Three dimensional non-ideal MHD moving-mesh simulations of the formation of protostellar accretion disks

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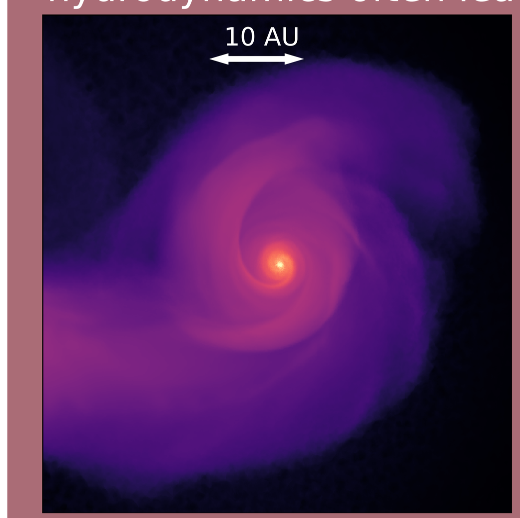
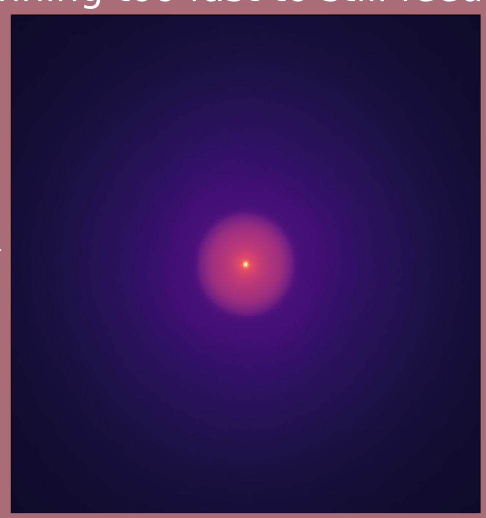
Non-ideal magnetohydrodynamics (MHD)

Realistic levels of magnetization in molecular cloud cores can stop formation of protostellar accretion disks through magnetic braking. On the other hand, pure hydrodynamics often lead to disk spinning too fast to still feed the protostar[1].



Magnetic braking

(here ideal MHD)



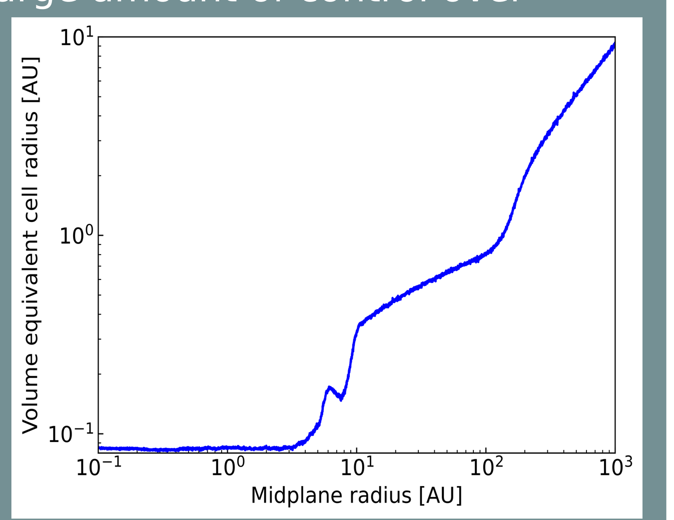
Left: Projections from simulations of the collapse of ~ 1 solar mass molecular cloud cores with identical initial conditions[2], but with and without magnetic fields. On the right, a large amount of angular momentum has been extracted from the disk due to the resistance of field lines to azimuthal bending.

However, these cores are known to be poorly ionized[1], so ideal MHD is no longer a good description. → **Non-ideal MHD**: Dissipation of current (**Ohmic diffusion**), drift between charged and neutral species (**ambipolar diffusion**), drift between opposite charges (**Hall effect**). However, there are significant uncertainties about the underlying chemistry. We use the publicly available NICIL[3] here.

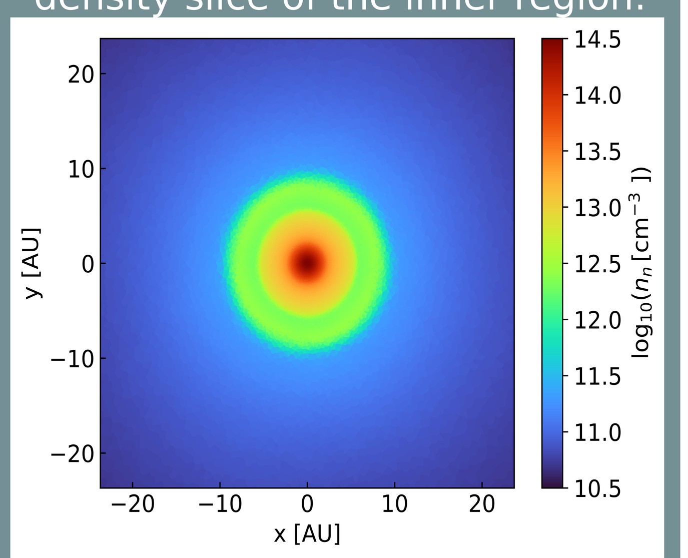
Non-ideal MHD with AREPO

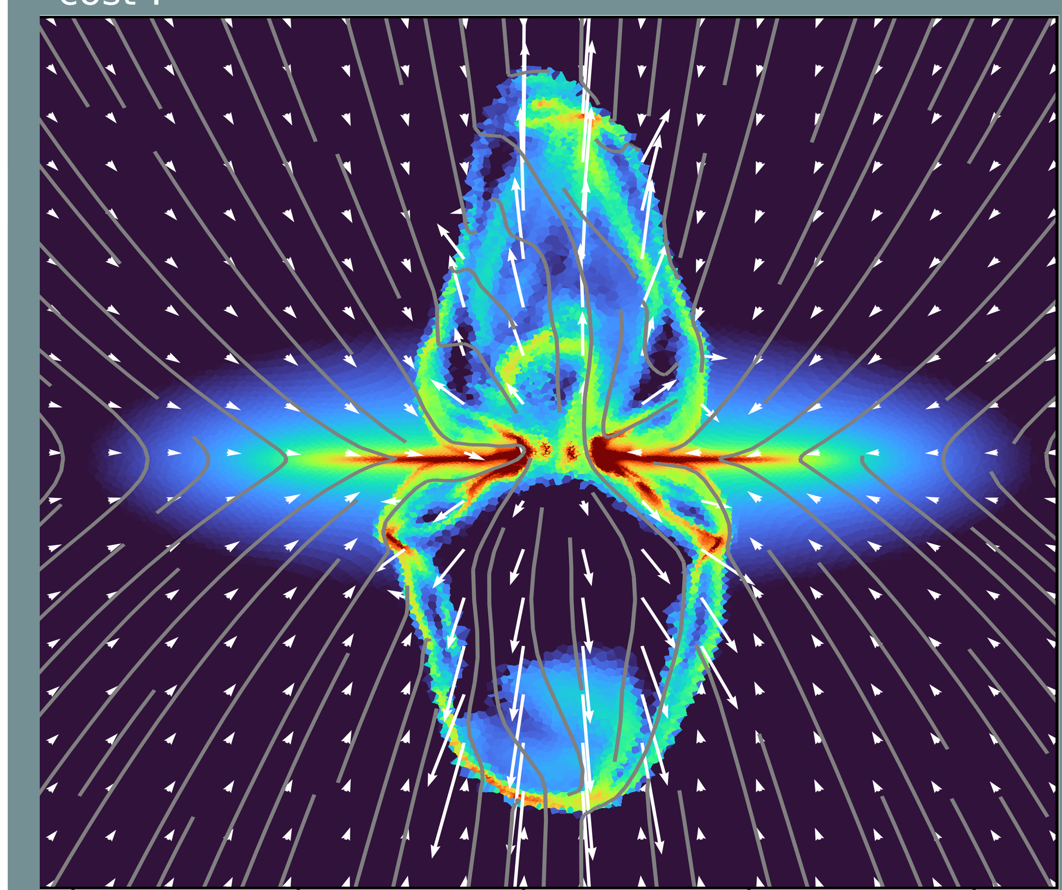
We utilize the moving mesh code **AREPO**[4], which combines Lagrangian and Eulerian numerical methods. The computational domain is spit into cells, usually given by the **Voronoi tesselation** belonging to a number of **mesh-generating points** which are approximately **co-moving with the fluid** and hydro-calculations are performed on this grid. In this way, as in a smoothed-particle-hydrodynamics (SPH) code, the **resolution is automatically higher in denser regions**, which is essential in simulating protostar formation due to the large difference in densities between envelope and stellar core. On the other hand, AREPO needs no artificial viscosity or resistivity and is very flexible in terms of refinement, e.g. providing the ability to have a maximum and minimum of cells, thereby also giving a large amount of control over the minimum timestep.

The non-ideal MHD fluxes are calculated via an explicit solver[5] which imposes a timestep limit that scales as the surface area of the cell, often becoming very strict at high resolution. Right : Resolution in the midplane of the disk as a function of radius from the center in a run including Ohmic diffusion. The volume minimum is clearly visible close to the center and is sufficient to run the simulation close to stellar core densities without imposing artificial limits on diffusivity coefficients, as was necessary in other work to reduce computational cost[6].



Corresponding face-on number density slice of the inner region:

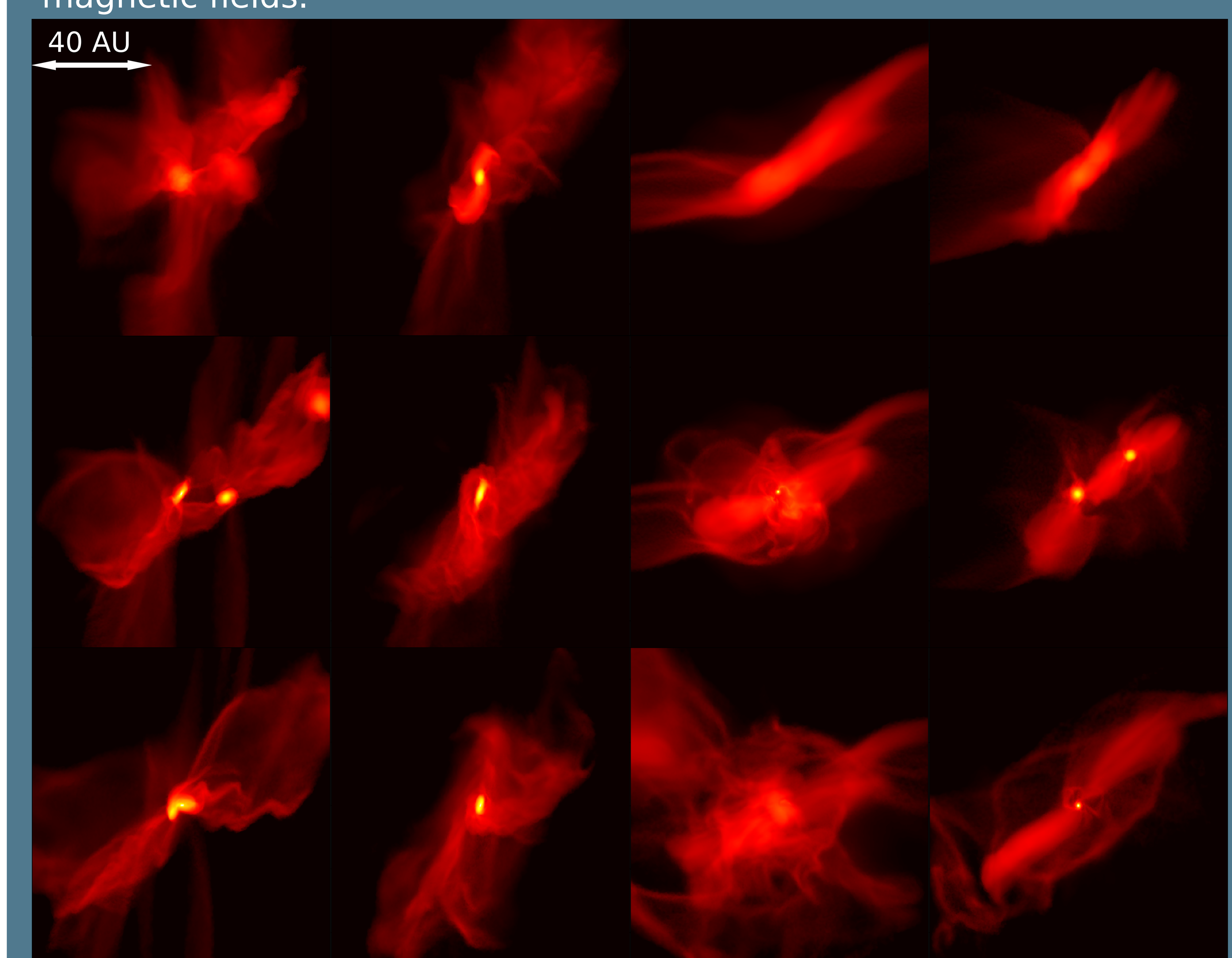




Cells also automatically follow outflows. Left: Edge-on slice (~10^3 AU diameter) of an ideal MHD run, with number density as color, magnetic field lines in gray and velocity as arrows. One could refine such cells further with e.g. a shock criterion.

Importance and impact of turbulence

The interstellar medium is highly **turbulent**[7], and this turbulence likely has a substantial effect on star formation within it. We therefore set up cloud cores with identical realizations of a turbulent power spectrum consistent with Larson's scaling relation with and without magnetic fields.



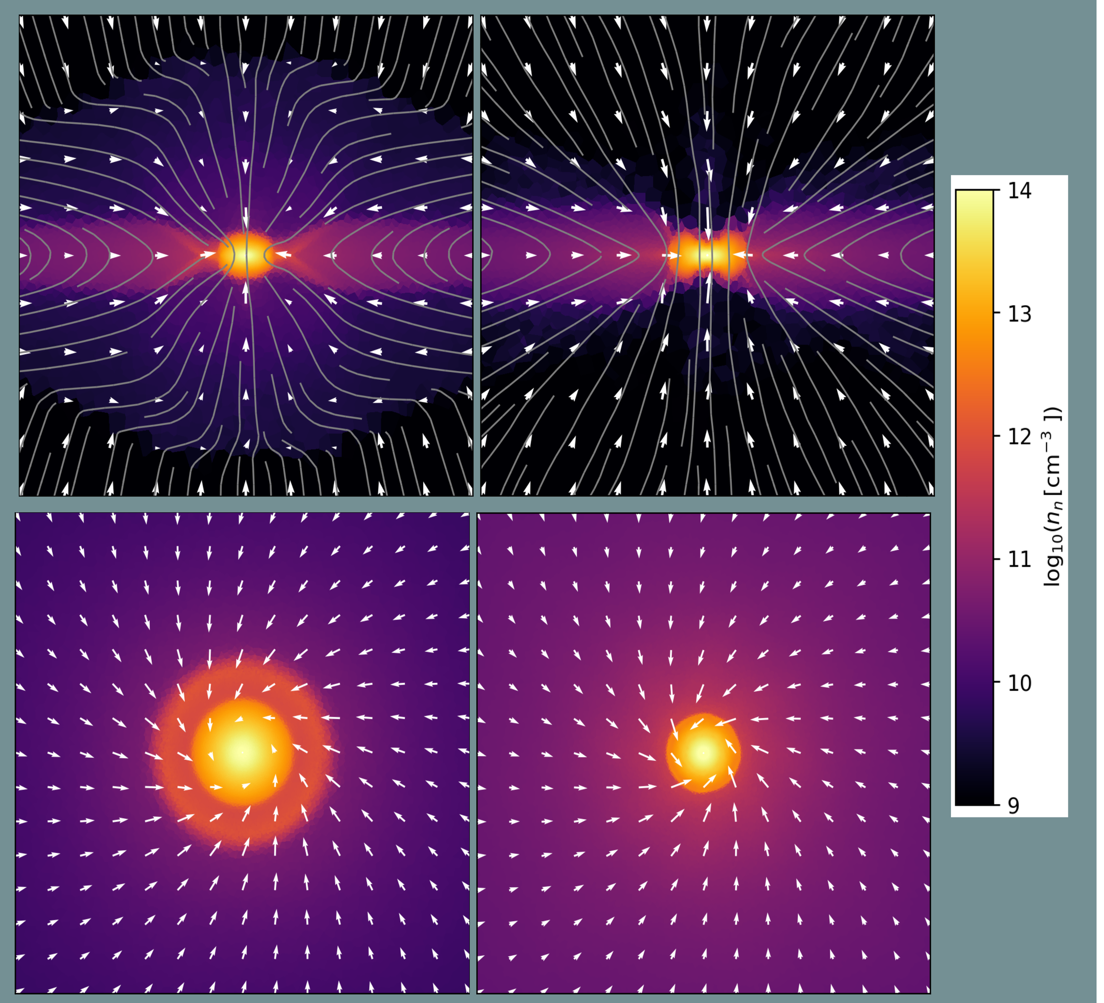
1st and 2nd column: No MHD, stronger turbulence on the right.
3rd and 4th column: Same in ideal MHD.

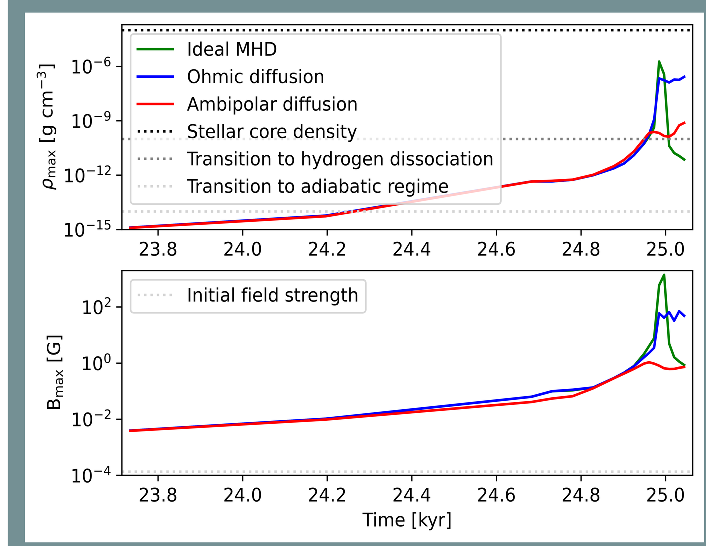
Disk formation is suppressed with magnetic fields, and the gas follows the larger scale magnetic fields - until outflows occur, which are observed in all runs.

Influence of different non-ideal MHD effects

The inclusion of non-ideal MHD effects has a large effect on the morphology and evolution of first hydrostatic core, disk, and further. In the early phase (up to and including the formation of the hydrostatic core), ambipolar diffusion is the dominant effect, and substantially hinders the pinching of the magnetic field into an **hourglass shape**. Ohmic diffusion becomes dynamically important only at high densities, but then modifies the **outflow structure** (see below). The Hall effect mostly acts in between these regimes, and is impacted by the **alignment between rotation and magnetic field**.

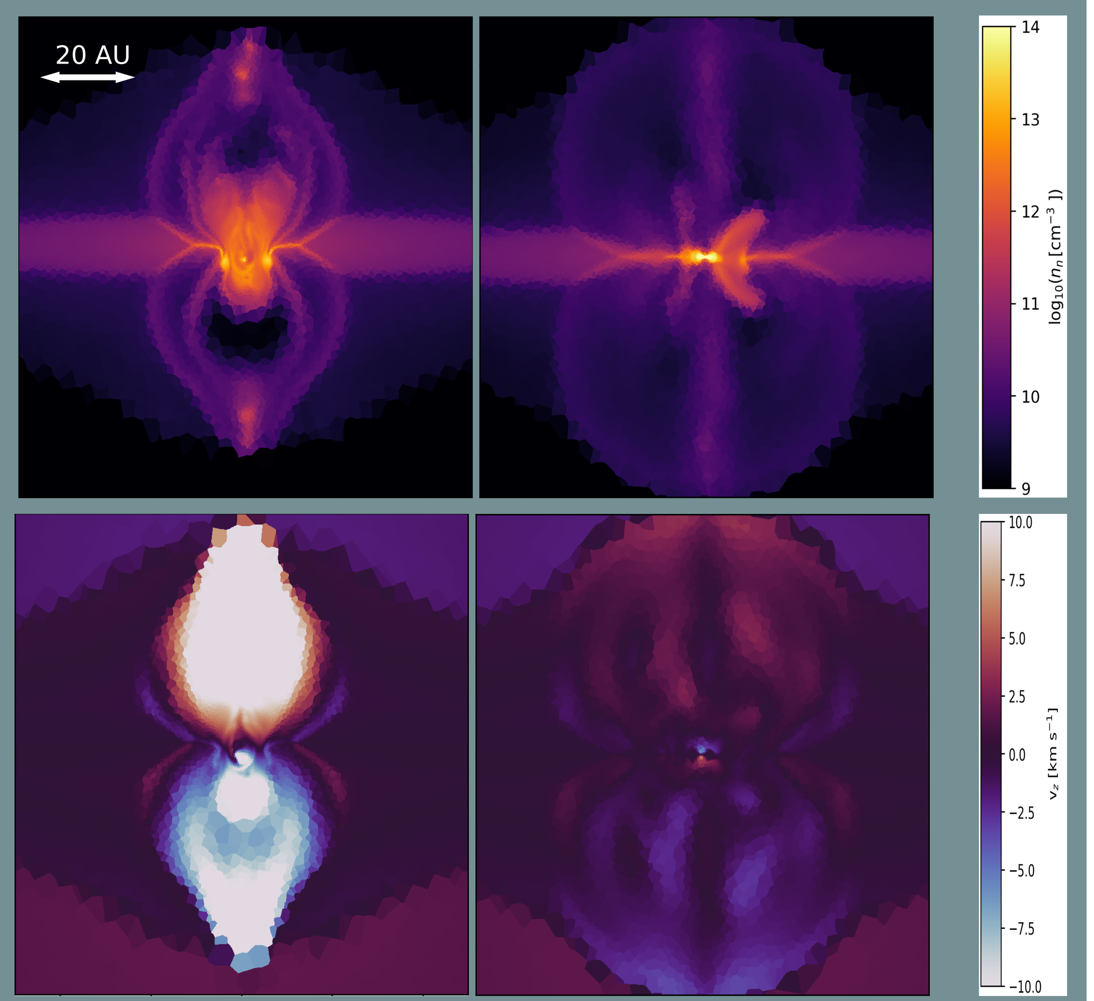
On the ritght, top: Edge-on slices (~10^2 AU diameter) in ideal MHD (left) and with all effects in an anti-aligned configuration (right) at approximately the same maximum density. Magnetic field lines in gray, velocity (~1 km / s) as white arrows. Bottom: Face-on view, arrow-scaling is the same. The rotation velocity is clearly higher in the non-ideal MHD case and leads to a more extended flattened distribution, while the ideal MHD core is supported more so by magnetic and thermal pressure as well as magnetic tension.



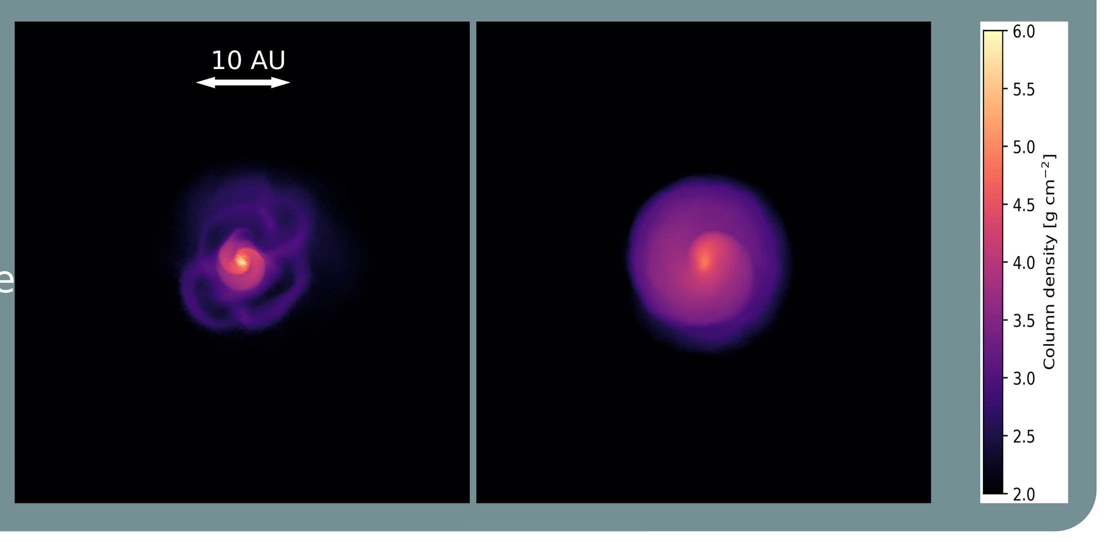


Above: Evolution of maximum density and magnetic field strength in different runs (including the other effects with ambipolar diffusion leads to largely the same results at the earlier times). The plot also includes the transition densities in the barotropic equation of state.

Right: Outflows in ideal MHD simulation (left) and with Ohmic diffusion (right). The top panels show density, the bottom panels velocity in the direction perpendicular to the plane of the disk. In ideal MHD, the outflow is substantially faster and more collimated, both likely due to a stronger magnetic field, in the latter case the azimuthal component in particular. This strong outflow is enough to completely destroy the disk structure at least temporarily.



Bottom: This is not true of the weaker one with Ohmic diffusion (left panel, face-on projection). The right panel shows a run with pure ambipolar diffusion – both have **rotation-supported disks**.



Conclusion

- Magnetic fields are an important component in star formation
- Non-ideal MHD effects must be included due to the low degree of ionization in molecular cloud cores
- Diffusion of the magnetic field reduces the impact of magnetic breaking and leads to the formation of rotationally supported disks
- AREPO can deal with a large dynamical range of densities and cells automatically move with the gas, which also includes the rotation in the accretion disk

Outlook

- Investigate interplay between turbulence and non-ideal MHD effects
- Increase resolution further
- Run for longer time, investigate long term effects of outflows and return of ejected gas
- Compare different chemical models
- Include radiative transfer
- Run non-isolated runs which start from a turbulent ISM

References

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