Solar transition region in the quiet Sun and active regions

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The solar transition region (TR), in which above the photosphere the temperature increases rapidly and the density drops dramatically, is believed to play an important role in coronal heating and solar wind acceleration. Long-lasting up-flows are present in the upper TR and interpreted as signatures of mass supply to large coronal loops in the quiet Sun. Coronal bright points (BPs) are local heating phenomena and we found a different Doppler-shift pattern at TR and coronal temperatures in one BP, which might be related to the twisted loop system. The dominant energy loss in the lower TR is the Ly–α emission. It has been found that most Ly–α radiance profiles are stronger in the blue peak, an asymmetry opposite to higher order Lyman lines. This asymmetry is stronger when the downflow in the middle TR is stronger, indicating that the TR flows play an important role in the line formation process. The peak separation of Ly–α is found to be larger in coronal holes than in the quiet Sun, reflecting the different magnetic structures and radiation fields between the two regions. The Lyman line profiles are found to be not reversed in sunspot plume and umbra regions, while they are obviously reversed in the surrounding plage region. At TR temperatures, the densities of the sunspot plume and umbra are a factor of 10 lower than of the plage, indicating that the sunspot plasma emitting at TR temperatures is higher and possibly more extended above sunspots than above the plage region.

Keywords: Solar transition region, corona, solar wind, sunspots, UV radiation.

1. Introduction

The solar transition region (TR), in which above the photosphere the temperature increases rapidly and the density drops dramatically, is believed
to play an important role in coronal heating and solar wind acceleration. Most of the TR emission comes from the VUV (vacuum ultraviolet) range of the electromagnetic spectra. And thus spectroscopic diagnostics in the ultraviolet spectral range can provide ample information on the structures and properties of the TR.

It was believed that the network pattern is the dominant emission structure in TR images. The magnetic structures in the network are a combination of diverging funnels and low-lying cool loops. The funnels can be connected to the solar wind, or just legs of large coronal loops. Observational results and theoretical models of the TR were reviewed by Refs. 3 and 4.

The spectral range of the SUMER (Solar Ultraviolet Measurement of Emitted Radiation) instrument onboard SOHO (Solar and Heliospheric Observatory) includes hundreds of emission lines formed in the TR. Through combined analyses between the data obtained by SUMER and other instruments, we have studied the magnetic structures and plasma properties of the TR in the quiet Sun and in active regions. In this paper we summarize the main results of our recent works. For the sake of simplicity, we divide the TR into three parts according to the temperature: lower TR (8000 K to 30000 K), middle TR (30000 K to 600000 K), and upper TR (600000 K to 1000000 K).

2. Flows in the TR

Since three decades ago, it has been found that emission lines formed in the middle TR are on average redshifted by several km/s. The magnitude of the redshift is positively correlated with the line radiance, and thus much larger in network than in internetwork regions.

With increasing temperature, the average Doppler shift of TR lines turns from red shift into blue shift. Patches of blue shift on the Dopplergrams of upper TR lines like Ne viii are found everywhere in coronal holes. These blue shift are interpreted as signatures of the nascent solar wind and believed to be associated with magnetic funnels which originate from supergranular boundaries.

In the quiet Sun, magnetic funnel structures might also exist. In Ref. 19, we have shown a quiet-Sun funnel structure reconstructed from photospheric magnetic field observation. The typical funnel structure is: several small funnels originating from different supergranular boundaries expand with height, and finally merge into a single wide open field region. One may speculate that coronal funnel structures in coronal holes should
be of a similar form, yet the merging height might be different.

However, most of the quiet-Sun funnels do not associate with significant Ne VIII blue shift. In fact, large blue shifts are found mainly in network junctions and associated with legs of large coronal loops. Thus they are more likely to be signatures of mass supply to coronal loops rather than solar wind outflows.

The relationship between the red shift of cool lines and blue shift found at higher temperatures is not well understood. In coronal holes, the blue and red shifts were regarded as the upflow and downflow after magnetic reconnection between open field lines in coronal funnels and their side loops.\textsuperscript{17,18}

In the quiet Sun, the scenario of continuous reconnection might also be the case, if the magnetic polarities of side loops are opposite to those of funnel-like loop legs,\textsuperscript{19,21,36} thus enabling reconnection. The outflows produced by reconstructions around a funnel tend to converge towards the center of the funnel. In contrast, the hot plasma trapped in low-lying loops are pulled down when they cool, and the downflows are stronger at the boundary of the network where side loops are accumulated. Thus, the bi-directional flows are likely to be detected as the not-fully-cospatial blue shift of Ne VIII and red shift of emission lines formed in the middle TR.\textsuperscript{16,22} An alternative mechanism, as suggested in Ref. 23, is the heating and cooling process: Cool plasma (in photosphere and chromosphere) might continuously enter any loop leg through a certain process from outside, but then flow up and speed up after heating occurred, leading to a strong blue shift of lines formed in the upper TR. Due to the onset of possible (radiative) cooling effects, the flow might again decelerate above a certain height (perhaps in the lower corona) and finally turn downwards and accelerate under gravity, which may lead to emission by the dense plasma at lower temperatures and then cause the red shift of middle-TR lines.

In summary, we conclude that the dominant flows at upper-TR temperatures in quiet-Sun coronal loops are long-lasting upflows rather than siphon flows. once the mass is supplied into coronal loops and goes upward to the loop apexes, it may fall downward when cooling is switched on. Sometimes the coronal loops might transiently open due to magnetic reconnection and thus can release mass into the ambient corona or even into the solar wind. The steadiness of the observed shifts suggests that all these processes should occur continuously and persistently, indicating the existence of "coronal circulation".\textsuperscript{25}
Coronal hole

Quiet Sun

Fig. 1. Schematic presentation of the magnetic structures of the transition region in coronal holes (upper) and quiet Sun (lower). The top and bottom of the TR are indicated by the two white bars in each funnel or loop leg. The TR downflows and upflows in upper layers are marked in red and blue, respectively. The yellow bars indicate the supergranular boundaries. The figure is adapted from Ref. 31.

3. TR structures in coronal holes and in the quiet Sun

Figure 1 illustrates different magnetic structures in coronal holes and in the quiet Sun. In CHs the dominant magnetic structures are coronal funnels which are connected to the solar wind. Most of the magnetic loops reside in the lower part of the solar atmosphere. There are almost no large loops.\textsuperscript{26–28} Thus, in CHs magnetic funnels can expand strongly through the TR, as revealed by the temperature variation of TR features in Ref. 26. While magnetic loops of different sizes are crowded in the quiet Sun, so that large coronal loops can not expand drastically with height and the dense cool
loops only permit a weaker expansion of the loop legs.

Through correlation analyses between 3-D extrapolated magnetic field and EUV spectroscopic observations, we can roughly estimate the emission height of TR lines. This method is based on the concept of magnetoconvection, with the magnetic field being frozen in the plasma flow. If we regard the emission height of Ne \text{viii} as the top of the TR, we can study the spatial extension of the TR emission. Based on the results in Ref. 29, Ref. 17, and Ref. 30, the height extension of the TR is approximately 4-10 Mm in coronal holes and only 2-4 Mm in the quiet Sun. So the TR is higher and more extended in coronal holes than in the quiet Sun. However, because of the strong non-uniformity and dynamics, these height ranges are only a rough estimate and might vary with time and locations.

4. Cool and hot components of a coronal bright point

Coronal bright points (BPs) are small-scale bipolar features representing local heating in the TR and lower corona. The energization of BPs may result from the interaction between two magnetic fragments of opposite polarities,\textsuperscript{32} magnetic reconnection along separator field lines,\textsuperscript{33} or current sheets induced by photospheric motions.\textsuperscript{34}

![Fig. 2. Dopplergrams of the EUV lines. The approximate time when the BP was scanned is shown in the lower right corner of each map. The black contours outline the positions of the BP as seen in different wavelengths. The figure is adapted from Ref. 35.](image-url)

The height (or temperature) dependence of BPs properties has not been well studied. In the study of Ref. 35, we combined the spectra obtained by SUMER and EIS (EUV Imaging Spectrometer), and investigated the different emission morphology and Doppler pattern of a BP at lower and
higher temperatures. We found that the transition from the cool to the hot component of the BP occurs at a temperature of about $\log (T/K) = 5.7$. From Figure 2 we can see a totally different boundary between up- and downflows in the BP (almost perpendicular) for lines with lower and higher temperatures. The different boundary might be a result of a syphon flow along a loop system which twists or spirals at its upper segment.

The different emission morphology and Doppler pattern between the cool and hot components of the BP may also imply a different powering mechanism of the two components. Ref. 36 proposed a two-stage heating process, in which magnetoconvection-driven reconnection occurs in and supplies energy to the cool BPs, whereupon the increased energy supply leads to an expansion of the loop system, which interacts with the overlying coronal magnetic flux through fast separator reconnection and produces hot BPs. From magnetograms taken before and after the observation periods of SUMER and EIS, we found indeed a signature of flux cancelation. We also found an agreement between the separators in the magnetic skeleton and the orientation of the hot component of the BP. The flux cancelation and separator reconnection are likely to power the cool and hot components of the BP, respectively. Thus, our observations seem to support the two-stage powering mechanism.

5. Ly-$\alpha$ and Ly-$\beta$ radiance profiles in the quiet Sun and in coronal holes

Hydrogen is the most abundant element in the solar system and its resonance lines, especially the Ly-$\alpha$ line, play a key role in the overall radiative energy transport of the solar atmosphere. In fact, the Ly-$\alpha$ line is the strongest emission line in the VUV spectral range and the energy loss through its emission is the most important radiative loss in the lower TR. Also, the spectral irradiance at the center of the solar Ly-$\alpha$ line profile — in previous observations hampered by geocoronal absorption — is the main excitation source responsible for the atomic hydrogen resonant scattering in cool cometary and planetary material. Moreover, the Lyman line profiles are very useful to diagnose the fine structures in solar prominences and non-thermal effects in flares.

Despite its importance, in the past 12 years high-quality observations by the SUMER spectrograph could only be completed for the higher Lyman lines, but not for Ly-$\alpha$, since its high radiance would saturate the detectors. In June 2008, for the first time, an unconventional method (partly closing the aperture door) was applied to reduce the incoming photon flux.
to a level of about 20% and thus acquire undisturbed solar Ly–α profiles.

Fig. 3. Ly–α profiles in different radiance bins (left) and Doppler-shift bins (right). The figure is adapted from Ref. 45.

The initial results have been presented in Ref. 45 and Ref. 46. We found that most Ly–α profiles are strongly reversed at the center, indicating a very strong radiative transfer effect. As shown in Figure 3, most Ly–α profiles are asymmetric with a stronger blue peak, which is opposite to profiles of higher order Lyman lines. This result is unexpected and detailed modeling work is needed to understand it. Moreover, we found a clear correspondence between the asymmetry and the redshift of middle-TR lines like Si iii: the asymmetry tends to be more prominent if larger downflows
are present, indicating that downflows might play a fundamental role in the process of line profile formation. Thus, static TR models have to be revised. Also interplanetary models of hydrogen scattering may need to be reconsidered in view of the new direct and undisturbed measurement of the irradiance at the line center.

The spatial distribution of Ly\textsuperscript{-}\textalpha profiles was studied in Ref. 46 and we found that profiles tend to be less reversed in the network than in internetwork regions. In the network, magnetic loops of different sizes and funnels are crowded in the chromosphere and TR, and the Lyman line emission originates from the outskirts of these structures. While in the internetwork region, only cool low-lying loops are present and most of the Lyman line emission sources are located at a much lower height as compared to the network. Thus the opacity in the internetwork is enhanced and the Lyman radiation penetrating the upper layers will be more strongly absorbed.

The peak separation of Ly\textsuperscript{-}\textalpha profiles was also investigated in Ref. 47 and it turned out to be larger in coronal holes than in the quiet Sun, which might be related to the different magnetic structures as shown in Figure. 1. Another possibility is that the radiation field is much reduced in coronal holes and thus there are more hydrogen atoms in the corona, leading to more absorption of the profiles.

Another interesting phenomenon is that the asymmetries of the Ly\textsuperscript{-}\textalpha profiles show no clear difference, while the Ly\textsuperscript{-}\textbeta profiles are significantly different in coronal holes and in the quiet Sun. Most of the Ly\textsuperscript{-}\textbeta profiles have a stronger red peak in the quiet Sun, while in coronal holes most or a significant portion of Ly\textsuperscript{-}\textbeta profiles are stronger in the blue peak. Thinking about the different situation of flows in the two regions, we speculate that this difference might be related to the solar wind outflow in coronal holes. In order to understand this result, a combination of new observations and NLTE modeling is needed.

6. Properties of the TR above sunspots

Sunspots and plages are frequently formed in active regions. Spectral lines formed in the upper-TR often show significantly enhanced radiation at locations overlying sunspot umbrae. These plume-like emission features are usually termed sunspot plumes. A sunspot plume might be the common footpoints of several long-reaching loops. It usually has one end point anchored in the umbra and the other can reach far from the sunspot. We performed a detailed study of the sunspot reference spectra obtained by SUMER, and found that the TR above sunspots has some distinctive prop-
properties compared to the surrounding plage regions.\textsuperscript{49}

The lower order hydrogen Lyman line profiles in plage regions are obviously reversed and stronger in the red peak, similar to those in the quiet Sun. This similarity might be due to the similar magnetic structures in the two regions. In both regions, the Lyman line emission originates by a large fraction from the chromosphere, and is strongly absorbed in the upper chromosphere and lower TR. On the contrary, the Lyman line profiles are found to be almost not reversed in sunspot umbrae and plumes,\textsuperscript{48,49} which might indicate that the ratio between the chromospheric and TR contributions to the Lyman line radiation is reduced so that there is less absorption. This might also indicate that the TR is more extended above sunspots. Our density diagnostics suggests that the densities of the umbra and plume are a factor of 10 lower than of the plage, at TR temperatures. This result might suggest that the TR above sunspots is higher than in the TR above plage regions. Our scenario indicates that the sunspot TR temperature should be much lower than the surrounding temperature at the same heights, similar to the temperature structure of sunspots proposed by Ref. 50.

The DEM analysis is helpful to study the thermal structure of the solar atmosphere. Ref. 51 performed the first DEM analysis for sunspot plumes by using CDS (Coronal Diagnostic Spectrometer) spectra. Since the CDS spectra include very few low-temperature lines, their DEM curves were not well determined at the low-temperature part. In Ref. 49, SUMER spectra was used for the first time to derive DEM curves of the sunspot umbra, penumbra, plume, and plage region. We found that the DEM curve of the plume is clearly different from those of other regions. It peaks at a lower temperature of around $\log(T/K) = 5.45$, which exceeds the DEM of other regions by one to two orders of magnitude at these temperatures. The low-temperature part of the DEM curves has been well established in our study. We found that at $\log(T/K) \leq 5.0$, the slope of the DEM curve is similar in the four regions, indicating that the thermal structure in this temperature range is similar everywhere in and around the sunspots.

The reason why the plume emission is so strong at upper-TR temperatures is very puzzling. We think that it might be the result of a large filling factor. The strongly enhanced emission at TR temperatures and the reduced continuum may explain the fact that many normally weak lines become prominent in sunspot plumes.
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