SUMER OBSERVATIONS CONFIRM THE DYNAMIC NATURE OF THE QUIET SOLAR OUTER ATMOSPHERE: 
THE INTERNETWORK CHROMOSPHERE

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ABSTRACT

On 1996 March 12, 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 s 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 internetwork 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" diameter areas. At any time they occur over about 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 ultraviolet (λ > 912 Å) 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. The 3 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 and Stein), while the line observations indicate that important ingredients are missing at higher layers in the simulations.

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 heading: 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, Avrett, & Loeser 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 one-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 Solar Ultraviolet Measurements of Emitted Radiation (SUMER) (Wilhelm et al. 1995) on SOHO. Can spectral features that have varying sensitivities to the gasdynamics 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 transition on the dynamics of the solar chromosphere? When is imaged onto a crossed delay line microchannel plate detector of size 360 × 1024 pixels. Roughly 40 Å (in first order) of the solar spectrum can be placed on the detector at any given time. The spatial resolution is about 1" × 2" (1" slit width, 1" sampling along the slit). A spectral resolution element (pixel size) is about 40 mA (first order) or 20 mA (second order).

The sequence of SUMER observations discussed here was obtained on 1996 March 12 (see Table 1). The 1" × 120" 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 790 Å as part of the commissioning activity. The initial slit position cuts through several network arches but no plage. The most likely “typical” internetwork 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 hr, with 1 hr 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 1 hr time sequences, not during the time sequences. Thus, over each 1 hr time series the slit mapped out the same 10 × 120 arcsec² 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° wide spectrograph slit every tₜ = 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⁻¹), 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. Observations and Data Reduction

SUMER is a normal incidence spectrograph that operates between wavelengths of 660 and 1600 Å (first order, and half of 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 × 1024 pixels. Roughly 40 Å (in first order) of the solar spectrum can be placed on the detector at any given time. The spatial resolution is about 1" × 2" (1" slit width, 1" sampling along the slit). A spectral resolution element (pixel size) is about 40 mA (first order) or 20 mA (second order).

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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 Letter 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, and wavelength calibrations. To relate observed intensities to simulations, we also need a radiometric calibration.

High signal-to-noise ratio 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 March 12 was taken February 28. Unfortunately, it was found that the flat-field pattern of sensitivity variations (±50%, peak-to-
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, and line widths. 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 Figure 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 (bottom) and O i 1355, O i 1358, C i 1364 (top), at a typical internetwork 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 top panels, and 20, 6, and 100 counts pixel$^{-1}$ for the bottom panels, respectively. The scaling makes the continuum most visible in the top 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 width at half-maximum intensity values 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 12 s later in C ii and 25 s 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 per exposure on the detector. The term $\bar{v}$ is given in Doppler units of km s$^{-1}$, and $v_{\lambda} = c(\lambda - \lambda_{0})/\lambda_{0}$, where $\lambda_{0}$ is the rest wavelength of line center.

Figure 2 (Plate L3) 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 is shown to highlight internetwork regions. The intensity data ($I_{\text{cont}}$ and $I_{\text{tot}}$) reveal the spatial extent along the slit and the omnipresence of the bright grains. In the internetwork region ($x = 90–105$) there are intensity brightenings with 3$^\circ$–8$^\circ$ 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 7. The radiation temperature at 1300 Å varies between 4400 K and 5000 K with an rms variation of 86 K. This is consistent with the simulations by Carlson & Stein (1994).

On timescales longer than $t_{\text{row}} = 383$ s (6.4 minutes), the typical number of repetitions of grains at each $x$ position seen in Figure 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 they can also be seen just individually and up to the full observation time of 1
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 data set.

The velocity data \( \tau \) show interesting properties. The bright grains are seen as regions of blueshifted emission (see, e.g., \( x = 95 \) at time \( t = 670 \) s in Figs. 1 and 2). The C II \( \tau \) data reveal a remarkable oscillatory behavior that consists of \( 5^\circ-15^\circ \) 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 Figures 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 \( \tau \) data also show horizontal propagation (inclined structures in Fig. 2). Oscillatory behavior in \( \tau \) 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 Figure 2, where the grains are seen as flat-bottomed brightenings (sudden brightenings on timescales down to the 15 s 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 1319 Å shows qualitatively a very different behavior from N I 1199 Å. 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 internetwork 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 \( 3^\circ-8^\circ \) 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 nondetection 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 upward into a magnetic “canopy,” perhaps concerning different propagation modes (MHD effects), or energetically nonconnected 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 gasdynamics through observing new spectral features.

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Fig. 2.—Continuum intensity (left), total line intensity (continuum intensity subtracted; middle), and line Doppler shift (right) as functions 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 (blueshift) bright. All data from the same time series.

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