O VI and H\textsubscript{2} Lines in Sunspots

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Abstract. Sunspots are locations on the Sun where unique atmospheric conditions prevail. In particular, the very low temperatures found above sunspots allow the emission of H\textsubscript{2} lines. In this study we are interested in the radiation emitted by sunspots in the O VI lines at 1031.96 Å and 1037.60 Å. We use SOHO/SUMER observations of a sunspot performed in March 1999 and investigate the interaction between the O VI lines and a H\textsubscript{2} line at 1031.87 Å found in the Werner band. The unique features of sunspots atmospheres may very well have important implications regarding the illumination of coronal O\textsuperscript{+5} ions in the low corona, affecting our interpretation of Doppler dimming diagnostics.

1. Introduction

The O VI lines at 1031.96 Å and 1037.60 Å are far more intense in sunspots than in the Quiet Sun (Foukal et al. 1974; Curdt et al. 2001). The contribution of sunspots to the total integrated disk spectrum seen by O\textsuperscript{+5} ions in the corona is therefore non negligible. This has important consequences on the interpretation of observed O VI lines in the corona (Morgan & Habbal 2005). Our goal is to understand the formation mechanisms of these lines in sunspots. We present an analysis of SUMER observations of a sunspot from March 18, 1999. We discuss the interaction between the O VI lines and the emission line of molecular hydrogen H\textsubscript{2} at 1031.87 Å.

2. Observations

We use the reference spectrum obtained by the SUMER spectrometer onboard the SOHO spacecraft on March 18, 1999 (Schühle et al. 1999). These observations were made with the detector B and lasted for 7 hours. The spectrometer slit (0.3″ × 120″) was kept at a fixed position centered on the sunspot (Fig. 1 left) and compensation for the solar rotation was turned on. From the MDI continuum intensity we estimate the location of the sunspot umbra to be between 364″ and 382″ on the SUMER slit (Fig. 1 right). The surrounding penumbra is between 344″ and 364″, and between 382″ and 392″. The upper and lower parts of the slit are on the quiet sun. These features will now be denoted U, P, and QS, respectively.

The two panels of Fig. 2 show how the intensities of the O VI lines are affected by the different physical conditions in the quiet sun, in the penumbra,
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Figure 1.  Left: MDI image of sunspot with SUMER slit.  Right: MDI continuum intensity along SUMER slit.

Figure 2.  Left: Integrated intensity of O VI $1032\,\text{Å}$ (+) and $1038\,\text{Å}$ (*) lines.  The line intensities are enhanced in the sunspot region compared to the quiet sun, particularly in the penumbra/umbra interface.  Right: Intensity ratio of O VI lines along SUMER slit.

and in the umbra.  The integrated intensities have been determined by a simple integration over the line profiles.  The intensity profile of the O VI lines is similar to what has been observed by, e.g., Foukal et al. (1974).

An interesting and important feature is that the ratio between the two lines significantly deviates from its average value.  While it is around 2 on QS, it reaches values greater than 8 in the southern umbra/penumbra interface.  This implies that the coronal O$^{5+}$ ions, which are sensitive to the disk radiation, are illuminated by a radiation field which may very well be different from the averaged one (QS) that is usually assumed.  Doppler dimming diagnostic techniques using the O VI doublet line ratios, are sensitive to the value of the ratio on the disk.  Adopting a value of 2 for the line ratio and a homogeneous disk could lead to spurious results of ion speeds in the corona considering the impact that sunspots can have on the disk radiation field.  This is due to the presence of H$_2$ emission at $1031.87\,\text{Å}$ (Bartoe et al. 1979) in the 1–1 Werner band.  This molecular line is excited by resonance fluorescence from the O VI line.
3. Line Formation

The two panels in Fig. 3 present the integrated intensities and intensity ratio of the two NV lines at 1239 and 1243 Å from the same data set as O VI. The NV and O VI doublets are in the lithium-like sequence. The NV doublet is very similar to O VI (same collisional excitation coefficient ratio and similar temperature of formation), so the NV 1239/1243 intensity ratio should be close to 2 at all temperatures, even across the sunspot. This proves the special case of O VI due to its interaction with the H\textsubscript{2} lines in the Q3 band.

Furthermore, the SUMER data shows that the C II lines at 1036.3 and 1037 Å are fainter in the sunspot region. This is expected as the lines of first ions are reduced in intensity over sunspots (Bartoe et al. 1979). This may in turn have implications for the pumping of the coronal O VI 1037 Å line at speeds above \( \sim 100 \) km/s.

Figure 4 helps us to quantify the amount of H\textsubscript{2} molecular emission present in the SUMER sunspot observations by assuming that the integrated intensity at 1032 Å is normally the double of the intensity at 1038 Å. This figure also presents the normalized intensity profiles of four H\textsubscript{2} Werner band lines across the sunspot. These lines are not blended with other UV lines, therefore they predict what the 1031.87 Å 1–1 line would look like in the absence of interaction with O VI. The relative intensity of all these lines agree closely with the calculated emission transition probabilities (see Schühle et al. 1999). We can see that H\textsubscript{2} and O\textsuperscript{5+} interaction is significant in the sunspot area only.

4. Conclusion

The sunspot’s molecular H\textsubscript{2} line interacting with the O VI lines is one of many in the H\textsubscript{2} Werner band. Theory gives relative intensities for each line, and this theory has been tested by Schühle et al. (1999) on the SUMER sunspot data. This means that we can know very closely the H\textsubscript{2} emission in the 1–1 band at 1031.87 Å, which is the one that pumps the O VI 1031.9 Å, just by looking at a clean line (e.g., the 1–3 band at 1119 Å) and multiplying by the theoretical intensity ratio between the two given in Bartoe et al. (1979).
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Figure 4. Normalized intensity profiles of four unblended H$_2$ Werner band lines across the sunspot. The solid line shows the difference I(O VI 1032)-2×I(O VI 1038). The enhancement of intensity at the sides of the sunspot is interesting, and is possible evidence of ambipolar diffusion of H$_2$ from the umbra, that is, H$_2$ and other neutrals can diffuse across the near-vertical magnetic field of the sunspot umbra (Kuhn & Morgan 2006).

In a future work we will model a slab of oxygen ions in the transition region above a sunspot and calculate the 1032 and 1038 line intensities emitted by the slab purely by collisions. Then, using a radiative transfer code, we will add the H$_2$ line intensity at the bottom of the slab, and study the pumping of O VI 1032 Å that ensues.

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