論文の内容の要旨

Study of solar chromospheric heating mechanism with numerical simulation

（太陽彩層加熱メカニズムの数値的研究）

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The chromosphere is the intermediate layer between the photosphere and the corona, characterized by a drastic change of pressure, density, and plasma beta. Magnetic field protruded from the network region forms flux tubes. As the height increases, the flux tube expands and merges with adjacent tubes in the chromosphere, separating the chromosphere into two regions, which are the low-beta region in the flux tube and the high-beta region below the magnetic canopy.

The energy balance in the chromosphere is dominated by mechanical heating and radiative loss. What is the heating source is still under debate, especially in the low-beta chromosphere. Waves, reconnection, and dissipation of small structures are the main candidates for the chromospheric heating problem. We mainly focus on the wave heating mechanism since there is plenty of observational supporting evidence.

Previous researches provide different wave heating scenarios and comparison among them is necessary. However, it is difficult as the previous theoretical works usually use the artificial model that can include only one or a few mechanisms. On the other hand, previous studies using realistic simulations usually focus on synthesized observation without investigating the detailed physics about the heating mechanisms or the propagation of waves.

This study aims to investigate the propagation of MHD waves in realistic simulations and quantitatively determine the role of different wave modes in chromospheric heating. We perform two-dimensional and three-dimensional realistic MHD simulations from the convection zone to the corona with local thermodynamic

equilibrium radiative transfer in the photosphere and approximated chromospheric and coronal radiative loss. From the simulation results, we identify the shocks by filtering the regions with large negative divergence of velocity. After identification of shocks, we separate fast and slow MHD waves by identifying the relation between magnetic pressure and gas pressure in the upstream and the downstream regions. We further calculate the contribution to chromospheric heating through the measurement of entropy jump. The methods including basic equations of the simulation, shock identification, and heating rate calculation are introduced in detail in Chapter 2.

In Chapter 3, we show the results of the two-dimensional simulation. It is found that the shock heating rate is consistent with the radiative cooling rate. Fast magnetic waves play an important role in heating the low-beta chromosphere. Low-beta fast magnetic waves are generated by mode conversion from fast acoustic waves in the high-beta region. We also estimate the potential heating rate from ambipolar diffusion. The result shows that, on average, ambipolar diffusion does not considerably heat the chromosphere.

In Chapter 4, we validate our main conclusion that the fast magnetic wave is significant in heating the low-beta chromosphere by three-dimensional simulation. It is expected that the percentage of the heating contributed from fast magnetic waves could be overestimated in the two-dimensional simulation since Alfvén wave vanishes. We confirm that fast magnetic wave heating is significant in a substantial range of the chromosphere even in the three-dimensional geometry. On the other hand, the difference from the two-dimensional simulation is that the slow wave becomes dominant in heating at a higher position. This is interpreted as a consequence of the magnetic structure.

The most important new results of our study are that (1) we study the propagation of waves in detail by identification of different modes of waves and calculate the shock heating rate in realistic simulation, and (2) we propose that the fast magnetic wave makes a significant contribution to chromospheric heating.