THE LOWER TRANSITION REGION AS SEEN IN THE H I LYMAN-α LINE

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ABSTRACT

The SUMER spectrometer aboard SOHO has been used to acquire several raster images and temporal series of quiet-Sun targets at both disk centre and the limb. Spectra have been recorded simultaneously in the H I Lyman α and the Si III 120.6 nm line. Both spatial and temporal maps of the integrated radiances appear very similar in the two lines, despite the huge difference in optical thickness, a result showing the H I Lyman α to be a good diagnostic of the dynamics and morphology of the lower transition region. Oscillations can be detected and studied at all observed locations. At disk centre, the 3 minute oscillations are sporadically observed in the inter-network but also at locations at the edges of network lanes, while 5 minute oscillations clearly dominate the network. At the limb, evidence of 3 to 5 minute oscillations is found at the base of spicules.
Moreover, H I Lyman α spectra shows a high degree of variability, revealing also the signature of explosive events. The combination of high spectral purity images and slit spectra in the H I Lyman α line would therefore be an exceptional new tool to investigate the nature of the solar transition region. This line is therefore of interest for both, a high resolution channel in the EUI instrument and for the EUS spectrometer.

1. INTRODUCTION

Imaging and spectroscopy of the inner solar corona are fundamental to achieve the main science goals of Solar Orbiter, particularly to:

- investigate the links between the solar surface, corona and inner heliosphere,
- explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere.

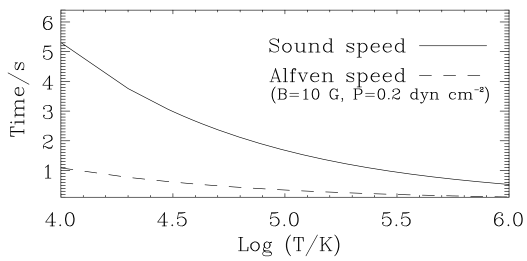

Figure 1: Time needed by plasma moving at either the sound or Alfvén speed to transit 80 km (imager pixel size) as a function of the temperature.

To provide a comprehensive picture of the solar inner corona, a selection of lines/band-passes covering a wide temperature range is crucial. Images and spectra taken in cool lines (log T/[K] ≈ 4 to 4.5) are particularly important in establishing the links between the larger scale coronal ($T \geq 1$ MK) structures and the photospheric magnetic field measured by VIM.
The unique mission profile, enabling observations from close-up view points (0.22 to 0.25 AU), imposes both scientific and technical constraints. In fact, the proximity to the Sun will provide high spatial resolution (80 to 160 km) even with the small (1 meter class) instrumentation foreseen. To take full advantage of such high resolution, exposure times need to be of the order of (few to several) seconds. Figure 1 shows the time needed by plasma moving at either the sound or the Alfvén speed to transit 80 km (imager pixel size). On the other side, the increased irradiance seen by the spacecraft (up to 20 solar constants) imposes the reduction of the apertures to only a few centimetres. The above considerations force to select band-passes centred on the stronger emission lines, with a particular interest to include also cooler lines.
Figure 2 shows the average radiance spectrum of the quiet Sun, where the Lyman α line of hydrogen appears as the strongest feature. The large radiance and the possibility of using high-efficiency optical components, allow high time resolution observations (≈1 s) also with a small aperture of few (≥ 3) centimetres (aperture size driven by diffraction) and spectral purity above 90% [1]. A novel solution for coping with the thermal load in normal-incidence telescopes is also available [2].

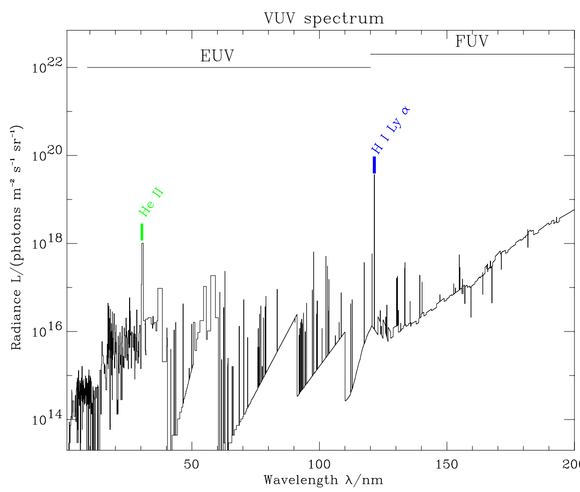

Figure 2 : Quiet Sun VUV radiance spectrum (from irradiance values by Heroux & Hinteregger [3]).

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The Lyman-α (*1s* $^2S_{1/2}$ – *2p* $^2P_{3/2,1/2}$) transitions of neutral hydrogen could, hence, provide a powerful diagnostic for studying the region between the upper chromosphere and the lower transition region (TR).
In this region most of the expansion of the photospheric magnetic field has already taken place (especially in active regions and the network, but also in the inter-network), and it is important for studies of the coupling of the solar outer atmosphere with the underlying photosphere. It is through this region that the energy produced in the convection zone must pass to reach and heat the solar corona. Waves and/or magnetic reconnection and currents generated by the motions of the magnetic field at photospheric level are candidates for coronal heating. The study of their signatures in the H I Lyman α profile can help us understanding such phenomena.
Being optically thick, the H I Lyman α line is formed over a wide range of temperatures and is strongly dependent upon the temperature structure of the upper chromosphere and lower TR, and on the dynamics of the structures within the resolution element [4, 5]. Observations of the line profile can, hence, provide constraints for models of the solar atmosphere.
The SUMER instrument aboard SOHO is located at the first Lagrangian point, well outside the hydrogen geocorona. With its precise radiometric calibration, it permits us to study the morphology and dynamics of the lower TR in the dominant emission line in unprecedented detail and with high accuracy. It also allows us to compare the observed structures with those observed simultaneously in optically thin lines, assessing in such a way the validity of the H I Lyman α line as a diagnostic of the morphology and dynamics of the lower TR.

2. OBSERVATION AND INSTRUMENTATION

The observations discussed here were obtained with the SUMER spectrometer [6] using the A detector. Since May 2004 detector A has started showing a deterioration of the ADC such that only the first 58 rows were still useable at the time of observations. All data were acquired using the narrow 0.3″×120″ slit on the bottom part of detector A. SUMER has a spatial resolution of 1.5″ [7] (about 1000 km on the Sun at the SOHO-Sun distance).

3. MORPHOLOGY OF THE LOWER TR

Figures 3 shows the quiet-Sun network structures near disk centre in the H I Lyman α line as compared to images obtained in the optically thin lines Si III λ 120.6 (6×10^4 K), N V λ 123.8 (1.8×10^5 K), and O V λ 62.97 (2.5×10^5 K). The data in Si III λ 120.6, in particular, are obtained simultaneously in time and space with those in H I Lyman α and reveal a close similarity despite the large opacity of the H I line. The images in the O V and N V line show more structuring and more spatial variations. It is unclear how much of this difference is due to larger temporal variations in N V and O V.
Figure 4 shows instead the solar quiet limb. Spicules are best visible in the H I Lyman α image, while the on-disk area appears quite similar to that seen in the Si III line. From these results we find the H I Lyman α line radiance to be a good diagnostic of the lower TR.

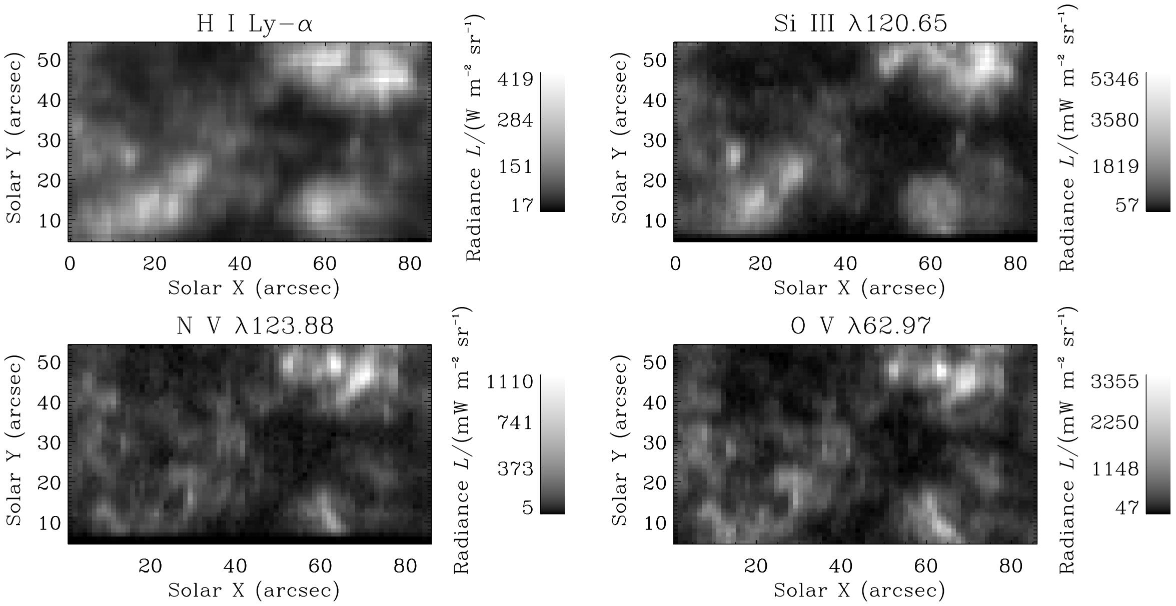

Figure 3: Square-root maps (rasters) of the integrated radiance of selected spectral lines obtained with SUMER on a quiet region near disc centre. The H I Lyman α and the Si III rasters are simultaneous in time and space.

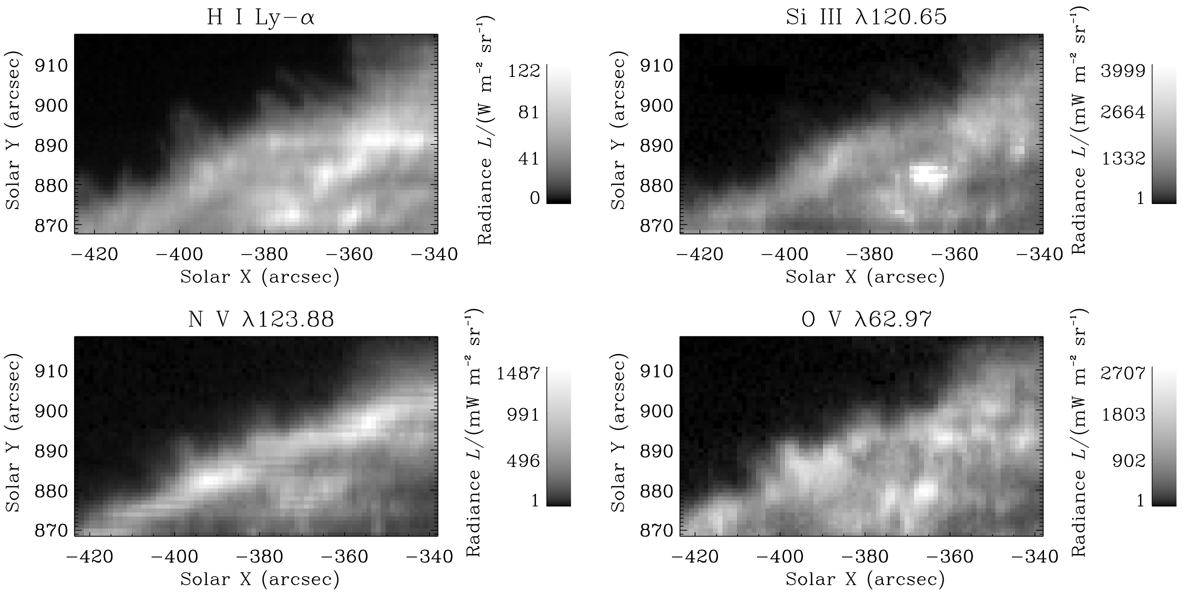

Figure 4: Same as Figure 3 but obtained at the solar limb.

4. THE DYNAMICS OF THE QUIET-SUN TR

Spectroscopy is certainly the best tool to study the dynamics of the solar atmosphere. In fact, besides spectrally pure images, it also provides information on both resolved and unresolved line-of-sight (LOS) motions. However, the field of view (FOV) covered by stepping the solar image over the entrance slit is inversely proportional to the observing cadence. On the other side, imagers can achieve high temporal resolution measurements of the band-pass integrated radiance over a large FOV. In these cases, the spectral purity of the selected band-pass is very important for the correct interpretation of the observed radiance variations. The SUMER spectrograph was used to record sit-and-stare slit images in the H I Lyman α line to investigate the variability of the integrated line radiance: the ideal target of an imager.

The observation of periodic or quasi-periodic variability of the radiances of lines formed in the upper chromosphere and low TR is of particular interest for the understanding of the dynamics of the so-called non-magnetic chromosphere in inter-network areas, as well as the magnetic network itself.

Figure 5 shows the time variability of the H I Lyman α and Si III radiances and clearly underlines the variable nature of the quiet-Sun lower TR. Figures 6 and 7 show time series of the H I Lyman α line radiance at selected positions along the slit. Oscillations with a period around 3 min are sporadically observed in bursts of short duration (≈15 minutes) in the inter-network (see Figure 6) but also in locations at the edges of network lanes. Longer bursts of 5 minutes oscillations are also sometimes observed in the inter-network, while they clearly dominate in the network (see Figure 7). All the above results are clearly revealed by wavelet analysis [8]. Si III data yield the same picture, although the lower S/N limits the analysis mostly to the network. At the limb, time variability is dominated by spicules and macrospicules which appear to rise to heights of 15″ to 30″ above the limb. Figure 8 shows the temporal evolution of the north limb in H I Lyman α. Some spicules show a quick (≈100 s) rise up to around 15″ to 30″, followed by a slower fall back (200 to 300 s). An indication of a periodicity of about 10 min in their appearance is also found. Figure 9 shows the temporal evolution of the H I Lyman α line radiance at a position of 1″ to 2″ above the limb (defined from the maximum along the slit of the radiance of the continuum near the Si III line, here not shown). At this location we find clear signatures of oscillations with periods around 3 minutes. Wavelet analysis reveals oscillations with periods between 3 and 5 minutes, particularly well visible in the Si III line [8].

Thus, oscillations appear to be a common feature across the solar disk. A high spectral purity H I Lyman α imager, as that described by [1], will provide the temporal and spatial behaviour of these wave packets over a large FOV, and will allow us to study their relation with the photospheric magnetic and velocity fields provided by VIM. The EUS spectrograph, at selected locations, will allow tracking the propagation of such waves across the solar atmosphere. A spectral band encompassing the H I Lyman α is foreseen for EUS [9], ensuring perfect synergy between the imager and the spectrograph.

High spatial and temporal resolution H I Lyman α spectra will also be important to understand the dynamic transient phenomena that characterise the solar TR.

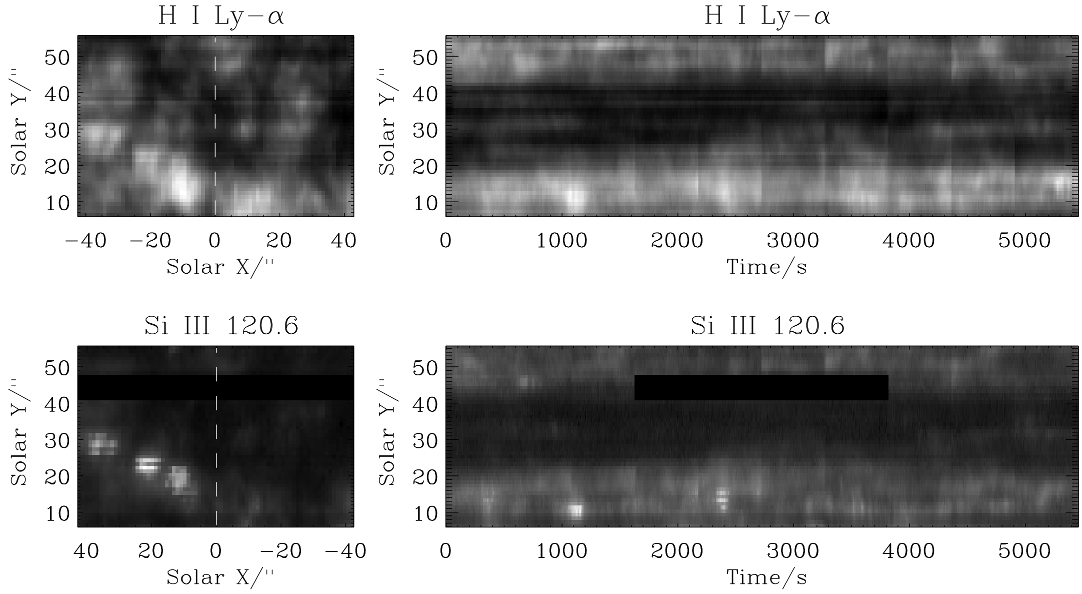

Figure 5: Square-root radiance images (left panels) observed on 6 October 2005. The vertical dashed lines indicate the position of the slit at the start of the temporal series shown on the right panels. Black areas are unusable data due to the presence of dead pores in the micro-channel plates of the detector.

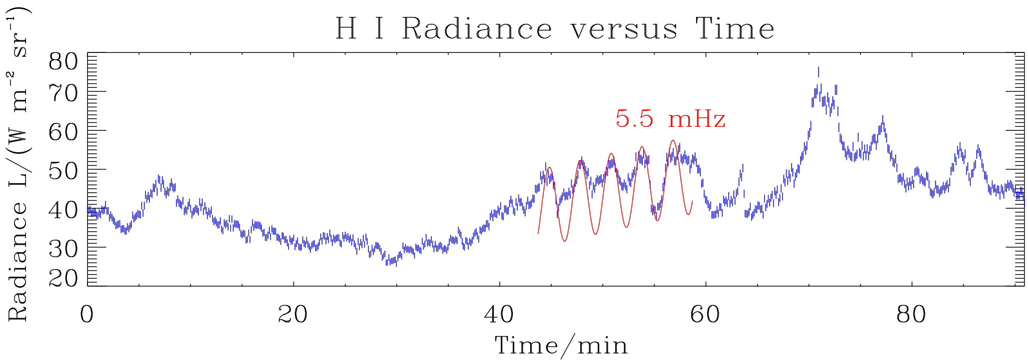

Figure 6: H I Lyman α line radiance time series at an inter-network location (Solar Y=29", in Figure 5). Oscillations with a period of about 3 minutes (5.5 mHz) can be easily seen and are outlined by a sinusoidal function.

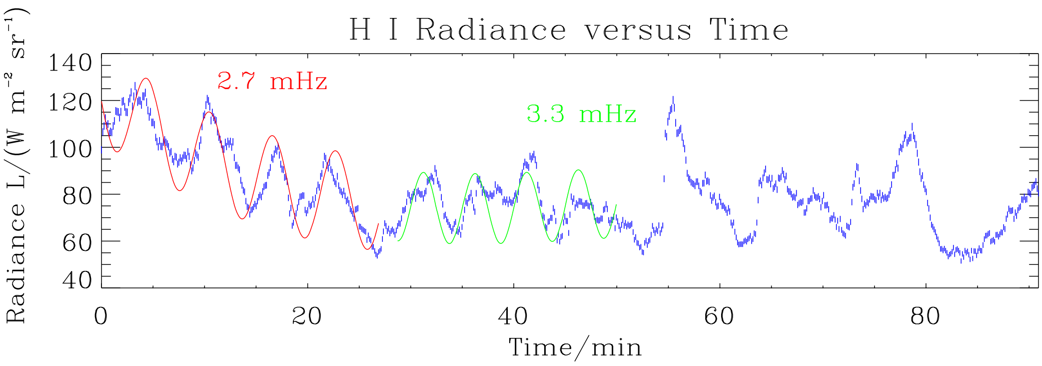

Figure 7: H I Lyman α line radiance time series at a network location (Solar Y=51", in Figure 5). Oscillations with periods of about 5 (3.3 mHz) to 6 minutes (2.7 mHz) can be easily seen and are outlined by sinusoidal functions.

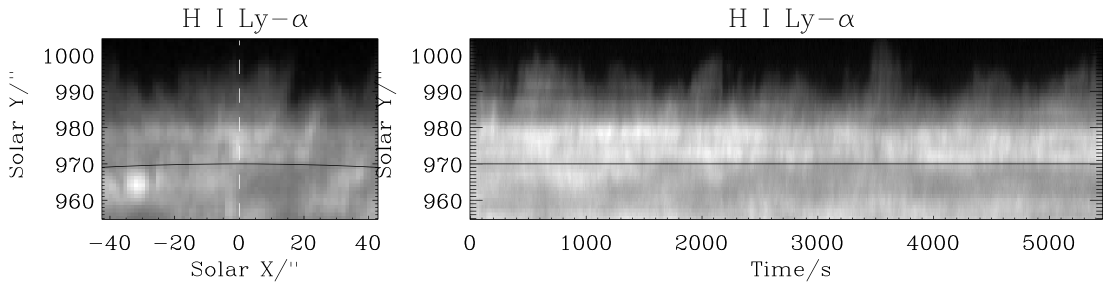

Figure 8: Same as the top panel of Figure 5 but at the solar limb. Square-root radiance images obtained on 12 October 2005 at the north limb. In this dataset spicules show a periodicity of about 10 min in their appearance. Some of them (at t=400 s, 1200 s and 3400 s) show a quick rise (≈100 s) and a slower fall back (≈300 s). The solid line marks the position of the solar limb (as seen in the continuum nearby the Si III line).

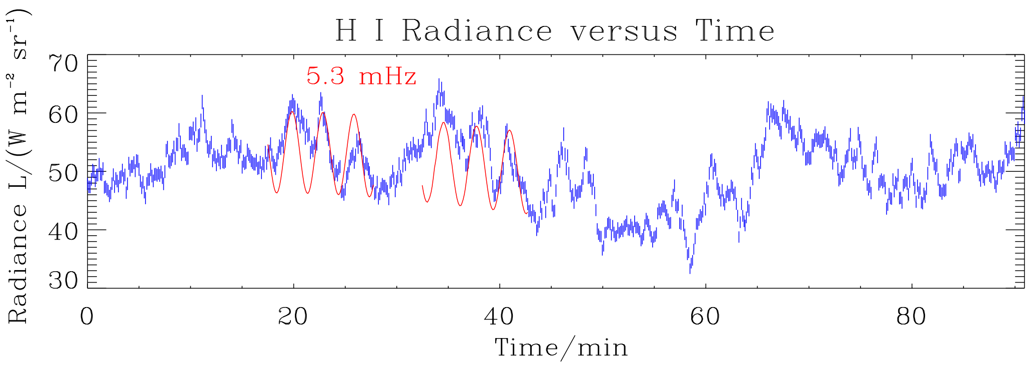

Figure 9: H I Lyman α line radiance time series in a region at 1" to 2" above the limb (defined from the position of the radiance peak in the continuum near the Si III line, see Figure 8). Oscillations with periods of about 3 minutes (5.3 mHz) can be easily seen and are outlined by sinusoidal functions.

Explosive events (EEs), in particular, are characterized by strongly non-Gaussian line profiles due to velocities up to 200 km s^{-1}, and are generally believed to be the result of magnetic reconnection [10]. They are usually observed in optically thin emission lines formed between 5×10^4 K and 7×10^5 K. Figure 10 (right column) shows such an event as identified from the Si III spectral profile. The corresponding H I Lyman α profile also shows enhanced wings with respect to quiet Sun profiles. Again a combination of images and spectra in this line would permit significant advances in the understandings of these events.

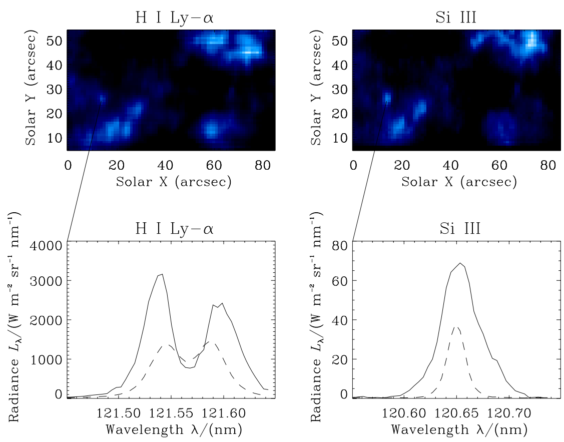

Figure 10: Example of the signature of transition region EEs in the H I Ly-α line. Radiance maps (top) and spectral profiles (bottom) from 16 April 2005 are showed. The dashed lines refer to the profiles obtained by averaging along the slit, above and below the EE location. The H I Lyman α profile is characterized by strongly enhanced wings in EEs with respect to the quiet profile.

5. FROM SUMER TO SOLAR ORBITER

The observations of the TRACE spacecraft [11] have clearly shown a corona that is characterised by structures still unresolved (or only partially resolved) even at its unprecedented 350 km resolution. SUMER raster images, such as the ones used in this paper, have a spatial resolution of about 1000 km. To get an idea about the kind of improvement that will be reached by the instruments on Solar Orbiter, we have taken images obtained by the VAULT rocket experiment [12] in the

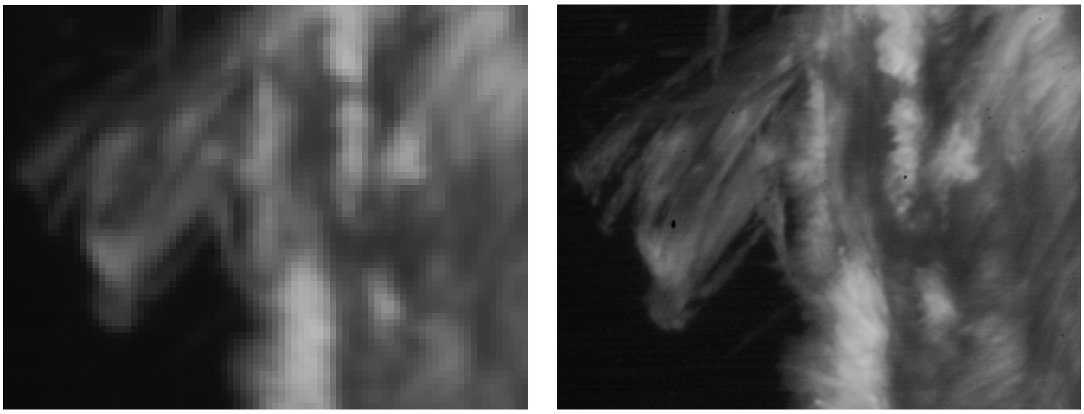

Figure 11: A 60×46 Mm² extract from a VAULT image in H I Lyman α. On the left panel the original image was convolved with a 2-D Gaussian function of ≈1000 km FWHM (SUMER spatial resolution) and then binned to the SUMER pixel size (≈725 km). On the right panel, the full-resolution (≈250 km) VAULT image is shown. The Solar Orbiter high-resolution H I Lyman α imager will further improve the picture by reaching a resolution of about 160 km or better (depending on the final aperture size). The VAULT images are courtesy of the Vault team (http://wwwsolar.nrl.navy.mil/rockets/vault/).

H I Lyman α line with a spatial resolution of 250 km. The left panel of Figure 11 shows a part of one such image, after having been convolved with a 2-D Gaussian function of ≈1000 km FWHM (SUMER spatial resolution) and then binned to the SUMER pixel size (≈725 km). The right panel shows the same FOV (a 60×46 Mm² extract from a VAULT image) at full resolution. Solar Orbiter images and spectra in the H I Lyman α line will attain even higher resolution (160 km or better) allowing a more detailed study of solar features.

6. CONCLUSIONS

SUMER raster scans and temporal series obtained simultaneously in the H I Lyman α and in the optically thin Si III 120.6 nm lines clearly show that the H I line is a good diagnostic of the morphology and dynamics of the lower TR. Its integrated radiance reveals oscillations to be an ubiquitous feature across the quiet Sun. At the limb, spicules are clearly seen and signatures of oscillations with periods between 3 and 5 minutes are detected at their base (1″ to 2″ above the limb). H I Lyman α spectra are very sensitive to the temperature stratification and dynamics of the solar lower TR, showing also signatures of transient events such as explosive events. They may provide further constraints to future models of the solar atmosphere.

The large photon flux and the possibility of using high efficiency optics (at the 121 nm wavelength) make it possible to build small remote-sensing instruments which are still capable of making high spatial and temporal resolution observations. The combination of a high resolution imager in the H I Lyman α line with a spectrograph, encompassing this line in one of its spectral bands, would be an extremely powerful instrument for studies of the solar atmosphere, and should therefore find its place in the payload of Solar Orbiter.

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