Stellar Atmosphere Codes III

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What physics need to be included when modeling the solar chromosphere?
Boundaries

• Dynamics and energy supply from the convection zone
  • lower boundary should be in the convection zone

• Magnetic field topology should be contained in the box
  • upper boundary in the corona

• large enough box to contain return flux

• Open system
  • open top and bottom boundaries
Energy balance

- Radiation in strong lines from H, Ca, Mg, He
  - non-LTE 6-12 levels per element
  - incident coronal radiation field
- Radiation in very many weak lines
  - many frequencies needed
  - non-LTE Fe: many levels needed
• Radiative transfer in energy balance in 3D simulations
  • non-locality - parallelization
  • frequency integration
  • scattering

\[ \Phi = \int_0^\infty \chi_\nu (S_\nu - J_\nu) \, d\nu \]

\[ \Phi = \int_0^\infty \epsilon_\nu \chi_\nu (B_\nu - J_\nu) \, d\nu \]
Energy balance

- Shock dissipation
  - high spatial resolution
- Conduction
  - time-scales short
- Magnetic field
  - reconnection
  - high wave speeds: time-scales short
- Particle beams
Ionization equilibrium

• Timescales for hydrogen ionization balance long
  • need to solve rate equations for hydrogen
MHD?

- Chromosphere mostly neutral
- ion-neutral effects
- non-Maxwellian distribution functions
- kinetic modelling
Can we do this?

- In principle, yes
- 20 km resolution, 50 Mm box, NLTE H+Ca+He+Mg:
- 6 million years on 5000 CPUs for one hour of solar time
- In practice, no
The chromosphere is challenging to model

- Testbed for approximations/methods
  - non-LTE
  - non-equilibrium ionization
  - shocks
  - ion-neutral effects
  - magnetic fields/reconnection
The MHD equations

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

\[
\frac{\partial e}{\partial t} + \nabla \cdot (e \mathbf{u}) + p \nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c - \eta j^2 + Q_{visc}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}
\]

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{uu} + \tau) = -\nabla p + \mathbf{j} \times \mathbf{B} - g \rho
\]

with some equation of state... \( T_g, p_g = \text{EOS}(e, \rho) \)
Bif-rost
**BIFROST**


<table>
<thead>
<tr>
<th>6th order scheme, with “artificial viscosity/diffusion”</th>
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<tbody>
<tr>
<td>Open vertical boundaries, horizontally periodic</td>
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<tr>
<td>Possible to introduce field through bottom boundary</td>
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<table>
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<tr>
<th>“Realistic” EOS</th>
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<tr>
<td>Detailed radiative transfer along 24 rays</td>
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<tr>
<td>- Multi group opacities (4 bins) with scattering</td>
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<tr>
<td>- NLTE losses in the chromosphere, optically thin in corona</td>
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<th>Conduction along field lines</th>
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<tr>
<td>- Operator split and solved by using multi grid method</td>
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<tr>
<td>- Non-equilibrium Hydrogen ionization</td>
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<th>Non-equilibrium Helium ionization</th>
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<tr>
<td>- Generalized Ohm’s Law</td>
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Optically thin losses

The graph shows the distribution of losses as a function of temperature. The y-axis represents the logarithm of the energy loss in ergs per s^-1 per e^- per H, while the x-axis represents the temperature in kK. Different lines denote various types of losses, with total being the sum of all types. The graph highlights the dominance of certain losses at different temperature ranges.
Escape probability
Optically thick hydrogen cooling
Optically thick cooling recipe
“enhanced network” simulation
http://sdc.uio.no/search/simulations
IRIS Technical Note 33; Carlsson et al 2016, A&A 585, A4
We will discuss 3 simulations

1. enhanced network. Two main polarities 8 Mm apart
2. Quiet Sun. Only local dynamo field $\langle |B|(z=0) \rangle = 39$ G
3. Coronal hole = Quiet Sun + 2 G vertical field
$|B| = 52$ G

enhanced network
Transition region corrugated
\(<|\mathbf{B}|> = 39 \, \text{G}\) quiet Sun
enhanced network
quiet Sun
coronal hole
quiet Sun
$\beta = 1$
quiet Sun
Mg k peak intensity

![Graph showing Mg k peak intensity with different lines representing IRIS QS, IRIS plage, and Enhanced network.](image-url)
k2 peak separation

Simulation

Observations
• Chromospheric structure and dynamics critically dependent on the magnetic field topology
• Interaction of ambient and emergent field important
• All spatial scales matter
• too narrow profiles
Too narrow profiles

Need flatter temperature structure:
more heating low down

Need more chromospheric material

• Lack of numerical resolution
• Ion-neutral effects
• Magnetic field history
Effects of numerical resolution

Δx = 48 km

Δx = 24 km

Δx = 12 km

Δx = 3 km
Uz at z=0

Δx=48 km

Δx=24 km

Δx=12 km

Δx=3 km
Non-Equilibrium ionization

Figure 8. Joint probability density function of height and logarithmic temperature. The figure includes data from the time interval 1000–3000 s. The three horizontal plateaus (at 6, 10, and 22 kK) in the LTE simulation indicate preferred temperatures when using the LTE equation of state. These temperatures are associated with the LTE ionization of H\textsubscript{I}, He\textsubscript{I}, and He\textsubscript{II}. The plateaus vanish when we introduce non-equilibrium hydrogen and helium ionization.

Figure 9. Differential emission measure averaged over the time interval 1000–3000 s. The HELIUM run DEM does not have a bulge associated with the preferred temperature at $T = 22$ kK, like the other three runs. It has a higher value than the other three runs in the temperature range 11–18 kK.

Figure 10. Occurrence of helium ion fractions as a function of temperature for He\textsubscript{II} in the top panel, and He\textsubscript{III} in the bottom panel. Each column has been normalized to increase readability. Median values and CHIANTI values are overplotted.
Public release of Bifrost simulations
Bifrost coordinate system

Variables on staggered grid

Internal units (Mm, hs, \(10^{-7}\) g cm\(^{-3}\), Mm/hs etc)

\(* U_x, B_x\)

\(* U_y, B_y\)

\(* U_z, B_z\)

\(* e, \rho, T_g\)
FITS files

Variables all cell centered

SI units (Mm, s, kg m\(^{-3}\), m/s, T, etc)

\[ * \quad e, \rho, T_g, U_x, U_y, U_z, B_x, B_y, B_z, ... \]
Format

- Level 2: $D(x,y,z)$ one file per variable per timestep (481 MB)
- Level 3: $D(x,y,z,t)$ one file per variable (76 GB)
- Level 2 $\rightarrow$ Level 3 with provided SW
- Level 3 transpose ($D(z,t,x,y)$) with provided SW

```
  it=385+indgen(157)
  br_make_fits_level3,'en024048_hion',it,'lgtg'
  br_transpose_fits_level3,'BIFROST_en024048_hion_lgtg_im.fits'
```
Variables

- $e, U_x, U_y, U_z, \rho, B_x, B_y, B_z$
- $T_g, P_g, N_e$

en024048_hion: 831 GB
FITS

BIFROST_en024048_hion_lgtg_385.fits

SIMPLE = T / Written by IDL: Fri Jul 12 22:13:21 2013
BITPIX = -32 / Number of bits per data pixel
NAXIS = 3 / Number of data axes
NAXIS1 = 504 / 
NAXIS2 = 504 / 
NAXIS3 = 496 / 
EXTEND = T / FITS data may contain extensions
INSTRUME='Bifrost ' / Data generated by the Bifrost code
OBJECT = 'en024048_hion' / Bifrost run name
BTYPE = 'lg(tg)' / Data variable
BUNIT = 'K' / Data unit
CDELT1 = 0.0476190 / [Mm] x-coordinate increment
CDELT2 = 0.0476190 / [Mm] y-coordinate increment
CDELT3 = 0.0971498 / [Mm] (non-uniform) z-coordinate increment
CRPIX1 = 1 / Reference pixel x-coordinate
CRPIX2 = 1 / Reference pixel y-coordinate
CRPIX3 = 1 / Reference pixel z-coordinate
CRVAL1 = 0.00000 / [Mm] Position ref-pixel x-coordinate
CRVAL2 = 0.00000 / [Mm] Position ref-pixel y-coordinate
CRVAL3 = -2.44401 / [Mm] Position ref-pixel z-coordinate
CTYPE1 = 'x' / [Mm] Label for x-coordinate
CTYPE2 = 'y' / [Mm] Label for y-coordinate
CTYPE3 = 'z' / [Mm] Label for z-coordinate
CUNIT1 = 'Mm' / Unit for x-coordinate
CUNIT2 = 'Mm' / Unit for y-coordinate
CUNIT3 = 'Mm' / Unit for z-coordinate
RUNID = 'Bifrost_cb24bih' / Run ID for identification of input files
ELAPSED = 3850.00 / [s] Time of snapshot
DATA_LEV= 2 / Data level
ZTAU51 = 0.0613866 / [Mm] Average height of tau(500nm)=1
ORIGIN = 'ITA/Oslo' / Origin of data
COMMENT Variables from .idl file:

...
Documents

- Paper describing simulation characteristics
- ITN 33 giving technical details
  - format, keywords, auxiliary software
Enhanced network

en024048_hion (1600s)

- 24x24x17 Mm (2.5 Mm below, 14.5 Mm above z=0)
- 504x504x496 grid
- 48 km horizontal, 19-97 km vertical
- polarities separated by 8 Mm
- $<|B|>=30-50$ G

http://sdc.uio.no/search/simulations
Radiative transfer products

- NUV passband
  - Mg II h&k + background lines
- 252 x 252 grid, vertical rays
- FITS files
  - Intensity as function of wavelength
  - $z(\tau_{\nu}=1)$ as function of wavelength

- ITN 35 describes format, approximations etc
The Future - EXASCALE computing
Scaling problems

• Traditional domain decomposition
  • Split the problem into a large number of sub-domains
  • Each sub-domain needs extra (guard-) cells from neighbouring domains
  • Guard cells are communicated with MPI – must be finished before updates
    • Sensitive to latency outliers – worst case rules!
  • All sub-domains are updated simultaneously, using the same time step
    • The larger the problem, the more wasteful this is
Way out - asynchronous computation

- Task based, asynchronous computation over OpenMP and MPI
  - Allow sub-domains to update semi-independently
    - Requires (only) that a number of (~ \( \frac{1}{2} \) a dozen) time-slices are saved
  - Each task has a list of generalized neighbors, which it depends on
    - Oversubscription of tasks (~ x50), executing asynchronously \( \Rightarrow \) keeps all cores busy!
DISPATCH code framework

- Uses **asynchronous evolution** of sub-domains (patches)
- Uses **local time steps**; determined independently for each patch
- Uses **task-based scheduling**, via OpenMP inside nodes
- Uses **neighborhood-limited MPI** between nodes
- Uses **any preferred solver inside** patches, balancing speed against quality and guard zone requirements
  - Can include **Multiple-Domain-Multiple-Physics**
    - e.g. PIC codes for kinetic simulations inside MHD
    - dust+gas dynamics for planet formation
- Also allows **adaptive mesh refinement**
  - *no* modification of solver required
  - a solver is always presented with a complete 3D cube, on a single core

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ABSTRACT
We introduce a high-performance simulation framework that permits the semi-independent, task-based solution of sets of partial differential equations, typically manifesting as updates to a collection of ‘patches’ in space-time. A hybrid MPI/OpenMP execution model is adopted, where work tasks are controlled by a rank-local ‘dispatcher’ which selects, from a set of tasks generally much larger than the number of physical cores (or hardware threads), tasks that are ready for updating. The definition of a task can vary, for example, with some solving the equations of ideal magnetohydrodynamics (MHD), others non-ideal MHD, radiative transfer, or particle motion, and yet others applying particle-in-cell (PIC) methods. Tasks do not have to be grid-based, while tasks that are, may use either Cartesian or orthogonal curvilinear meshes. Patches may be stationary or moving. Mesh refinement can be static or dynamic. A feature of decisive importance for the overall performance of the framework