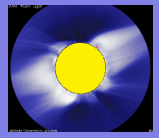
Current Status & Problems of sw3D

Informal talk at TP4

Theoretische Physik I & IV
Ruhr-Universität Bochum, Germany



Equations & Tests
Application to SW . . .
Radial Symmetry?

1. Equations & Tests

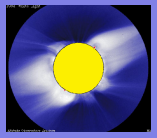
1.1. MHD equations (single fluid)

$$
\begin{aligned}
\partial_t\ \rho &= -\nabla\cdot(\rho\mathbf{v}) \\
\partial_t(\rho\ \mathbf{v}) &= -\nabla\cdot(\rho\mathbf{v}\ \mathbf{v}) - \nabla p + \mathbf{j}\times\mathbf{B} - \rho\ \nabla\Phi_{\rm grav} \\
\partial_t\ \mathbf{B} &= -\nabla\cdot(\mathbf{v}\ \mathbf{B} - \mathbf{B}\ \mathbf{v})\ + \eta\nabla^2\mathbf{B} - \nabla\eta\times\mathbf{j} \\
\partial_t E &= +\nabla\cdot[(p+E)\ \mathbf{v}] + Q
\end{aligned}
$$

$$
\text{where}\left[\begin{array}{rcl}
\gamma &=& 5/3 \\
p &=& \rho\ T\ \text{(ideal gas e.o.s)} \\
E &=& \dfrac{\rho\ v^2}{2} + \dfrac{B^2}{2} + \rho\ \Phi_{\rm grav} + \left\{\begin{array}{ccc} p/(\gamma-1) & : & \gamma\neq 1 \\ 0 & : & \gamma = 1 \end{array}\right.
\end{array}\right]
$$

1.2. Basic Tests

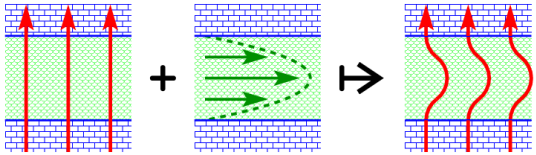
- Extensive (M)HD testing: advection 1D/2D, (strong) shock tube, Brio & Wu, Sedov explosion
- B field: implemented & tested on (Cartesian) 1D/2D settings
  - decay of $\mathbf{B}(x,t)_{t=0} = \exp(-x^2)\mathbf{e}_y$
  - plus:

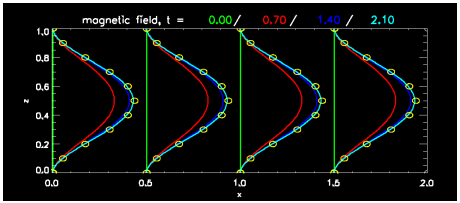


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1.3. Code Testing I: simplified Hartmann flow

- incompressible tube flow, $\mathbf{v} = v(z)\ \mathbf{e}_x$ static
- deformation of $\mathbf{B}$ $\propto$ (resistivity η)$^{-1}$

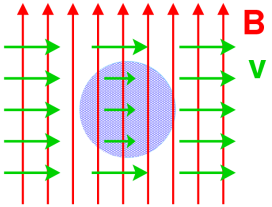




1.4. Code Testing II: Alfvén wings

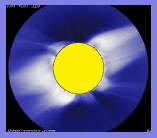
- $t = 0$: $\mathbf{v} \perp \mathbf{B}$, homog.
- $t > 0$: $\mathbf{v}$ local 'slow-down'

models a non-magnetic body in plasma flow (e.g. planet/ moon/satellite in SW/ mageto-sphere)



Animations:

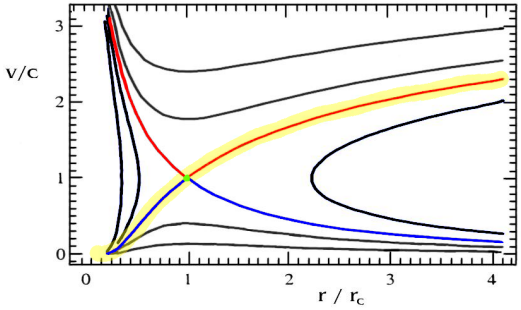
- velocity
- gas pressure
- **B** field



2. Application to SW Modeling

...where $\Phi = -GM_{\rm Sun}/r$
Init: Parker wind solution.

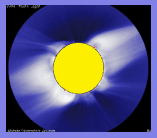
$$\begin{cases} \partial_r(r^2\ \rho\ v) &=& 0 \\ v\ \partial_r v &=& -\dfrac{\partial_r \rho}{\rho} - \dfrac{GM_{\rm Sun}}{r^2} \\ p &=& c^2\ \rho \quad \wedge \quad c \propto \sqrt{T} \end{cases}$$



$$\Rightarrow \quad \frac{u^2-1}{2u}\frac{\partial u}{\partial r} = \frac{1}{x} - \frac{1}{x^2} \qquad \text{where} \quad u := \frac{v}{c} \wedge x := \frac{r}{r_c} \wedge r_c := \frac{GM_{\rm Sun}}{2c^2}$$

2.1. "Propaganda" plots

- Isothermal with "CME"
- Non-Isothermal with axisymmetric heating
- Non-Isothermal with radial heating plus "CME"
- Early attemps with $B \neq 0$ suffer from $\nabla \cdot \mathbf{B}$ issue.



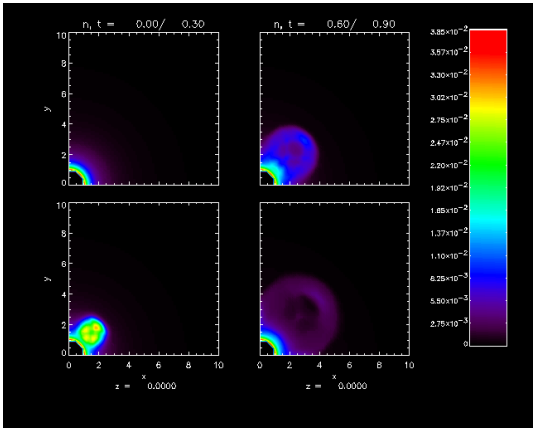
Equations & Tests
Application to SW . . .
Radial Symmetry?

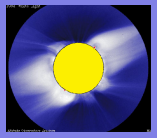
2.2. Isothermal expansion of 'disturbance'

density :	1 particle/cm^3
length :	$R_{\text{Sun}} = 7 \cdot 10^5$ km
time :	$\tau := R_{\text{Sun}}/v_{\text{sound}} \approx 45$ min
velocity :	$v_{\text{sound}} \approx 250$ km/s ($\Leftrightarrow T \approx 4 \cdot 10^6$ K)

CME anim [ρ only]

CME anim [ρ & $\mathbf{v}$]



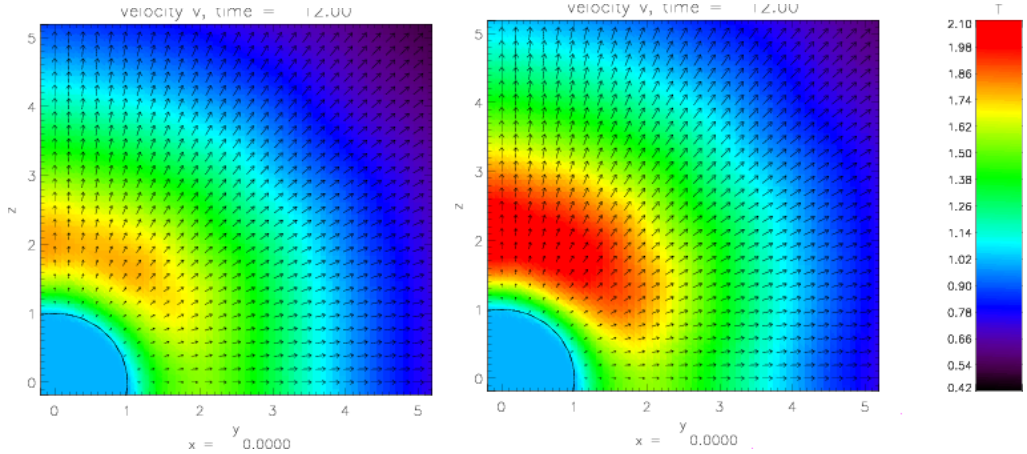


2.3. Non-isothermal 'quiet Sun' solution

Full energy equation requires (axially symmetric) heating

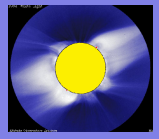
$$Q(r,\vartheta) \propto \frac{1}{r^2}\exp\left[-1.4\left(\frac{r}{R_{\rm Sun}}-1\right)\right](1+w\cos\vartheta)$$

to compensate for adiabatic cooling → System converges into stationary state.



$w = 0.25$ $w = 0.50$

plasma temperature T (color coded) & velocity $\|\mathbf{v}\|$ (arrows)



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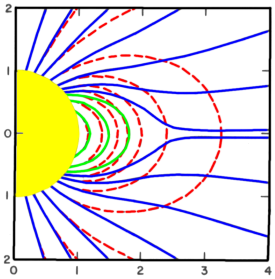
2.4. Magnic field of the 'quiet' Sun

Idea: **dipole** + **Solar wind**

$\Longrightarrow$

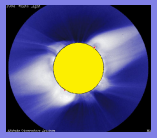
region	flow	magnetic field
polar ($\vartheta < 45°$)	strong	**lines** $\to \infty$
equator	weak	**arch-shaped**

Animations: **B** field | **v** field



2.5. $\nabla \cdot \mathrm{B}$ at the Solar surface

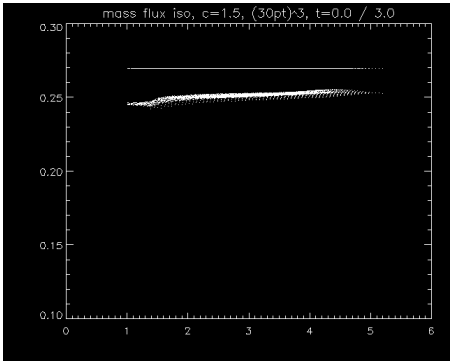
Anim:
$(\nabla \cdot \mathbf{B})/\|\mathbf{B}\|$

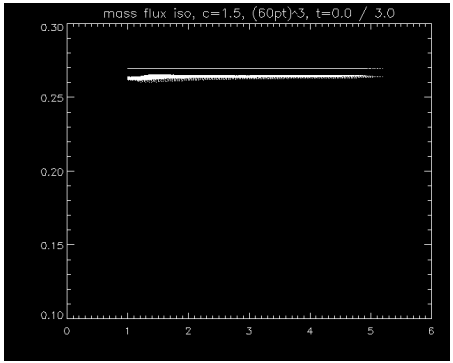


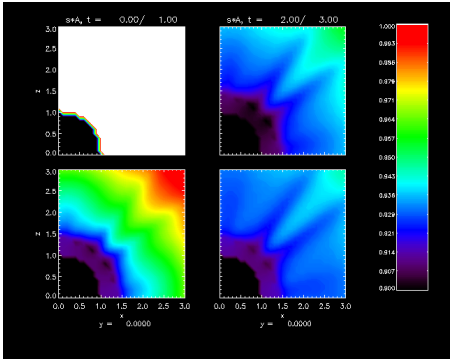
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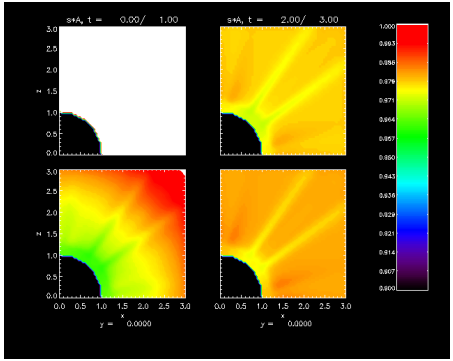
3. The Radial Symmetry Problem

3.1. Mass flux for isothermal runs ($\gamma = 1$)



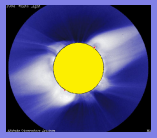






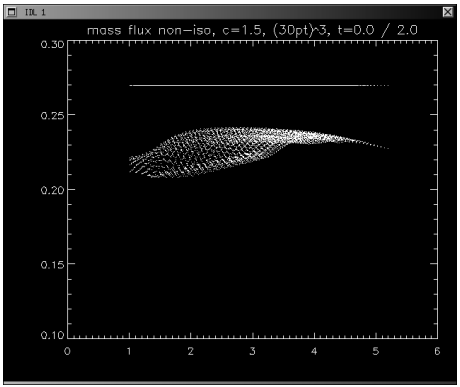
30^3 pts

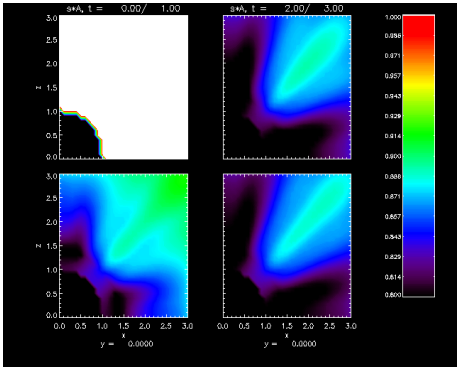
60^3 pts



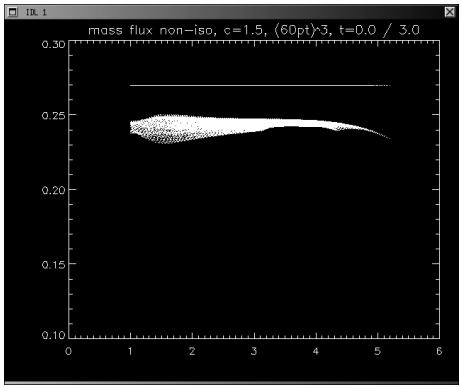
Equations & Tests
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Radial Symmetry?

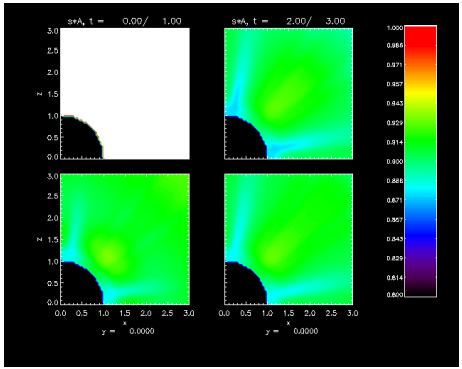
3.2. Mass flux for non-isothermal runs ($\gamma \neq 1$)



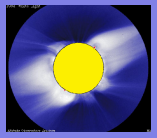


30^3 pts





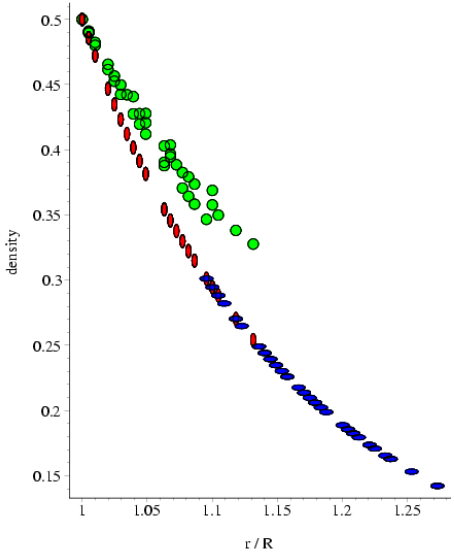
60^3 pts

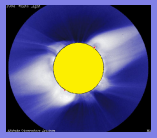


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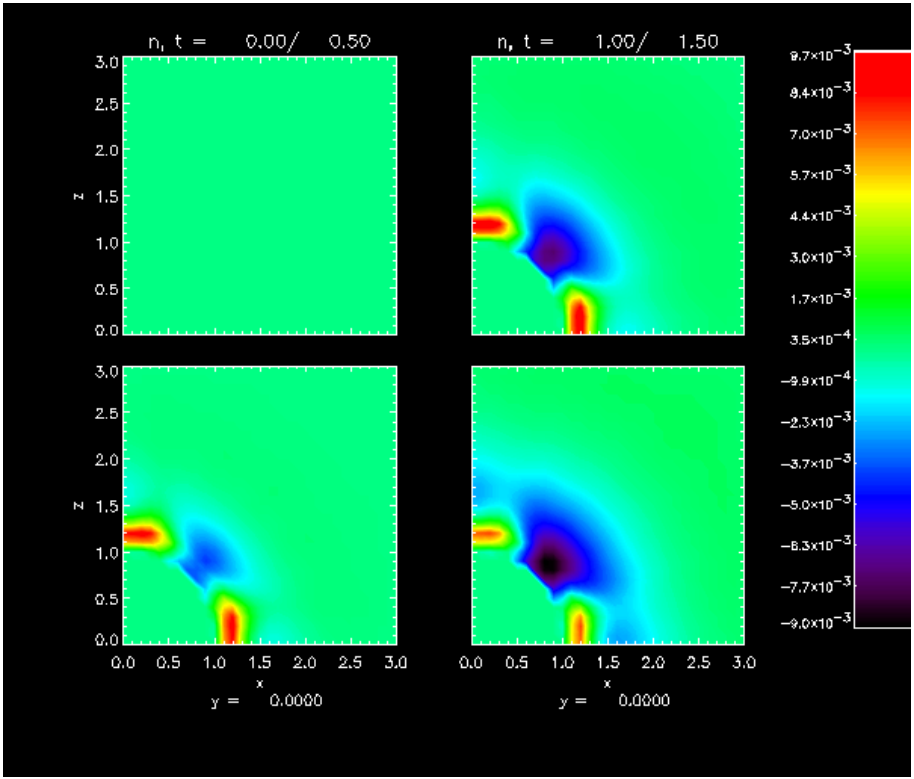
3.3. Interpolation Methods

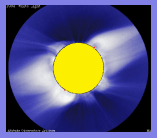
1. **Linear interpolation** (→ Felix): Not good close to the Sun (see image).
2. **6-Point stencil**: Fpoints now closer to curve. No real improvement seen.
3. **disregard surface values for ρv**: mass flux adapts everywhere onto new level
4. **increase Fp-layer thickness to $2\sqrt{3}\Delta x$**: improvement in Fp-layer, scatter width unchanged.
5. **use $\rho v_i r^2$ for averaging**
6. **align vectors before averaging**
7. **take cell average rather than center value**: somewhat different, not better.





From previous runs with other params ($c = 1$, ...):
departure of ρ from initial state





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