A&A 442, 1087–1090 (2005)
DOI: 10.1051/0004-6361:20053714
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Astronomy & Astrophysics

Very long period activity at the base of solar wind streams

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Received 28 June 2005 / Accepted 18 July 2005

ABSTRACT

Using time series data of spectral lines originating from a wide range of temperatures in the solar transition region, above a polar coronal hole, from SUMER (Solar Ultraviolet Measurements of Emitted Radiation) on SoHO (Solar and Heliospheric Observatory), we report on the detection of very long (≈170 min) periodic intensity fluctuations, above the limb. Our data also reveal long periodicities (10–90 min), previously observed with other SoHO instruments. With the acoustic cut-off frequency implying a maximum allowable period of ≈90 min, it is unclear whether these intensity fluctuations are due to waves or are the result of a recurrent magnetic reconnection process.

Key words. Sun: solar wind – Sun: transition region – Sun: corona

1. Introduction

It is known that quasi-periodic fluctuations are present in open coronal structures. The high-cadence EIT/SoHO (171 Å) observations of DeForest & Gurman (1998) represent, probably, the first detection of such MHD waves in polar plumes. These authors noticed bright features propagating outward at ≈75–150 km s^{-1} with periods of 10–15 min. Based on the speed, which is close to the sound speed expected at $T \approx 1 \times 10^6$ K ($c_s = 147$ km s^{-1}), and on the density modulation inferred from the EUV brightness variation, they concluded that the observed fluctuations were compressive slow magneto-acoustic waves propagating along plumes. Banerjee et al. (2000a) investigated the temporal behaviour of polar plumes in the transition region (TR) line O v 629 Å with CDS/SoHO, noting the presence of long period (20–30 min) compressional waves. Banerjee et al. (2001) extended this study to inter-plumes and reported on even longer periodicities (≤70 min) over a wider temperature range. Ofman et al. (1997, 2000) searched for slow-mode compressional MHD waves with the UVCS/SoHO white light channel, further away from the Sun. They reported quasi-periodic variations in the polarization brightness in both plume and inter-plume regions. Significant peaks were found around 1.6–2.5 mHz (6–10 min), with a coherence of ≈30 min. It is likely that the waves detected at 1.9 $R_{\rm Sun}$ by Ofman et al. (1997, 2000) with UVCS and the waves seen by DeForest & Gurman (1998) at 1.2 $R_{\rm Sun}$ with EIT are the same as the ones seen close to the limb by Banerjee et al. (2000a) using CDS.

Teriaca et al. (2003) has presented evidence that the fast solar wind streams come from inter-plume regions. Here, we present the results of a search for the presence of periodicities close to the solar limb, in an inter-plume region, from a time sequence of ≈14 h (probably the longest time series taken in a coronal hole with SUMER). This dataset has a wide temperature coverage of the TR, with lines originating from $\approx 8 \times 10^4$ to 6.3×10^5 K.

2. Data and method of analysis

The time sequence analysed in this Letter was taken in the South polar coronal hole with the SUMER spectrometer (Wilhelm et al. 1997) on 25 February 1997. The SUMER slit was fixed along the polar axis close to the pole. The slit is 1″ wide (the solar-x direction) and 300″ long (on solar-y; North-South). The total time of the observation is 835 min (00:03:10.69–13:58:37.52), with ≈60 s exposure time. In Fig. 1 we plot the SUMER pointing on an EIT image taken about half way through the observing time. SUMER had the rotational compensation switched off. The slit moved ≈47.6″ at its base on the solar disk and ≈7.4″ at its central position $y = -950.25''$ (see horizontal lines in Fig. 1), and as we go towards the limb the movement of the Sun goes to zero. Therefore, in our region of interest – off-limb – the solar rotation is practically absent

Article published by EDP Sciences and available at http://www.edpsciences.org/aa or http://dx.doi.org/10.1051/0004-6361:20053714

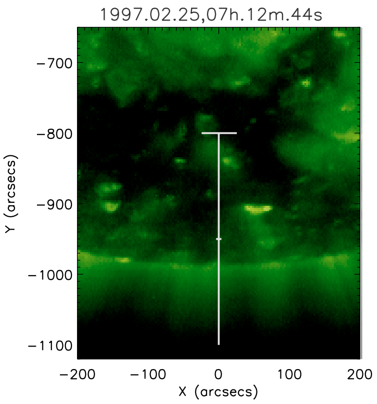

Fig. 1. The coronal hole from the Sun's South pole in the light emitted by Fe XII 195 Å observed with EIT on 25 Feb. 1997. The vertical line represents the fixed position of the SUMER slit, with the horizontal lines showing how much the Sun rotated during the time series observation.

during the observation. The image shows that the slit was positioned within an inter-plume lane, although close to a plume. For details on the data reduction procedures applied, see Xia et al. (2005) who used the same dataset for a morphological study of EUV spicules.

We study the integrated flux variations of four lines: N III 764.36 Å ($\approx 8 \times 10^4$ K); N IV 765.15 Å (1.2×10^5 K); O V 760.42 Å (2.5×10^5 K); Ne VIII 770.41 Å (6.3×10^5 K). Comparing the (background subtracted) flux with the intensity (computed as in Popescu et al. 2004), we find a 2–3% difference, with the flux being higher at maxima values. As regards the Doppler velocity, although at several off-limb locations it shows a clear blue/red structure (e.g. in macrospicules – see Xia et al. 2005), in fainter structures (spicules and especially in between them) the lines are not strong enough to show clear shifts.

We search for periodicities in the flux of the lines at different off-limb locations, averaging over 2″ on solar-y. We produce power spectra using two different tools: the wavelet and the Fourier transform. Details on the wavelet analysis, which provides information on the temporal dependence of a signal, are described in Torrence & Compo (1998)[1]. For the convolution of the time series in the wavelet transform we choose the Morlet function as defined in Torrence & Compo (1998). To determine whether or not the oscillations found are real, we implemented the Linnell Nemec & Nemec (1985) randomization method that estimates the significance level of the main peak in the wavelet spectrum. The use of the randomization technique was done according to O'Shea et al. (2001). Here we use a randomization with 250 permutations. Secondly, we also use the Fourier transform (Jenkins & Watts 1968) in a similar way as Doyle et al. (1999). The significance levels for this transform were estimated using the fact that for a wide range of noise types (e.g. Poisson in this case) the noise power follows the χ^2 distribution with 2 degrees of freedom (Jenkins & Watts 1968). This allows one to construct significance levels using the integral probability of this χ^2 distribution, after first adopting the Leahy normalization, see Doyle et al. (1999) and references therein.

[1] See `http://paos.colorado.edu/research/wavelets/`

3. Results

Four examples of the wavelet transform applied to the flux of our spectral lines are illustrated in Fig. 2. In each example, the top panel shows the integrated flux variation in counts/60 s over time, with the overplotted line representing its trend, computed by a 50-pt running average. When applying the wavelet transform we did not de-trend the signal, as we are interested in the long-time periodicities. The bottom left panel is the wavelet spectrum; and the bottom right panel is the global wavelet spectrum, which is the sum of the wavelet power over time at each oscillation period. The dark-coloured regions from the wavelet spectrum show the locations of the highest power. Cross-hatched regions indicate the "cone of influence", where edge effects become important. The thick white line in the wavelet spectrum refers to the first maximum power. Only locations with a probability ≥95% are considered real (not due to noise). P1 is tested against the first maximum power found at any period in the randomized data. The top dashed line in the global wavelet spectrum marks the highest period cut-off (≈300 min). The multiple peaks in the global spectra indicate that the signal is composed of oscillations with different periods (see the horizontal lines in the right panel). These range from 11 to 66 min in the TR lines and from 18 to 93 min in Ne VIII, plus a strong 170 min period in all lines. We concentrate here on the very long (170 min) period.

For all examples from Fig. 2, P1 ≈170 min. We have chosen the flux at 5″ above the continuum limb for the lower temperature lines because this very long periodicity is more obviously visible (even by eye) than at other locations. For Ne VIII, there is no such periodicity at this location. Instead, a similar periodicity begins to show further up, e.g. above the Ne VIII limb (considering the continuum limb 0″, the Ne VIII limb is at ≈11″ and for the other lines the limb is at ≈3″). The ≈170 min periodicity in this line is best seen a few pixels above its own limb, e.g. at 15″. In summary, it is seen from 0″ to 10–15″ in the low temperature lines and from ≈10″ up to ≈40″ in Ne VIII.

The second tool we have employed is the Fourier transform – see Fig. 3 that illustrates the results for the same variables as in Fig. 2. The peak at 0.1 mHz = 166.7 min is clearly seen. We do not take into account the smaller frequency (<0.1 mHz) as it would correspond to a third or a half length of our time series. As in the wavelet analysis, a range of shorter periods down to 11 min was observed. The significance of the peaks was tested using a 95% significance test, which in this case has a value of ≈18 (not plotted). The main peak at ≈170 min is statistically significant.

The time resolution is high at low period values for both transforms (especially for the Fourier, whose resolution is ≤0.1 min). But it decreases towards higher values, e.g. the 170 min period has a resolution of ±9% in the wavelet and ±17% in the Fourier transform.

4. Discussion

Analyses of SUMER and UVCS data (Teriaca et al. 2003; Banerjee et al. 2000b) have shown that UV line widths are larger in inter-plumes than in plumes, suggesting inter-plumes

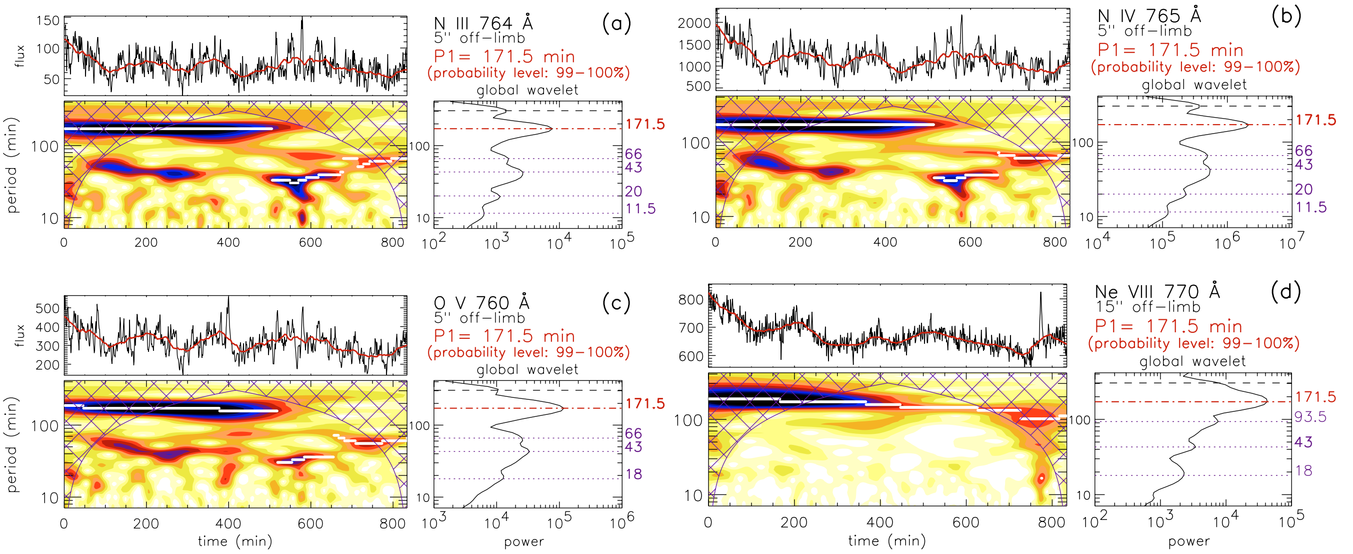

Fig. 2. Wavelet results for different lines, as labeled. In each set, the top panel shows the variation of the line flux (averaged over 2″ on solar-y) over time, in counts/60s. The continuous overplotted line is a running average over 50 min. The wavelet power spectrum is given in the lower panel, with the white line showing the first maxima. P1 is the period corresponding to the first maximum power in the global wavelet power spectrum (*right panel*). In the global wavelet, the top dashed line is the maximum allowed period (≈300 min). The horizontal lines indicate the periods that appear in each dataset.

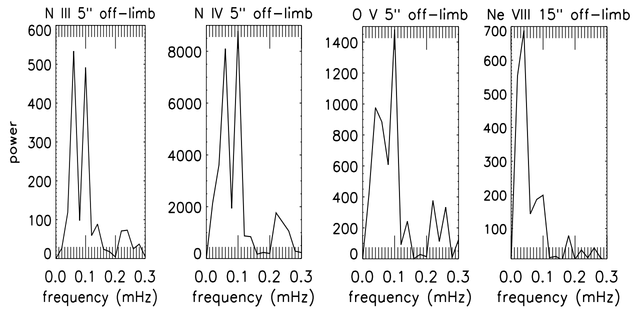

Fig. 3. The Fourier power spectrum for N III 764 Å; N IV 765 Å; O V 760 Å at 5″ off-limb and Ne VIII 770 Å at 15″ off-limb.

to be the site from where the fast solar wind emanates. This argument is obviously supported by the fact that the plasma density is lower in inter-plumes. Thus, the periodic intensity fluctuations detected here and by others in inter-plumes could play a relevant role in accelerating the fast streams of particles leaking from coronal holes, along open magnetic field lines.

In addition to the long 10–90 min periods, the data presented here show a very long periodicity of ≈170 min seen 5″ above the limb in the flux of three TR lines (N III 764 Å, N IV 765 Å and O V 760 Å) and 15″ off-limb in the Ne VIII 770 Å line. This type of very long periodicity has not been reported before.

Our observations were made off-limb in an inter-plume region. However, because of line of sight effects and the proximity of plumes to the slit location, we can not rule out contributions from both plumes and inter-plumes. Also, since we are dealing with single slit data, there is always the possibility that a feature is moving in and out of the slit. Judge et al. (2001) noted that over a ≈260 min interval, SUMER pointing was stable to within 0.2″ thus well within the 1″ slit width used here. Hence, if a feature was moving into and out of the field-of-view, it should be very intense in order to produce the required brightness changes. No such feature is observed; moreover, in Ne VIII the intensity increase occurs over a 30″ length along the slit, hence we rule out features moving in and out of the slit's field of view as an explanation for the intensity oscillations. Furthermore, all known SUMER corrections have being applied, including a correction for SUMER's thermoelastic oscillations (Rybak et al. 1999), which nevertheless affects only the wavelength shifts, therefore the Doppler velocity, whose variation we do not study here.

As this is the first time we detect in a SUMER dataset the presence of long and very long period oscillations, we look to other SoHO instruments to see if such variability has been observed. As mentioned in the Introduction, various instruments have reported wave variability in open coronal structures, but not higher than 70 min. These periods have been generally interpreted as a signature of slow propagating (acoustic) waves. This is based on the fact that the slow modes, being compressional in nature, produce a modulation in the density and EUV fluxes and thus, the observed integrated flux modulations (which is not the case for Alfvén waves). Although longer-term variability of 8–27 h (not necessarily waves) have been reported in filaments (Foullon et al. 2004), it is difficult to see the connection with the present observations.

At first sight, the newly detected very long (170 min) periods might appear as just another mode of the long (10–90 min) oscillations, due to magneto-acoustic waves, but there are theoretical constraints to this idea (see discussion below). An alternative possibility is that they could be the result of a periodic process, like for example some recurrent reconnection taking place in the chromospheric network boundaries.

In an isothermal atmosphere, the acoustic cut-off frequency is given by $\Omega_{ac} = \gamma g/2c_s$ (Roberts 2004). In the corona, we may take $\gamma = 5/3$, $g = 0.274$ km s^{-2} and $c_s = 200$ km s^{-1}, which gives a cut-off period $P_{ac}(2\pi/\Omega_{ac}) \approx 91.7$ min. Thus, under isothermal conditions, one would not expect to see any acoustic type of wave with periods as long as 170 min in the corona. But assuming the solar atmosphere as being purely isothermal is an approximation, thus the cut-off period calculated on such ideal conditions may not mimic the complicated temperature structure of the real atmosphere, and one should not rule out deviations from these numbers. For example, in a recent simulation, De Pontieu et al. (2005) showed that photospheric oscillations with acoustic cut-off frequency of 4.8 mHz or slightly lower can actually tunnel to higher up in the atmosphere as long as they are guided along an inclined magnetic flux tube. This non-verticality of the flux tube decreases the cut off frequency, allowing the lower frequency modes to tunnel through. Polar plumes (inter-plumes) can very well act as wave guides. Thus, if slow waves with very long periods are generated somewhere in the middle atmosphere, this mechanism could allow them to eventually tunnel through to the corona.

In a recent paper, Nakariakov et al. (2004) have demonstrated that some form of quasi-periodic oscillations can yield a tadpole wavelet spectrum: a narrow spectrum tail precedes a broadband head (with some resemblance with our wavelet phase plots), but they pointed out that their quasi-periodicity results from the geometrical dispersion of the guided fast magnetoacostic wave modes (propagating within a closed magnetic loop). In our case, if the oscillations are due to slow magnetoacoustic modes (presumably they are propagating through open magnetic structures), the periodicity could be prescribed by the *source*. For example, perhaps they are produced in the chromospheric network boundaries at the base of the coronal holes, where magnetic reconnections are usually present.

Whatever the mechanism is that produces them, these 170 min periodicities add a significant new piece of information to the puzzle of mapping the periodic phenomena of the solar atmosphere. Future models need to explain the long period nature of the variability, lasting ≈550 min, with an amplitude of 15 to 20% of the total intensity.

Acknowledgements. Armagh Observatory's research is grant-aided by the N. Ireland Dept. of Culture, Arts & Leisure. This work was partially supported by the Program for Research in Irish Third Level Institutions for Grid-enabled Computational Physics of Natural Phenomena (Cosmogrid) and by PPARC grant PPA/G/S/2002/00020. SUMER is financially supported by DLR, CNES, NASA and ESA PRODEX programme (Swiss contribution). SUMER and EIT are part of SoHO (ESA & NASA). We wish to thank the Royal Society, the British Council and DST-India for T&S support within the UK and India. We also thank Ignacio Ugarte-Urra and Chia-Hsien Lin for help in using the wavelet analysis.

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