論文の内容の要旨

Characterization of the EUV Hydrogen Lyman Transitions in the Solar Atmosphere
(太陽大気における極紫外水素ライマン線の特徴に関する研究)

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The Sun's outer atmosphere (corona) is much hotter at several million K than its surface (photosphere) that only reaches ~ 6,000 K. The reason why the outer atmosphere has a higher temperature than the lower part that is closer to core, i.e., energy source of the star, is one of the most important mysteries in the astrophysics and is defined as the "coronal heating" problem. To produce and maintain the corona, we need mechanisms to non-thermally transport the photospheric turbulent energy to the upper atmosphere in some forms without dissipations, and then, to convert them into the heat.

To solve the mystery, it is essential to understand the physics and plasma conditions in the chromosphere, the interface atmosphere of the energy source and the region where the energy is converted into the heat, i.e., the photosphere and the corona. This is because the chromosphere is also heated by non-thermal energy transport and dissipation, and is full of dynamic phenomena which have a role on heating the corona, such as jets and magnetic reconnection. However, the intermediate plasma conditions in the chromosphere make complicated an accurate realistic modeling of its dynamics and the radiative transfer, thus interpreting the observations of chromospheric emission. Hence, our access to the chromospheric spectral lines is limited. For a better understanding of the atmospheric heating, we have to access new spectral windows that fill the diagnostic gaps in the chromosphere.

In this dissertation, we suggest that the hydrogen Lyman transitions, which fall in the extreme ultraviolet (EUV) regime, are good candidates for the purpose. On the other hand,

our knowledge on the spectroscopic and formation properties of the Lyman lines is far from satisfactory because of limited observations of the lines and difficulties on modeling the chromospheric spectral lines.

Motivated by the situation mentioned above, we focus this dissertation on characterizing the spectral features of the Lyman lines, in particular Lyβ, by solving the full non-local thermal equilibrium (NLTE) radiative transfer considering the partial redistribution (PRD) effects and numerically modeling the Lyman spectra. We relate the response of its core, wing, and spectral shape to the atmospheric properties in the chromosphere and reveal how the Lyβ bridges the diagnostic gaps and how the line contributes to solving the coronal heating problem.

In Chapter 2, we firstly synthesized Lyβ spectra emerging from the 3D realistic simulated atmosphere (Gudiksen et al., 2011; Carlsson et al., 2016). We found that the core forms in the upper chromosphere of T ~ 23,000 K. The Doppler shifts found for the line core correspond to the vertical velocity at the formation height in the model atmosphere, and the core intensities are well correlated to the squared electron density and the solar features' geometry there. We concluded that the Lyβ core is an excellent diagnostic to probe the upper chromosphere.

We also computed the response function to some physical parameters with the 1D FAL-C atmospheric model (Fontenla et al., 1993) and found the wing's response to temperature perturbations in 1.1-2.1 Mm and to the line-of-sight (LOS) velocity perturbation in 1.7-2.1 Mm, respectively. Thus, the Lyβ wing is sensitive to lower atmospheric layers in the middle to upper chromosphere. In Chapter 3, we took a step further, aiming to understand the relation between the Lyβ spectral features, e.g., line asymmetries, and the atmospheric properties, e.g. temperature or LOS velocity, in the 3D realistic simulation. We applied a cluster analysis on the synthesized Lyβ spectra based only on the shape of the profile, which allowed us to determine 32 groups. We derived the relation between a typical spectral profile and the corresponding typical stratifications of the atmospheric parameters in each group. We discovered that we could narrow down the obtained 32 groups to six families of profiles that shared similar spectral features. This extra grouping helped us define the relationship between spectral shapes and atmospheric structures, as follows:

1. Regarding the temperature structure, a single peak Lyβ emerges from a narrower chromosphere having a transition region (TR) with a drastic temperature increase at low height. In contrast, Lyβ with central reversal originates from a broad and upward-extended chromosphere with a smooth temperature increase in a TR.
2. Regarding LOS velocity structure, these are two types of families of self-reversed Lyβ. A Lyβ spectrum having a strong emission peak at shorter wavelengths (i.e.,

blue peak) than that at longer wavelengths (i.e., red peak) originates from a positive velocity gradient in the middle to upper chromosphere. In contrast, a stronger red peak corresponds to a negative velocity gradient there. We statistically discovered a correlation between the peak asymmetries and the velocity gradients.

3. A small fraction of synthesized spectra has a bright emission at their wing and continua, caused by temperature enhancements at lower atmospheric layers, just above the temperature minimum. Converging flows may heat up the plasma in the lower atmosphere.

The spatial distribution of the six families on the magnetic loop structure in the 3D model atmosphere reveals that the Lyβ with deep core reversal (and a stronger red peak) corresponds to the loop top where the LOS is perpendicular to the magnetic field.

In Chapter 4, we further applied the cluster analysis on observations of Lyβ spectra taken by the *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER, Wilhelm et al., 1995; Lemaire et al., 1997) instrument on board the *Solar and Heliospheric Observatory* (SoHO, Domingo et al., 1995) spacecraft. We discovered that deeply reversed Lyβ spectra tend to be distributed at the boundary of magnetic field concentrations, in particular, between positive and negative magnetic patches, which is consistent with that found in the synthesized spectra. We detected some discrepancies between synthesized and observed spectra, though. For example, the spectra with bright continuum emissions found in the synthesized spectra are not detected in the observations.

Furthermore, we added Lyα spectra to our analysis in Chapter 5. We studied the relationship between the Lyα and β peak asymmetries and the structure of the LOS velocity. We found that the peak asymmetry relation is associated with the height where the downflow peak is located. Regarding their asymmetries, previous observations revealed that the combination of Lyα with a stronger blue peak and Lyβ with a larger red peak is preferred in the disk center quiet Sun. Our findings on the asymmetries will be helpful to deduce the chromospheric velocity structure accurately.

Previous observations revealed a pervasive downflow in the upper-chromosphere and the TR, and an upflows in the lower corona. The Lyβ asymmetry is related to the trend in the vertical velocity stratification. However, the structures derived by realistic MHD simulations or by Doppler shift analysis of multiple EUV lines are not consistent with the red-asymmetry preference of Lyβ, and more detailed spectroscopic observations resolving the chromosphere are required (Chapter 6).

In conclusion, these studies revealed the Lyman lines potentially fill the chromospheric diagnostic gaps and help us understand the physical properties there, which has a crucial role in heating the upper atmosphere. In future observations, the strong emission of Lyman lines will enable high cadence spectroscopic observations, and with them, the identification of the wave modes and estimation of the energy flux of high-frequency MHD waves. For tall protruding structures, such as spicules, the diagnostic gaps are more significant, and an observation with multiple chromospheric lines, including the Lyman transitions, will be a powerful tool to detect waves propagating through them, and to trace the heating process at its upper edge. Our new diagnostic capability, i.e., the peak asymmetry of Lyβ, can be applied to quantify an acceleration at the root of a spicule, which will allow us to distinguish its formation process. Space-born EUV spectrometers will achieve these proposed observations in the next generation of the 2020's, i.e., the *Solar-C (EUVST)* and *Solar Orbiter*/SPICE, and our achievements in this dissertation will be theoretical rationales to interpret the Lyman spectra taken in the future observations.