DYNAMIC BEHAVIOUR OF THE UPPER SOLAR ATMOSPHERE: 
SUMER/SOHO OBSERVATIONS OF HYDROGEN LYMAN LINES

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ABSTRACT

We present first observations of the temporal evolution of hydrogen Lyman lines, made by the SUMER spectrometer on SOHO. A time series of about 33 min was obtained on 1997, June 5. The entrance slit has crossed a quiet-Sun region of 115.3° with two intranetwork structures (cells) and the bright network regions. A data set of 59 spectra with 30 s exposure time was obtained, using the SUMER tracking system to compensate for the solar rotation. For our analysis, we have selected three Lyman lines Ly 5, Ly 9 and Ly 15 which are formed at different depths in the upper chromosphere. In the cell interiors, we have detected significant periodic intensity variations with a Fourier transform power peak at 3.3 to 3.5 min which is consistent with 3 min intranetwork oscillations. They seem to be associated with spatially unresolved `clusters' of grains. In the bright network regions, we detect slower oscillations of 6.9 to 7.6 min. These waves seem to propagate upwards as we deduce from a phase shift between the three Lyman lines studied. The phase velocity was estimated to be roughly 3 km s$^{-1}$. Finally, we discuss the potential usefulness of the hydrogen Lyman lines for diagnostics of the temperature structure of the upper solar atmosphere. Our observations, in particular the fact that we see all Lyman lines in emission all of the time, put certain constraints on the temperature gradients above the region where numerical simulations predict a decrease of the mean kinetic temperature.

Key words: solar chromosphere, oscillations, hydrogen Lyman lines

1. INTRODUCTION

New theoretical studies that have appeared during the last few years put into question hitherto widely accepted semi-empirical models of the solar atmosphere. Radiation-hydrodynamical simulations of the non-magnetic internetwork structure (cell interior) reveal remarkably good agreement between the observed and computed temporal variation of the Ca II H line (for a review see Carlsson & Stein 1997). In such models, the equations of radiation hydrodynamics are solved for the lower atmosphere (up to 1800 km) which is driven by vertically propagating acoustic waves. Ab initio simulations predict significant temporal variations of the temperature in a highly dynamical atmosphere and show that the mean temperature is in fact decreasing with height, in contrast to what one gets from static semi-empirical models of Vernazza, Avrett, & Loeser (1981) (VAL models).

Higher in the atmosphere, selected UV lines of different species (neutral or singly ionized) exhibit a similar three minute oscillatory behaviour as Ca II lines but are observed to be in emission all of the time (Carlsson, Judge, & Wilhelm 1997; see also Judge, Carlsson, & Wilhelm 1997 for the network behaviour). These SUMER/SOHO observations are thus not consistent with abovementioned simulations. One of the main questions posed by Carlsson et al. (1997) is thus 'does the time-averaged gas temperature continue to decrease with height, as in the case of an ab initio, one-component non-magnetic model...?'

From all what was said above, we see that new observations and simulations are highly needed, namely those which will tell us something about the upper atmosphere. In this respect we have considered the Lyman series of hydrogen which has several advantages. First, the line cores are supposed to be formed in the upper chromosphere or at the base of the transition region, above the heights so far considered in

simulations. The series spans the range of heights where strong temperature gradients can be expected (at least this is the case for static VAL models) and therefore can be used to diagnose the time evolution of the temperature structure. The line cores of higher Lyman lines are sensitive to the kinetic temperature as demonstrated by Heinzl, Schmieder, & Vial (1997) and this is because the upper levels of corresponding transitions are strongly coupled to the kinetic temperature. These lines are also relatively strong and thus easily observable. Since hydrogen is the most abundant species and contributes – at these heights – almost entirely to the electron density, it represents the basic plasma component in the numerical simulations. Lyman lines also play an important role in the total energy balance of the upper atmosphere. From simulations, the time-dependent Lyman-line intensities can be synthesized and compared with observations.

In this paper we present first observations of the temporal evolution of the hydrogen Lyman lines, made by the SUMER spectrometer on SOHO. We obtained a data set from the slit crossing the quiet-Sun region with typical cell and network structures and we discuss the periodicities seen there.

2. OBSERVATIONS

SUMER – Solar Ultraviolet Measurements of Emitted Radiation – is a stigmatic, high resolution normal-incidence spectrometer that covers the spectral range between 400 and 1610 Å. With a spatial resolution close to 1" (about 715 km on the Sun) and spectral pixels of 40 mÅ (with subpixel resolution) it provides a unique opportunity to observe the whole hydrogen Lyman series plus the Lyman continuum. SUMER capabilities are described in detail by Wilhelm et al. (1995) and the inflight performance is presented in Wilhelm et al. (1997) and Lemaitre et al. (1997).

In this paper we analyze the data set obtained on 1997, June 5. We used the 1" × 120" slit, centered at position X=696.2" and Y=158.3" (SUMER coordinates system). Starting at 11:56:49 UT, we have obtained a set of 59 spectra with 30 s exposure time. Few extra seconds were required for the solar rotation tracking. The whole sequence thus lasted for ≈ 33 min. Four times during the whole time sequence, the on-board SUMER solar rotation tracking system has offset the X-pointing by 0.75" to compensate for the solar rotation. Therefore, the final position was X=699.2" with unchanged Y-pointing. We have observed a quiet-Sun region close to a narrow faint filament. The northern part of the slit has crossed the cell interior region, while the central part of the slit was placed over a bright network structure. The southern section of the slit cuts another dark internetwork region and finally ends with a network brightening.

The spectra were recorded on the central band of the detector and covered the spectral band from 933 Å to 943 Å including all Lyman lines from Ly δ to Ly 0 (suffix denotes the line serial number), plus part of the Lyman continuum. This is depicted in the average spectrum of Fig. 1. The dim section corresponds to the cell interior (internetwork region), the bright part represents the network enhanced emission.

The data set has been decompressed, flat-field corrected and corrected for the geometrical distortion of the detector. The wavelengths have been calibrated by a second order least-square fit using several unblended O I lines in our spectral window as wavelength standards. The averaged profile of our spectral window is also displayed in Fig. 1 (for detailed line identifications see Curdt et al. 1997).

3. RESULTS

Significant temporal variations of the intensities and shapes of all Lyman lines are observed. Here, we have selected Ly 5 (937.803 Å), Ly 9 (920.963 Å) and Ly 15 (915.329 Å), formed at different chromospheric heights. In Fig. 2 we show the temporal evolution of the Ly 5 central pixel (line center) intensity as a surface plot. Between spatial pixels 0 and about 39, we identify an internetwork region which is relatively dark. In the central part of the slit, we see the bright network. Then further to south, the morphology seems to repeat.

Inside a dark internetwork region, we note a weak brightening around pixel 20 which exhibits clearly an oscillatory behaviour. As a working hypothesis, we ascribe this feature to a cluster of spatially unresolved oscillatory grains. The typical size of Ca II K grains is 0.5 to 1.5 Mm (Rutten 1995), our spatial resolution along the slit was about 2". Moreover, higher in the atmosphere where these Lyman lines are formed, the chromospheric structures may appear more diffuse. Just by counting the number of intensity peaks over the observed time period of 33 min, one can arrive at a periodicity close to 3 min inside dark cell regions. For the bright network seen around pixel 60, the periods seem to be longer, about a factor of two. It is important to note that the emission profiles of the optically thick Lyman lines span relatively large atmospheric depths (see, e.g., Fig. 1 in Vernazza et al. 1981) and, therefore, in oscillation studies one should better use the line-center intensities rather than the integrated emission which would allow intensity variations to mix waves from different depths.

We have analyzed time variations of the three Lyman lines Ly 5, Ly 9 and Ly 15, for two dark internetwork regions and for the bright network region located around the slit center. For the latter the results are presented here. In Fig. 3 we display the central intensity variations for these lines (in arbitrary units, i.e. with different offset and scaling), for the spatial position px 52 to 54. In the long term, the intensity

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seems to be constant. We have performed a Fourier analysis on these data and obtained a power peak in the frequency range of 2.2 to 2.4 mHz. This corresponds to periods between 6.9 and 7.6 min which is about twice as long compared to periods found inside the cell interior. One can roughly identify a phase shift between oscillations in the three lines, indicating an upward propagating wave (higher serial members are formed deeper).

4. DISCUSSION AND CONCLUSIONS

We have presented first observations of a dynamical behaviour of higher Lyman lines in the quiet solar atmosphere. Inside the cells we have detected intensity oscillations in selected Lyman lines with periods of 3.3 to 3.5 min. These oscillations seem to correspond to 3 min oscillations in the chromospheric intranetwork regions, namely the bright grains (Carlsson & Stein 1997, Kalkofen 1997). If the 3 min oscillations we have detected are indeed related to the grains, we conclude that they arise from a 'cluster' of spatially unresolved grains and that these clusters have a diameter of several arcseconds. This seems to be consistent with 3" to 8" diameter blobs reported by Carlsson et al. (1997).

In the bright network regions, on the other hand, we found periods of 6.9 to 7.6 min, which are approximately twice as long compared to cell values. This is consistent with periodicities of about 7 min or longer reported for the magnetic network by Lites, Rutten, & Kalkofen (1993) (see also the discussion by Kalkofen 1997). However, the wave patterns detected in network positions as close as few arcseconds are not very well correlated. This may indicate that we see individual (but unresolved) magnetic flux tubes with the same kind of waves but random phase shifts. These waves seem to propagate upwards as we can deduce from a phase shift between three observed Lyman lines (Fig. 3). A mean time delay between Ly 5 and Ly 15 intensity maxima is around 36 s. Assuming that the height difference between the regions where the centers of these lines are formed is of the order of 10^2 km, we can estimate the phase velocity to amount very roughly to 3 km s^{-1}. Note that in the network study of Judge et al. (1997), periodicities of the order of 7 min or longer are not reported due to the missing solar rotation tracking in their observations.
Numerical simulations of Carlsson & Stein 1997 predict temporal variations of the temperature inside the cell interiors (grains). Temperature increases and decreases with height in the chromosphere exhibit an oscillatory character. Note that these simulations are restricted to chromospheric heights below 1800 km. The problem is how these simulations and the data can be extrapolated to the upper chromosphere and lower transition region where our observed Lyman lines are supposed to be formed (i.e., their line cores). Since we observe all these Lyman lines in emission all of the time, a continuation of the temperature decrease to these atmospheric layers is rather problematic. As Carlsson et al. (1997) state, there is something important missing from the calculations and we believe that our Lyman lines observations will help in identification of possible causes of such discrepancies.

From semi-empirical models of Vernazza et al. (1981), we have estimated the range of line formation heights and temperatures for the Lyman lines studied, using the model VAL-C (for which the ground-level populations are given): 2200 km and 24000 K for Ly 5; 2100 km and 12300 K for Ly 9, and 2097 km and 8970 K for Ly 15. It is clear that the true dynamical chromosphere will differ from such models, but this example is given here just to demonstrate the diagnostics power of the hydrogen Lyman series. Analysis of time series data on these lines is thus promising and can tell us, together with new improved simulations, more about the dynamical nature of the upper chromosphere and its temperature structure. Here it is interesting to note that our observation that the line-center intensities are decreasing with the increasing line serial number all of the time, together with an assumption that $b_i = n_i/n^*_i$ factor is always increasing with the height, lead automatically to a temperature increase at all times. This is due to a strong coupling of upper-level populations to the kinetic temperature.

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