New Opportunities: Flux Emergence Modeling

George H. Fisher

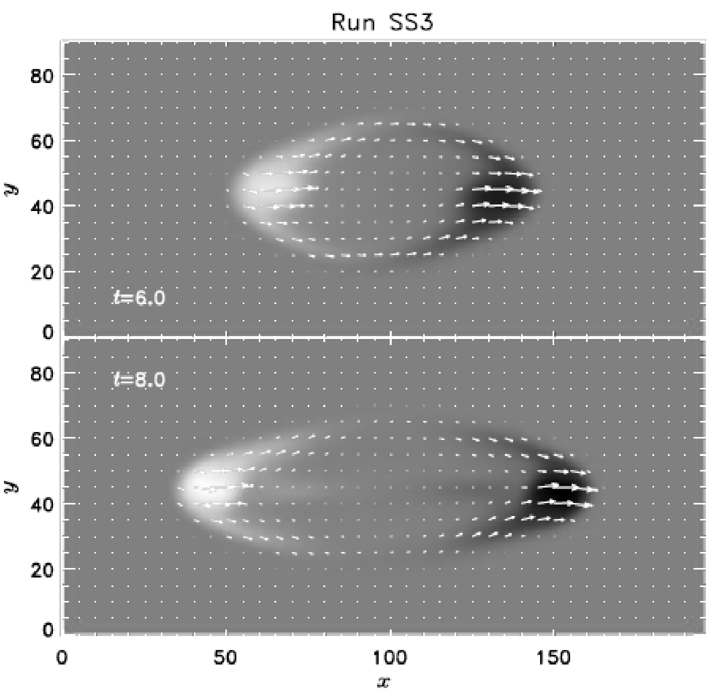
Space Sciences Laboratory

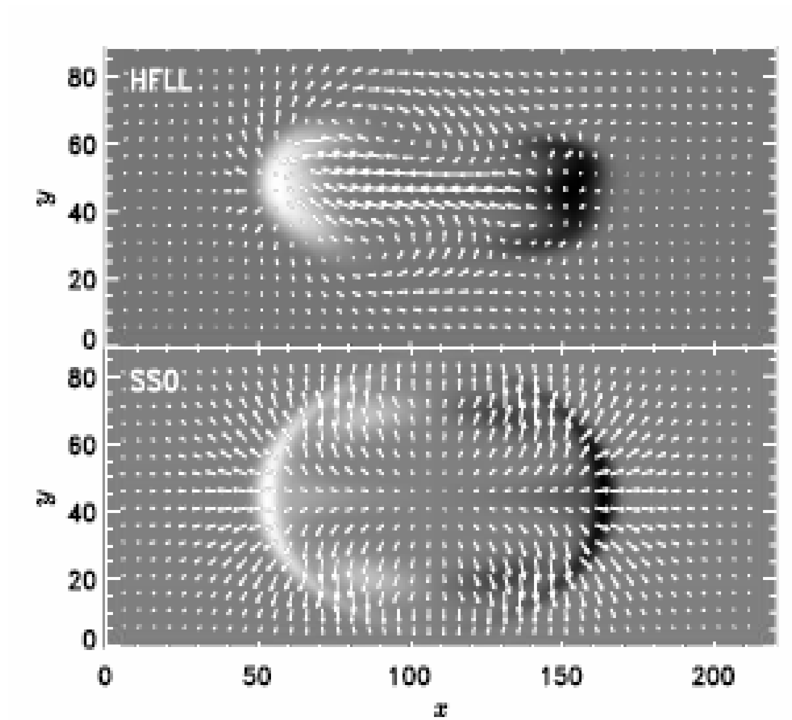
UC Berkeley

Brief Summary of three-dimensional MHD codes being used and/or developed by members our group at UCB that can be used to study magnetic flux emergence on the Sun:

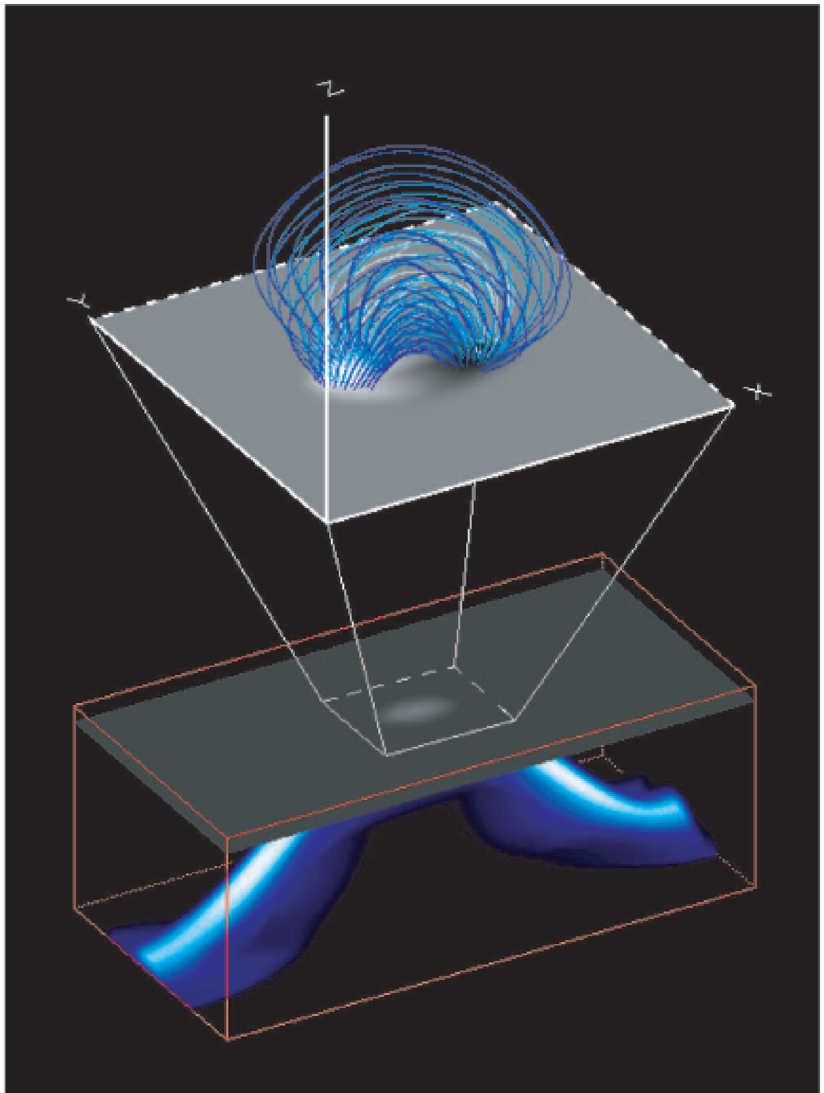
- **ANMHD** – Anelastic, 3-D Cartesian MHD code suitable for modeling chunks of the solar convection zone. *Status***:** mature and robust. Source code publicly available on web with GPLv2 license.
- **SANMHD** – Anelastic 3D global spherical MHD code designed for global models of the Sun's magnetic field in the solar interior. *Status:* Still being developed, promising spin-offs (e.g. high-order spherical harmonic transforms) exist now.
- **RADMHD** – Compressible 3D Cartesian MHD code specifically designed to model the Sun's upper convection zone, photosphere, chromosphere, and corona. *Status:* Working research code, available upon request from the developer, Bill Abbett. Will be publicly available as an open-source code in the future.

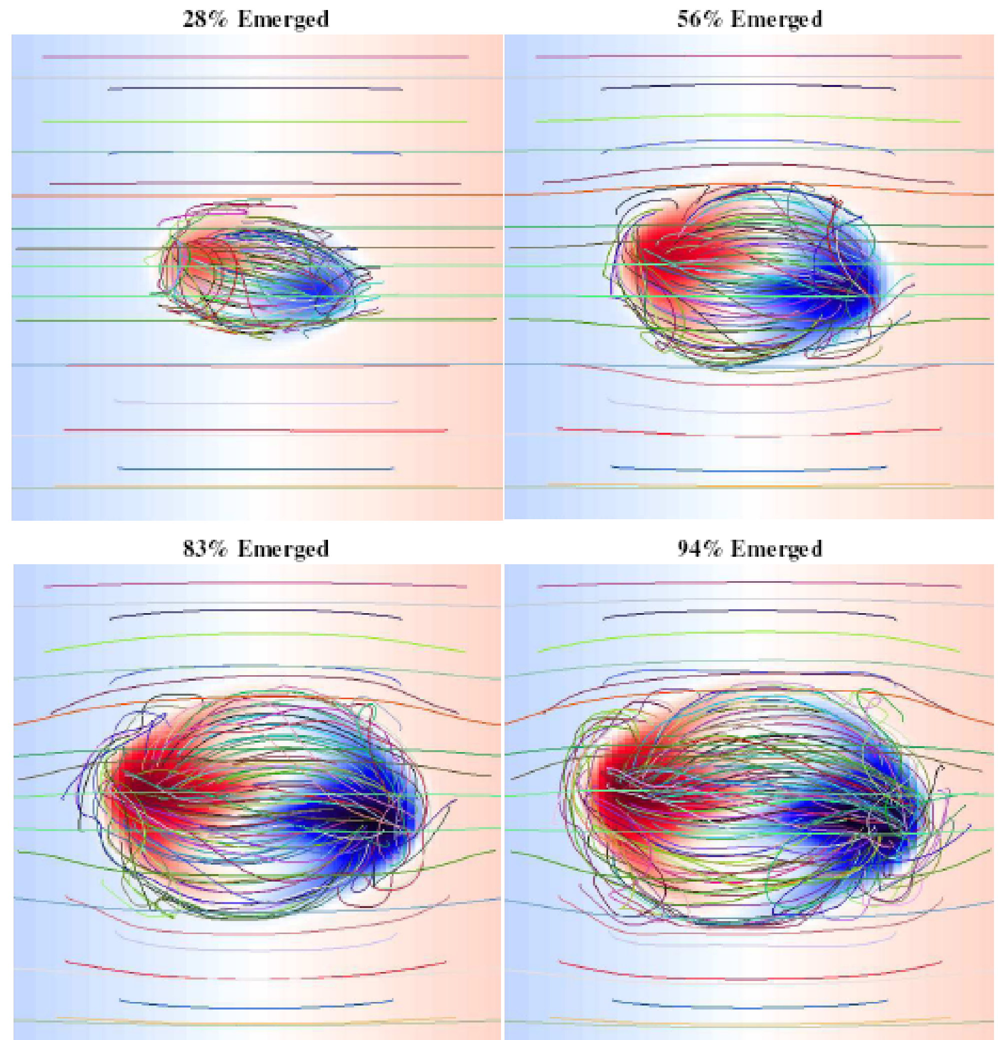
ANMHD: “magnetograms” near the photosphere from simulations of emerging active regions (Abbett, Fisher & Fan ApJ 540, 548 [2000], ApJ 546, 1194 [2001].)



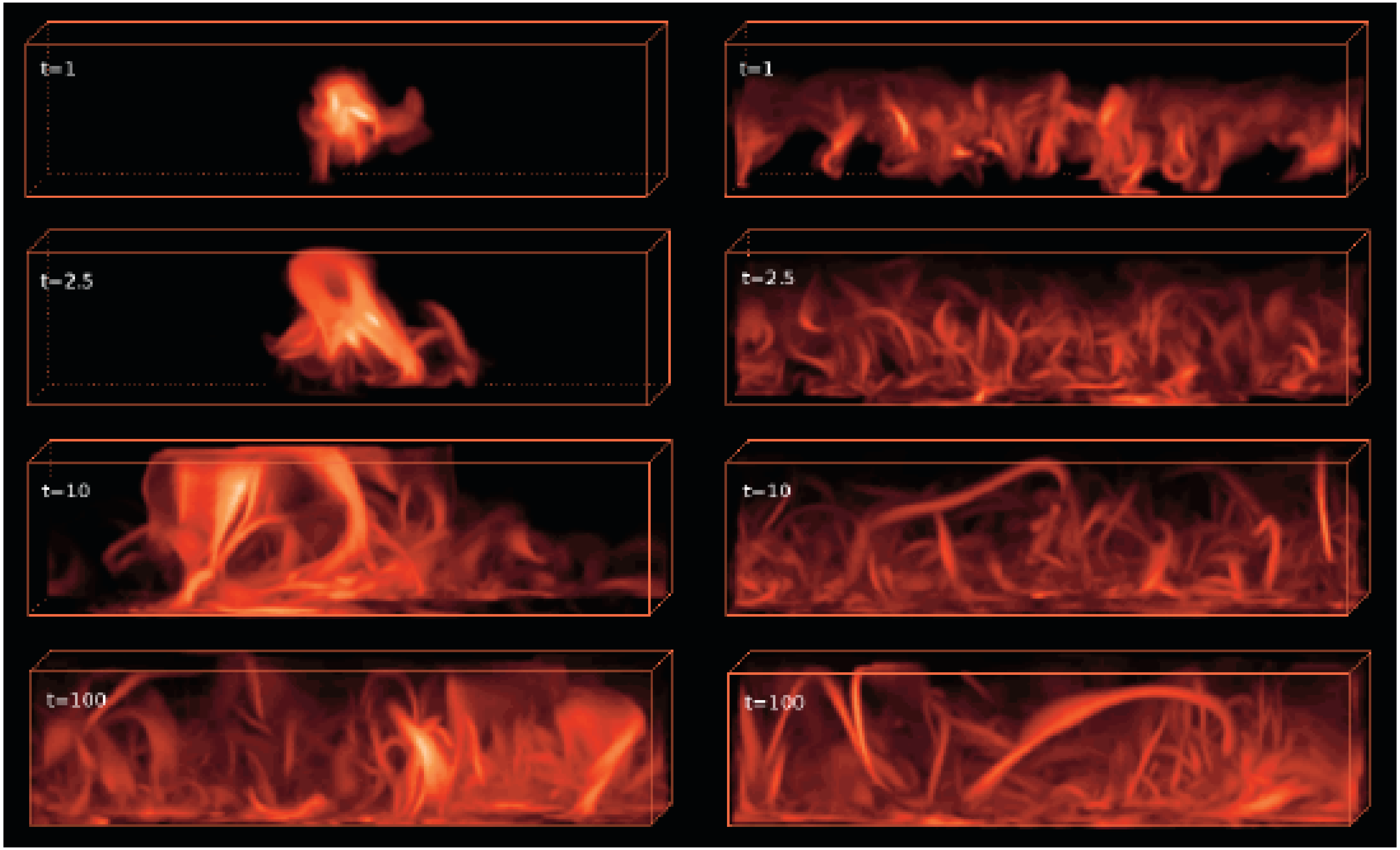


ANMHD has used to provide a time-dependent boundary condition for coronal MHD simulations using Zeus-3D (Abbett & Fisher, ApJ 582,475 2003) and MAS Abbett et al. 2004 JASTRP)

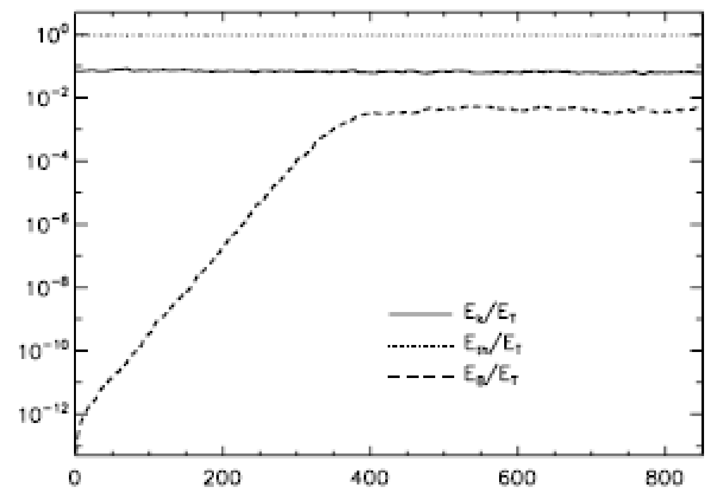


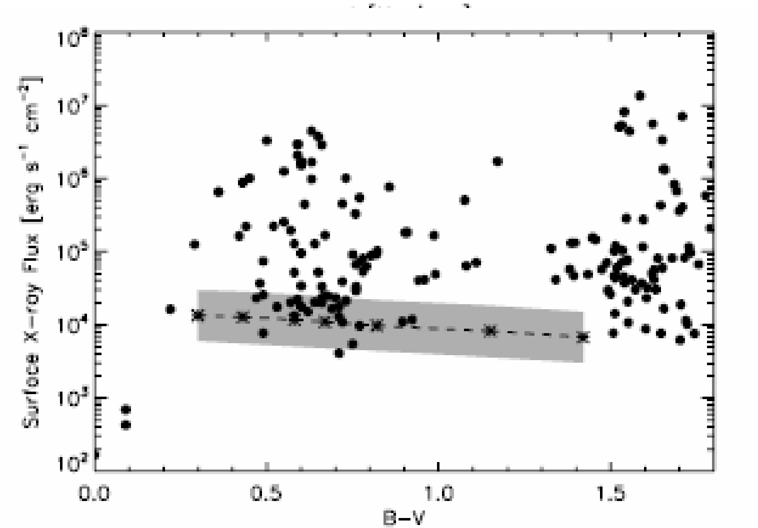


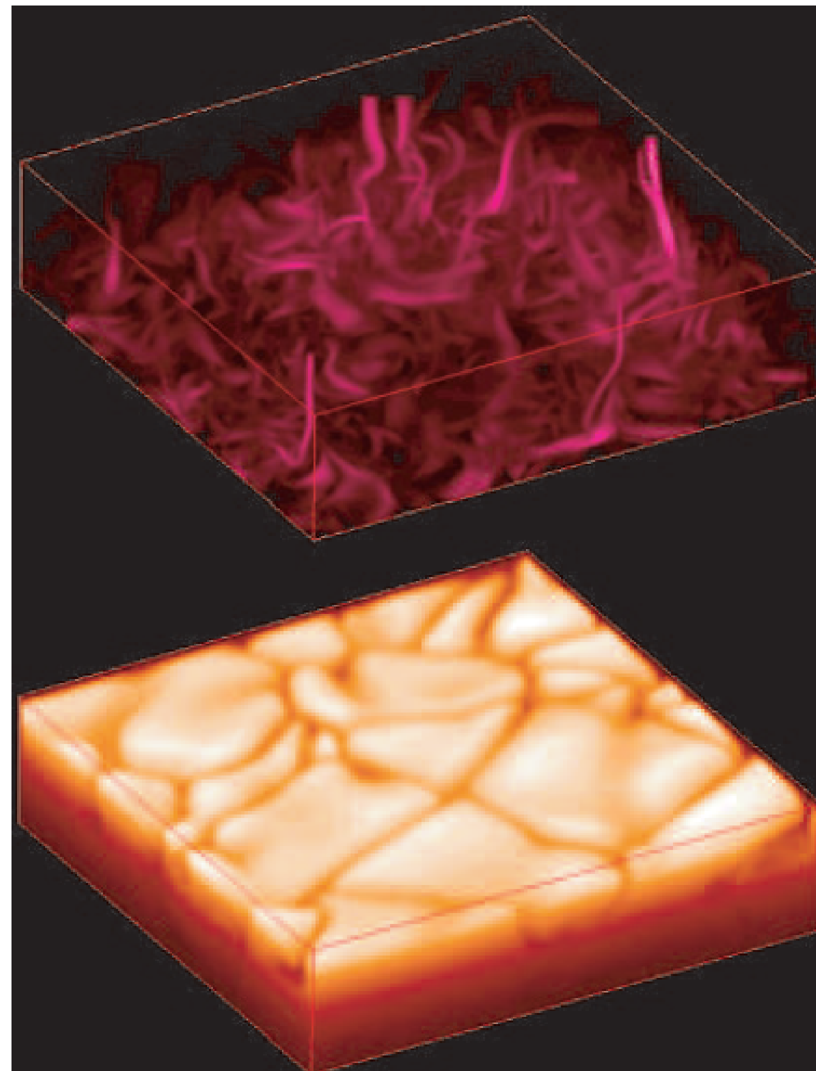
ANMHD study of turbulent convection and its effects on a tube (left) and sheet (right) of magnetic flux. From Abbett, Fisher, Fan & Bercik 2004, ApJ 612, 557.



ANMHD was used to demonstrate that turbulent convective dynamos could account for the minimum X-ray flux from the Quiet Sun and non-or slowly rotating dwarf stars (Bercik, Fisher, Johns-Krull & Abbett, ApJ 631, 529 (2005)





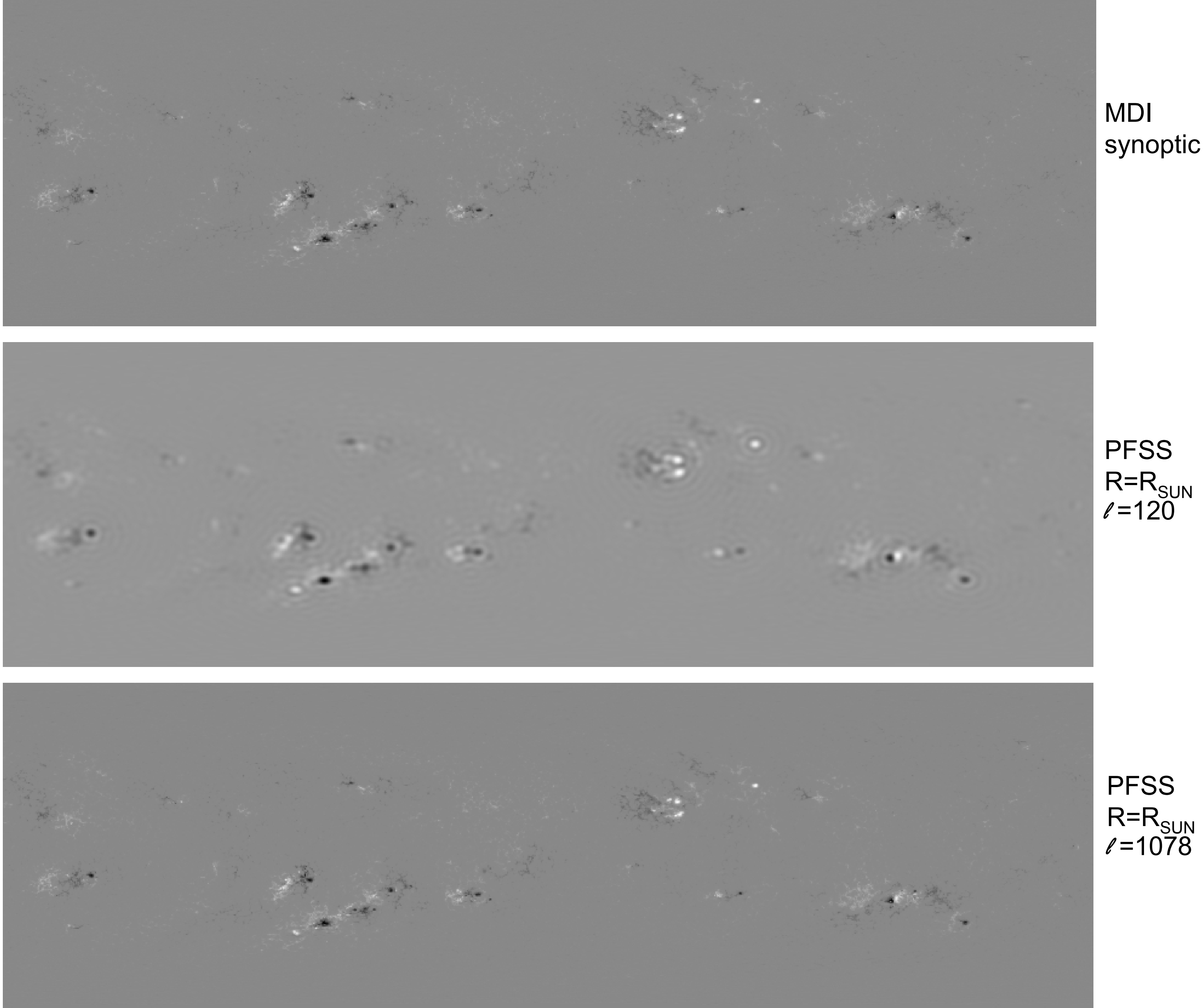


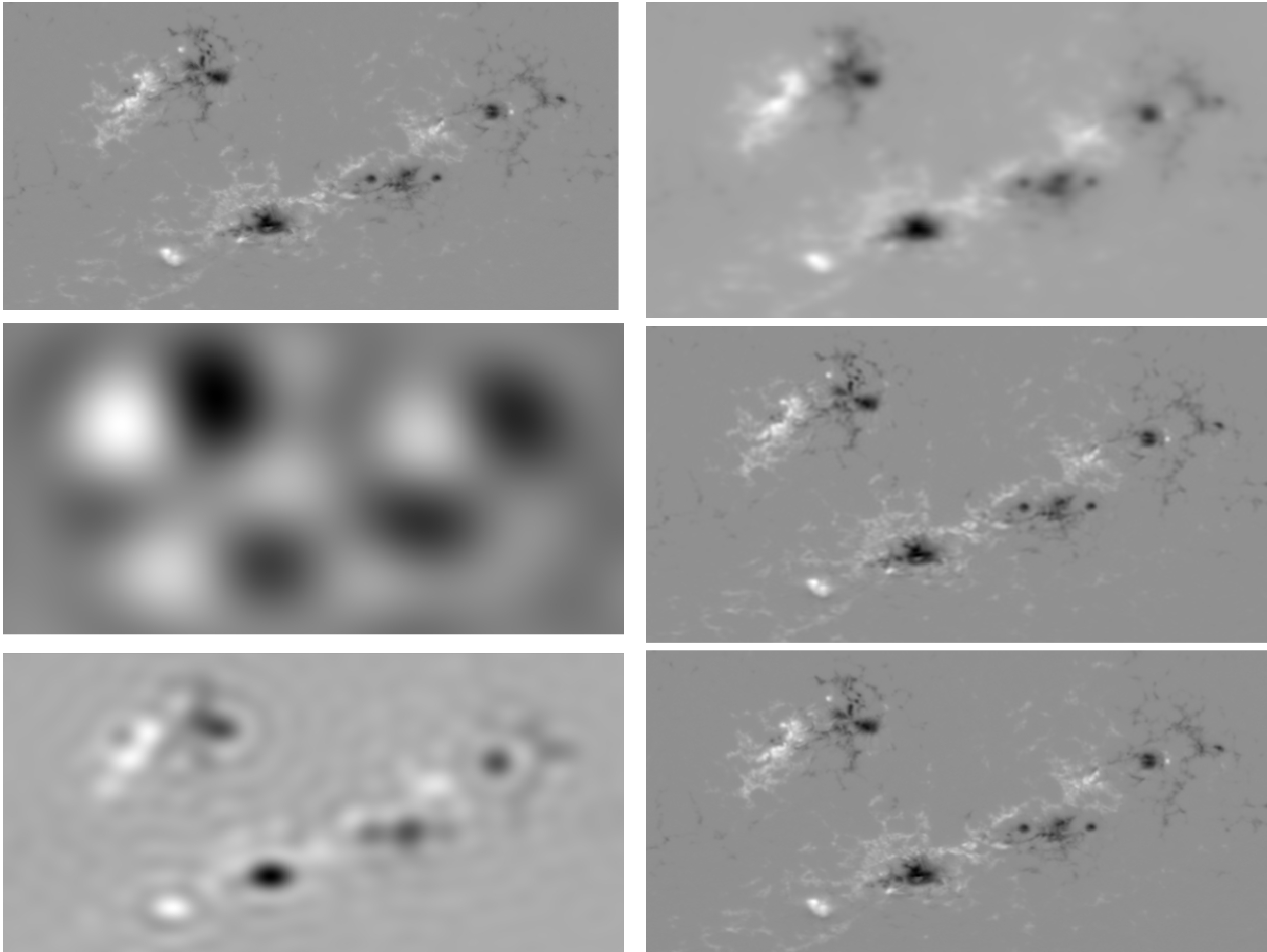
ANMHD code summary:

- The use of the anelastic approximation filters out sound waves, allowing for large time-steps. Appropriate for large β plasmas of solar interior, not appropriate for photosphere and above.
- Original version of code written by Yuhong Fan of HAO/NCAR. Re-written and revised over several years by Bill Abbett (1999-2002), and currently maintained by Dave Bercik of SSL/UCB. Numerical model is described in Fan et al. 1999, ApJ 521,460 and Abbett, Fisher & Fan (2001) ApJ 546, 1194.
- Code is spectral in horizontal directions, finite-difference in depth.
- Written in Fortran 77
- Typically, requires installation of FFTW3, BLAS, LAPACK (or similar packages)
- Binary output is fortran unformatted or SDF (see my talk on Thursday) files. IDL software provided to read results for either format.
- Code can be downloaded from solarmuri website (http://solarmuri.ssl.berkeley.edu).

Status of SANMHD

- Global, anelastic 3-D MHD model of the solar interior.
- Written in Fortran 95 (Bercik, Fisher, Abbett)
- Spherical-harmonic transform in horizontal directions, finite difference in vertical directions
- MHD code not functioning well, but we think we know what the problems are and are working to fix them
- Valuable spin-offs from SANMHD that exist now: High-order ($\ell > 1000$) spherical harmonic transforms that can be used for high-resolution PFSS models.


MDI synoptic
PFSS R=R$_{SUN}$ ℓ=120
PFSS R=R$_{SUN}$ ℓ=1078



RADMHD

- Developed by Bill Abbett at SSL, UC Berkeley
- Designed specifically to include the upper convection zone, photosphere, chromosphere, and lower corona in a single computational domain
- Fully compressible 3D Cartesian MHD code, written in Fortran 95
- Fully parallelized (MPI) for use on linux clusters
- This is an evolving “research” code

RADMHD: Numerical Techniques and Challenges:

A dynamic numerical model extending from below the photosphere out into the corona must:

- span a ~ 10 - 15 order of magnitude change in gas density and a thermodynamic transition from the 1 MK corona to the optically thick, cooler layers of the low atmosphere, visible surface, and below;

- resolve a ~ 100 km photospheric pressure scale height while simultaneously following large-scale evolution (we use the Mikic et al. 2005 technique to mitigate the need to resolve the 1 km transition region scale height characteristic of a Spitzer-type conductivity);

- remain highly accurate in the turbulent sub-surface layers, while still employing an effective shock capture scheme to follow and resolve shock fronts in the upper atmosphere

- address the extreme temporal disparity of the combined system

RADMHD: Numerical techniques and challenges

- For the quiet Sun: we use a semi-implicit, operator-split method.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} - \mathbf{\Pi} \right] = \rho \mathbf{g}$$

$$\frac{\partial B}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = -\nabla \times \eta (\nabla \times \mathbf{B})$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) = -p \nabla \cdot \mathbf{u} + \frac{\eta}{4\pi} \left| \nabla \times \mathbf{B} \right|^2 + \phi + Q$$

- **Explicit sub-step:** We use a 3D extension of the **semi-discrete** method of Kurganov & Levy (2000) with the third order-accurate central weighted essentially non-oscillatory **(CWENO)** polynomial reconstruction of Levy et al. (2000).

- **CWENO interpolation** provides an efficient, accurate, simple shock capture scheme that allows us to resolve shocks in the transition region and corona without refining the mesh. The solenoidal constraint on **B** is enforced implicitly.

RADMHD: Numerical techniques and challenges

- For the quiet Sun: we use a semi-implicit, operator-split method

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\boxed{\frac{\partial \rho \mathbf{u}}{\partial t}} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} + \boxed{\mathbf{\Pi}} \right] = \rho \mathbf{g}$$

$$\boxed{\frac{\partial \mathbf{B}}{\partial t}} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = \boxed{-\nabla \times \eta (\nabla \times \mathbf{B})}$$

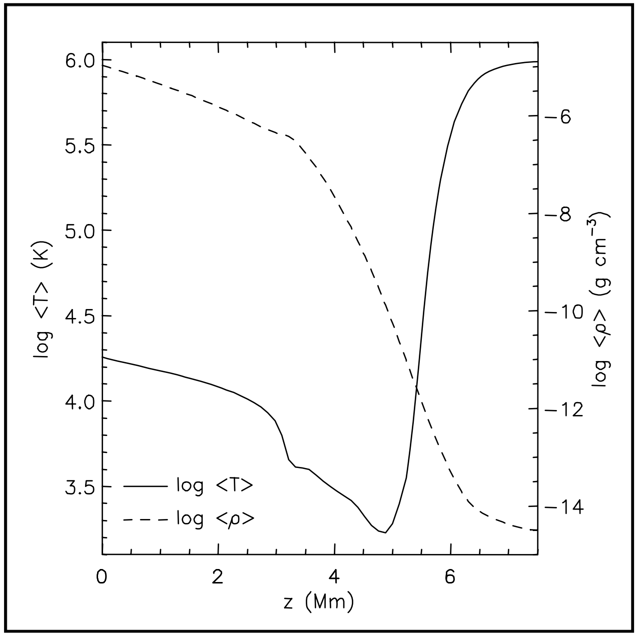
$$\boxed{\frac{\partial e}{\partial t}} + \nabla \cdot (e \mathbf{u}) = -p \nabla \cdot \mathbf{u} + \boxed{\frac{\eta}{4\pi} |\nabla \times \mathbf{B}|^2 + \phi + Q}$$

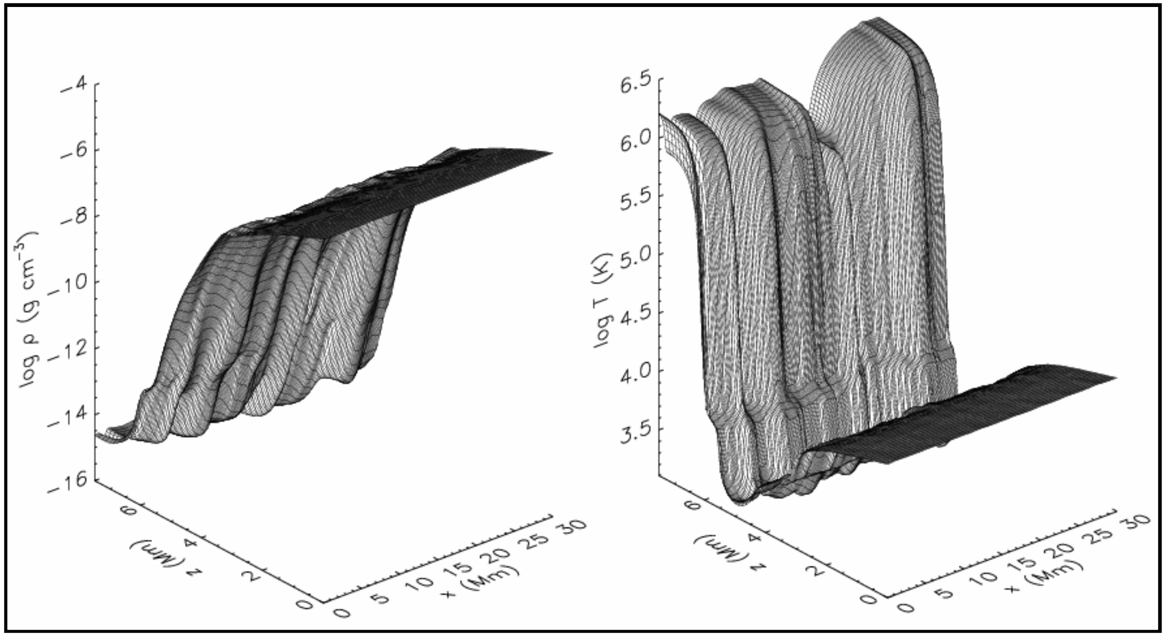
- **Implicit sub-step:** We use a **"Jacobian-free" Newton-Krylov (JFNK)** solver (see Knoll & Keyes 2003). The Krylov sub-step employs the generalized minimum residual **(GMRES)** technique.

- **JFNK** provides a memory-efficient means of implicitly solving a non-linear system, and frees us from the restrictive CFL stability conditions imposed by e.g., the electron thermal conductivity and radiative cooling.

RADMHD: Modeling the combined convection zone-to-corona system:

The thermodynamic structure of the model is controlled by the energy source terms, the gravitational acceleration and the applied thermodynamic boundary conditions. No stratification is imposed a priori.





The quiet Sun magnetic field in the model chromosphere

Magnetic field generated through the action of a convective surface dynamo.

Fieldlines drawn (in both directions) from points located 700 km above the visible surface.

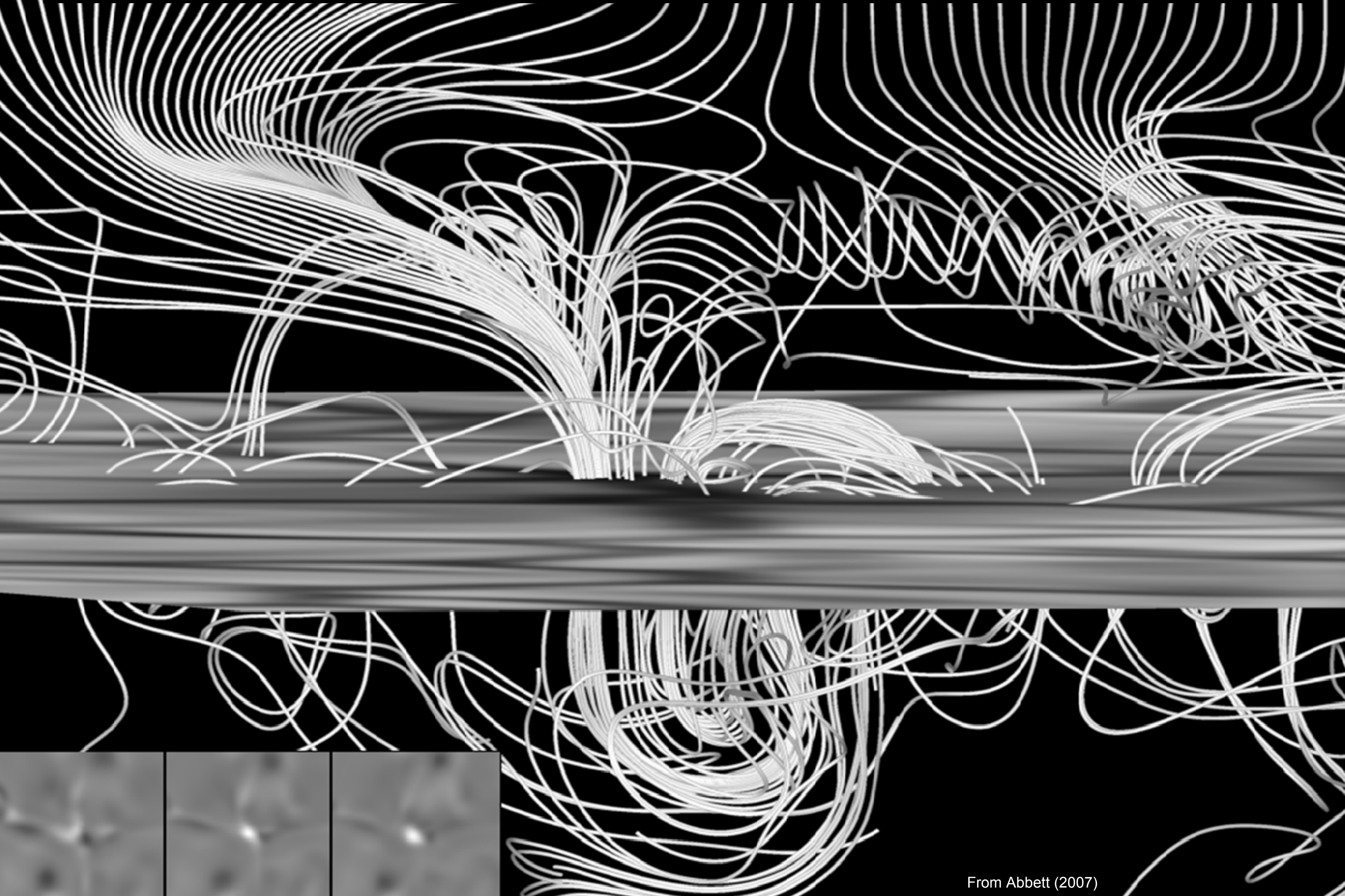
Grayscale image represents the vertical component of the velocity field at the model photosphere.

The low-chromosphere acts as a dynamic, high-β plasma except along thin rope-like structures threading the atmosphere, connecting strong photospheric structures to the transition region-corona interface.

Plasma-β ~ 1 at the photosphere only in localized regions of concentrated field (near strong high-vorticity downdrafts

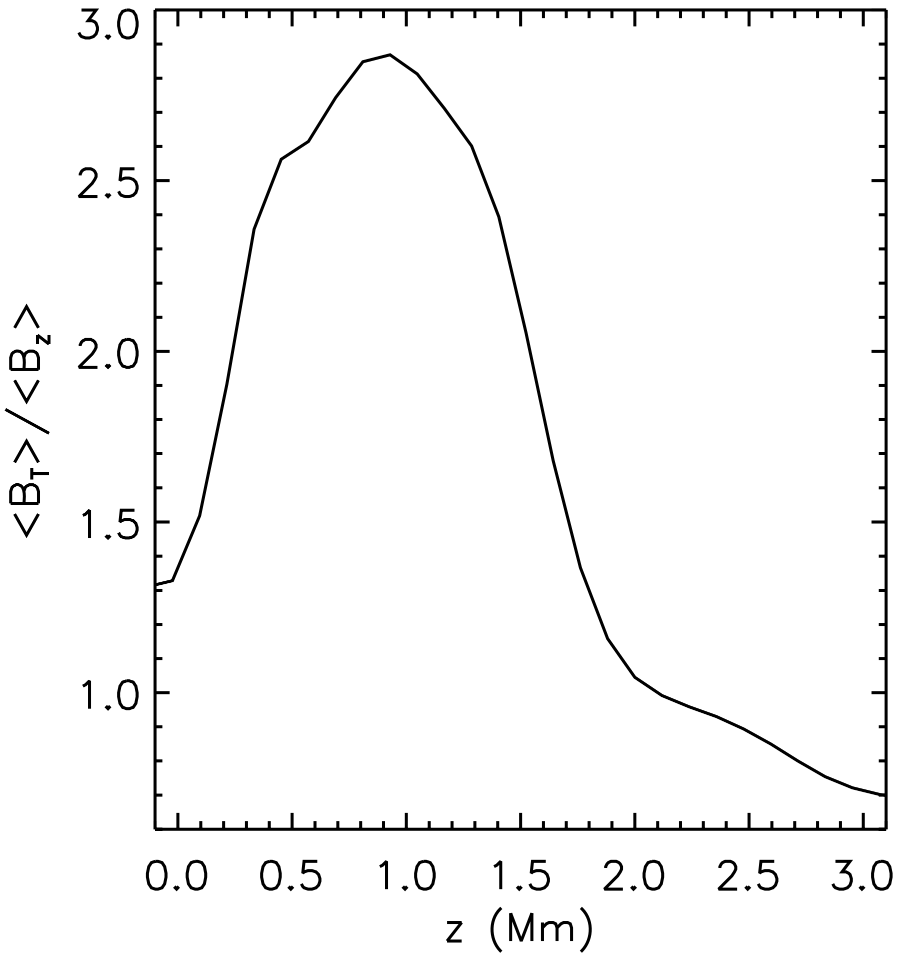
From Abbett (2007)

Flux submergence in the quiet Sun and the connectivity between an initially vertical coronal field and the turbulent convection zone



From Abbett (2007)

Average horizontal magnetic field as a function of height above the surface in the quiet Sun model atmosphere

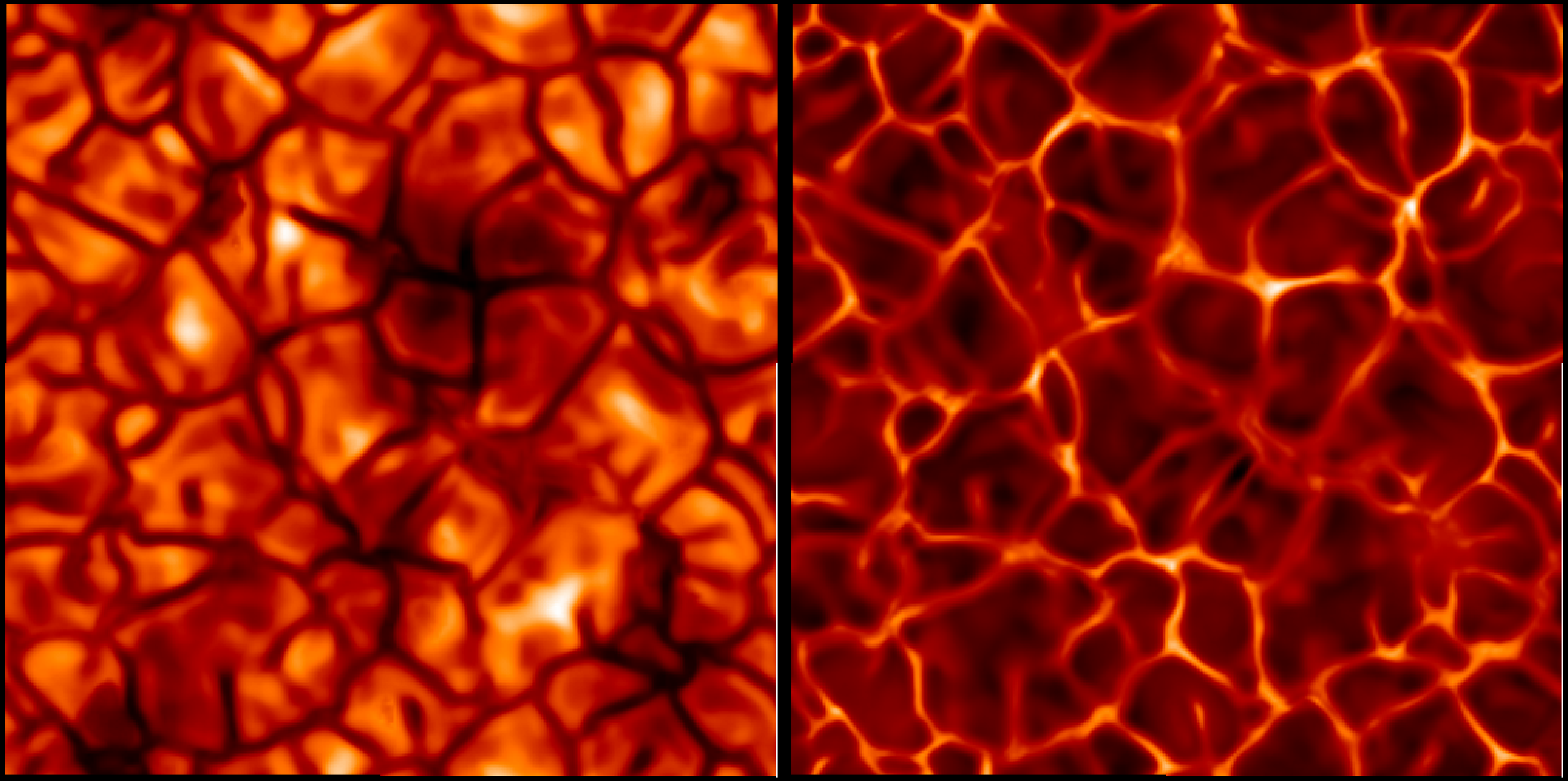


Horizontally averaged magnetic field strength at the visible surface is ~108 G, and drops to ~ 37 G in the low chromosphere. Corresponding values for the vertical component: ~71 G at the surface, falling to ~15 G in the low chromosphere.

The maximum values are roughly similar, ranging from ~1 kG at the surface to ~275 G in the low atmosphere

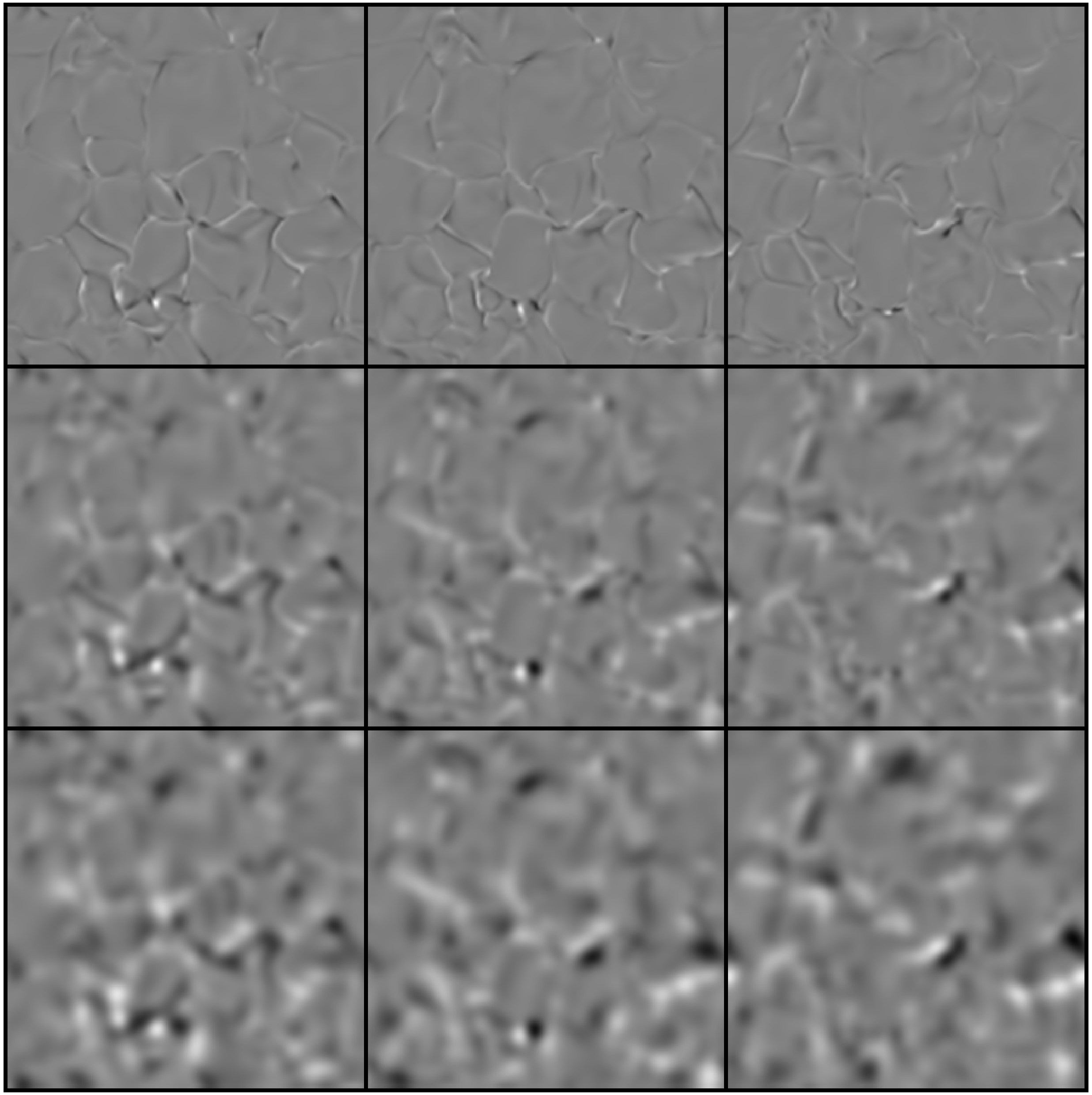
In the corona, the field becomes more vertically oriented, and drops to ~2.5 G on average

Reverse granulation



- A brightness reversal with height in the atmosphere is a common feature of Ca II H and K observations of the quiet Sun chromosphere.
- In the simulations, a temperature (or convective) reversal in the model chromosphere occurs as a result of the *p* div **u** work of converging and diverging flows in the lower-density layers above the photosphere where radiative cooling is less dominant.

Flux cancellation and the effects of resolution:



The Quiet Sun magnetic flux threading the model photosphere over a 15 minute interval. Grid resolution ~ 117 X 117 km Average unsigned flux per pixel: 34.5 G

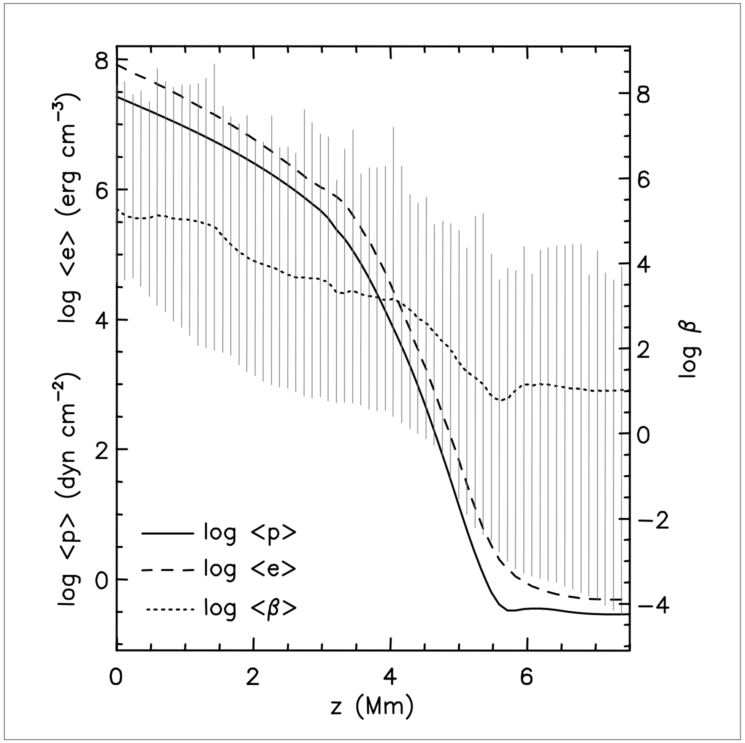
Simulated noise-free magnetograms reduced to MDI resolution (high-resolution mode) by convolving the dataset with a 2D Gaussian with a FWHM of 0.62” or 459 km. Average unsigned flux per pixel is now: 19.9 G

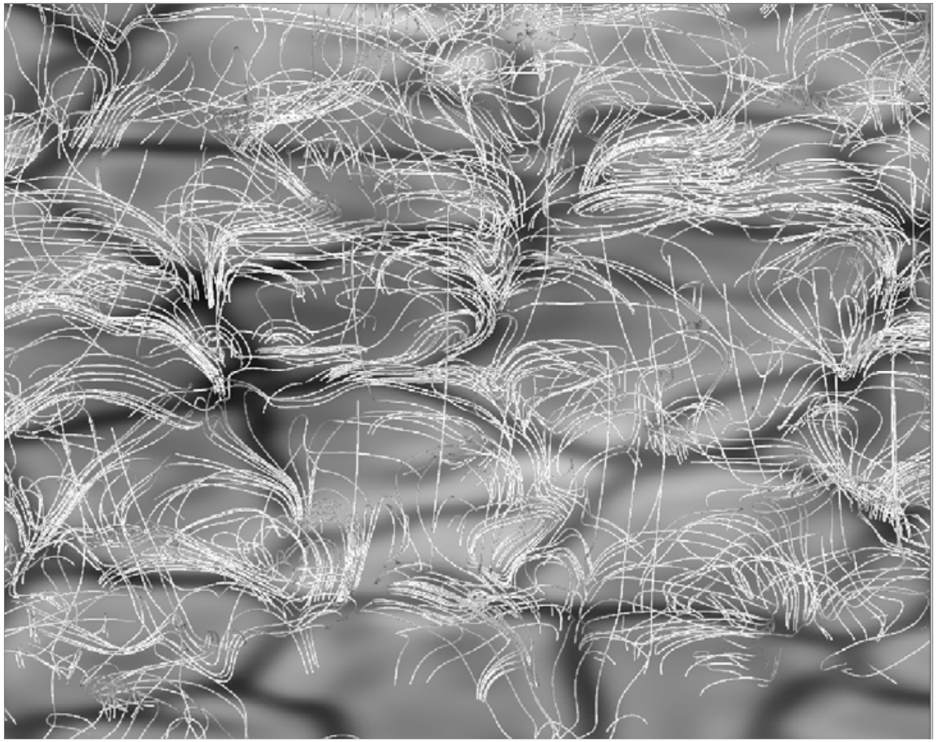
Simulated noise-free magnetograms reduced to Kitt Peak resolution. FWHM of the Gaussian Kernel is 1.0” or 740 km. Average unsigned flux per pixel: 15.0 G

Observed unsigned flux per pixel at Kitt Peak: 5.5 G

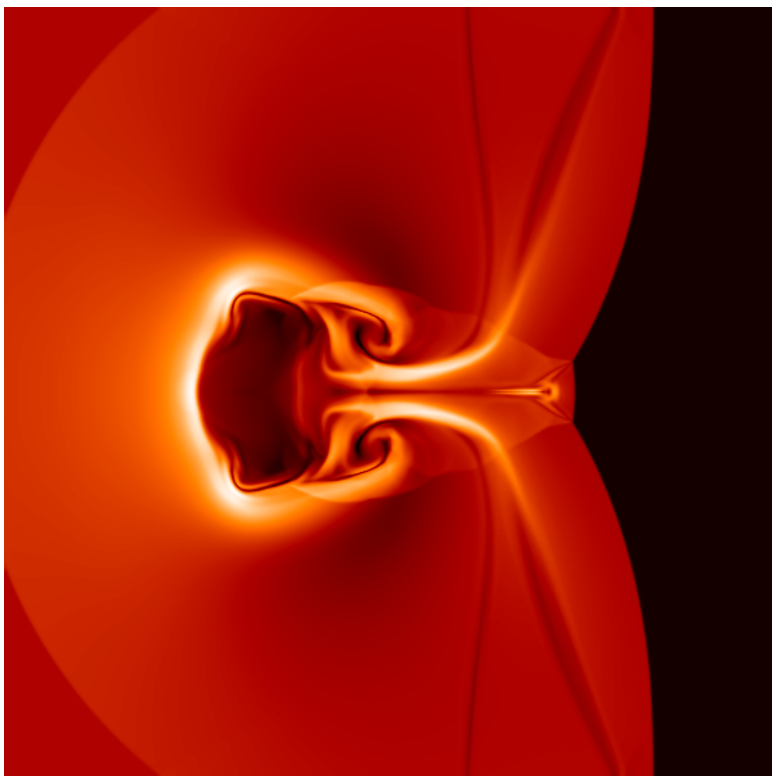
Characteristics of the quiet Sun model atmosphere:

Note: Above movie is not a timeseries!

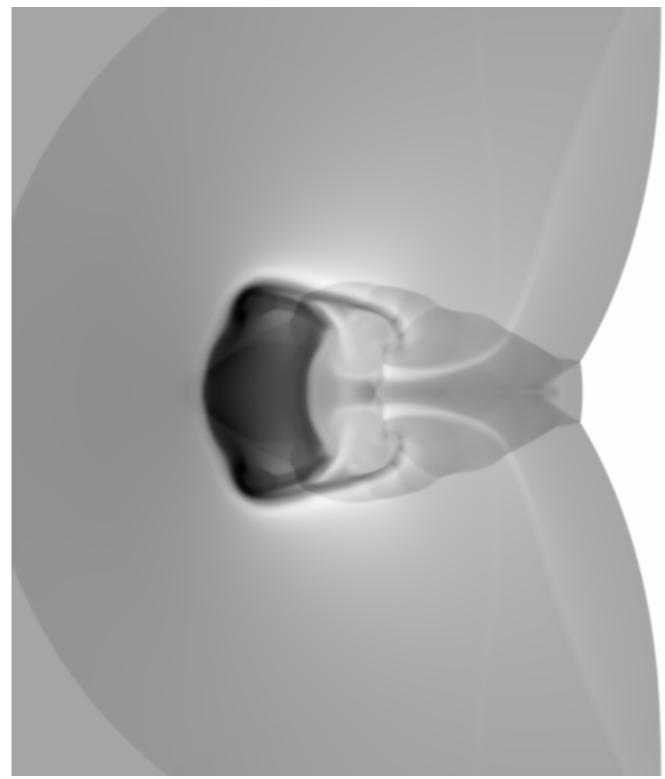




RADMHD can also be used to study astrophysical problems with high Mach-number shocks (example from “Cloud-shock” interaction problem, e.g. Gabor Toth J. Comp. Phys. 161, 605 (2000)



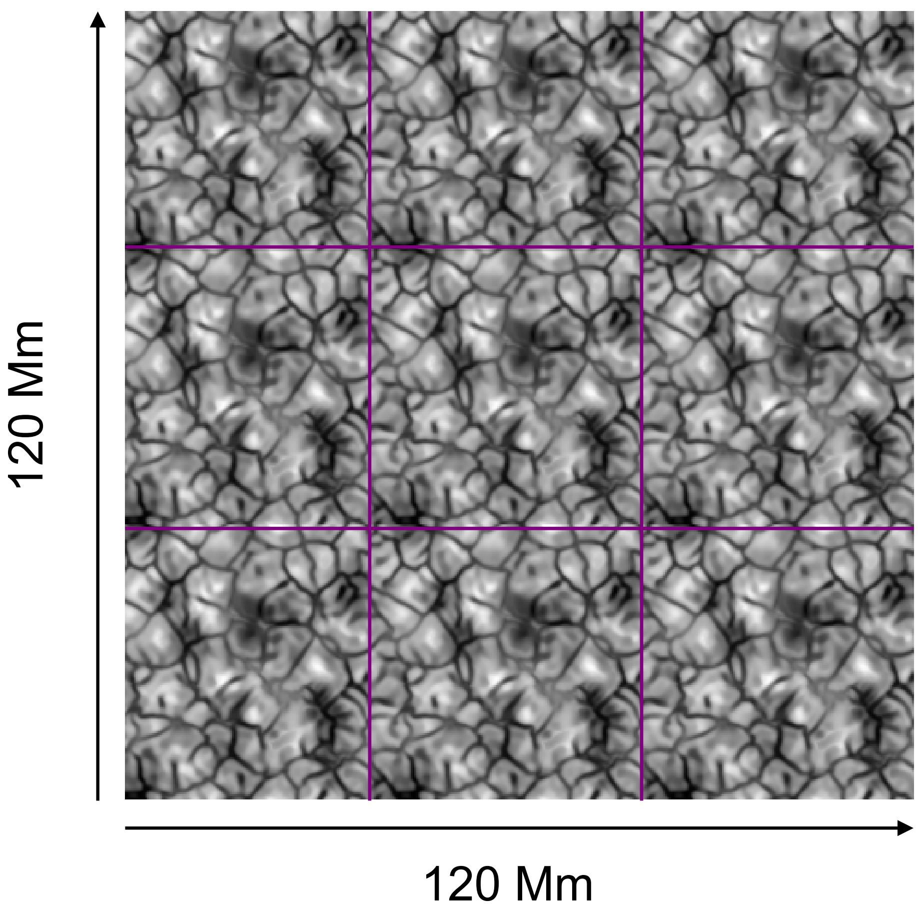
Log |B|



Log ρ

Recent progress and (near) future plans:

Increase domain size. Below: Starting state for a 128 node run on NASA's Discover cluster. Symmetry will be broken by a random entropy perturbation below the surface.



Release beta version of Radmhd-1.0 for further validation and testing by independent groups. Manchester (UM) and Roussev (UH) have agreed to test the model and provide feedback to Bill.

Perform AR emergence simulations once the background state is dynamically and energetically relaxed

Significantly **extend the coronal portion of the domain** using a non-uniform mesh