Accretion Disk Formation via Jupiter-Massed Gas Giant Protoplanetary Collisions

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Abstract

Accretion disks are flattened structures of rapidly rotating gas which accrete into a central compact object or young star. Accretion disks around central young stars are known as *protoplanetary disks*. Investigating the formation and evolution of these astronomical structures allows us to understand the process of planet formation and migration. In this project we study how planetary collisions can form protoplanetary disks and how these structures evolve and influence the central star. To achieve this we use PHANTOM, a smoothed-particle hydrodynamics code (SPH), to model accretion processes. SPH is a meshfree particle-based computational method for simulating astrophysical fluid phenomena. We set two protoplanets into opposite trajectories along a circular orbit 1 AU from the central star. In our models the gas giant protoplanets were assumed to have a fully convective core and were modelled as Jupiter-massed and Jupiter-sized polytropes. The central star was modelled as a simple Sun-massed sink particle since only gravitational effects were necessary for the simulation with an accretion radius of, $R_{acc} = 0.1$ AU. During the collision of the two protoplanets, the mass accretion rate onto the central sink particle was analyzed to see if any potential accretion disks would be created as gas began to in-fall around the central star when it reached a distance less than the specified accretion radius.

SPH Theory

Smoothed-Particle Hydrodynamics (SPH) is the computational method used throughout this project for the hydrodynamics simulations. Essentially the method tries to solve the Lagrangian form of the equations of hydrodynamics. The fluids are discretized onto a set of 'particles' of mass m that are moved with the local fluid velocity $\vec{u}$.[1] It is also important to note that viscosity considerations will be neglected, and as such the Navier-Stokes Equations can be simplified into the Euler Equations.

The first Euler equation is the continuity equation (mass conservation):

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u}) = 0 \Rightarrow \frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho(\vec{\nabla} \cdot \vec{u}).$$

The second Euler equation is momentum conservation:

$$\rho \frac{\mathrm{D}\vec{u}}{\mathrm{D}t} = \vec{\nabla} P + \vec{F}_{ext} \, ,$$

where $\vec{F}_{ext}$ represents non-fluid external forces.

The third Euler equation is energy conservation:

$$\frac{\mathrm{D}e}{\mathrm{D}t} = -\frac{P}{\rho} \vec{\nabla} \cdot \vec{u} + \dot{q} \, ,$$

where e is the internal energy and $\dot{q}$ is the external heat. Since SPH discretizes fluids onto 'particles', the fundamental question that helps us solve the Euler Equations is *"how can we compute the density of an arbitrary distribution of point mass particles?"*[2] A schematic diagram of the process of computing density is given by Fig. 1.

[1]Price, D., Wurster, J., Tricco, T., Nixon, C., Toupin, S., Pettitt, A., . . . Lodato, G. (2018). Phantom: A Smoothed Particle Hydrodynamics and Magnetohydrodynamics Code for Astrophysics. Publications of the Astronomical Society of Australia, 35, E031. doi:10.1017/pasa.2018.25

Results

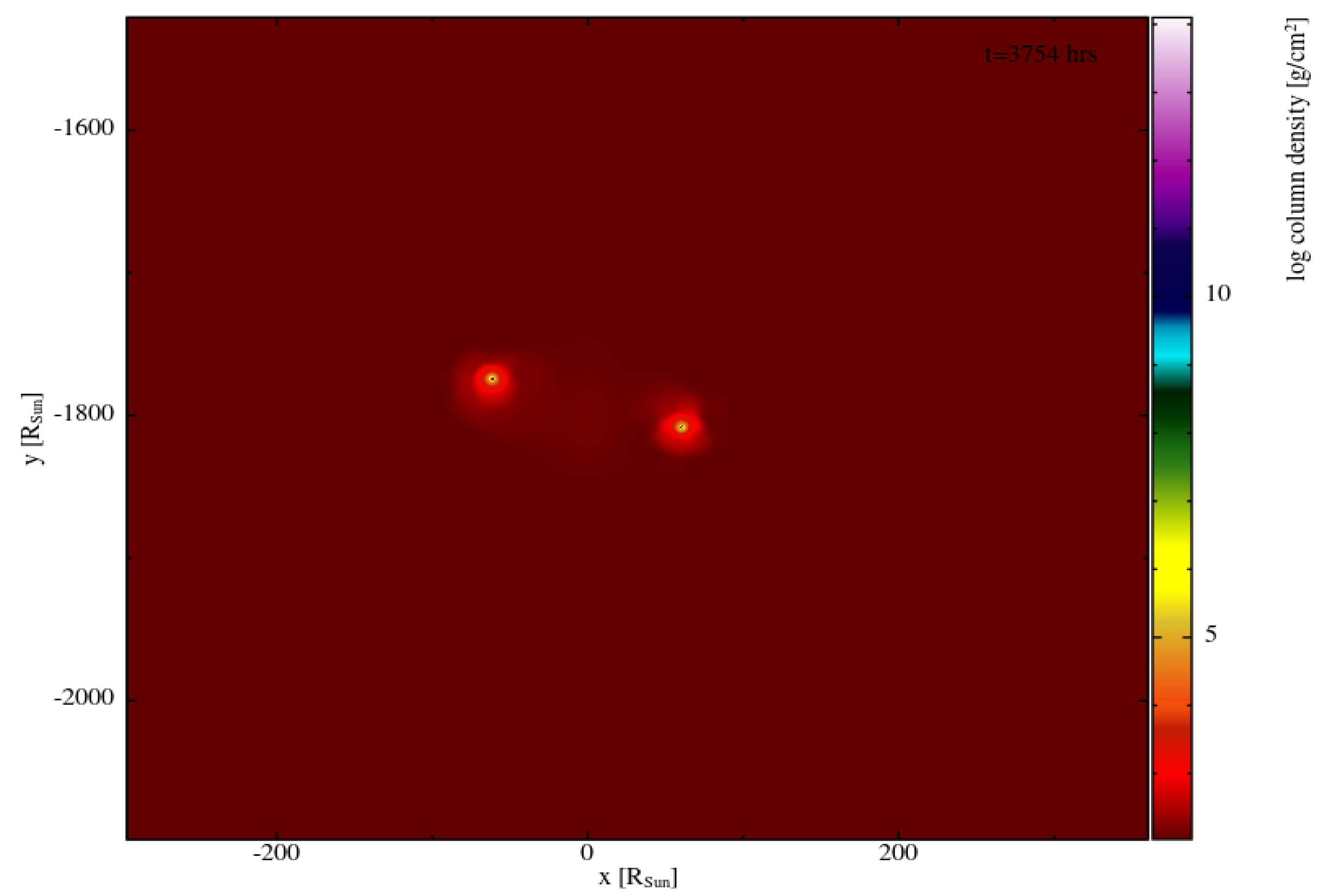

Fig. 2 (Simulation 1): The initial parameters of the model were protoplanets at f_1 = 0 radians and f_2 = π radians. At the timestep of 3754 hours, we can observe the closest approach of the two protoplanets to one another. It is apparent that a small amount of gas flow occurs between the protoplanets, but no collision occurs.

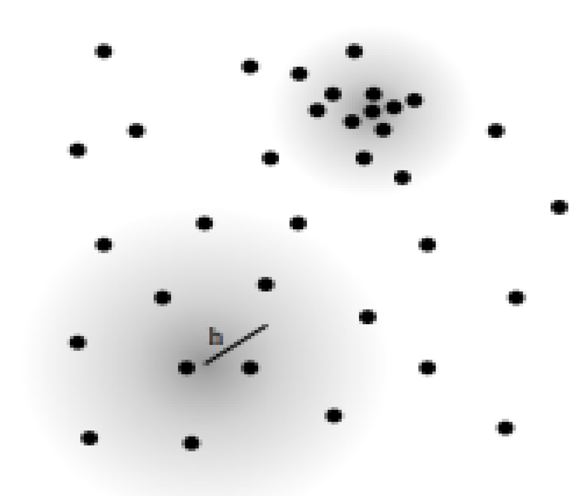

Fig. 1: The SPH approach of computing density is by taking a weighted sum over neighboring particles with the weight decreasing with distance from the sample point by a scaling factor of h.[2]

[2]Price, D.J. (2010). Smoothed particle hydrodynamics and magnetohydrodynamics. J. Comput. Phys., 231, 759-794.

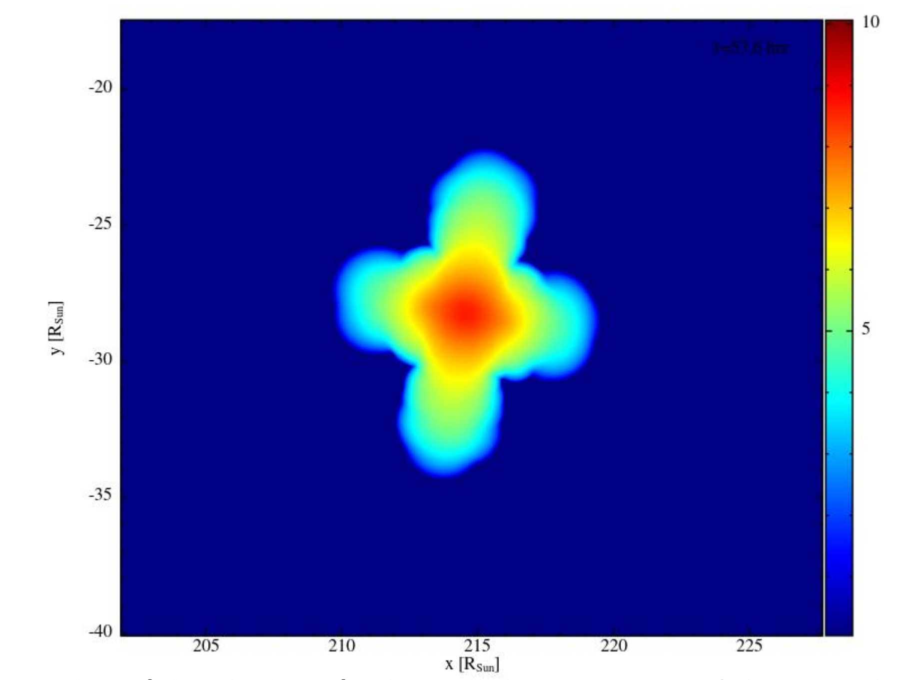

Fig. 3 (Simulation 2): The initial parameters of the model were protoplanets at f_1 = 0 radians and $f_2 = {}^{23}/_{12}\,\pi$ radians. At the timestep of 57.6 hours we observe the initial collision of the two protoplanets.

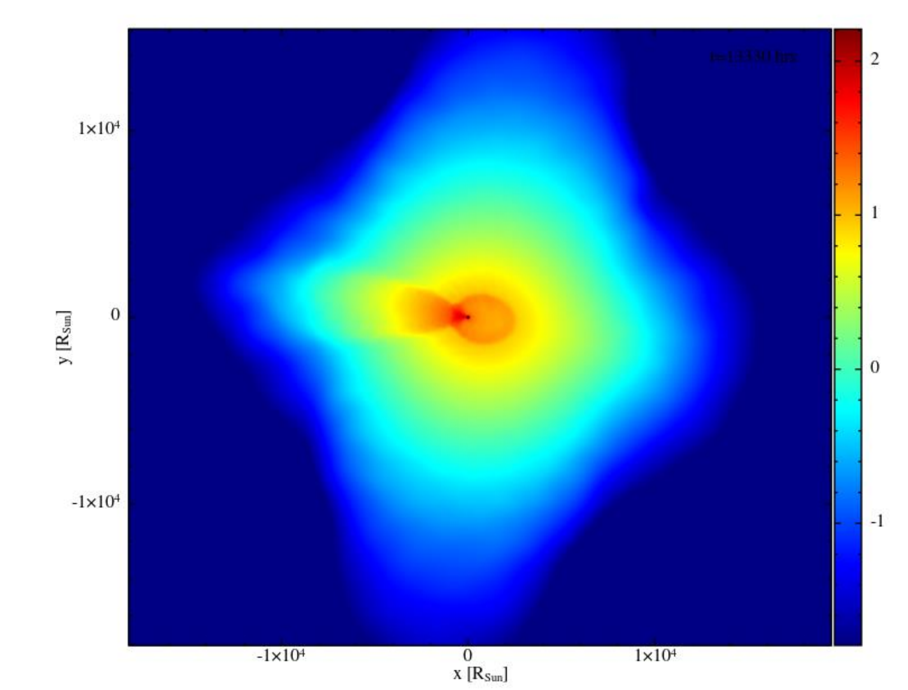

Fig. 5 (Simulation 2): At the timestep of 13330 hours we see the formation of a gas bubble emitting opposition to the jet.

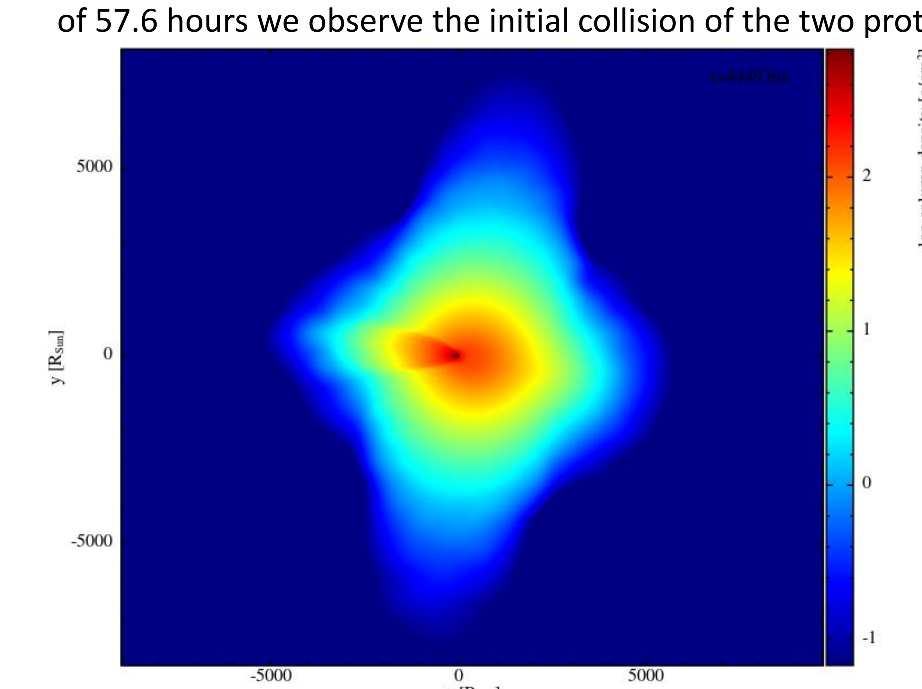

Fig. 4 (Simulation 2): At the timestep of 4449 hours was the formation of a protoplanetary disk, along with an accretion jet emanating from the center.

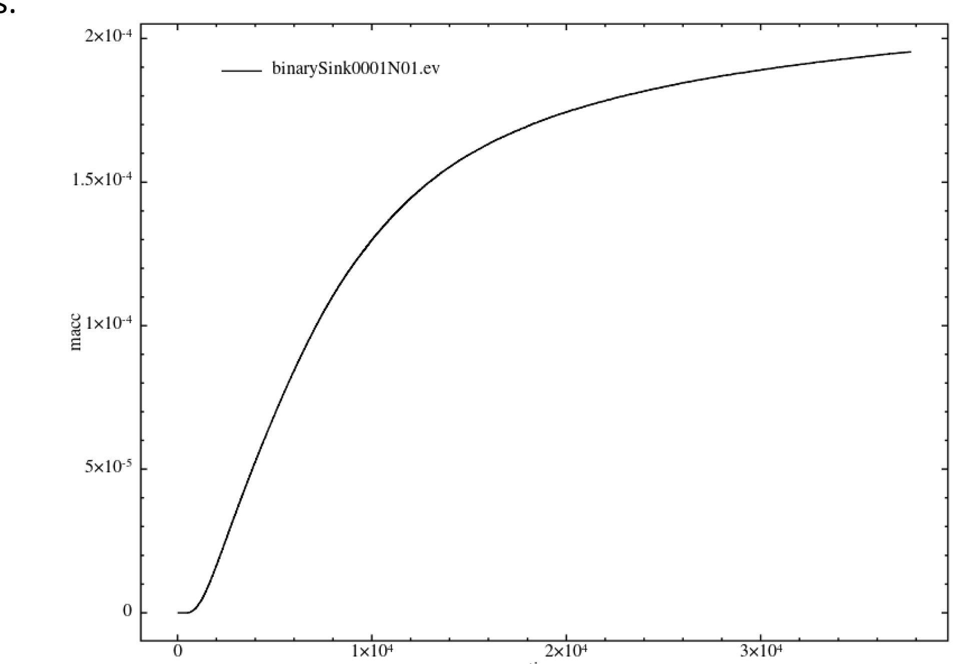

Fig. 6 (Simulation 2): The total simulation evolved up to a timestep of 37750 hours. The plot shows the mass accretion in solar masses versus time in hours.

Methods

Using the PHANTOM code, I was able to set up the protoplanets, which were treated as Jupiter-massed and Jupiter-sized polytropic stars. As such each protoplanet had a mass of $9.54588 \times 10^{-4} M_{\odot}$ along with a radius of $1.02763 \times 10^{-1} R_{\odot}$. Since the core is fully convective, we can infer an adiabatic process for an ideal monatomic gas. Thus, using the polytrope equation of state, $P = K\rho^{\gamma}$, we set the adiabatic index to $\gamma = \frac{5}{3}$. The sink particle being Sun-massed was $1 M_{\odot}$ with an accretion radius of, $R_{acc} = 0.1$ AU. Using an orbit with an eccentricity of 0 and a semi-major axis of 1 AU, the first protoplanet was kept at a fixed true anomaly of, f = 0 radians with a clockwise orbit in all simulations. We ran several different simulations, however, the two most notable were when the second protoplanet had a true anomaly of, f = π radians and $f = \frac{23}{12}\pi$ radians both with a counter-clockwise orbit. For the first simulation a total particle count of $n = 80000$ was used, while for the second simulation a total particle count of $n = 60000$ was used.

Discussion and Future Endeavors

We can see from the first simulation that there was never a collision between the two protoplanets (Fig. 2). This phenomenon can happen when tidal forces are locally more significant than the gravitation force towards the central star, perturbing the protoplanets' trajectories. However, at $t = 3754\ hrs$ we can see that there is some gas flow between the protoplanets attributed to tidal forces. Conversely, for the second simulation we see that a collision happened quickly, within $t = 57.6\ hrs$ (Fig. 3). By $t = 4449\ hrs$ we see that a sizable amount of matter had accreted which led to the formation of an accretion jet with a narrow opening angle shooting out of the center of the disk (Fig. 4). At around $t = 13330\ hrs$, a secondary gas bubble in the opposite direction has formed out of the center of the disk (Fig. 5). The total simulation shows the evolution of the disk up to $t = 37750\ hrs$. The mass accretion rate up to around $1.25 \times 10^4\ hrs$ is significantly faster than the mass accretion after that point with the total mass accreted approaching $2 \times 10^{-4} M_{\odot}$. What becomes evident from these conclusions is further experimentation is needed. For the first simulation further analysis is needed to determine whether tidal forces were significant enough to perturb trajectories and for the second simulation further simulations are needed to study how the planets' properties influence the formation and the structure of the newly formed accretion disk and the accretion jet/gas bubble.

Acknowledgments

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https://github.com/SudatKhan/ureca_repo