Realistic Modeling of Multi-Scale MHD Dynamics of the Solar Atmosphere

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Realistic 3D radiative MHD simulations open new perspectives for understanding the turbulent dynamics of the solar surface, its coupling to the atmosphere, and the physical mechanisms of generation and transport of non-thermal energy. Traditionally, plasma eruptions and wave phenomena in the solar atmosphere are modeled by prescribing artificial driving mechanisms using magnetic or gas pressure forces that might arise from magnetic field emergence or reconnection instabilities. In contrast, our "ab initio" simulations provide a realistic description of solar dynamics naturally driven by solar energy flow. By simulating the upper convection zone and the solar atmosphere, we can investigate in detail the physical processes of turbulent magnetosimulation, generation and amplification of magnetic fields, evolution of MHD waves, and plasma eruptions. We present recent simulation results of the multi-scale dynamics of quiet-Sun regions, and energetic effects in the atmosphere and compare them with observations. For the comparisons we calculate synthetic spectro-polarimetric data to model observational data from SDO, Hinode, and the BBSO New Solar Telescope.

Basic equations

Conservation of energy:

\[ \frac{\partial}{\partial t} \rho E + \nabla \cdot (\rho \mathbf{u} E) = \nabla \cdot (\mathbf{U} \cdot \nabla E) + \rho L + \nabla \cdot (\mathbf{k} \cdot \mathbf{J}) \]

where \( E \) is total energy, \( L \) is dissipation, \( \mathbf{k} \) is magnetic energy density, and \( \mathbf{J} \) is current density.

Conservation of momentum:

\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{T} + \nabla \cdot (\mathbf{k} \cdot \mathbf{J}) \]

where \( \mathbf{u} \) is velocity, \( p \) is pressure, \( \mathbf{T} \) is thermal stress tensor, and \( \nabla \cdot (\mathbf{k} \cdot \mathbf{J}) \) is the magnetic stress tensor.

Conservation of magnetic flux:

\[ \nabla \cdot \mathbf{B} = 0 \]

where \( \mathbf{B} \) is magnetic field.

Structure of the flow eruption

The height difference (in km) between a given location on the solar surface and in the photosphere is given by

\[ h(x, y) = \frac{\rho c}{\sqrt{g}} \int_{0}^{y} \sqrt{1 - \frac{2GM}{r}} \, dr \]

where \( \rho \) is density, \( c \) is sound speed, \( g \) is gravitational acceleration, \( M \) is mass of the Sun, and \( y \) is the vertical distance.

Comparison of Stokes I, V and (U+Q) images for different altitudes: (a) \( h = 780 \) km, (b) \( h = 625 \) km. The red-line profiles correspond to time and location marked by circle above.

Conclusions

Realistic MHD hydrodynamic simulations allow us to investigate important issues related to solar dynamo and its physical and astrophysical properties of solar conditions. This is achieved by solving the full magnetohydrodynamic equations on a high-resolution grid. It is important to model the solar atmosphere and solar magnetic fields and compare these observations with simulations to achieve a better understanding of solar dynamics.

The solar dynamo simulations are not only observed in transient solar eruptions over 120 degrees of the solar rotation, but also in high-resolution observational data. The simulations show that the magnetic fields are generated by dynamo processes, and the resulting magnetic field patterns are consistent with the observations. The simulations also show that the magnetic fields are generated by dynamo processes, and the resulting magnetic field patterns are consistent with the observations. The simulations also show that the magnetic fields are generated by dynamo processes, and the resulting magnetic field patterns are consistent with the observations.