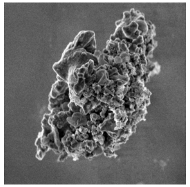
Numerical simulations of MHD wave propagation into Molecular Clouds

Leire Beitia-Antero[1−2], Ana Inés Gómez de Castro[1−2] and Juan Carlos Vallejo[1−2]

Zooming in on Star Formation, Nafplio
June 10th, 2019

[1]Aegora Research Group, Facultad CC. Matemáticas, Universidad Complutense de Madrid
[2]Department of Physics of the Earth and Astrophysics, Facultad CC. Físicas, Universidad Complutense de Madrid

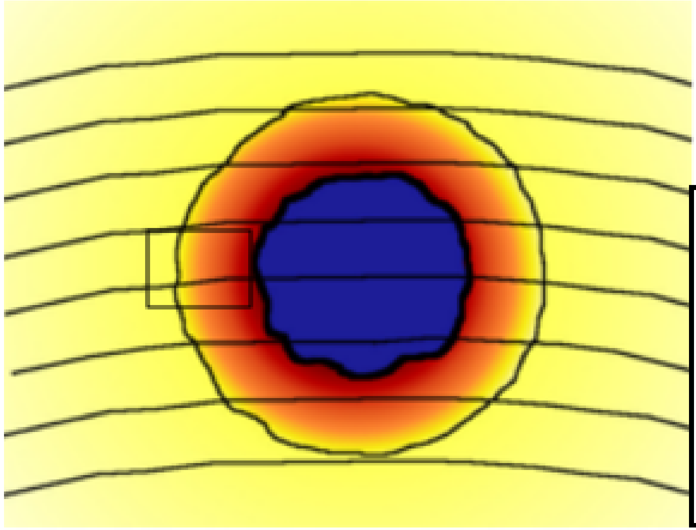


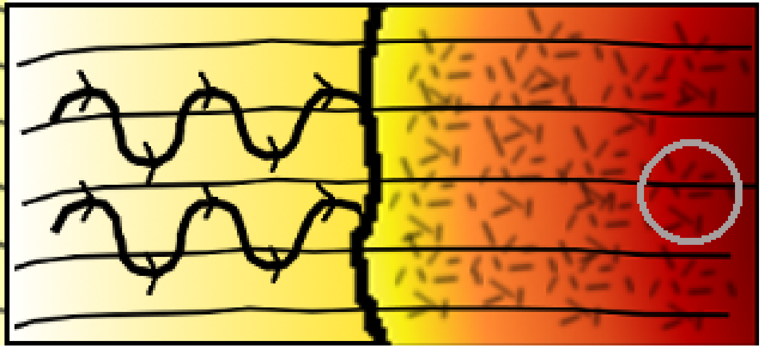
Molecular Clouds: more than stellar factories

Interstellar gas and dust grains are strongly correlated

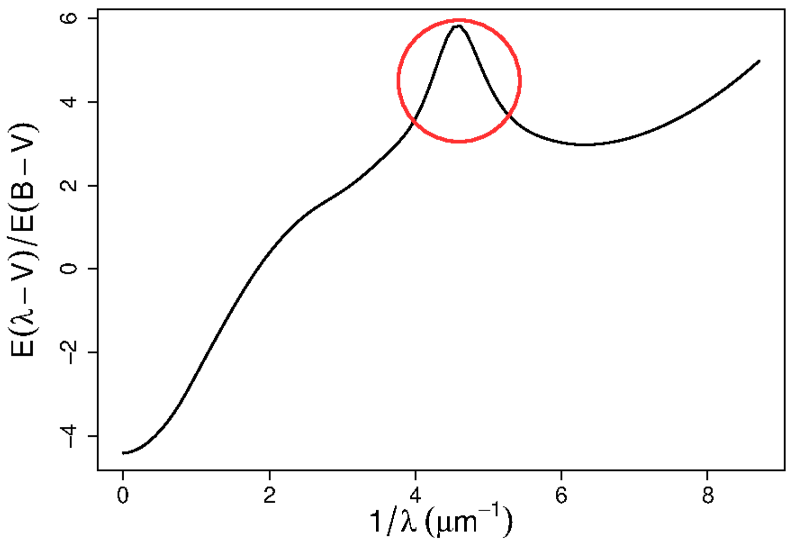
External layers of the clouds are partially ionized

Magnetic coupling to the Galactic field





The extinction curve



$$A_{bump} = 0.106 \pm 0.008 \frac{A_{NUV}}{A_K} + (2.0 \pm 0.3)$$

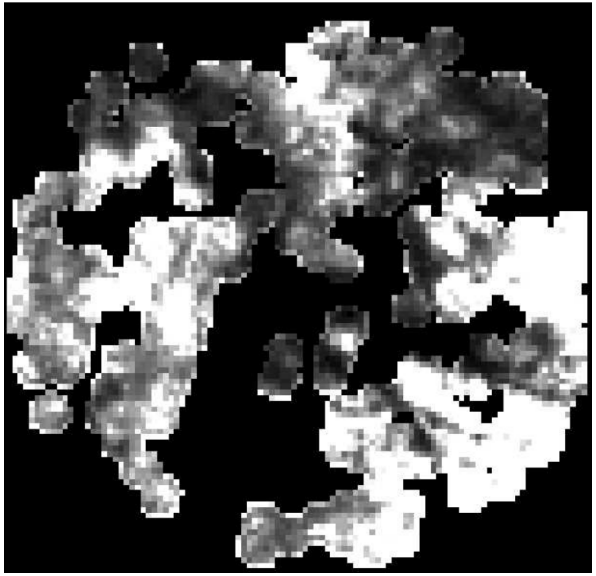
(Gómez de Castro et al., 2015)

UV bump is most likely produced by small dust particles (PAHs)

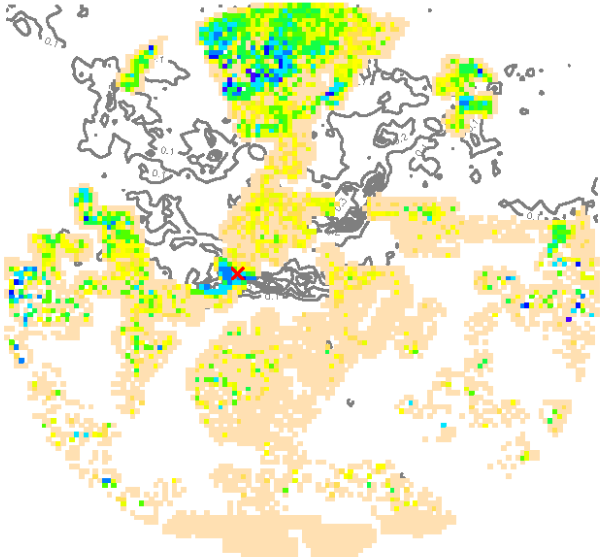
UV-small dust particles interaction is very effective

Molecular cloud outskirts and ultraviolet observations

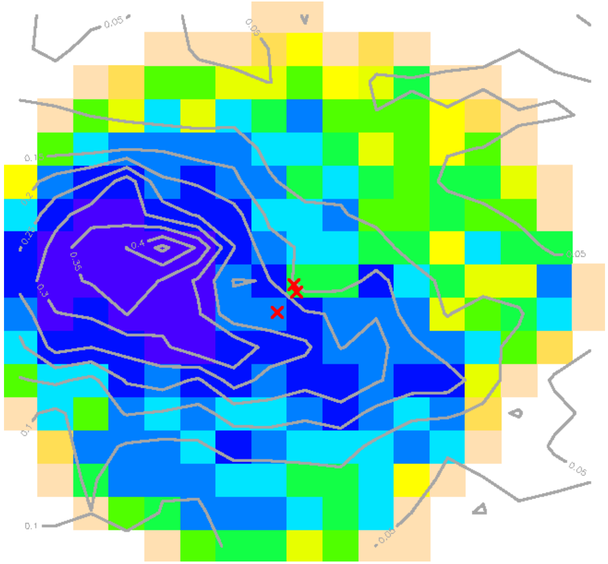
Taurus



Orion



Rosette



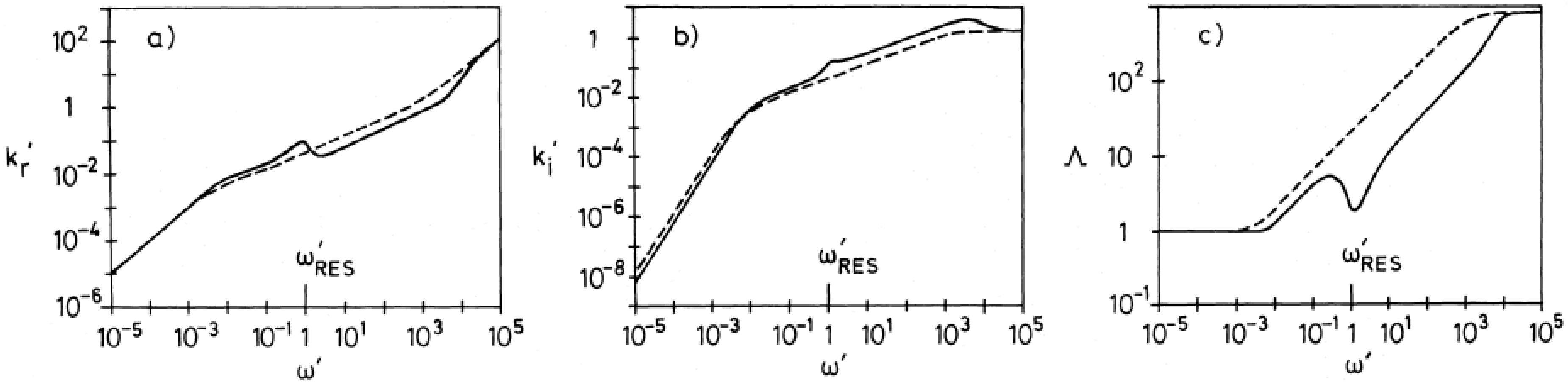
Gómez de Castro et al. (2015)

Beitia-Antero & Gómez de Castro (2017)

Low values of A_{NUV}/A_K in the maps indicate the depletion of small dust grains, either by destruction or grain growth

Dust grains and cloud-magnetic field coupling

Pilipp et al. (1987): *The effects of dust on the propagation and dissipation of Alfvén waves in interstellar clouds*



Five-fluid approach (solid line). Three-fluid approach (dashed line) plotted for comparison
Semi-analytical study

Numerical approach: Athena

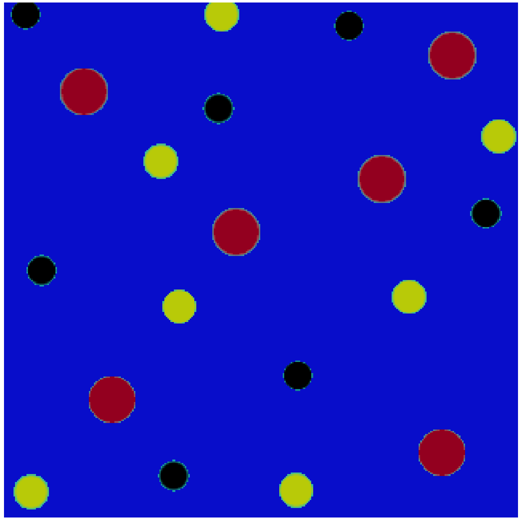
Introduction to Athena

Introduction

Athena is a grid-based code for astrophysical magnetohydrodynamics (MHD). It was developed primarily for studies of the interstellar medium, star formation, and accretion flows. Athena has been made freely available to the community in the hope that others may find it useful.

The current version (v4.2) implements algorithms for the following physics:

- compressible hydrodynamics and MHD in 1D, 2D, and 3D,
- special relativistic hydrodynamics and MHD,
- ideal gas equation of state with arbitrary γ (including $\gamma = 1$, an isothermal EOS),
- an arbitrary number of passive scalars advected with the flow,
- self-gravity, and/or a static gravitational potential,
- Ohmic resistivity, ambipolar diffusion, and the Hall effect,
- both Navier-Stokes and anisotropic (Braginskii) viscosity,
- both isotropic and anisotropic thermal conduction,
- optically-thin radiative cooling.



Background gas: neutrals + ions + electrons

Dust particles (neutral and charged) interacting with the gas

Particles module in Athena: equation of motion

Charged particles implementation by Lehe et al. (2009) [not public]:

$$\frac{\partial \vec{v}_{par}}{\partial t} = \vec{E} + \frac{Ze}{mc}(\vec{v}_{par}\, x\, \vec{B})$$

Implementation by Bai & Stone (2011): aerodynamic drag

$$\frac{\partial \vec{v}_{dust}}{\partial t} = -\frac{\vec{v}_{dust} - \vec{v}_{gas}}{t_{stop}}$$

Our modified equation of motion:

Interactions between particles
(still in progress)

$$\frac{\partial \vec{v}_{dust}}{\partial t} = -\frac{\vec{v}_{dust} - \vec{v}_{gas}}{t_{stop}} + \frac{Ze}{mc}(\vec{v}_{dust} - \vec{v}_{gas})\, x\, \vec{B} - \nu_{Coulomb}(\vec{v}_{dust} - \vec{v}_{gas}) - \sum_j C_j(\vec{v} - \vec{v}_j)$$

Electric drag
ions/electrons – charged grains

Particles module in Athena: numerical implementation

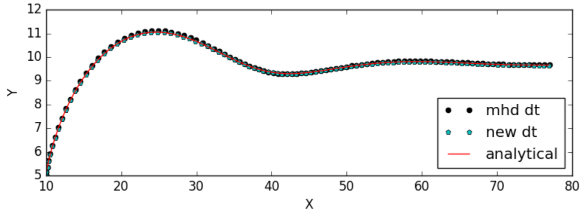
Semi-implicit integrator (Bai & Stone, 2011)

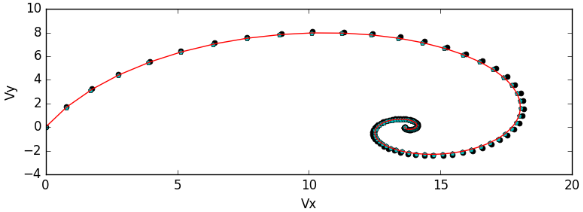
$$\frac{\partial \vec{v}}{\partial t} = \vec{a}(\vec{v}, \vec{x}, \vec{v}_{gas}, \vec{B})$$

$$\vec{v}^{n+1} = \vec{v}^{n} + ha\left(\frac{\vec{v}^{n+1} + \vec{v}^{n}}{2}, \vec{x}', \vec{v}_{gas}^{n+1/2}, \vec{B}^{n+1/2}\right)$$

$$d\vec{v} = h\Lambda^{-1}\vec{a}(\vec{v}^{n}, \vec{x}', \vec{v}_{gas}(\vec{x}')); \Lambda = 1 - \frac{h}{2}\frac{\partial \vec{a}}{\partial \vec{v}}$$

$$\frac{\partial \vec{a}}{\partial v} = \begin{pmatrix} -\frac{1}{t_{stop}} - \nu_{Coulomb} - \sum C_j & QB_z & -QB_y \\ -QB_z & -\frac{1}{t_{stop}} - \nu_{Coulomb} - \sum C_j & QB_x \\ QB_y & -QB_x & -\frac{1}{t_{stop}} - \nu_{Coulomb} - \sum C_j \end{pmatrix}$$





Timestep restrictions

$$\Delta t = \frac{CFL}{10} min\left(\frac{m_{dust} c}{Ze|\vec{B}|}, \Delta t_{MHD}\right)$$

Particles module in Athena: feedback

Continuity equation (negligible effect in our model, low ϵ)

$$\frac{\partial \rho_{gas}\vec{v}_{gas}}{\partial t}+\nabla\cdot\left(\rho_{gas}\vec{v}_{gas}\vec{v}_{gas}-\vec{B}\vec{B}+P_{gas}\vec{I}\right)=\rho_{gas}\epsilon\left(\frac{\bar{v}_{dust}-\vec{v}_{gas}}{t_{stop}}-\frac{Ze}{m_d c}\left(\vec{v}_{dust}-\vec{v}_{gas}\right)x\vec{B}+\nu_{Coulomb}\left(\vec{v}_{dust}-\vec{v}_{gas}\right)\right)$$

Induction equation – two alternatives:

1. Include dust grains effect in the coefficients of Ambipolar Diffusion, Hall effect and Ohmic resistivity (Bai & Stone, 2011) → not enough to study dust grain evolution

2. Implement a predictor-corrector scheme similar to that for the continuity equation

Energy equation

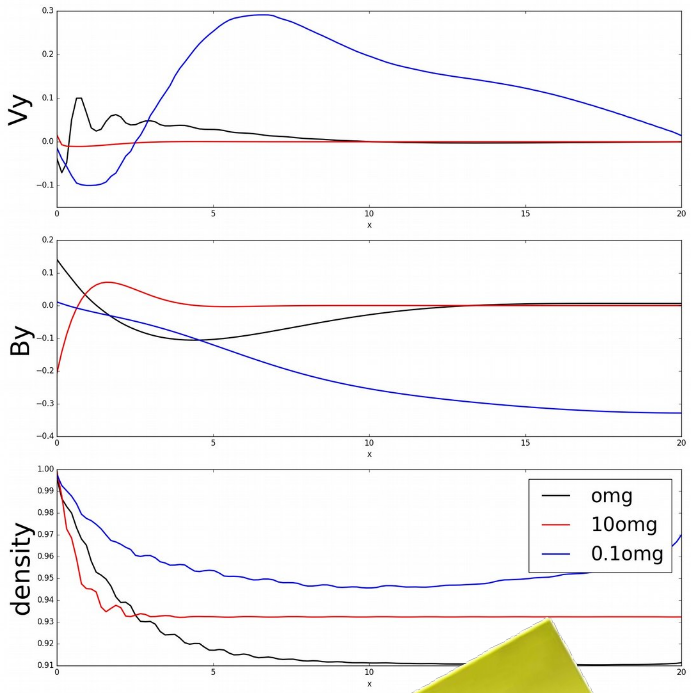
Summary and future work

Dust grains affect the dynamics of the molecular clouds, especially in the outer layers

We are adapting Athena's particles module to include the physics of charged dust grains

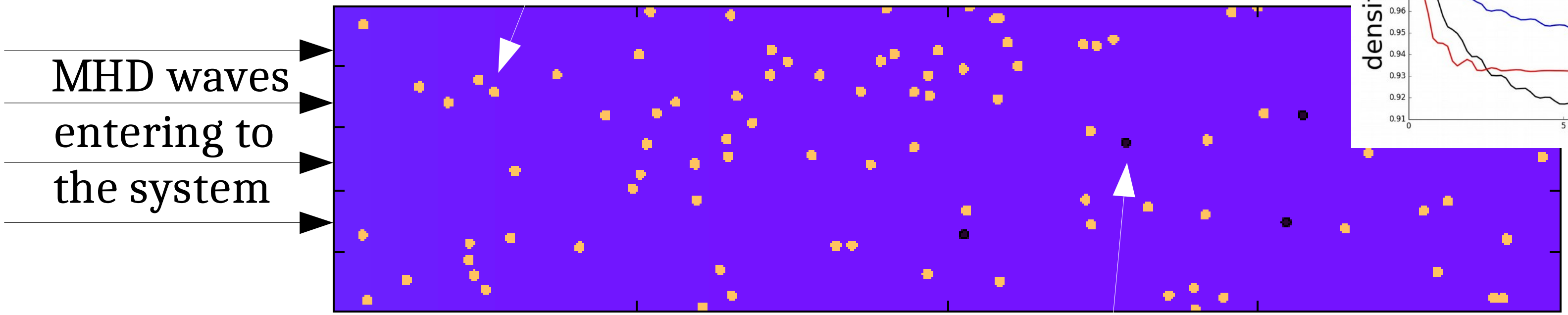
Feedback to the gas is still under implementation

Preliminary tests without particles



Charged grains

MHD waves entering to the system



Isothermal
Ambipolar diffusion and Hall effect

Neutral grains