SUMER Observations Confirm the Dynamic Nature of the Quiet Solar Outer Atmosphere: The Inter-network Chromosphere

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ABSTRACT

On 12 March 1996, during the commissioning phase of the SOHO mission, we obtained observations of the quiet Sun with the SUMER instrument. The observations were sequences of 15-20 second exposures of ultraviolet emission line profiles and of the neighboring continua. These data contain signatures of the dynamics of the solar chromosphere that are uniquely useful because of wavelength coverage, moderate signal-to-noise ratios, and image stability.

We focus on data for the inter-network chromosphere. The dominant observed phenomenon is an oscillatory behavior that is analogous to the 3 minute oscillations seen in Ca II lines. The oscillations appear to be coherent over 3-8 arcsecond diameter areas. At any time they occur over ~50% of the area studied, and they appear as large perturbations in the intensities of lines and continua. The oscillations are most clearly seen in intensity variations in the UV (λ > 912Å) continua, and they are also seen in the intensities and velocities of chromospheric lines of C I, N I and O I. Intensity brightenings are accompanied by blueshifts of typically 5 km s⁻¹. Phase differences between continuum and line intensities also indicate the presence of upward propagating waves. The detailed behavior is different between different lines, sometimes showing phase lags. Three minute intensity oscillations are occasionally seen in second spectra (C II λ1335), but never in third spectra (C III and Si III). Third spectra and He I λ584 show oscillations in velocity that are not simply related to the 3 minute oscillations. The continuum intensity variations are consistent with recent simulations of chromospheric dynamics (Carlsson & Stein 1994) while the line observations indicate that important ingredients are missing at higher layers in the simulations.

1The National Center for Atmospheric Research is sponsored by the National Science Foundation
The data show that time variations are crucial for our understanding of the chromosphere itself and for the spectral features formed there – the quiet Sun’s chromosphere is very dynamic and not “quiet”. The implications of these data should be considered when planning chromospheric work with instruments such as those on SOHO.

Subject headings: Sun: chromosphere
1. Introduction

Recent years have seen a fundamental change in our understanding of the nature of the solar chromosphere. This has resulted from a synthesis between observations, some aspects of which were already known by Hale & Ellerman (1904), and a specific class of theoretical models, developed only recently to the point where sensible comparisons with observations could be made (Carlsson & Stein 1994, 1995, 1997). In essence, the change implies that for regions of the chromosphere whose structure is not obviously controlled by magnetic fields, a dynamic and not static picture is needed to describe the structure and the emitted spectrum (see the review by Rutten 1994). The evidence for this is the remarkable qualitative agreement between observed profiles of the Ca II H line and profiles computed from dynamical models in which the equations of radiation hydrodynamics are solved for a stratified atmosphere driven by vertical acoustic velocity perturbations. The driving piston’s behavior was set through simultaneous observations of a photospheric absorption line. The ab-initio model profile calculations show features that evolve with time in a remarkably similar manner to those observed. While there remain some discrepancies and questions, we believe that the information content of the time-dependent Ca II line profile data, formed at heights less than 1 Mm above the photosphere, far exceeds the information content of other data used, for example, to construct more traditional models (e.g., Vernazza et al. 1981). It is clear that a static picture is very misleading, at least for the “unmagnetized” solar chromosphere.

The implications of this new development, if it survives further critical analysis, are far reaching. For instance, the theoretical models show that there is no evidence in existing observations for a quasi-static chromosphere (Carlsson & Stein 1994, 1995), in contradiction with earlier work. Chromospheric line emission (e.g., in Ca II lines), which in static models requires an outwardly increasing temperature structure, is instead produced by wave motion with no increase in the mean gas temperature. Chromospheric line absorption in CO molecules, which in static models is inconsistent with a 1-dimensional hot chromosphere, could in principle also be produced in the dynamical calculations. These examples show that, when dynamic evolution of the plasma is important, the whole foundation for using spectral features in static models to infer physical properties of the chromosphere (in this case Ca II emission and CO absorption) must be called into question.

An important next step is to confront dynamical models with more detailed observations. There are several pressing questions that can be addressed with data from a space-based UV instrument like SUMER (Wilhelm et al. 1995) on SOHO. Can spectral features that have varying sensitivities to the gas dynamics be accurately measured and used to get more information on the dynamics of the solar chromosphere? What is the cause of the different behavior exhibited by the Ca II H line in the chromospheric network (Lites et al. 1993)? Does the time averaged gas temperature continue to decrease with height, as is the case in an ab-initio one-component non-magnetic model, or increase as suggested by recently published Mg II observations (Staath & Lemaire 1995)? Is there a connection between the dynamics in network regions deep down and in inter-network regions higher up? What can we learn from studying the time dependence of other emission lines whose formation is poorly understood (e.g., lines of He I). Are the influences of seeing fully understood in ground-based data?

To begin to answer these questions we have initiated observing sequences with the primary emphasis of obtaining time-series of selected line profiles and continua with SUMER. In this paper we discuss observations of chromospheric spectral features obtained with SUMER during the commissioning phase of SOHO. These cover some network regions as well as regions that appear to share profile variations qualitatively similar to the Ca II data seen in the non-magnetic chromosphere. While full analysis of these data must await the results of radiation hydrodynamical simulations (under way), there are some important results that do not depend on such work, and these are reported here. An accompanying paper discusses the network behavior, the He I 584Å resonance line, and lines formed in the solar transition region.

2. Observations and Data Reduction

SUMER is a normal incidence spectrograph that operates between wavelengths of 660 and 1600Å (first order, and half this, second order). Areas of the Sun are imaged by the primary mirror onto slits of various sizes before the solar light is passed to the spectrograph. A portion of the diffracted light is then
imaged onto a crossed delay line microchannel plate detector of size $360 \times 1024$ pixels. Roughly 40Å (in first order) of the solar spectrum can be placed on the detector at any given time. The spatial resolution is $\sim 1 \times 2$ arcseconds (1 arcsecond slit width, 1 arcsecond sampling along the slit). A spectral resolution element (pixel size) is $\sim 40$ mÅ (first order), $\sim 20$ mÅ (second order).

The sequence of SUMER observations discussed here was obtained on 12 March 1996 (see table 1). The $1 \times 120$ arcsecond slit was illuminated by a region of the quiet Sun close to disk center. Immediately prior to the observing run a spectroheliogram was obtained in the O IV resonance lines at 790Å as part of the commissioning activity. The initial slit position cuts through several network arches but no plage. The most likely “typical” inter-network region, i.e. free from obvious strong transition region emission, lies between slit positions 90 and 105.

The total time taken for the time-series observations was about 4 hours with one hour for each of the four wavelength regions. For these particular observations no supporting observations were made from the ground or other instruments on SOHO. Unfortunately solar tracking, i.e. compensation for solar rotation, was active only between the four one hour time sequences, not during the time sequences. Thus, over each 1 hour time-series the slit mapped out the same $10 \times 120$ arcsecond$^2$ area. This must be kept in mind since without compensation, a completely new area of the Sun at disk center is rotated onto the 1 arcsecond wide spectrograph slit every $t_{new} = 383$s (using mean solar data from Allen 1973). Thus, we can only examine variations for a given area of the Sun on timescales substantially less than this, and we can examine differences between areas of different longitudes on timescales longer than this.

Grating positions were chosen to obtain profiles of lines at wavelengths listed in table 1. The exposure time used was 15 or 20 s, chosen to fit the telemetry constraints for the SUMER instrument (10.5 kbits/s) after which the detector (detector A) was read and prepared for the next exposure. Owing to telemetry constraints, a window of just 50 (spectral) by 120 (spatial) pixels was transmitted to the ground for each of the wavelength settings listed in table 1.

### 2.1. Data reduction

The raw data consist of time-series of “images” with wavelength on the x-axis and distance along the slit along the y-axis, one image for each exposure. Each image consists of raw counts per “pixel” on the detector. The sequence of 240 or 180 such images forms the “data cube”.

In the present paper we wish to study line profiles and continuum intensities as functions of time. Our data reduction requirements are thus to obtain line profiles with high relative photometric precision. Thus, we must reliably perform the following tasks: flat field corrections to account for pixel-to-pixel sensitivity variations; geometric corrections to account for distortion of the image of the slit projected onto the Sun in both the spectral and spatial directions; wavelength calibrations. To relate observed intensities to simulations we also need a radiometric calibration.

High signal to noise flat-field exposures contribute significantly to the degradation of the detector and are therefore not taken more often than about once per month. The flat-field exposure closest to our observing run of 12 March was taken 28 February. Unfortunately it was found that the flat-field pattern of sensitivity variations ($\pm 50\%$, peak-to-peak) was slightly displaced in the observations compared with the flat-field exposure. The following procedure was employed to obtain an optimum removal of pixel-to-pixel sensitivity variations: The mean images over the one hour observing sequence in each line was used as a starting point to fix co-alignment of the flat to the solar data. Each column was divided by the column mean (removing the spectral lines) and each row was thereafter divided by the row mean (removing intensity variations along the slit). The remaining image contains the small scale sensitivity variation pattern. This image was cross-correlated with the flat-field image to determine an optimum shift of the flat-field. Such a shift was determined individually for each line and the shifted flat-field was used subsequently. The maximum shift determined was 0.6 pixels in the wavelength direction and 0.9 pixels in the slit direction. In addition to the pixel-to-pixel variation in the flatfield there is an artifact from the AD-converter causing every second row to get higher counts. This effect does not shift in position with time and was therefore taken out before the shift of the flat-field and multiplied in again after the shift. The flat-fielded images were
corrected for geometrical distortion using data from T. Moran (private communication). The wavelength calibration was taken from the pre-flight calibration and is very inaccurate. Therefore, Doppler shifts discussed here are relative to the mean observed wavelength of the line. The radiometric calibration was taken from Wilhelm et al. (1997).

3. Results

We have examined the SUMER data using different methods, including Fourier spectra and various slices through and moments of the data cube, such as mean intensities, velocities, linewidths. The simplest and most illuminating way to see the gross properties of the data is to look at moments. More detailed analyses using power spectra or wavelets will be discussed in future papers.

First consider Fig. 1 which shows a slice through the data cube of one time-series at a single position along the slit. It shows the intensity as a function of wavelength and time for the three lines N I 1319, C I 1329, C II 1334 (lower panel) and O I 1355, O I 1358, C I 1364 (upper panel), at a typical inter-network slit position (x = 95). Each image is shown on a linear scale, each individually scaled. The average peak count rates are 20, 7 and 8 counts pixel\(^{-1}\) in the 15 s integration times for the three upper panels, and 20, 6 and 100 counts pixel\(^{-1}\) for the lower panels respectively. The scaling makes the continuum most visible in the upper panels and lower middle panel although the continuum signal is similar at all wavelengths (typically 1 count pixel\(^{-1}\) in 15 s). Continuum brightenings are very evident as horizontal bands. The time between two brightenings is typically 200 s. The brightenings are also seen in the line emission, especially in the N I and C I lines but the brightest ones also in C II (e.g., at times t=670, 2450 and 3100). The brightenings are always of longer duration (full widths at half maximum intensity are \(\sim 100\) s) in the N I line than in the two other lines (\(\sim 50\) s). The maximum intensity typically occurs first in the continuum and simultaneously in C I, about 12s later in C II and 25s later in N I. The time delays vary from grain to grain but are of similar magnitudes.

Next consider wavelength-integrated quantities: the total line intensity \(I_{\text{tot}}\) and the mean velocity shift \(\bar{v}\) computed from:

\[
I_{\text{tot}} = \int_{\Delta \lambda} (I_\lambda - I_{\text{cont}}) \, d\lambda
\]

\[
\bar{v} = \int_{\Delta \lambda} (I_\lambda - I_{\text{cont}}) \, v_\lambda \, d\lambda / I_{\text{tot}}
\]

where \(I_{\text{cont}}\) is a background continuum intensity. All intensity data are given in counts/exposure on the detector. \(\bar{v}\) is given in Doppler units of km s\(^{-1}\), and \(v_\lambda = c \cdot (\lambda - \lambda_0) / \lambda_0\) where \(\lambda_0\) is the rest wavelength of line center.

Fig. 2 shows \(I_{\text{cont}}, I_{\text{tot}}\) and \(\bar{v}\) as a function of spatial position and time for the N I 1319 and C II 1334 lines. Only a subset (spatial pixels x = 65 to 120) of slit positions are shown to highlight inter-network regions. The intensity data (\(I_{\text{cont}}\) and \(I_{\text{tot}}\)) reveal the spatial extent along the slit and the omni-presence of the bright grains. In the inter-network region (x = 90-105) there are intensity brightenings with 3-8 arcsecond spatial scale (along the slit) at all slit positions and in all the neutral lines. The C II 1334 line is qualitatively different but also shows bright grains correlated in time with the grains in the continuum and the neutral lines.

The continuum intensity brightens by up to a factor of seven. The radiation temperature at 1300 Å varies between 4400K and 5000K with an rms variation of 86K. This is consistent with the simulations by Carlsson & Stein (1994).

On timescales longer than \(t_{\text{new}} = 383\) s (6.4 minutes), the typical number of repetitions of grains at each x position seen in Fig. 2 can in principle be used to set limits on the spatial and/or temporal properties of the grains. Grains are typically seen in vertical strings (i.e., the same x position in plots similar to Fig. 2) for between 15 and 30 minutes, but can also be seen just individually and up to the full observation time of 1 hour. The durations in time and widths of the grains seen along the slit are consistent with the grains having a diameter of a few arcseconds. It is not possible to determine the “lifetime” over which a region generates grains from this dataset.

The velocity data (\(\bar{v}\)) show interesting properties. The bright grains are seen as regions of blueshifted emission (see, e.g., \(x = 95\) at time \(t = 670\) s in Fig. 1 and 2). The C II \(\bar{v}\) data reveal a remarkable oscillatory behavior that consists of 5-15 arcsecond long oscillatory striations of peak-to-peak amplitude \(\pm 2 - 3\) km s\(^{-1}\). These appear to be associated with the grains, as seen in Fig. 2 and 3. Note, however,
that the velocity signal appears coherent over larger areas, especially in regions of intermediate line intensity (see, e.g., $x = 80 - 90$ in Fig. 2). The $v$ data also show horizontal propagation (inclined structures in Fig. 2). Oscillatory behavior in $v$ of He I and Si III lines is common, but not simply correlated with the underlying cell flashes.

Several other general properties of grains emerge when the above data are considered with the other wavelength regions in our data set. All chromospheric lines show emission above the continuum everywhere, all of the time. The Ca II cell flash phenomena are seen in all lines of neutral C, N, and O and all continua. Continuum intensities show most clearly the signature of the grains: typical behavior is seen in Fig. 2, where the grains are seen as flat-bottomed brightenings (sudden brightenings on timescales down to the 15s integration times over several spatial pixels) followed by a decay in brightness that appears “fuzzy”, on timescales of $10^2$s or so. Different lines within the same atom or ion can show rather different time behavior, for example N I 1319Å shows qualitatively a very different behavior from N I 1199Å. Although obtained at different times (table 1), this behavior emphasizes the need for radiation (magneto-) hydrodynamic modeling.

Grains can be seen in second spectra (C II), but not in third spectra (Si III or C III). Measured line shifts (bulk fluid velocities determined from the first and zeroth wavelength moments of the intensities) typically yield a 5 km s$^{-1}$ blueshift during the bright phase of the grains.

### 3.1. Conclusions

Our main emphasis has been to present the qualitative behavior of UV lines and continua in the inter-network chromosphere as observed with the SUMER instrument, point out the salient features, and draw some preliminary conclusions. While radiation hydrodynamic calculations are needed for detailed interpretation of these data, there are some conclusions that can be drawn and we can speculate on others.

We can conclude that the grains appear to be 3-8 arcsecond diameter blobs. Thus, the photospheric p-modes, with whatever controls their upward propagation into the chromosphere, apparently provide a coherent driver over this area to produce observable grains of this size (this will be contrasted with the case of network time-series data in the following paper).

The grains are extremely common, covering typically 50% of the observed area at a given time.

The non-detection of any grain oscillations in third spectra (C III and Si III, traditionally classified as “transition region lines”), indicates that the upward propagating shocks that are assumed to be responsible for the oscillations seen in the other lines and continua are not responsible for the heating of the lower transition region. This is discussed in the following paper.

The continuum intensity variations are consistent with the simulations by Carlsson & Stein (1994, 1995, 1997). However, the simulations cannot qualitatively reproduce the behavior of the lines. In particular, they cannot produce the observed emission all of the time. Thus, something important is missing from the calculations- perhaps concerning the fate of shock waves propagating upwards into a magnetic “canopy”, perhaps concerning different propagation modes (MHD effects), or energetically non-connected material lying along the line of site (like magnetic flux-tubes). In any case this comparison verifies that SUMER can indeed provide new information on the gas dynamics through observing new spectral features.

Philip Judge is very grateful to NORDITA, and the Institute of Theoretical Astrophysics at the University of Oslo, for support of a 6 month collaborative leave in Oslo in 1996, and to UCAR for supporting that leave. We are very grateful to Philippe Lemaire for providing the O IV spectroheliogram.

The SUMER project is financially supported by DARA, CNES, NASA and PRODEX (Swiss contribution).

### REFERENCES


Fig. 3.— The behavior with time of intensity and Doppler shift of the continuum, N I and C II lines. The plots are summed over spatial pixels 93-97.


Table 1: SELECTED SUMER OBSERVATIONS FROM 12 MARCH 1996

<table>
<thead>
<tr>
<th>Item</th>
<th>Start UT</th>
<th>End UT</th>
<th>Exp.</th>
<th>Target lines</th>
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</thead>
<tbody>
<tr>
<td>...</td>
<td>09:14:04</td>
<td>10:11:32</td>
<td>15</td>
<td>O IV 790.112+790.199 (spectroheliogram)</td>
</tr>
<tr>
<td>1</td>
<td>10:31:26</td>
<td>11:31:26</td>
<td>15</td>
<td>O I 1358.51, (O I+C I) 1355.72, C I 1364.16</td>
</tr>
<tr>
<td>2</td>
<td>11:31:55</td>
<td>12:31:55</td>
<td>15</td>
<td>N I 1319.00, C I 1329.58, C II 1334.53</td>
</tr>
<tr>
<td>3</td>
<td>12:33:06</td>
<td>13:33:07</td>
<td>15</td>
<td>N I 1199.55, Si II 1196.39, Si III 1206.51</td>
</tr>
<tr>
<td>4</td>
<td>13:33:34</td>
<td>14:33:55</td>
<td>20</td>
<td>C III 1175.71, He I 584.334, C I 1156.03, O I 1152.15</td>
</tr>
</tbody>
</table>

Fig. 1.— SUMER data showing the intensity profile as a function of wavelength in Doppler units (x-axis, units of km s\(^{-1}\)) at spatial positions \(x = 95 - 96\) along the 1 × 120 arcsecond slit, and time (y-axis, units of seconds). Data for two separate timeseries are shown, the 1355 Å region in the upper panel, the 1319 Å region in the lower panel. The “grains” are seen as brightenings with an intermittent ∼3 minute periodicity and a characteristic spectral profile: brightenings are accompanied by a net blue shift of ∼5 km s\(^{-1}\). The x-axes have not been corrected for zero point offsets or long term drifts. Telemetry gaps occurred near 2800 and 3300 s (lower panel).

Fig. 2.— Continuum intensity (left), total line intensity (continuum intensity subtracted)(middle), line Doppler shift (right) as function of position along the slit (x-axis) and time (y-axis) for the N I 1319 line (top) and the C II 1334 line (bottom). The continuum intensity is given in counts (top left) and as the corresponding radiation temperature (bottom left). Doppler shifts are shown with upward velocity (blue-shift) bright. All data from the same timeseries.