Dusty Kelvin-Helmholtz Instabilities and the Molecular Cloud Connection

Tom Hendrix and Rony Keppens

Centre for mathematical Plasma-Astrophysics
KU Leuven, Belgium

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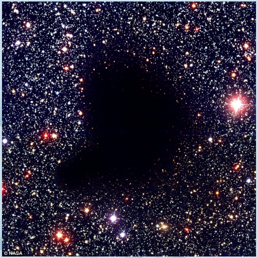
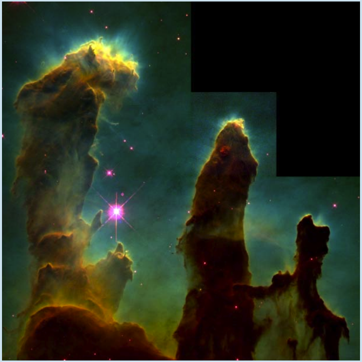
Dust in Space

Dust plays an important role in a broad range of locations in space. E.g.:

- Torus around SMBHs
- Molecular clouds (e.g. stellar formation)
- Protoplanetary disks
- Cometary outflows





Left figure: Barnard 68, credit VLT,ESO. Right figure: Starforming clouds in M16, credit HST, NASA

MPI-AMRVAC

Study dust dynamics using numerical simulation:

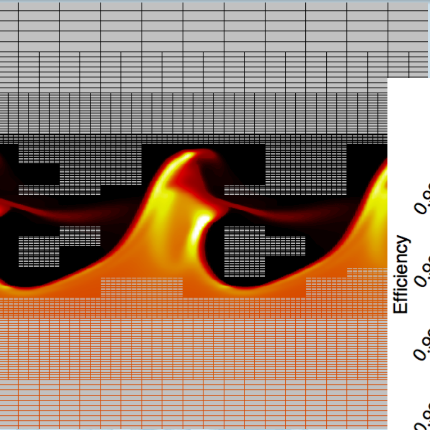
MPI-AMRVAC

- Grid based parallel code
- Adaptive mesh-refinement
- Several physics modules: HD, MHD, SRMHD, HD+Dust,...
- Additional physics plugins: ray tracing, radiative cooling, gravity, ...

Info: Keppens et al., 2012

Get it now at `homes.esat.kuleuven.be/~keppens/`

MPI-AMRVAC



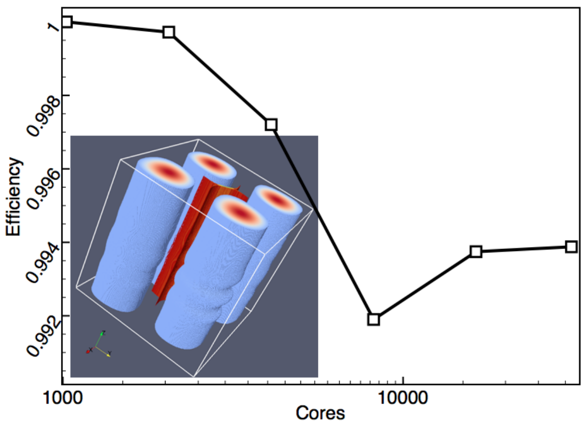


Figure: Weak scaling test

MPI-AMRVAC: HD multi-fluid dust module

Dust module

- Dust as extra fluids
- Dust is pressureless gas
- Every dust species has a set grain size and grain density
- Gas-dust coupling using combined Epstein + Stokes drag law

Grain size distribution

Following simulations:

- All dust fluids have same grain density, i.e. silicate densities ($\rho = 3.3$ g cm^{-3})
- Different species represent different parts of the canonical ISM size distribution ($n(a) \propto a^{-3.5}$)
- Grains radii a between 5nm and 250nm, each of the N dust fluids represents a part from $a_{min,i}$ to $a_{max,i}$, which are chosen by setting equal parts of the total dust mass in each dust fluid.
- Effective radius $\bar{a}_i$ is weighted by the drag force over the represented interval between $a_{min,i}$ and $a_{max,i}$
- System advance through 2^{th} order TVDLF scheme with a monotonized central limiter

MPI-AMRVAC: HD multi-fluid dust module

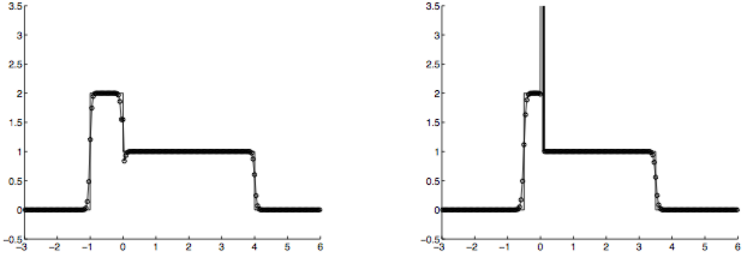


Figure: Pressureless Gas, LeVeque (2003)

Fluid description:

- Dust-Dust: tricky

$$1 > Kn = \frac{\lambda}{L} = \frac{1}{\sqrt{2}\pi 4 r_d^2 n_d L} \approx \frac{\rho_S r_d}{3\sqrt{2}\rho_d \Delta x}$$

- Dust-Gas: OK

Dusty Kelvin-Helmholtz Instability

Kelvin-Helmholtz Instability

Classical KHI:

- Shear induced instability
- No density or pressure difference needed
- Most simple setup: discontinuity in velocity is unstable for all wavelengths
- Stabilization can be introduced by surface tension of a transition layer

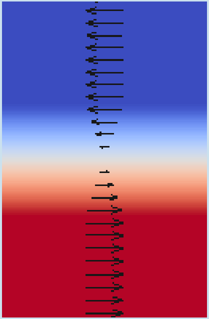
De Sterrennacht, Vincent van Gogh

Kelvin-Helmholtz Instability

Approach: We study the effect of dust on the KHI by comparing the analytical gas-only solution with gas+dust simulations.

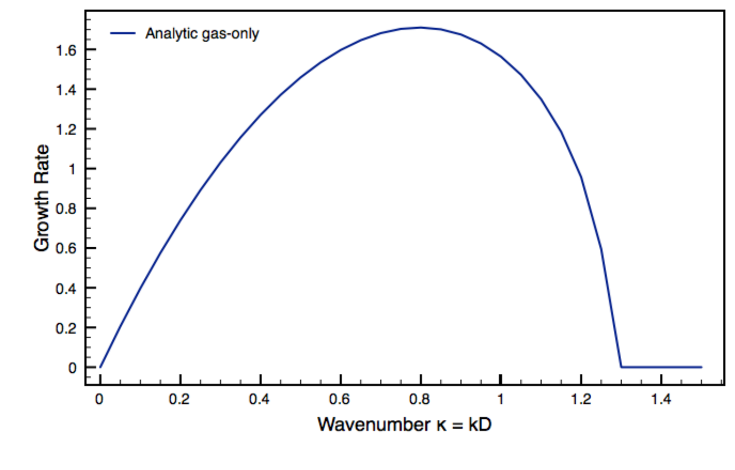
Setup:

- Stabilized configuration with two layers, separated by a thin layer.
- Uniform gas density.
- Effective resolution 1024×2048.
- Basic setup: 4 dust types, size distribution between 5nm and 250nm.
- Subsonic velocity difference.
- Physical values similar to molecular clouds.



Linear phase

We derive the dependency of the growth rate on the wavelength of the perturbation.



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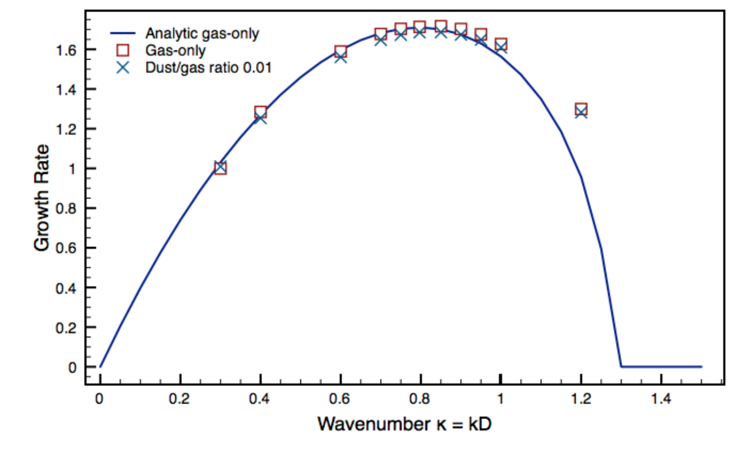

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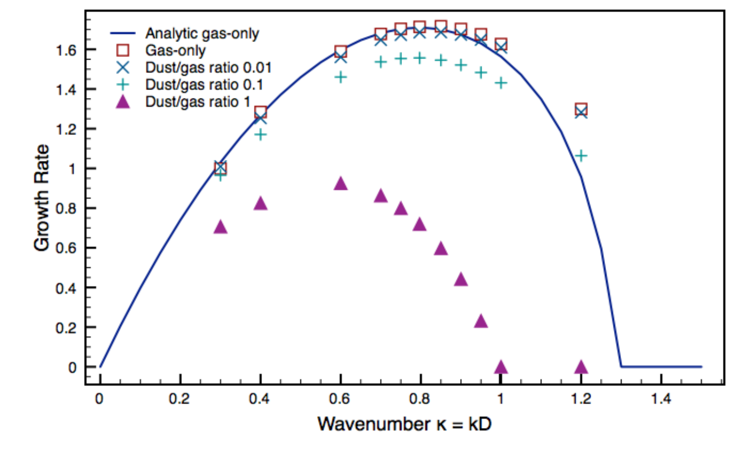
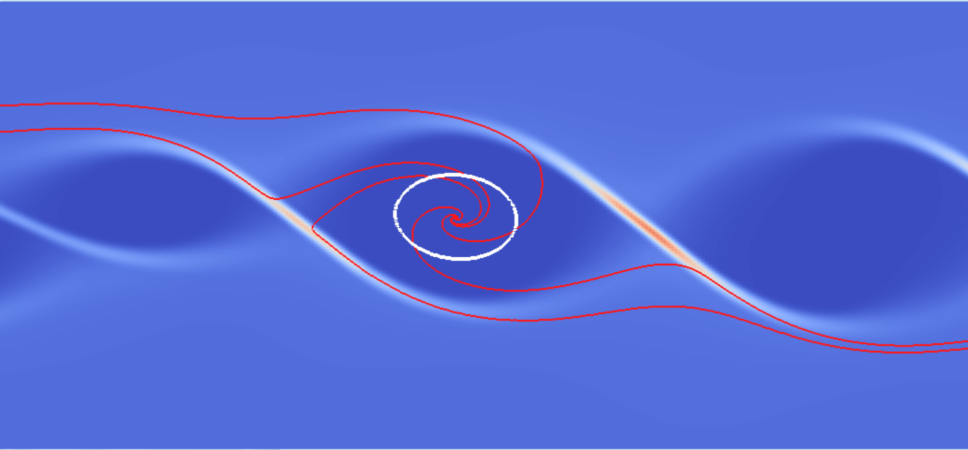


Kelvin-Helmholtz Instability

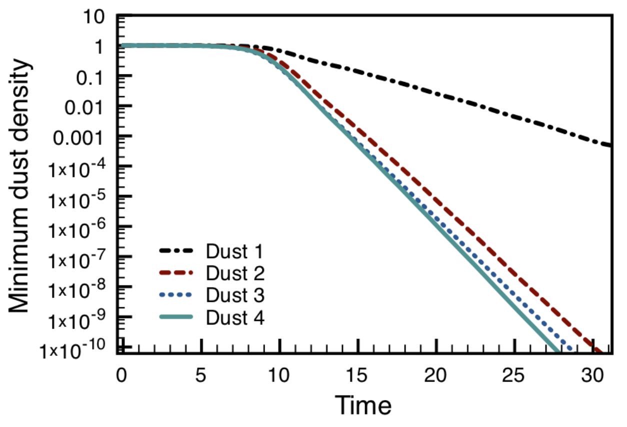
So, what does it look like?

Non-linear phase: The Dust Vacuum Cleaner



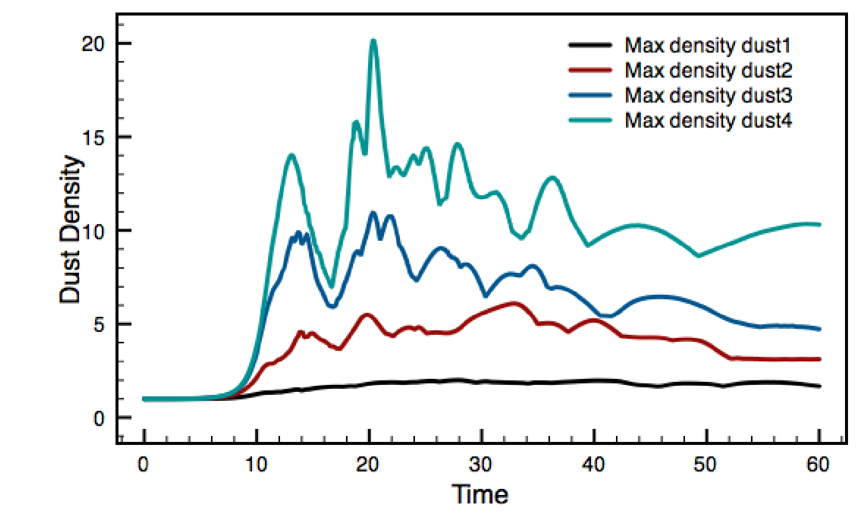
Non-linear phase: The Dust Vacuum Cleaner

Exponential decrease in dust density from start of non-linear phase:



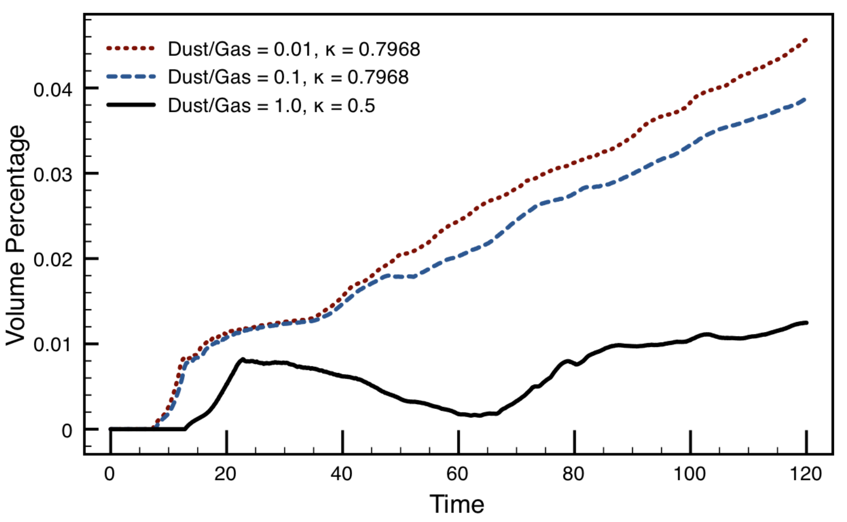
Non-linear phase: Dust Density Increase

Heavier dust species tend to clump to higher densities:



Non-linear phase: Dust Density Increase

Volume percentage of the increased dust densities grows linearly:



3D simulation

Extra full 3D instabilities in late non-linear stage:

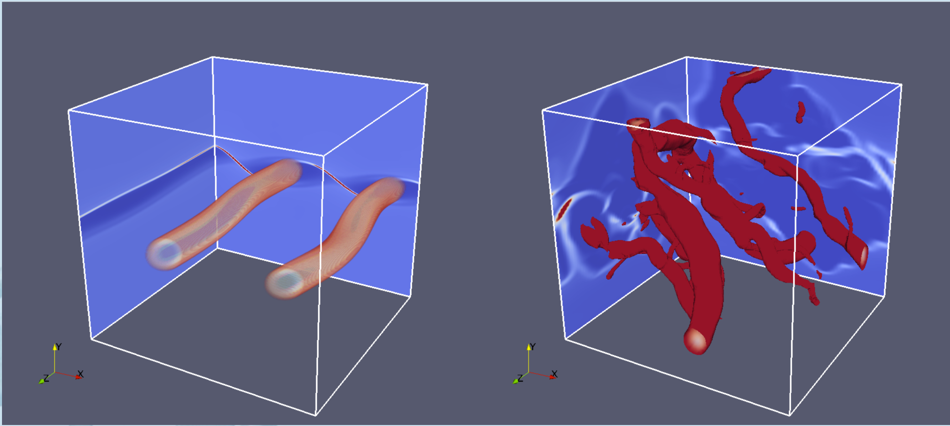
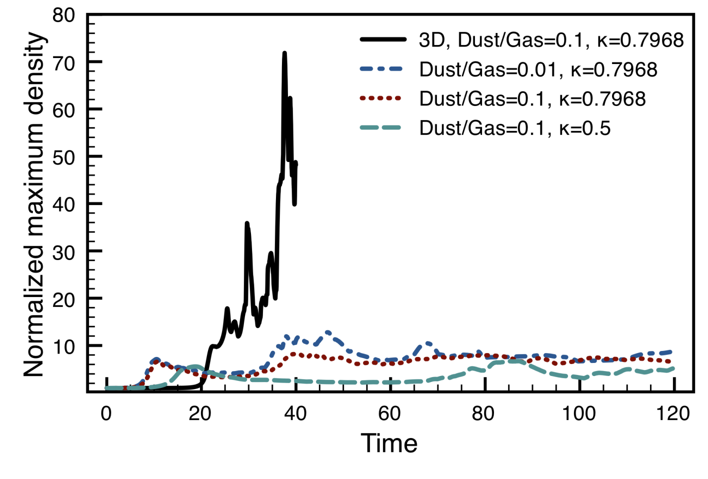


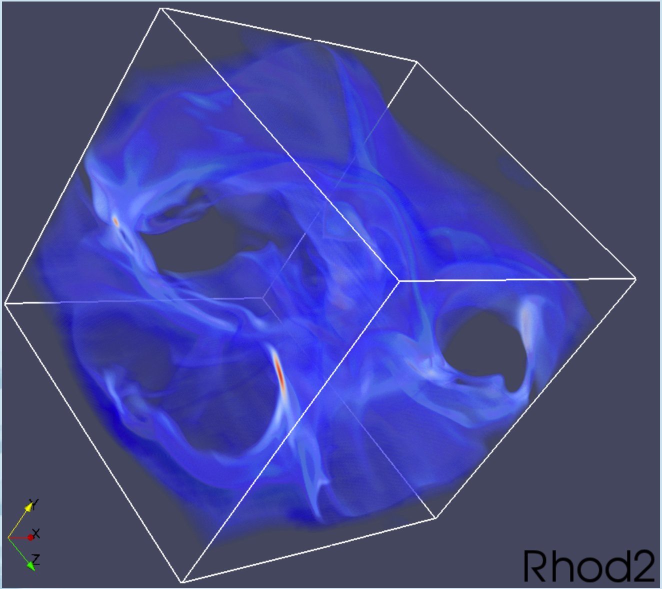
Figure: t=22 Figure: t=40

Non-linear phase: Dust Density Increase

3D effects lead to strong additional density increases:



Dust ends up in "filaments" along the vacuum bubbles:



Astronomical Reflection

We used physical values typical for molecular clouds.
Are our filaments related to those in molecular clouds?

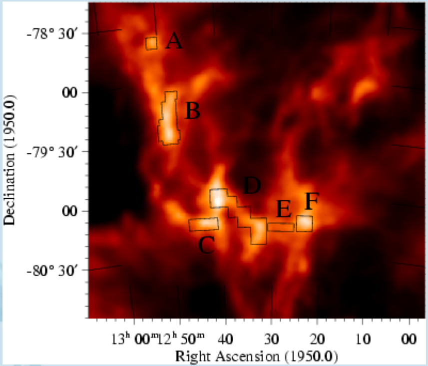


Figure: G.F.Gahm et al., Cham III IRAS map at 100 μm

Astronomical Reflection

Strong observational evidence for the existence of (dusty) KHI in the Orion molecular clouds was presented by Berné et al. (2010) and Berné & Matsumoto (2012).

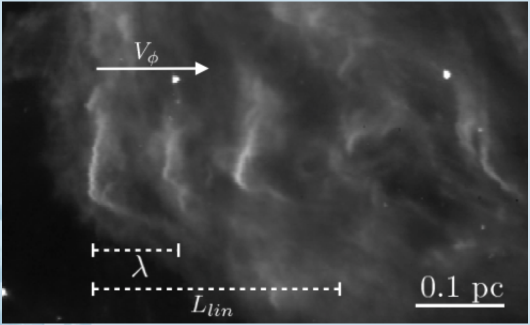


Figure: Berné & Matsumoto, 8 μm image of the Ripples in Orion

Astronomical Reflection

Probability column density functions:

- hydrodynamic turbulence leads to lognormal distributions (fitted with solid line)
- extra exponential tail observed for high densities
- proposed to be due to self-gravity
- Extra tail for low densities?

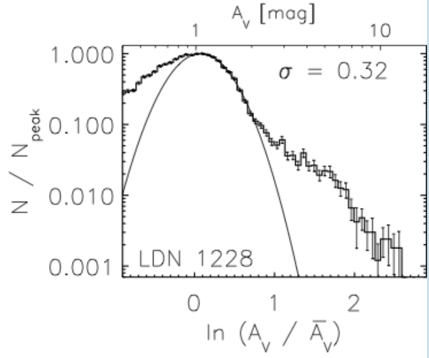
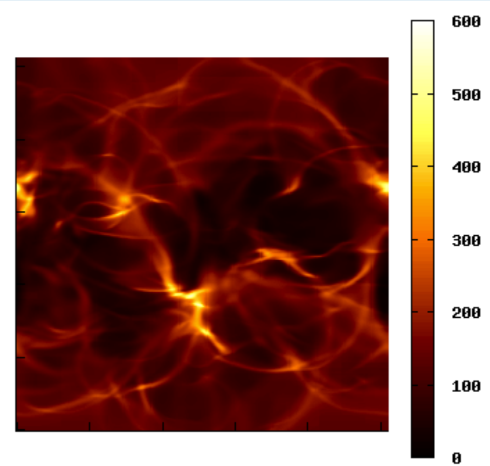


Figure: Kainulainen et al. 2009

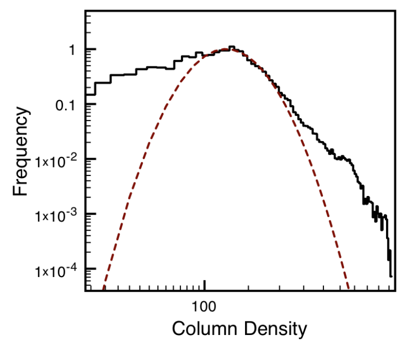
Astronomical Reflection

Artificial observations from 3D simulations:



Astronomical Reflection

Allow us to make similar probability distributions:



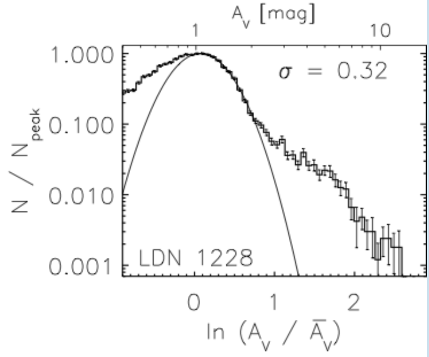


Figure: Kainulainen et al. 2009

Take-home message:

- Dust (dynamics) is important!
- Dust slows the KHI
- Density increases up to two orders of magnitude
- KHI as explanation of observed PDFs in molecular clouds

Gas equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla p = \sum_{d=1}^{N} \mathbf{f_d}, \quad (2)$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(p+e)\mathbf{v}] = \sum_{d=1}^{N} \mathbf{v} \cdot \mathbf{f_d}, \quad (3)$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho v^2}{2}, \quad (4)$$

Drag force:

$$\mathbf{f_d} = -(1-\alpha)\pi n_d \rho a_d^2 \Delta \mathbf{v} \sqrt{\Delta \mathbf{v}^2 + v_t^2} \quad (5)$$