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The EUV Spectrum of Sunspot Plumes Observed by SUMER on SOHO

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Abstract. We present results from sunspot observations obtained by SUMER on SOHO. In sunspot plumes the EUV spectrum differs from the quiet Sun; continua are observed with different slopes and intensities; emission lines from molecular hydrogen and many unidentified species indicate unique plasma conditions above sunspots. Sunspot plumes are sites of systematic downflow. We also discuss the properties of sunspot oscillations.

*Key words***.** Sun: EUV spectroscopy—sunspot—oscillation.

1. Introduction

According to Foukal (1974), sunspot plumes (SP) are regions with bright emission in transition region lines, I, with $I \geq 5\ \bar{I}$, which have an extent of a significant part of the white light sunspot. 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 not yet understood. We will present a brief account of recent findings of spectroscopic features seen in SP and also on sunspot oscillations. In contrast to earlier, moderately resolved observations (e.g., Noyes *et al.* 1985), we have a selection of SP EUV spectra with unprecedented spectral resolution. We report on spectral features as continua and emission lines, including molecular emission, and present plasma diagnostic results using line pairs in our spectral range. The systematic downflow observed in SP and the coherent oscillation seen in the sunspot umbra may both be associated with the observation of more than 100 peculiar lines, which are not observed anywhere else on the Sun.

2. The instrument and data acquisition

The Solar Ultraviolet Measurements of Emitted Radiation (SUMER) is a high-resolution telescope and spectrometer on board SOHO (Solar and Heliospheric Observatory). SOHO orbits around the first Lagrange point, *L*1, in continuous view of the Sun. The spectrometer disperses stigmatic images of the slit covering the wave length range from 660 Å to 1610 Å in first order. Second order lines are superimposed on the first order spectrum. The angular scale of a pixel is ≈ 1 arcsec. Doppler flows down to 1–2 km s^{-1} can be detected with centroiding techniques. The instrument has been described in detail by Wilhelm *et al.* (1997).

Until now more than 30 sunspots have been observed. This includes studies with high temporal resolution in selected emission lines as well as spectral scans which cover the full spectral range of the instrument

2.1 *Observation of continua and emission lines*

From a spectral scan, obtained at a sunspot area on 1999 March 18th, we have separated the plume profile for comparison to an average quiet-Sun spectrum (Curdt *et al.* 1999). This shows that the thermal continuum around 1400 Å is depressed by a factor of ≈ 10, compatible with a temperature drop of 600 K at the bottom of the atmosphere. It is also seen that the Lyman continuum of the SP has a steeper slope and is enhanced by almost a factor of two near the Lyman limit (cf. Fig. 1). The plasma is optically thin for Lyman lines, thereby suggestive of low-density in the emitting source.

The emission peaks in lines with a formation temperature of $10^{5.5}$ K and there is no emission from lines hotter than 10^6 K, an observational fact in support of results of Maltby *et al.* (2000). Within our spectral.range we found >100 peculiar lines, which are not present in quiet-Sun spectra and are also not observed in the corona. Some of them are seen in streamer spectra and half of them remain unidentified. They seem to belong to the 3- to 6-fold ionized species, and their emission requires plasma conditions not found anywhere else on the Sun.

Eight lines of the H_2 Werner bands fall into the SUMER spectral range. They are excited by resonance fluorescence through the strong O vi 1032 line (Schühle *et al.* 1999). H_2 emission is found everywhere in the sunspot umbra, but not outside.

2.2 *Spectroscopic diagnostics and sunspot oscillations*

Systematic studies of Maltby *et al.* (2000) have shown that SP always have down-flows of up to 25kms^{-1}; sunspots with no SP can also have upflows; redshifted features often terminate in the plume area; the plume contours appear displaced in lines formed at different temperatures.

Within the SUMER spectral range we have many line pairs which can be used for density diagnostics. In Table 1 we list measurements from 8 selected line pairs observed in SP, using the atomic calculations of Laming *et al.* (1997). The results are consistent and yield densities between 8.3 and 9.5, again an indication for low-density plasma compared to typical active region values.

Many authors have reported of periodic phenomena seen in sunspots. Recently, Maltby *et al.* (2000) and Brynildsen *et al.* (1999) found a coherent 3-minute oscillation in O v observations, affecting the whole umbra (cf. figure 3 in Brynildsen *et al.* 2000). They have shown that the oscillations seen in both intensity and in Doppler velocity have a phase shift of almost 180°. They also found phase differences between oscillations seen in lines of different temperatures and conclude, that this observation is compatible with the concept of upward propagating acoustic waves.

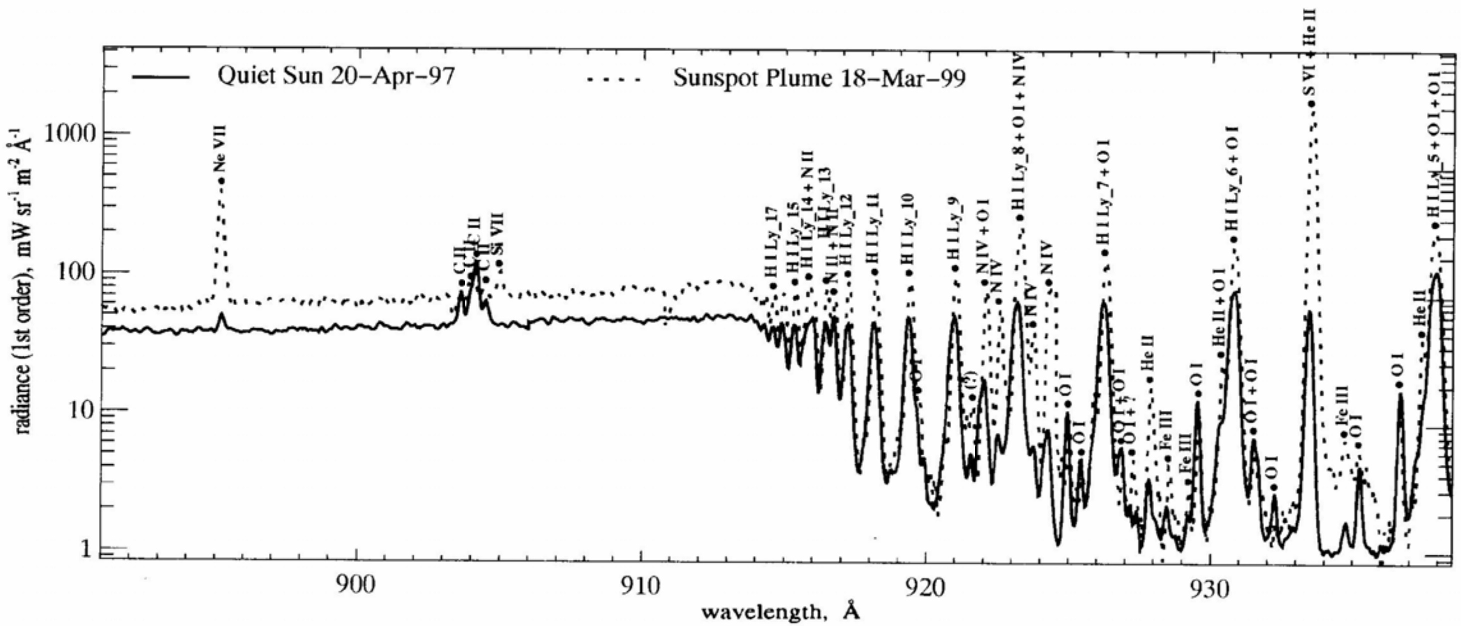

Figure 1. The average quiet-Sun spectrum around the Lyman limit (solid, lower curve) compared to the spectrum of a SP (dotted, upper curve).

Table 1. Density diagnostic measurement 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

3. Discussion

We suggest that the observations might all be related and fit into an interpretation model as shown in Fig. 2. We have demonstrated that the plasma seen in SP has low density. On the other hand, it is surprisingly cold, $10^{5.5}$ K to 10^6 K. Therefore we believe that the high emission measure is not compatible with thermal equilibrium. The non-collisional excitation process could be related to continuous inflow under high magnetic field conditions, finally hitting denser material – irrespective of whether this is proper bulk flow or not. Another source could be the damping of acoustic waves propagating upward from the oscillating surface.

4. Conclusion and Acknowledgements

Sunspots – subject to variations with the solar cycle – are possibly anchored deep in the solar interior. In conclusion, our effort has been to understand their transition into the solar atmosphere with spectroscopic techniques.

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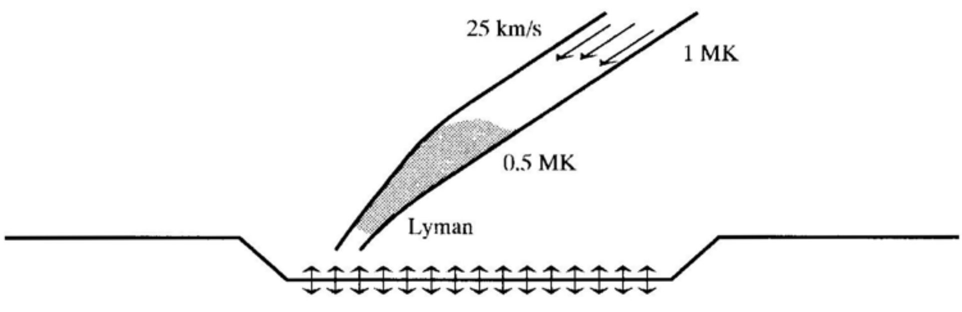

Figure 2. Cartoon showing an open loop sticking out of the oscillating sunspot umbra. Over the cold bottom of the atmosphere a spot of high emission plasma is located—the termination point of a colder loop supplying inflowing plasma, which is finally condensing and hitting denser material.

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