Radiative MHD in Massive Star Formation and Accretion Disks

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IAUS 259, Tenerife, November, 04. 2008
Radiative MHD with “Makemake” and “Pluto”:

We developed a fast 3D frequency-dependent radiation transport module, called Makemake [7], and implemented it successfully with the freely available MHD-code Pluto [6].

Features of Makemake:

- Geometries: Cartesian, Cylindrical and Spherical coordinates in 1, 2 and 3D.
- Gray (opacity-averaged) Flux-Limited Diffusion approximation
  + Frequency-dependent Irradiation (1st order Ray-tracing).
- MPI-parallelized modern GMRES-solver using the PETSc-library [3].

Performance of Makemake:

- CPU-time comparable or even faster than hydro step (compared with an accretion disk setup in Pluto).
- Parallel speedup higher than hydro-solver.
- Accuracy for a single object source (setup adopted from the Pascucci Radiation Benchmark Test [4]) comparable to full frequency-dependent Monte-Carlo radiative transfer method (but incredible faster than MC!).

References:

Radiative MHD with “Makemake” and “Pluto”:

Results of the comparison of Makemake with the Monte-Carlo based radiative transfer code RADMC [5].

- Accuracy for a single object source (setup adopted from the Pascucci Radiation Benchmark Test [4]) comparable to full frequency-dependent Monte-Carlo radiative transfer method (but incredible faster than MC!).

References:
Application I: Massive Star Formation

Setup (adopted from Yorke & Sonnhalter 2002):

- Massive core with outer Radius = 0.1 pc.
- Total Mass = 60 \( M_{\text{sol}} \).
- Density drops with \( r^{-2} \).
- Temperature = 20 K.
- Initial Angular Momentum = 0 (1D) or \( 5 \times 10^{-13} \) Hz (2D).

Included Physics (in different runs):

- Isothermal.
- Adiabatic.
- Diffuse cooling (infrared dust emission).
- Irradiation feedback from central star.
- Radiation pressure feedback from central star.
- Frequency-dependent irradiation and radiation pressure.
Application I: Massive Star Formation

Results 1D:

- Frequency-dependent radiation pressure limits the final stellar mass to \( \sim 30M_{\text{sol}} \) (~50% \( M_{\text{tot}} \)).

\[
\begin{align*}
M_{\text{star}} \ [M_{\text{sol}}] & \quad \text{Isothermal} \\
\text{Time [1000 years]} & \quad \text{Frequency-dependent Radiation Pressure}
\end{align*}
\]
Application I: Massive Star Formation

Results 2D:

- Due to angular momentum conservation the adiabatic collapse forms a several 100 AU torus as well as polar cavities.
- The prior free-fall era leads to a $10 \, M_\odot$ star.
- Further accretion is only possible via gravitational, radiative or magnetic instabilities.

Both panels:
- Left color = Radial Velocity (blue Infall, red Outflow)
- Left contour = Density (log)
- Right color = Density (log)
- Right contour = Temperature (log)
Application I: Massive Star Formation

Next steps:
- Frequency-dependent 2D runs.
- 3D simulations of Gravitational Instabilities in the resulting disk/torus.
- 3D simulations of developing MRI in the resulting disk.

See also “Application II”.

Both panels:
Left color = Radial Velocity (blue Infall, red Outflow)
Left contour = Density (log)
Right color = Density (log)
Right contour = Temperature (log)
Application II: MRI in accretion disks

Setup:
- Proto-planetary disk in hydrostatic equilibrium.
- Toroidal magnetic field with constant plasma beta about 25.
- A small random velocity seed drives to MRI.
- Radial boundary: Perfect conductive massive plate.
- Vertical and azimuthal boundary: Periodic.

Code and configuration:
- Pluto 3.0 with
  - Second order Godunov scheme (hlld)
  - Upwind constraint transport (ct) - Consistent electromotive force reconstruction (emf)
Application II: MRI in accretion disks

Results:

- Within the first 100 inner orbits a highly magnetized corona is forming (plasma beta < 1), while the midplane of the disk remains at large plasma beta values susceptible for the MRI (see azimuthal averaged plasma beta in Figure II.1).

Figure II.1: Logarithmic plasma beta for 100x25x25 (left), 200x50x50 (middle) and 400x100x100 (right) after 10 orbits (at 5 [AU]) in turbulent state.
Application II: MRI in accretion disks

Results:

- Within the first 100 inner orbits a highly magnetized corona is forming (plasma beta < 1), while the midplane of the disk remains at large plasma beta values susceptible for the MRI (see azimuthal averaged plasma beta in Figure II.1).
- For all studied resolutions the turbulence converges against an alpha value about 0.01 (see Figure II.2).

![Figure II.1: Logarithmic plasma beta orbits (at 5 [AU]) in turbulent state.](image1)

![Figure II.2: Maxwell-Stress evolution for three diff. Resolutions. The values converge against each other.](image2)
Application II: MRI in accretion disks

Next steps:

- First MRI-runs including Makemake radiative transfer are currently performed on our cluster.
- Non-Ideal Radiative MHD with temperature-dependent dynamical resistivity.

Figure II.1: Logarithmic plasma beta (at 5 [AU]) in turbulent state.

Figure II.2: Maxwell-Stress evolution for three different resolutions. The values converge against each other.
Interested?

For more details about our projects, access to our code, hints or remarks of any kind:

- Visit www.mpi.a.de/~kuiper → Research → Radiative Transfer for MHD.
- Mail to kuiper@mpia.de.
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Thanks for your attention
and
enjoy your stay!