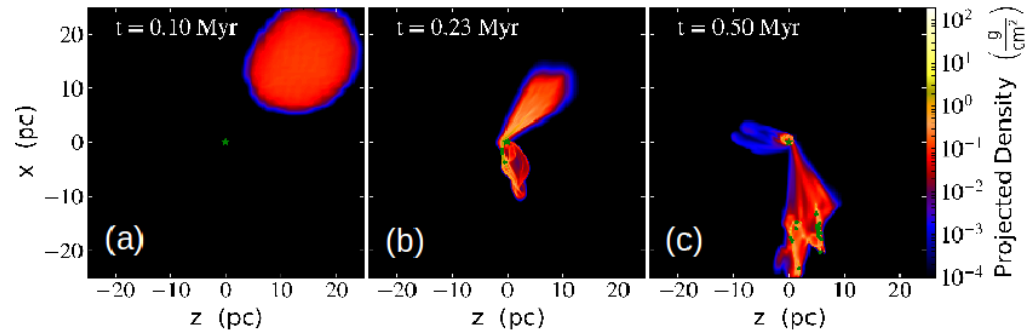

Fig. 2. Temporal evolution of one of the molecular clouds orbiting the SMBH of the Milky Way; the green star highlights the position of the SMBH, while the green dots represent the sink particles formed in the simulation.

in the south of the CNR, it is elongated in this direction with sizes of about 15 pc x 7,5 pc (Ferrière 2012) and shows signatures of interactions with this ring of cold gas (Liu et al. 2012; Takekawa et al. 2017). Furthermore, there are indications of recent star formation inside the +20 km/s cloud (Lu 2015), as in the case of our best model (panel (c) in Figure 2). Finally, the ring of gas forming in the simulation has a size comparable to that of the CNR and it is surrounded by several small gas streamers, as observed (e.g. Liu et al. 2012; Hsieh et al. 2017, Figure 3).

The poor scalability of RAMSES has unfortunately forbidden us from re-running our best model by adding stellar radiation and chemistry.

For this reason, we decided to rather run another set of simulations, similar to those already described, but with a central binary of supermassive black holes. The goal of this additional work is to investigate the impact of a molecular cloud on the orbit of two black holes, as already partially studied by (Goicovic et al. 2016, 2017). This study is particularly interesting in view of future observations of merging SMBHs by the LISA mission. For this project, the cloud has an initial distance of 10 pc, a radius of 5 pc and a mass of $5 \times 10^3 M_\odot$

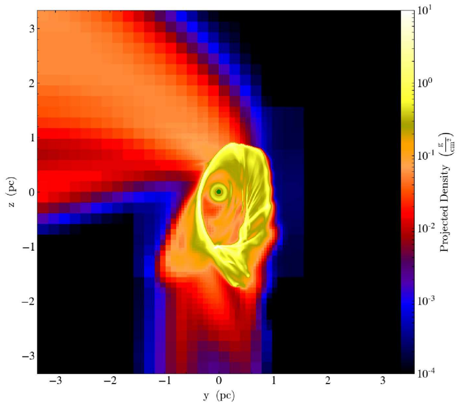

Fig. 3. Zoom-in on the ring of molecular gas forming in our best simulation, at about 1 pc distance from the SMBH.

and $5 \times 10^4 M_\odot$, but we also varied the SMBH binary orbital eccentricity (0, 0.3 and 0.7) and mass ration ($M_1/M_2 = 1, 1/3$, for $M_1 = 7.5 \times 10^5 M_\odot$), accounting for 12 simulations in total.

We are currently analysing this further set of simulations. Figure 4 shows a projection of the gas density around the two black holes, for one of the simulations: as visible, in this time snapshot 2 small disks of gas formed around each of the two black holes (whose position

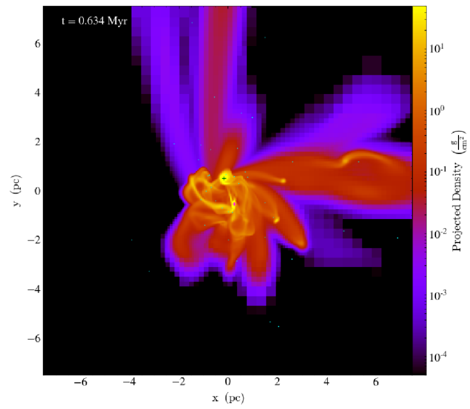

Fig. 4. Zoom-in on the 2 supermassive black holes, in one of our simulations

is marked by the green and magenta crosses), while a larger circumbinary ring of gas is still assembling. Considering the encountered technical issues, we are not planning to apply for larger HPC projects (ISCRA/PRACE) in the next future. Nonetheless, once the scalability problems of the code will be solved, such project could certainly be used (and it was indeed born) as a needed guide for simulations of the same kind, but including further physical ingredients, such as stellar radiation and chemistry. These simulations will require larger computational resources and they will most likely be carried out in the framework of ”heavier” HPC projects, compared to the present one.

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