THE TRANSITION REGION ABOVE SUNSPOTS

Werner Curdt[1] **and Enrico Landi**[2]

[1]*Max-Planck-Institute for Solar System Research, 37191 Katlenburg-Lindau, Germany*
[2]*E.O.Hulburt Center for Space Research, NRL, Washington DC 20375, USA*

ABSTRACT

We review results from spectroscopic observations of sunspots in the vacuum ultraviolet wavelength range. The solar atmosphere above sunspots is very special and entirely different compared to other parts of the solar surface. The transition region, which is normally a thin layer extends very high in altitude above sunspots and is filled by rather cool, low-density plasma. It is unclear, whether this is related to the strong, unipolar magnetic field in quasi-open magnetic field lines above sunspots. Sunspot plumes are sites of systematic downflow into a bottom layer, which is coherently oscillating with a 3-minute period.

Key words: Sun: transition region; Sunspot; EUV spectroscopy.

1. INTRODUCTION

Here we continue earlier work (Curdt et al. 2000) and present results from observations of sunspot plumes obtained by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectroscope (Wilhelm et al. 1995) and the Coronal Diagnostic Spectrometer instrument (Harrison et al. 1995) on the Solar and Heliospheric Observatory (SoHO). Part of our communication is based on systematic work of the Oslo group (cf., references in sections below). New insights, complementing a recent communication (Curdt & Landi 2006) on this subject, justify an expanded presentation.

The term sunspot plume was defined by Foukal et al. (1974) as an extended area, where the transition region emission is five times brighter than on average and which has at least some overlap with the umbral part of a sunspot. Although - according to this exact definition - not all sunspots carry a plume we use the term 'sunspot plume' as synonym for 'transition region above a sunspot', simply assuming that such a feature is always present, although sometimes more and sometimes less prominent. A typical example is shown in Fig. 1. Here, white contours outline the white-light umbra and penumbra. The area of bright transition region emission

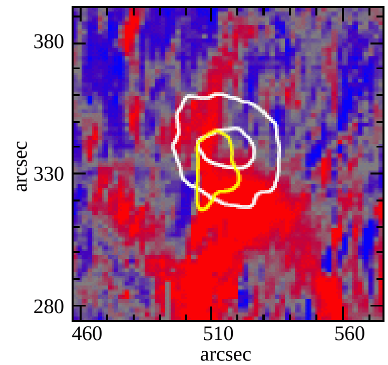

Figure 1. Typical example of a sunspot plume observed on 1 June 1996 in active region NOAA 8559 (cf., Maltby et al. 1999 for more examples). White contours outline the white-light umbra and penumbra, the yellow contour outlines the area of bright O V *emission defining the sunspot plume. Redshifted features terminate in the plume area.*

outlined in yellow, i.e., the sunspot plume, is anchored in the umbra and points away from the sunspot. We interpret this as a projection effect when mapping a 3-dimensional loop-like structure onto the disk.*

2. SPECTRAL FEATURES

2.1. Continua

The continuum emission of a sunspot is remarkably different compared to average quiet Sun radiation as illustrated in Fig.2. The Lyman continuum of the sunspot plume is enhanced by almost a factor of 2 - similar to bright network emission - but here the Lyman lines are optically thin (Curdt et al. 1999). In contrast the black body radiation around 1450 Å is depressed by a factor of > 10. This reduction is restricted to the sunspot umbra, which clearly indicates that the emission emerges much lower in the atmosphere and that in these lower chromospheric layers temperatures are reduced by more than 2500 K as compared to the average quiet Sun.

* A coloured preprint is available at www.mps.mpg.de/homes/curdt

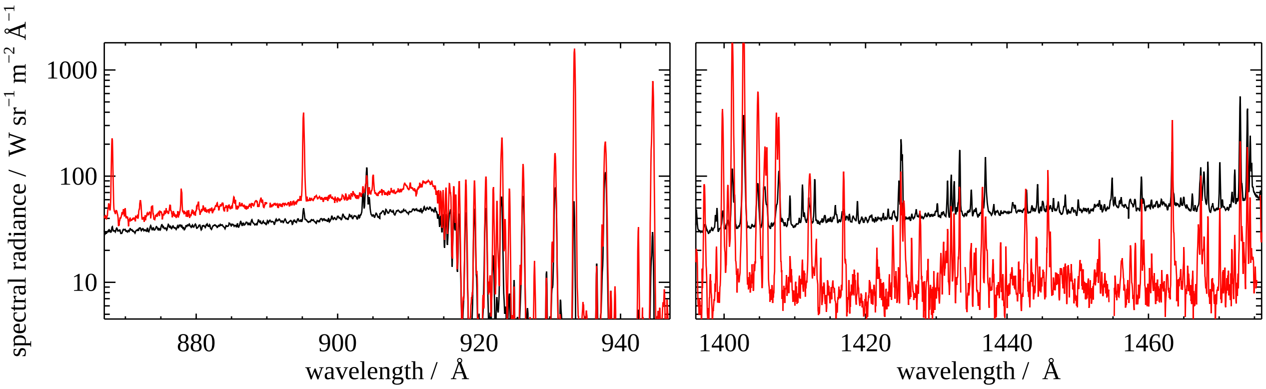

Figure 2. Sections of the average quiet-Sun emission (black) in the SUMER spectral range compared to the emission of a sunspot plume (red). Poisson noise accounts for the much lower count numbers in the plume spectrum.

2.2. Peculiar lines

In sunspot plumes the emission peaks in lines with a formation temperature around $10^{5.5}$ K. There is no emission from lines hotter than 10^6 K. In plume spectra more than 100 'peculiar' lines are present, half of them unidentified. We call them peculiar, because they are not observed anywhere else on the Sun (Curdt et al. 2001). Some of them may be present in streamer spectra (Curdt et al. 2004). They all seem to belong to the same temperature class of 4- to 8-fold ionized species. We conclude that above sunspots unique plasma conditions prevail. It is not clear, whether these are based on a special combination of N_e and T_e, or whether a different excitation process accounts for this specific emission.

Table 1. 1-0 to 1-7 lines of the C-X Werner bands in Å

index	wavelength
1-0	989.73
1-1	1031.87
1-2	1075.03
1-3	1119.08
1-4	1163.81
1-5	1208.94
1-6	1254.12
1-7	1298.85

2.3. Molecular emission

Eight lines of the H_2 Werner bands fall into the SUMER spectral range, the 1-4 branch near 1163 Å being by far the strongest. H_2 emission is found everywhere in the sunspot umbra, but not outside. The emission is strongest near the umbra-penumbra boundary, a fact, which is not very well understood. The observed branching ratios comply with theoretical values. The Werner-Band is excited by resonance fluorescence through the bright O VI emission line at 1032 Å. In a recent paper Schühle (1999) completed earlier work of Bartoe et al. (1979) and compared the observed branching ratios to theoretical values communicated by Allison & Dalgarno (1970) . From the observed column density Bartoe derives temperatures below 4000 K at the sunspot chromosphere.

2.4. Downflows

Sunspot plumes always have systematic downflows of up to 25 km/s and often elongated redshifted features terminate in the plume area (cf., Fig.1). The Oslo group has also found that plume contours appear displaced in lines formed at different temperatures (Maltby et al. 1999). This again seems to be a projection effect of a 3-dimensional non-radial feature.

3. DENSITY DIAGNOSTIC

The emissivity em_{ij} in a selected optical thin spectral line due to a transition from an excited level j to a lower level i is given by the expression

$$em_{ij} = \frac{hc}{\lambda_{ij}} \cdot \frac{N_j}{N_{ion}} \cdot \frac{N_{ion}}{N_{el}} \cdot \frac{N_{el}}{N_H} \cdot \frac{N_H}{N_e} \cdot N_e A_{ji} \quad (1)$$

where the terms denote the photon energy, the population of the excited level, the ionization fraction of the element under consideration, its abundance relative to hydrogen, the hydrogen to electron number density in a fully ionized plasma, and finally the transition probability. which is a function of temperature, electron density, abundance and oscillator strength following the fundamental rules of atomic physics. Other than for an allowed line, where the decay of the upper level is purely radiative, for forbidden transitions electron collisional de-excitation competes with radiative decay thus providing a tool to measure the electron density of the emitting plasma. We have used the Chianti code (Dere et al. 1997) to calculate plume densities from 8 line pairs and found coronal values between 8.3 for hotter species and 9.5 for cooler species. A similar result has been reported by Brosius & Landi (2005).

Table 2. Density diagnostic measurements using selected line pairs.

line pair			species	ratio	log N_e / cm^{-3}
895.15	/	887.27	Ne VII	>1000	>9
693.98	/	706.06	Mg IX	11	8.3
999.29	/	1005.84	Ne VI	1.6	9-10
872.12	/	880.33	Mg VIII	1.8	8-9
772.26	/	782.36	Mg VIII	1.8	9.3
1445.76	/	1440.49	Si VIII	10	>8
759.44	/	761.13	O V	8	9.6
922.52	/	923.60	N IV	1.9	9.5

4. SUNSPOT OSCILLATIONS

The 3-minute oscillation in transition region emission is obvious and has been reported in literature by many authors. Comprehensive work was done by the Oslo group. In Fig.3 we show an *x-t* plot for the intensities and an *v-t* plot for LOS velocities, observed in the transition region emission of O V (Brynildsen et al. 1999).

Brynildsen used a half-period difference technique $\{\, x(t) - x(t - T/2) \,\}$ to enhance the amplitudes. The spatial and temporal coherence is remarkable. From the spatial coherence it is clear that the sunspot is oscillating as a whole. The temporal coherence seems to be at least half an hour. Recent work of the Oslo group has shown that oscillations seen in intensity and in Doppler velocity have a phase shift of almost 180° (Brynildsen et al. 2000). It

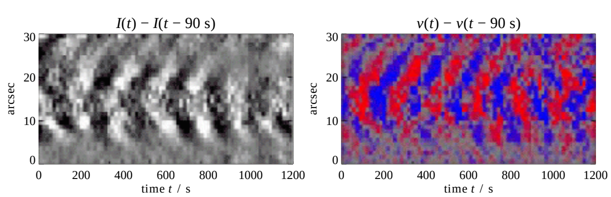

Figure 3. Coherent oscillation of a sunspot plume during a time series of 20 min seen in O V *spectral radiance and in Doppler shift (Maltby et al. 1999).*

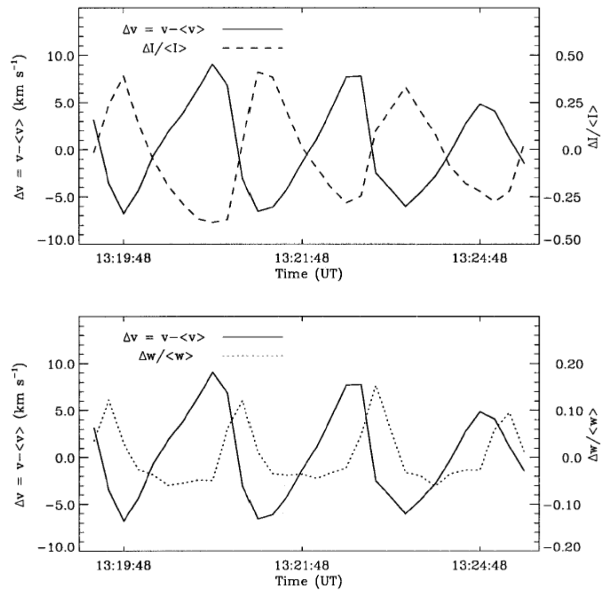

Figure 4. Observed O V *sunspot oscillations in NOAA 8378. Top: line-of-sight velocity variation and relative peak line intensity. Bottom: line-of-sight velocity variation and relative line width (Brynildsen et al. 2000).*

seems that the oscillations are not strictly sinusoidal, but have a triangular to saw tooth likeness (cf., Fig.4). The authors found that the oscillation is not restricted to the sunspot plume, but that actually the whole umbra is affected. They also found phase differences between oscillations seen in lines at different temperatures and there conclusion is, that this observation is compatible with the concept of upward propagating acoustic waves.

5. SYNOPSIS

The synopsis of the results presented here fits to an empirical model as illustrated by the cartoon shown in Fig.4, which can explain all observed features. The transition region, which in the normal quiet Sun is only a thin layer separating chromosphere and corona extends into the sunspot plume and beyond. The chromosphere and transition region is oscillating more-or-less coherently with a 3-minute-period. Like many other authors we assume that this oscillation is driven from below. Above the cooler bottom of the atmosphere a spot of high emission plasma is located; this is the termination point of a relatively cool loop supplying inflowing plasma.

This plume is at transition region temperatures and has a low density. Despite its low density and temperature it is strongly emitting. The reason for this is not clear. It may be related to the inflow and just mark the termination point, where the inflow hits denser material. It could also be related to the oscillations and the damping of upward propagating waves, or it may be a mixture of both. But there can also be a totally different explanation, namely a

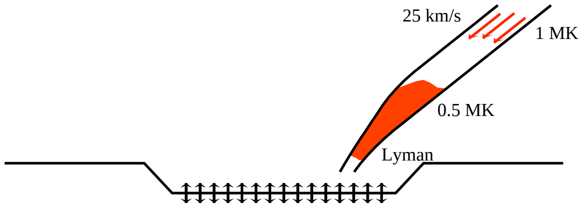

Figure 5. Cartoon showing a quasi-open loop system sticking out of the oscillating sunspot umbra. Over the cold bottom of the atmosphere a spot of high emission plasma is located - the termination point of a cooler loop supplying inflowing plasma, which is finally condensing and hitting denser material.

non-collisional excitation process, which - in some way related to the magnetic field - may also be associated with the observation of the peculiar lines mentioned in section 2.2. We are fully aware that such an explanation could compromise the density diagnostic results presented in section 3.

Interestingly, the percentage of sunspots which carry a plume varies with the solar cycle and seems to peak around solar minimum, an effect which is also not yet understood. As a curiosity, a similar behaviour is well known from polar plumes. Future work both observational and theoretical may give an answer, whether this is related to the quasi-open magnetic field configuration or whether this is pure coincidence. As a first step we will make an effort to identify or at least to understand the physics of those peculiar lines.

ACKNOWLEDGMENTS

This work has benefited from collaboration with the Oslo group. We thank in particular N. Brynildsen, who helped with some of the figures in this communication. The SUMER project is financially supported by DLR, CNES, NASA and the ESA PRODEX Programme (Swiss contribution). SUMER is part of SOHO, the Solar and Heliospheric Observatory, of ESA and NASA.

REFERENCES

[Allison & Dalgarno 1970] Allison, A.C., Dalgarno, A. 1970, Atomic Data 1, 289

[Bartoe et al. 1979] Bartoe, J.-D., F., Brueckner, G.E., Nicolas, K.R. et al. 1979, MNRAS 187, 463

[Brosius & Landi 2005] Brosius, J. & Landi, E. 2005, ApJ 632, 1196

[Brynildsen et al. 1999] Brynildsen, N., Leifsen, T., Kjeldseth-Moe, O., Maltby, P., & Wilhelm, K. 1999, ApJ 511, L121

[Brynildsen et al. 2000] Brynildsen, N., Maltby, P., Leifsen, T., Kjeldseth-Moe, O., & Wilhelm, K. 2000, Sol. Phys. 191, 129

[Curdt et al. 1999] Curdt, W., Brekke, P., Schühle, U., Wilhelm, K., & Dwivedi, B.N. 1999, in J.-C. Vial and B. Kaldeich-Schürmann, ed., *Proc. SOHO 8*, ESA SP-446, 251

[Curdt et al. 2000] Curdt, W., Dwivedi, B.N., & Feldman, U. 2000, J. Astrophys. Astr. 21 (3&4), 397

[Curdt et al. 2001] Curdt, W., Brekke, P., Feldman, U. et al., 2001, A&A 375, 591

[Curdt et al. 2004] Curdt, W., Landi, E., & Feldman, U. 2004, A&A 427, 1045

[Curdt & Landi 2006] Curdt, W. & Landi, E. 2006, in O. Selam ed., *Proc. Solar and Stellar Physics through Eclipes, Side*, ASP, in press

[Dere et al. 1997] Dere, K.P., Landi, E., Mason, H.E., Monsignori Fossi, B.C., & Young, P.R. 1997, A&AS 125, 149

[Foukal et al. 1974] Foukal, P.V., Huber, M.C.E., Noyes, R.W. et al. 1974, ApJ. 193, L143

[Harrison et al. 1995] Harrison, R.A., Sawyer, E.C., Carter, M.K. et al. 1995, Sol. Phys. 162, 233

[Maltby et al. 1999] Maltby, P., Brynildsen, N., Fredvik, T., Kjeldseth-Moe, O., & Wilhelm, K. 1999, Sol. Phys. 190, 437

[Schühle et al. 1999] Schühle, U., Brown, C.M., Curdt, W., & Feldman, U. 1999, in J.-C. Vial and B. Kaldeich-Schürmann, ed., *Proc. SOHO 8* ESA SP-446, 617

[Wilhelm et al. 1995] Wilhelm, K., Curdt, W., Marsch, E. et al. 1995, Sol. Phys. 162, 189