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LETTER

Letter to the Editor

Intensity oscillations in a sunspot plume

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Abstract. Observations of a sunspot plume (a compact feature, bright in the transition region line of O V 629.7 Å at 2.2×10^5 K), seen above a sunspot in the active region AR8249, have been made with a 15-second time resolution with the Coronal Diagnostic Spectrometer on SOHO. Intensity of the O V 629.7 Å line in the sunspot plume oscillates with an amplitude of up to ten percent and periods of 167 and 182 seconds. The same oscillations are also seen in the Ne IV 543.9 Å, Ne V 572.4 Å and Ne VI 562.8 Å lines ($1.7 - 4 \times 10^5$ K) but with a lower signal-to-noise ratio. Inspection of data for several other sunspots shows that all sunspot plumes show the intensity oscillations of the O V 629.7 Å line and other transition region lines in the $1.7–4 \times 10^5$ K temperature range.

Key words: Sun: oscillations – Sun: sunspots – Sun: transition region – Sun: UV radiation

1. Introduction

The Solar and Heliospheric Observatory (SOHO) has been providing new results on the dynamical nature of the solar transition region and corona. In particular, a topic that attracts a lot of interest is a search for a dynamical behaviour of magnetic loops in active regions. Characteristic features of active regions with sunspots are so-called 'sunspot plumes' - compact sources which appear very bright in the transition region lines emitted between $1.8–4 \times 10^5$ K, in particular, in the O V 629.7 Å line at 2.2×10^5 K, and are located above or very near to sunspots. They were first seen in Skylab data by Foukal et al. (1974) and Foukal (1976). SOHO observations of the sunspot plumes made by the Coronal Diagnostic Spectrometer were discussed by Fludra et al. (1997), and their properties further studied by Maltby et al. (1998) and Brynildsen et al. (1999b). Those observations were made on time-scales from 10 minutes to several days. Fludra et al. (1997) demonstrate that the bright sunspot plumes can be long-lived features, persisting for several days, with one case suggesting a lifetime of at least one month. Very few observations of plumes with higher time resolution exist. Fludra et al. (1997) showed examples of variability of bright transition region features in an active region on timescales of a few minutes. In this paper we present the first high cadence observations of a sunspot plume made with the CDS with 15-second time resolution and a 4-arcsecond spatial resolution. We report the finding of the intensity oscillations seen in the transition region line of O V 629.7 Å, emitted at temperatures around 2.2×10^6 K and Ne IV-VI lines at $1.7–4 \times 10^5$ K. We apply the Fourier transform and find the oscillation periods of 167 and 182 seconds. From inspection of data for five other sunspots we conclude that the intensity oscillation of transition region lines are always present in sunspot plumes. Sect. 2 describes the observational data, Sect. 3 describes the analysis and results, and the discussion is given in Sect. 4.

2. Data

The SOHO Coronal Diagnostic Spectrometer (CDS; Harrison et al. 1995) is a dual spectrometer and consists of a Wolter-Schwarzschild type II grazing incidence telescope focused at the common entrance slit of a pair of spectrometers via a scan mirror. The data discussed in this paper were recorded by the Normal Incidence spectrometer using a 2×240 arcsec slit to produce a rastered image and a 4×240 arcsec slit for high-cadence observations. The observations were taken by selecting the central 71 pixels along the slit, to cover $120''$ (half of the slit length) in the vertical (solar North-South) direction.

The data are processed using a standard CDS calibration software. Cosmic-ray strikes are detected and removed, and the CDS data are corrected for the CCD read-out bias, the flat-field image, detector 'burn-in' due to the repeated exposure of strong lines, and converted from counts/pixel to photon-events/pixel. The following spectral lines were observed (in brackets we give the temperature of the peak emissivity of these lines): Ne IV 543.9 Å (1.7×10^5 K), Ne V 572.4 Å (2.8×10^5 K), Ne VI 562.8 Å (4×10^5 K), O V 629.73 Å (2.2×10^5 K) and Mg IX 368.07 Å (9.8×10^5 K). While the plume was seen in all transition region lines, the O V 629.7 Å line was the most intense and the oscillations were most prominent in this line. Therefore, we discuss mostly the O V 629.7 Å line and briefly mention the neon lines. The total intensity in these lines was calculated by summing the whole line profile and subtracting the background.

A $2' \times 2'$ rastered image was made by the CDS in the O V line using a $2'' \times 240''$ slit on 23 June 1998 between 10:10 and 10:47 UT. Fig. 1 shows a $1' \times 1'$ subfield of the raster centered near a

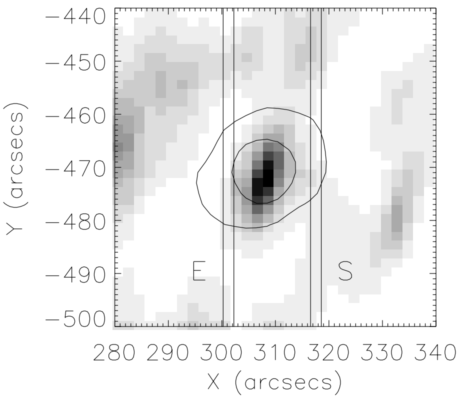

Fig. 1. A rastered image in the O V 629.7 Å line taken in the active region AR8249 on 23 June 1998 between 10:10 UT and 10:47 UT. Only 25% of the raster's area is displayed. The contours show the edge of the sunspot's umbra and penumbra. The vertical lines show the location of the CDS slit at the beginning ('S') and at the end ('E') of the high-cadence observations. The colour table is reversed, i.e., dark areas correspond to greater intensities.

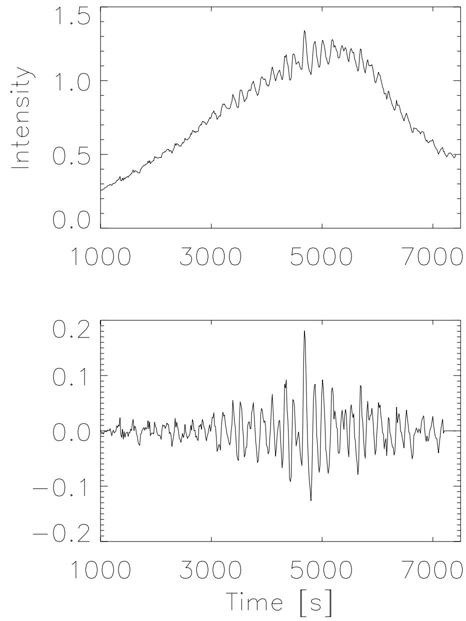

Fig. 2. a *Top panel:* The time history of the O V line intensity (photon-events s^{-1} $\times 10^{-3}$), spatially integrated over four pixels along the slit between $Y = -469''$ and $Y = -475''$ in Fig. 1. **b** *Bottom panel:* The intensity variation from the top panel after subtracting a slowly varying trend.

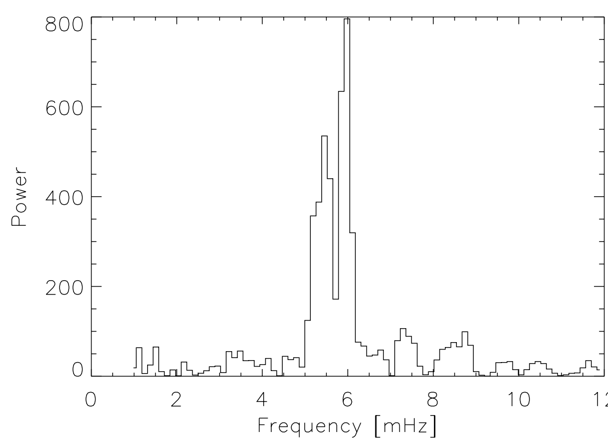

Fig. 3. The Fourier power spectrum of the O V time series from Fig. 2a, obtained with windowing (using a Hamming window). The power is normalised as described in the text.

sunspot. The intense compact source at coordinates $X = 308''$, $Y = -475''$ is a sunspot plume. Its peak intensity is over 10 times greater than the averaged intensity per pixel outside the plume area. The contours show the edge of the sunspot's umbra and penumbra, determined from the white-light observation made by the SOHO/MDI instrument at 12:41:34 UT and rotated back in time to 10:31:51 UT, i.e., to the time when the sunspot plume was observed by the CDS.

Following the raster, high cadence CDS observations on 23 June 1998 were made between 10:47:10 UT and 12:50:53 UT, using a $4'' \times 240''$ slit which was pointed to the right-hand side of the sunspot plume at the pointing of X=318$''$ (the slit location marked 'S' in Fig. 1) and kept in this position for two hours of observations, while the plume moved across the slit with the solar rotation. At the end of the observation the slit was at the location marked 'E'. Only the data from the central 120 arcseconds of the slit were recorded. The duration of each exposure was 10 seconds, and 4.86 seconds elapsed after each exposure before the next exposure was taken. The exposures are therefore taken every 14.86 seconds. The time series has 500 data points and lasts for 7423 seconds.

3. Results

Fig. 2a shows the time history of the O V line intensity at the brightest part of the plume, summed over four spatial pixels between $Y = -469''$ and $Y = -475''$ in Fig. 1. The O V intensity curve has two distinct components: the slowly varying component is due to the spatial distribution of the intensity of the source in the horizontal East-West direction, which appears as time variability when the plume gradually rotates into the field of view of the slit and then moves out of the field of view. The slowly-varying component is modulated by a fast varying component. Since the time in which a feature rotates across the 4 arcseconds width of the CDS slit is 24 minutes, the fast varying component are the intensity oscillations in the source itself. The slowly varying trend has been estimated by calculating a 30-point running average. Fig. 2b shows the signal after subtracting the slowly varying component. It can be seen from comparing Fig. 2a and 2b that the amplitude of the oscillations is 5–10 percent of the intensity, with one outburst close to a 20 percent amplitude.

To determine the power spectrum of the whole time series from Fig. 2a we have used a Fast Fourier Transform. Note that we apply the Fourier analysis to the original time series without subtracting the trend. Fig. 3 shows the power spectrum obtained with windowing, using a Hamming window. The windowing is used to eliminate leakage of power from strong components at very low frequencies, corresponding to the slowly varying trend, to higher frequencies. The lowest frequencies below 1 mHz have not been displayed in Fig. 3 to better show the relevant part of the power spectrum.

The statistical significance of the spectral power is estimated assuming that the incoming photons have a Poisson distribution and following the discussion given by Doyle et al. (1997, 1998). The power spectrum in Fig. 3 is normalized so that a power P_j at a frequency j is $P_j = |a_j|^2 \times 2/N_{\rm phot}$, where $N_{\rm phot}$ is the total number of photons in the series s_k, $k = 1, ..., N$, and a_j are the Fourier components $a_j = \sum s_k e^{2\pi ijk/N}$. Each P_j has a χ^2 distribution with 2 degrees of freedom. Let the probability that an individual power P_j exceeds the detection level $P_{\rm det}$ due to noise be α. When investigating n_t statistically independent powers P_j, the probability that all n_t powers are less than $P_{\rm det}$ is $(1-\alpha)^{n_t}$. Therefore, the probability that at least one or more of the n_t powers exceeds the detection level $P_{\rm det}$ due to noise is $\epsilon = 1 - (1-\alpha)^{n_t} \approx \alpha n_t$. The detection level $P_{\rm det}$ is now defined by the equation:

$$\epsilon/n_t = Q(\chi^2 = P_{\rm det}|2) \quad (1)$$

where $Q(\chi^2|2)$ is the integral probability of the χ^2 distribution with 2 degrees of freedom. The detection level $P_{\rm det} = 2ln(n_t/\epsilon)$ (Doyle et al. 1998). Adopting $\epsilon = 0.001$ for the 99.9% confidence level, and $n_t = N/2$–2 (the zero frequency and the Nyquist frequency are excluded), we have $P_{\rm det} = 24.9$.

It can be seen that the peak of the spectral power in Fig. 3 is over 20 times greater than the 99.9% confidence level. Most of the power is concentrated in the frequency range $5.1 - 6.1$ mHz. The main peak has a frequency of 6.0 mHz which corresponds to a period T of 167 seconds, and the smaller peak has $f =$ 5.5 mHz ($T = 182$ seconds).

The intensity oscillations are also seen in the neon lines, although the neon time series are noisier. The Ne IV 543.9 Å line has the same shape of the power spectrum as the O V line, with the larger peak at 6.0 mHz and the smaller peak at 5.5 mHz. The larger peak is 1.7 times greater than the 99.9% confidence level. The normalised peak of the power spectrum of the Ne V 572.4 Å time series is equal to the 99.9% confidence level. In the power spectrum of the Ne VI 562.8 Å time series the relative strength of the peaks at 5.5 and 6.0 mHz is reversed, with the 5.5 mHz peak stronger than the 6.0 mHz peak. When the Ne VI 562.8 Å series is summed over the same four spatial pixels as the previous lines, the power peak is significantly lower than the confidence level. However, when the summing is made over eight spatial pixels (13″), the signal-to-noise improves and the power peak at 5.5 mHz reaches the 99.9% confidence level. The 6.0 mHz peak is significant only at 90% confidence level.

A Gaussian profile was fitted to the O V line profiles in the time series to search for oscillations in the velocity. The shift in position of the line peak was less than 0.1 of the spectral pixel width (i.e. less than 5 km s^{-1}). Any possible oscillations at this level are below the CDS detection capability and will not be addressed in this paper.

4. Discussion

In this paper we report on the detection of intensity oscillations found in a sunspot plume, based on observations of spectral lines emitted at temperatures 1.7–4×10^5 K made with a high spatial resolution of $4''$. The sunspot plumes are compact features located close to sunspots, very bright when seen in lines emitted at transition region temperatures between 1.7×10^5 and 4×10^5 K (e.g., O V 629.7 and Ne VI 562.8 Å). The sunspot plume location does not emit at coronal temperatures. For example, they are not seen in Mg IX 368 Å images (9.8×10^5 K) (Fludra et al. 1997). The sunspot plumes appear to be contained in one leg of large loops that are rooted in the sunspot, while the other leg extends a large distance away from the sunspot (Brynildsen et al. 1999b; O. Kjeldseth-Moe, private communication). Although the sunspot plume analysed in this paper lies in projection almost exactly over the sunspot's umbra, generally this does not have to be the case and some sunspot plumes overlie the penumbra, sometimes only partially (Fludra et al. 1997, Brynildsen et al. 1999b). Therefore, there is a distinction between sunspot plumes and the observations of the transition region directly above the sunspots (when the sunspot umbra is not obstructed by sunspot plumes). The plumes are distinguished by their high intensity of the transition region lines, and while they are located close to sunspots, their exact orientation relative to the sunspot is variable.

The detected sunspot plume oscillations at temperatures 2.2×10^5 K have a dominant period of 167 seconds, with a significant power also at 182 seconds. This is very close to the period of chromospheric oscillations. Although the relative amplitude of the oscillations is only of the order of 5–10 percent of the measured intensity, with one wavetrain of 20 percent amplitude, the absolute signal is very strong due to the fact that sunspot plumes seen in the spectral line of O V 629.7 Å are the brightest features in the transition region of active regions. Therefore, the oscillations have little noise, in contrast to some oscillations found in the quiet sun observations. The periodicity is readily apparent even from the raw data. The peak power in these oscillations is over 20 times greater than the 99.9% confidence level that would result from statistical noise. Three Ne IV−VI lines that were recorded simultaneously with the O V line show the presence of oscillations in a temperature range 1.7–4.0×10^5 K. We have found evidence that at higher temperatures (4×10^5 K) the power peak at 5.5 mHz becomes dominant over the peak at 6.0 mHz.

From the intensity oscillations alone it is difficult to unambiguously point to a mechanism responsible for these oscillations. Additional observations including velocity measurements are needed to test the velocity-intensity phase relationship. However, below we mention some possibilities based on past observations and interpretations of sunspot oscillations.

Even though the sunspot plume is a feature distinctly different from the sunspot itself, plumes are confined in a strong magnetic field rooted in the sunspot umbra. Therefore, it is possible that the same type of mechanism could be responsible for the oscillations in sunspot umbra and sunspot plumes.

Oscillations in intensity and velocity in sunspot umbrae have been observed in the chromospheric and transition region lines with periods 120–200 seconds (e.g., Gurman et al. 1982; Gurman and Leibacher 1984, and references therein). Gurman et al. (1982) interpret these oscillations as evidence of upwardly propagating acoustic waves in the transition region. This is supported by a recent observation of oscillations in the transition region lines above sunspot umbra and penumbra made by Brynildsen et al. (1999a) which they also identify as upward propagating acoustic waves. The acoustic waves with periods 140–185 seconds could be generated in models of fast-mode magneto-atmospheric waves (Thomas and Scheuer 1982). Alternatively, Gurman and Leibacher (1984) discuss a model of acoustic waves generated by subphotospheric perturbation of the sunspot atmosphere by the global p-modes.

Examining other high-cadence observations of sunspot plumes made with the CDS in five different active regions we find that all sunspot plumes show intensity oscillations in the O V 629.7 Å, Ne VI 562.8 Å and other transition region lines emitted at temperatures between 1.7×10^5 and 4×10^5 K. We therefore infer that the oscillations presented in this letter are a typical feature of the sunspot plumes.

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