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Letter to the Editor

Plumes and oscillations in the sunspot transition region

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Abstract. The suggestion that sunspot transition region oscillations are a typical feature of the sunspot plumes is examined. The present observations show 3 min oscillations in the umbra that end at the umbral rim. We find that sunspot plumes located above the umbra show these oscillations, in contrast to plumes above the penumbra. These two findings suggest that the oscillations may be a property of the umbral transition region.

Key words. Sun: oscillations – Sun: transition region – EUV radiation – sunspots

1. Introduction

The detection of umbral flashes in the sunspot chromosphere (Beckers & Tallant 1969) promised to reveal crucial information about the physics of sunspots and initiated a series of investigations on oscillations, see reviews by Lites (1992) and Spadaro (1999). The oscillatory power shows a dominant peak in the 3 min band from the cold regions where the CO vibration-rotation band transition at 4.66 μm originates (Livingston et al. 1998), through the sunspot chromosphere (e.g., Lites 1986) and into the transition region between the chromosphere and the corona (Gurman et al. 1982). In this paper the focus is on the 3 min oscillations in the sunspot transition region.

The Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) and the Transition Region And Coronal Explorer (TRACE; Handy et al. 1999) have given fresh life to investigations of oscillations in sunspots and active regions. Consider briefly the waves observed in active regions. Berghmans & Clette (1999) have detected intensity perturbations, propagating upwards along coronal loops. The perturbations are probably caused by slow magneto-acoustic waves (e.g., Nakariakov et al. 2000). Shine (2000) has found that prominent intensity oscillations occur wherever the loops overlay sunspots. Thompson et al. (1999) has revived the interest for "Morton waves". These waves propagate predominantly radially away from the flare site and are probably fast magneto-acoustic waves (Uchida 1968).

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Extensive observing programmes with the Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995) by Fludra (1999, 2001) and the Solar Ultraviolet Measurements of Emitted Radiation (SUMER; Wilhelm et al. 1995) by Brynildsen et al. (2000) and Maltby et al. (1999), have given new information about the 3 min transition region oscillations above sunspots. On most items, such as the wave period, the different investigations gave similar results. Brynildsen et al. (1999a) have compared the observations with the predictions of acoustic wave theory and found the observations to be compatible with upward-propagating acoustic waves, as proposed by Gurman et al. (1982). The waves are linear in some sunspots, but show a non-linear character in others.

However, Fludra (1999) and Brynildsen et al. (2000) presented different conclusions regarding the connection between enhanced EUV line emission above sunspots, called sunspot plumes, and the 3 min oscillations. Recall that "A sunspot plume is observed if the contours for peak line intensity $I \geq 5\overline{I}$ are located with a considerable fraction of the emission inside the white light sunspot." (Brynildsen et al. 1999b). Here $\overline{I}$ denotes the average peak line intensity in the observed area, $120'' \times 120''$. Fludra (1999) found oscillations in transition region lines in a sunspot plume and suggested that these oscillations could be present in other sunspot plumes. This suggestion was questioned by Brynildsen et al. (2000), who found the largest oscillation amplitudes above the central part of the umbra. Recently, Fludra (2001) presented further examples of oscillations in sunspot plumes in three more active regions, and also found oscillations outside plumes. He concluded that a likely

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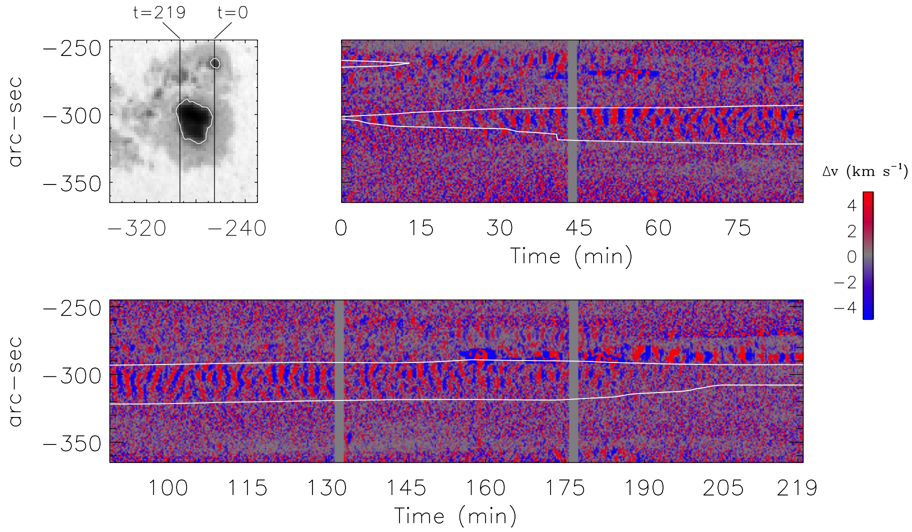

Fig. 1. Observed O v $\lambda629$ oscillations in relative line-of-sight velocity, $\Delta v = v - \overline{v}$. Motion towards (away from) the observer is shown in blue (red). The umbral rims are marked with white colour. The slit positions at the start ($t = 0$) and end ($t = 219$) of the SUMER observations are marked on the Michelson Doppler Imager (MDI; Scherrer et al. 1995) sunspot image of NOAA 8996, oriented with north up and west to the right. The scales in arc-sec are in a reference system where the origin coincides with the centre of the solar disk.

interpretation is that oscillations occur both in the sunspot plumes and in the lower intensity plasma adjacent to the plumes. Below we present observations of three sunspots, increasing our SUMER oscillation data set to nine sunspots. We acknowledge that oscillations occur in sunspot plumes as observed by Fludra (1999), but emphasize that we also observe sunspot plumes without oscillations. The observed locations of the oscillations lead us to the hypothesis that they are a property of the umbral transition region. If the hypothesis is correct, sunspot plumes located above the umbra should show oscillations, whereas plumes located above the penumbra should not show oscillations.

2. Observations

Our ongoing investigation of the sunspot atmosphere is based on two joint observing programmes with participation of several SOHO instruments and TRACE. In this paper the focus is on SUMER observations of NOAA 8989, 8996, and 8998, obtained on 9 May 2000, 05:30–11:12 UT, 16 May 2000, 12:46–16:27 UT, and 17 May 2000, 19:16–22:57 UT, respectively. The SUMER spectra are obtained with an exposure time of 15 s while the solar rotation moves the image of the sunspot over the $0.3'' \times 120''$ slit (positioned $290''$ east of the solar disk centre). From consecutive exposures with detector A, we extract spatial and spectral windows equal to $120'' \times 2.2$ (1.1) Å in the first (second) order of the grating. The spectral windows are centred on the transition region lines N v $\lambda\lambda$ 1238, 1242 in the first order and O v $\lambda629$ in the second order of the grating. The latter spectral window includes the chromospheric Si II $\lambda1260$ line. The N v $\lambda1238$ line is positioned on the bare part of the detector, whereas the other lines are positioned on the KBr part.

After each series of 160 or 171 spectra, corresponding to 2 400 s or 2 565 s, the observations are interrupted for ≈97 s to obtain the slit locations with respect to the sunspot by the rear slit camera. The wavelength scale is derived from the wavelength positions of numerous chromospheric C I lines, observed with the full detector width, $120'' \times 45$ (23) Å in a 100 s exposure. The data reductions include corrections for the fixed pattern noise, defects of the detector and corrections for the geometrical distortions (Wilhelm et al. 1995; Dammasch et al. 1999). The precision in the relative line-of-sight velocity determination is estimated to be 1 km s^{-1} for O v $\lambda629$, 2 km s^{-1} for N v $\lambda1242$ and 3 km s^{-1} for Si II $\lambda1260$.

3. Results

Figure 1 shows the O v $\lambda629$ relative line-of-sight velocity, $\Delta v = v - \overline{v}$, observed while the sunspot image of NOAA 8996 moved across the slit. Evidently, sunspot oscillations are present above the large umbra. Note the abrupt decrease in the oscillation amplitude at the umbral rim. An area with dominating frequencies close to 6 mHz and 9 mHz is located between 20 and 55 min at $-270''$. We cannot claim detection of penumbral oscillations since a small umbra is present in the area. At first sight the variations close to the northern rim of the umbra between 160 and 219 min may appear quasi-periodic. However, the power spectra show that the variations are irregular and caused by activity, a topic outside the scope of this paper. The N v $\lambda1242$ observations give a similar plot.

For the three sunspots observed in May 2000, Fig. 2 shows the spatial distributions of the O v $\lambda629$ peak line intensity, I, and the line-of-sight velocity, v. The sunspot plumes are marked with yellow contours. Also shown are

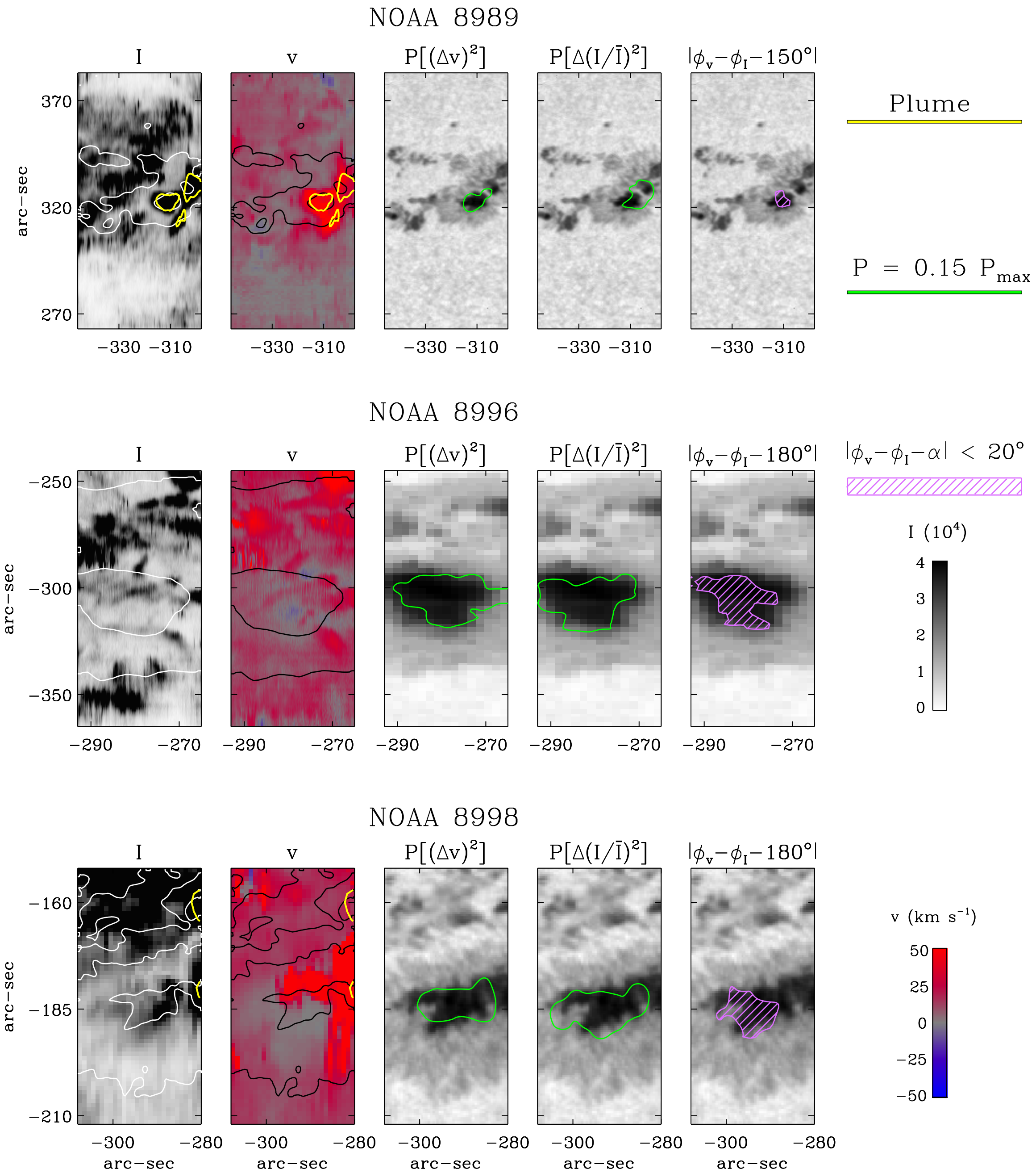

Fig. 2. Left to right: spatial distributions of the O V λ629 peak line intensities, followed by the time-averaged line-of-sight velocity, the oscillation power , $P[(\Delta v)^2]$, in relative line-of-sight velocity, the oscillation power, $P[(\Delta I/\overline{I})^2]$, in relative peak line intensity, and the phase difference $|\phi_v - \phi_I - \alpha|$, where $\alpha = 150°$ or $180°$. The sunspot plumes are marked with yellow contours. To ease the comparison the oscillation results are overlaid white-light images from TRACE, MDI, and TRACE, respectively. The white and black contours in the two leftmost frames outline the umbra and penumbra boundaries of the white-light images. Note that the scales differ from one sunspot to another.

the oscillation powers in relative line-of-sight velocity and relative peak line intensity within the frequency range 5–8 mHz. The phase difference between velocity and intensity is measured by the quantity $|\phi_v - \phi_I - \alpha|$, where $\alpha = 150°$ or $180°$.

Consider first the results for NOAA 8996 (Fig. 2, *middle*). Plumes are absent in this sunspot. Most of the oscillation powers, $P[(\Delta v)^2]$, and $P[(\Delta I/\overline{I})^2]$, in relative line-of-sight velocity and relative peak line intensity are located within the contour $P = 0.15\ P_{\rm max}$. We find that this contour is located close to the rim of the umbra. In the umbra the phase difference $|\phi_v - \phi_I - 180°| < 20°$. Hence, the transition region oscillations occur exclusively above the umbra in NOAA 8996.

The observations of NOAA 8998 cover only part of two plumes, but show that the plumes are not centred above the umbra. Also in this case the contour $P = 0.15\ P_{\rm max}$ and the phase difference $|\phi_v - \phi_I - 180°| < 20°$ are located

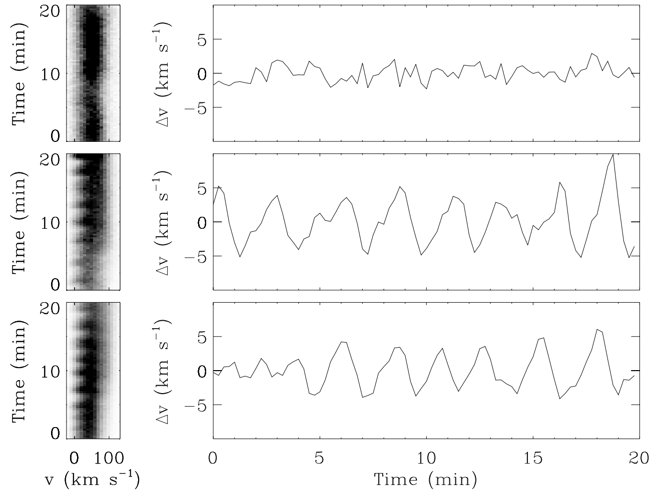

Fig. 3. O v λ629 temporal variations in NOAA 8989 in the plume above the penumbra (*top*), the plume above the largest umbra (*middle*), and the plume above the western umbra (*bottom*). The variations in relative line-of-sight velocity, Δv, are shown (*right*).

close to the umbral rim. Thus, also for NOAA 8998 the oscillations occur above the umbra.

The sunspot in NOAA 8989 again shows oscillations above the umbrae, see Fig. 2 (*top*). This sunspot has three sunspot plumes, one above the penumbra and two located above the umbrae. Figure 3 gives the O v λ629 temporal variations in the sunspot plumes above the penumbra and the two umbrae. Interestingly, the plume above the penumbra shows no oscillations, whereas the plumes above the umbrae show oscillations in relative line-of-sight velocity. The corresponding oscillations in relative peak line intensity occur with the maxima nearly coinciding with the maxima in velocity directed towards the observer. Observations in the N v λ1242 line give similar results.

The power spectra of the oscillations in NOAA 8989 and 8996 show a dominant peak at or close to 6.7 mHz, corresponding to a period of 150 s. In NOAA 8998 the corresponding period is 130 s. These periods are within the interval 120–200 s derived by Fludra (2001). The observed phase differences of 180° in NOAA 8996 and 8998 and 150° in NOAA 8989 imply that the maxima in peak line intensity coincide with or occur close to the maxima in velocity directed towards the observer. Since the sunspots are located relatively close to the centre of the solar disk, this agrees with the interpretation of the oscillations as upward-propagating acoustic waves.

In NOAA 8996 the recordings of the Si ii λ1260 line allow a detailed comparison with the O v λ629 observations. We find that the lines have the same dominating period and high coherence in velocity and intensity. The O v λ629 oscillations occur with a time delay of several seconds after the Si ii λ1260 oscillations. Similar results were obtained for the NOAA 8378 region by Brynildsen et al. (2000).

4. Concluding remarks

Combining the results presented above with the results for six previously studied sunspots, we find (1) three sunspots (NOAA 8151, 8156, and 8989) without oscillations in the plumes located above the penumbra, (2) four sunspots (NOAA 8378, 8470, 8487, and 8989) with oscillations in the plumes located above the umbra, and (3) each of the nine sunspots show oscillations above the umbra. Hence, sunspot plumes located above the umbra show oscillations, whereas plumes above the penumbra are without oscillations. We have not detected the transition region counterpart of the chromospheric penumbral waves and suggest that the oscillations presented above are a property of the umbral transition region.

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