Radiative MHD simulations of the interconnected solar interior and atmosphere

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Radiative MHD simulations have provided a vital information on radiative and magneto-hydrodynamic processes, which lead to appearance of a variety of observational features in the solar atmosphere. On the other hand, a number of observed phenomena remain inadequately explained, potentially due to some fundamental physical effects not yet included in the computational models. The overarching theme connecting these observed phenomena is the transport of energy from the solar interior to the outer layers of the sun. A number of mechanisms have been proposed to explain how exactly the energy is transported in the solar atmosphere, but it is still unclear if there is and which is the dominant one.

One of the mechanisms, proposed to be primary, is based on transfer and absorption of the waves in magnetic fields, which physically link the solar interior with the outer atmosphere. Such waves are generated by turbulent motions in the sub-photosphere, propagate along the magnetic field concentrations and get absorbed in the upper layers of the solar atmosphere. In my talk, I will discuss a number of magneto-hydrodynamic simulations which demonstrate that these waves propagate along the magnetic field lines with Alfvén speed and exhibit the properties of Alfvén waves. Due to their torsional nature, they can be easily confused with the vortex motions. These waves are ubiquitous in the simulations with different magnetic fields, and the energy confined in them is sufficient to maintain the energy balance in the solar atmosphere (Shelyag et al 2012).

Mechanical energy stored in waves in solar magnetic field concentrations still needs to be transformed into the local thermal energy. I will demonstrate that presence of the neutral component in photospheric and chromospheric plasmas provides a plausible mechanism for the energy conversion. I will review a number of simulations, which consider partial ionization effects and provide strong support for this proposed energy conversion and transport mechanism (Shelyag et al 2016). I will demonstrate both radiative magneto-convection model with partial ionization, and a simplified single magnetic flux tube model, which demonstrate significant conversion of the wave mechanical energy into local heating.

Finally, I will discuss radiative diagnostics of the simulated models, which helps to connect the simulations and observations. Torsional motions and vortex flows in the solar photosphere are nearly incompressible and cause little or no variation in the continuum intensity or shapes of the photospheric line profiles. Furthermore, short timescales of waves in photospheric magnetic fields may prevent their detection. The geometry of these waves, however, suggests they may be observable away from the disk centre, where horizontal torsional component of velocity vector becomes line-of-sight component and may produce observable Doppler shift. I will present simulated solar off-disk centre and limb observations, where torsional motions in magnetic field concentrations result in appearance of emissive wings of photospheric absorption lines, similar to the profiles observed with Hinode SOT by Lites et al (2010) and associated therein to radiative scattering. In the idealized simulations I will show, scattering and other multi-dimensional effects are not included, and the emission wings are produced by temperature enhancements in photospheric magnetic field concentrations together with Doppler shifts produced by the waves (Shelyag, 2015). The radiative diagnostics I will present, where the existence of multiple features clearly linked to torsional flows and oscillations, strongly suggests further observational campaigns with modern observational instruments, aiming at the solar limb observations with high cadence and spatial resolution.

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