PROTOPLANETARY DISK ASSEMBLAGE AND EVOLUTION REVISITED WITH EFFECTS OF NON-IDEAL MAGNETO-HYDRODYNAMICS. Y.-N. Lee[1,2], S. Charnoz[1], P. Hennebelle[2], F. Pignatale[3], B. Commerçon[4] , [1]Institut de Physique de Globe de Paris, France, (ynlee@ipgp.fr), [2]Département d'Astrophysique, AIM/CEA Saclay, France [33]Muséum National d'Histoire Naturelle, France, [4]Ecole Normale Supérieure Lyon, France.

Introduction: It is now commonly accepted that the formation and processing of the building blocks of our Solar System, i.e., rocky materials, water ice, and carbon complex compounds, might have occurred earlier than what was thought before, during the initial collapse of the prestellar core and the formation of the protoplanetary disk. Very few existing works take into account the building phase of the protoplanetary disk when studying the formation and transport of refractory materials. Due to the complexity of this problem, a simplified hydrodynamic model has long been a convenient choice.

The main goal of this study is to self-consistently form the protoplanetary disks starting from the collapse that takes into account the environmental effects and large scale physics. The big challenge is to include non-ideal magneto-hydrodynamic (MHD) effects, which become important at the disk scale, while not taken into account by most of existing models. With the help of numerical simulations that allow to follow the complex non-linear physics, we will provide a working recipe for studies of the disk dynamics, thermal evolution of different gas and dust species, and their changes in chemical composition.

Background: We first present some established facts that this study is based on. Some of them have been known for a long, while explanations still missing; others are rather recent discoveries or technical improvements. With the gathered information, it is now possible to understand the early phase of Solar System formation and evolution more realistically.

Cosmochemistry. The analyses of chondritic meteorites and cometary materials show mixed compositions that have formed under very different conditions. In particular, the calcium-aluminum rich inclusions (CAI), the most refractory component that have formed very close to the protostar at high temperature, define the time zero of the Solar System [1]. However, they are found to be present everywhere in the Solar System. This implies that important mixing and transport have taken place in the early disk.

Protoplanetary disk observation. Recent observations show that the class 0 disks are mostly small [2], with sizes below 50 au, which is in contradiction with the rapid disk size growth expected from previous models (see the classical models below). Moreover, the protoplanetary disks seem to be magnetized, which is a reasonable fact since there is always magnetic field inherited from larger scales when collapse happens.

Non-conservation of angular momentum. Looking at the hierarchical collapse of astronomical objects, the specific angular momentum decreases with the decreasing size of the object [3]. This implies that the transport of angular momentum occurs, probably through different mechanisms, at all scales, and this is actually what allows the star to finally form at the center of a rotationally supported disk. At scales larger than the disk, the magnetic field threading the collapsing object plays an important role through the magnetic breaking and sends away the angular momentum.

Non-ideal magneto-hydrodynamics. The ideal MHD couples the magnetic field lines to the gas movement, and this flux-freezing behavior leads to high magnetization in dense regions or winded and packed field lines in rotating objects. In such conditions, non-ideal effects become important. The hall effect redistributes the field line due to the drift of charged particles in the field, and the ambipolar diffusion leaks the magnetic field outwards through the collision between neutral and ionized particles. The processes of the protostellar disk formation fall in the regime where the ideal assumptions start to fall apart. It was only in the last decade that the computational power made possible the proper description of theses effects, and this has revolutionized the picture of how disks are allowed to form in the presence of the magnetic breaking.

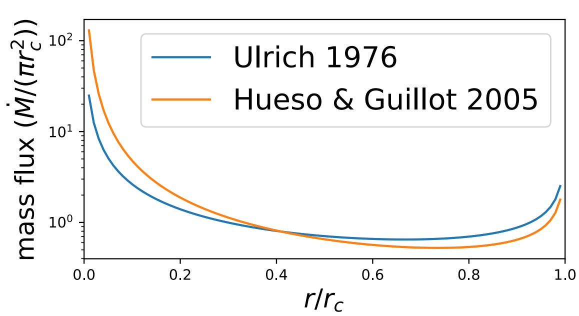
Numerical simulations. Most of the disk evolution simulations start with an existing disk, with or without accretion. On the other hand, the simulations of star formation from collapsing molecular clouds barely resolve the interior of the prestellar core, not to mention the protoplanetary disk. There is a tremendous gap to be filled between the pc-scale prestellar core and the au-scale protoplanetary disk. Collapse problems are multi-scale and require a large dynamical range of resolution, which makes the simulations extremely expensive in both computational power and storage memory.

Classical models of non-magnetized disk assemblage: The collapse of the prestellar core has been historically treated with axisymmetric and non-magnetized assumptions due to their simplicity and lack of observation evidences to support the contrary, [4]. Before introducing our numerical simulations, we briefly review the classical model.

Collapse of a prestellar core: a purely hydrodynamic scenario. One classical example of the collapse of a prestellar core is the similar isothermal sphere (SIS) [5], which describes an inside-out collapse of mass shells that accrete onto a central star with constant mass accretion rate. This solution has been applied do numerous disk assemblage models for its simplicity.

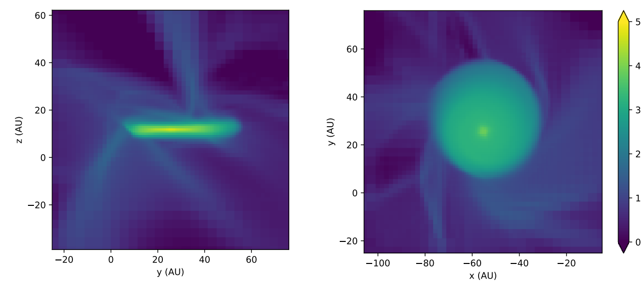
The disk is formed by introducing a small amount of rotation into the prestellar core, while assuming that the collapse solution stays unaffected at large scales. Due to angular momentum conservation during the collapse, the rotation becomes non-negligible and leads to the formation of a flattened structure in the centermost region around the star. However, very few studies have looked at how exactly the prestellar core collapses to form a star surrounded by a protoplanetary disk, because the breakup of the spherical symmetry complicates the problem.

A simple way to look at this problem is to consider a shell mass with a certain angular velocity and to derive how this mass is distributed when it arrives onto a disk. This accretion onto the disk is conventionally expressed as the source function, that describes the mass flux as function of the position in the disk and the time. By assuming that the particles follow parabolic trajectories [6] or fall directly on a circular orbit while conserving the angular momentum [7], different source functions can be derived. The figure below shows two examples of source function, as a function of the radius normalize to the centrifugal radius and the source function normalized to the averaged mass flux, from this classical view point of disk assemblage. Most of the material arrive in the inner part of the disk and can be significantly heated by the protostar. In this scenario, the edge of accretion is always defined by the centrifugal radius, which is derived directly from the initial amount of cloud rotation and increases with time.



Self-Consistent Protoplanetary Disk Formation: In more realistic cases, where the presence of the magnetic field and it non-ideal effects are non-negligible, the numerical simulation becomes an indispensable tool, We use the MHD code RAMSES [8] to simulation the collapse of a magnetized prestellar core of one solar mass. The adaptive mass refinement scheme allows to solve the collapse problem by focusing the resolving power at the central dense region. A weak solid body rotation is introduced initially, and a disk forms naturally during the collapse. Magnetic field and turbulence are also introduced to mimic the conditions of the prestellar core. We test several setups with different initial parameters.

Conclusions: The figure below shows edge-on and face-on snapshots of the disk accreting from a turbulent envelope. Considering non-ideal MHD effects [9], [10], the disk size is regulated by the interaction between the rotation and the field lines, growing slowly in time. With these simulations, we are able to measure the source function and describe the assemblage of the disk as function of the space and time. The results will then be applied to study the chemical evolution inside the forming disk [11], and can also serve as a recipe for any future studies of early disk evolution.



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