TRANSITION REGION VELOCITIES AND LINE PROFILES IN THE SUNSPOT REGION NOAA 7981

N. Brynildsen\textsuperscript{1}, P. Brekke\textsuperscript{1}, T. Fredvik\textsuperscript{1}, S. V. H. Haugan\textsuperscript{1}, O. Kjeldseth-Moe\textsuperscript{1}, P. Maltby\textsuperscript{4}, R. A. Harrison\textsuperscript{2}, C. D. Pike\textsuperscript{2}, T. Rimmele\textsuperscript{3}, W. T. Thompson\textsuperscript{4}, K. Wilhelm\textsuperscript{5}

\textsuperscript{1}Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway
\textsuperscript{2}Space Science Dept., Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
\textsuperscript{3}National Solar Observatory, Sacramento Peak, Sunspot, NM 88349, USA
\textsuperscript{4}Applied Research Corporation, 8201 Corporate Drive, Landover, MD 20785, USA
\textsuperscript{5}Max-Planck-Institut für Aeronomie, D-37189 Katlenburg-Lindau, Germany

ABSTRACT

Based on EUV spectra of a medium size sunspot and its surroundings, NOAA 7981, observed with CDS and SUMER on SOHO, we derive line-of-sight velocities and study the line profiles for a series of emission lines formed in the transition region and the corona. The flow field in the low corona is found to differ markedly from that in the transition region. In the transition region the relative line-of-sight velocity shows an upflow in the umbra. Relatively large areas with downflow cover part of the penumbra. The spatial extent of these areas with upflow and downflow increases with increasing temperature, but the whole flow field changes character as the temperature increases from the upper transition region to the low corona. The whole sunspot transition zone appears to be moving downwards and we discuss the relation between this finding and the tendency for transition region lines to show a net redshift.

Several of the transition region spectral line profiles are observed to show two line components with Gaussian shape and line-of-sight velocities that differ markedly. In small regions with spatial extent of a few arcseconds we detect enhanced continuum emission underlying explosive events. The similarities between explosive events with continuum emission and the moustaches observed in H\textsubscript{alpha} close to sunspots are so striking that we are tempted to introduce the term “Transition region moustaches”.

Key words: EUV; sunspots; solar physics.

1. INTRODUCTION

Both in the photosphere and the chromosphere the flow is concentrated in channels that very likely follow the magnetic field lines. Although the flow is found to be non-stationary both in the photosphere and the chromosphere, the general character of the flow field is maintained for a larger part of the lifetime of the sunspot. Both the flow and the magnetic field lines have large components in the horizontal direction in the photosphere and chromosphere, corresponding to a fanning out of the magnetic field of the sunspot in these layers. In higher layers we expect the vertical component of the flow field to be more important. Observations confirm this prediction, but presently the picture is rather complicated and conflicting results have been published (e.g. Kjeldseth-Moe et al., 1988, 1993; Dere, Schmieder, and Alissandrakis, 1990; Gurman, 1992). For the corona itself, few observations are available, see Brekke et al. (1997).

2. OBSERVATIONS

The observations were proposed and planned as a SOHO Joint Observing Programme (JOP018) for simultaneous sunspot observations from space and from the ground. Here we present observations of the largest sunspot in NOAA 7981 and its surroundings, obtained on August 2, 1996 between 10:58:42 and 14:29:59 UT with the Normal Incidence Spectrometer (NIS) of the Coronal Diagnostic Spectrometer – CDS (Harrison et al., 1995) and the spectrometer Solar Ultraviolet Measurements of Emitted Radiation - SUMER (Wilhelm et al., 1995). The observed sunspot was slightly elongated in the E–W direction and the white light image showed an umbral size of 20'' x 16'' and a penumbral size of 50'' x 42''. Since the sunspot was situated rather close to the disk centre, $\theta = 16''$, (cos $\theta = 0.96$), upflows and downflows may be measured as line-of-sight velocities without any appreciable reduction, whereas only large velocities in the horizontal plane will be noticeable.

A large fraction of the observing time was used to raster an area of 120'' x 120'', moving the narrow spectrometer slits of CDS and SUMER perpendicular to the slit direction in steps of 2.0'' and 1.14'', respectively. The observational material contains data from five CDS raster observations, each with a duration of 25 minutes and a slit width of 2.0''. The SUMER raster observations were obtained with detector A, a slit width of 0.3'', and consist of rasters for a se-
Figure 1. Spatial distributions of relative line-of-sight velocities, derived from raster observation with CDS in the 2" slit width mode, between 11:10 and 11:35 UT on August 2, 1996. The velocities are measured relative to the average velocity in each image which covers an area of approximately 120" x 120". Relative velocities between 30 km s\(^{-1}\) away (red) and -30 km s\(^{-1}\) towards (blue) the observer are shown. The accuracy criterion to the line-of-sight velocity is set equal to or less than 5 km s\(^{-1}\) for He I and O V, 15 km s\(^{-1}\) for O III, O IV, Ne VI and Mg IX and 25 km s\(^{-1}\) for Fe XVI. Regions with an evenly white colour did not satisfy these accuracy criteria. Positions are given relative to the disk centre. The white light image was taken with the RISE/PSPT telescope (e.g. Coulter and Kuhn, 1994) operating at the Rome site.
Figure 2. Spatial distributions of relative line-of-sight velocities, derived from raster observation with SUMER ( detector A) in the 0.3" slit width mode. The velocities are measured relative to the average velocity in each image which covers an area of approximately 120" \times 120". Relative velocities between 30 km s^{-1} away (red) and -30 km s^{-1} towards (blue) the observer are shown. The images are co-aligned, oriented with north up and west to the right. Positions are given relative to the disk centre. The white light image was taken with the RISE/FSPT telescope (e.g. Coulter and Kuhn, 1994) operating at the Rome site.
3. LINE-OF-SIGHT VELOCITIES VERSUS TEMPERATURE

Figures 1 and 2 show the relative line-of-sight velocities for different spectral lines observed with CDS and SUMER, respectively. The relative line-of-sight velocity is derived by applying a method whereby a single Gaussian shaped profile is adjusted to fit each of the observed line profiles. Note that these line-of-sight velocities are measured relative to the average velocity for the whole area in each image, velocities between 30 km s\(^{-1}\) away from (red) and -30 km s\(^{-1}\) towards (blue) the observer are shown. In both illustrations the images are shown in order of increasing line formation temperature, starting from the upper left hand corner. The white light image was aligned with the SUMER EUV images using the rear slit camera of SUMER. The alignment of the CDS and SUMER images was done by using the O V 629 Å line, observed with both instruments.

Since the spectral line intensities differ considerably from one line to another in the CDS observations, the uncertainty in the line-of-sight velocity determination in Figure 1 will differ. The accuracy criteria to the line-of-sight velocity are given in the Figure 1 caption. Considerably higher accuracies are obtained in the SUMER observations presented in Figure 2. We estimate the uncertainty in the relative line-of-sight velocity to be equal to 1 km s\(^{-1}\) for SUMER.

Figure 1 gives insight into the variation of the flow field as a function of line formation temperature within the transition region and corona. Whereas two regions with downflow are clearly visible in the central part of the image in the transition region lines, O III, O IV, O V and Ne VI, the same area is dominated by an upflow in the low corona. From a comparison of flow fields in Ne VI 562 Å and Mg IX 368 Å it is apparent that the flow field changes markedly between the upper part of the transition region and the low corona. The change in flow field cannot simply be described as an increase in the characteristic scales, since relatively narrow structures are seen in Mg IX 368 Å, with orientations that differ markedly from the structures seen in the velocity maps of the transition region. Rather, it appears that the whole flow field changes character between the transition region and the low corona.

Figure 2 gives in detail the change in shape and extent of the downflow and upflow region as function of temperature within the transition region. Comparing the positions of the two extended downflow regions in N V, O V, O VI, and Ne VIII we note that the separation between the two regions increases with increasing line formation temperature. Figure 3 illustrates the increase in the spatial extent of these flow regions with the increase in line formation temperature. Assuming that the velocity is oriented along the magnetic field lines, this increase in spatial extent with increasing temperature suggests a fanning out of the magnetic field lines with increasing temperature.

3.1 Mass flux

For optically thin lines the spectral line intensity is proportional to the square of the gas density and the mass flux up (down) is proportional to the upflow (downflow) velocity multiplied by the square root of the line intensity. The relative velocity is known with relatively high accuracy and we have therefore calculated the mass flux up (down) relative to the average velocity for the sunspot region. We have determined the ratio of the mass flux down to the mass flux up for a region 120" × 80" observed with both instruments. We find that the mass flux down is higher than the mass flux up by a factor up to 3.7 for the SUMER observation of O V 629 Å, unless the whole area is moving upwards or the area filling factor changes with the direction of motion. Since the "absolute" velocity show that the whole transition region appears to be moving down, see below, an explanation is needed for this lack of balance between mass fluxes, see Brynildsen, Kjeldseth-Moe, and Maltby (1996).
Figure 3. Spatial extent of regions with relative line-of-sight velocities values larger than 20 km s$^{-1}$ away (dark) and towards (bright) the observer. The results are plotted at different heights, such that an increase in height corresponds to an increase in line formation temperature.

4. AVERAGE LINE-OF-SIGHT VELOCITY VERSUS TEMPERATURE

Neither CDS nor SUMER have on-board absolute calibration sources, and the wavelength scale was determined by using a set of neutral and single ionized spectral lines, formed in the chromosphere and known to show small line-of-sight velocities. With few calibration lines available in the CDS wavelength range we will concentrate on the SUMER wavelength scale, which was determined from one deep exposure for each wavelength region. Since the position of the slit is known for the deep exposure we may deduce the absolute velocity also for the short exposure observation at the same slit position within the raster and the average line-of-sight velocity for the whole region.

Figure 4 shows the average line-of-sight velocity versus line formation temperature. In earlier studies the behavior above log T = 5.0 has been debated (e.g. Brekke 1993; Achour et al., 1995), but no definite conclusions could be drawn due to lack of observations at higher temperatures. With the present observations of the O VI and Ne VIII lines, it seems clear that the redshift is still present at log T $\approx$ 5.8. The redshifts presented in Figure 4 are smaller than the results obtained recently from SUMER observations for the quiet Sun (Brekke, Hassler, and Wilhelm, 1997). At first sight this appears to be in conflict with previous results which showed larger redshifts in active regions than in the quiet Sun. In a separate study (Brynildsen et al. - this issue) we analyze different data reduction procedures and suggest that the differential redshift between the transition region and chromospheric emission lines emerges from a correlation between the intensity and wavelength shift in the transition region lines.

5. LINE PROFILES

A large fraction of the line profiles could be fitted with a single Gaussian profile. We have studied the non-thermal line broadening as a function of temperature and will report on the results in a publication submitted for publication. Here we consider the more complicated line profiles. Several line profiles consist of two or three Gaussian line components with line-of-sight velocities that differ markedly, suggesting more than one flow speed within the same spatial resolution element. The multiple flow concept was introduced by Kjeldseth-Moe et al. (1988) and discussed in detail by Kjeldseth-Moe et al. (1993). The present observations confirm and extend our knowledge about multiple flows.

In small regions with spatial extent of a few arcseconds, located close to the sunspot, we observe enhanced transition region line emission, combined with extreme line broadening. These features, called explosive events, are found both in active and quiet Sun regions, and are characterized by a small spatial extent ($\sim 2^\prime$), velocities of $\sim 100$ km s$^{-1}$, often both towards and away from the observer at the same location, and lifetime in the range 20 s to 200 s (e.g. Brueckner, 1980; Kjeldseth-Moe and Cheng, 1990). Recent observations of explosive events with SUMER are discussed by several authors, see Wilhelm et al. (1997) and references given therein.

Here we want to draw attention to the detection of an enhanced continuum emission underlying the line emission in explosive events. The detection of the enhanced continuum was made possible by the deep exposures (50 – 200 s), primarily taken for wavelength calibration purposes. This kind of enhanced continuum emission was found in spectra centered on 1045, 1246, 1403, and 1557 Å. Hence, it is possible that all explosive events have an associated enhanced continuum emission, which is too weak to be detected from short exposures.

Figure 5 (middle) shows a section, 1024 – 1050 Å, of the spectrum that was obtained with one of the deep exposures. At two positions along the slit we ob-
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