IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

Dynamics of active regions observed with TRACE(*)

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(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — I present results of an international joint observing campaign, which was carried out in September 2000, to study the oscillatory behaviour of active regions. In this contribution I will concentrate on oscillations in the higher layers of the solar photosphere as observed with the UV filters of the Transition Region and Coronal Explorer (TRACE). I study the distribution of oscillatory power in an extended active region. I can find a number of well-known chromospheric dynamic phenomina like running penumbral waves, enhanced 5 min power in the plage and network regions and strong 3 min power in the internetwork. In addition, I find that the 3 min power in the surroundings of the active region is decreased, an effect that has not been observed before. From the topology of the magnetic field I infer that this can be explained by an interaction of the acoustic wave field with the expanding magnetic field of the active region.

PACS 95.75.Wx – Time series analysis; time variability.
PACS 96.60.Ly – Oscillations and waves; helioseismology.
PACS 96.60.Na – Chromosphere and chromosphere-corona transition; spicules.
PACS 96.60.Qc – Sunspots, faculae, plages.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

In September 1999 and 2000 an international joint observing campaign was carried out (1) to study the oscillatory behaviour of active regions with a variety of instruments, different observing modes and all heights in the solar atmosphere. In this contribution I will concentrate on oscillations in the high photosphere/low chromosphere as observed with the Transition Region and Coronal Explorer (TRACE) [1]. I will study the distribution of oscillatory power in an extended active region that contains a sunspot, surrounding plage and patches of quiet sun with network and internetwork.

(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.
(1) JOP097, see http://sohowww.nascom.nasa.gov/soc/JOPs/jop097.txt

2. – Observations and analysis

I have selected data taken on 29 September, 2000, between 8.00 and 12.00 UT. TRACE observed in three of its UV filters which are centered at 1550 Å, 1600 Å and 1700 Å, cycling through these three filters in a cadence of 30 s. We observed active region AR 9172 which was located at $x = -315''$, $y = 98''$ on the solar disk. TRACE has a spatial resolution of $1'' \times 1''$ and the final field of view after data reduction was $165'' \times 256''$. In the following I show results of the 1700 Å filter. This filter covers mostly UV continuum (see [1]) and according to the standard VAL model [2] the light primarily comes from right below the temperature minimum region. The data reduction consists of the following steps: subtraction of a dark image, normalization to exposure time, taking out high-intensity pixels due to high energetic particles (during passes through the Earth's radiation belt), correction of differential solar rotation and image drift due to the TRACE telescope. After this procedure one has a time sequence of intensity for each pixel of the image. Finally, I calculate power spectra using a Fast Fourier Transform, which includes a linear detrending and a 10% cosine apodisation.

In the following, I am taking into account the fact that any kind of measurement always includes errors (which can be systematic or of other kind). A detailed error analysis of TRACE EUV data has been carried out by [3] and various sources of noise have been identified. To get an approximation of the influence of noise in the Fourier domain and thus to have an estimate of the significance of the peaks in the power spectra, I performed a randomisation test. This method has, *e.g.*, been used to test the significance of periods of variable stars by [4], who also give a detailed discription of this test. More recently it has been applied to wavelet spectra of active region oscillations by [5] and [6].

The randomisation test is based on the assumption that, if there is not any periodic signal in the time series data, then it represents noise. If this is the case, then any other representation of the measured quantities is also noise and will happen with the same likelihood as the original sequence. Thus, we test our hypothesis (namely that there is NO periodicity in the data) by randomly changing the order of the observed numbers and comparing the resulting randomised power spectra with the power spectrum of the original sequence. The proportion of permutations that give a power value greater or equal to a original power peak will then provide an estimate for the probability p that there is NO periodic signal (or in other words, the probability is high that a random sample of the observed numbers produce the observed peak in the power spectrum).

The randomisation was carried out 100 times for the time sequence of each pixel. All power peaks with a probability of more than 5% were set to zero (which means we accept all power peaks that have a probability of more than 95% that a period is actually present). Further details of this analysis and modifications of this method can be found in [7].

After the randomisation test there is no power left beyond 6.5 mHz. The power at low frequencies (< 2 mHz) is influenced by the evolution of the solar structures, short-term brightenings that happen occasionally and also by instrumental effects and the reduction procedure. Two different frequency domains are of interest, one at 3.3 mHz (5 min) and the other one at 5.5 mHz (3 min periods). Thus, I integrate all power peaks in the range of 2.3–4.3 mHz and 4.5–6.5 mHz.

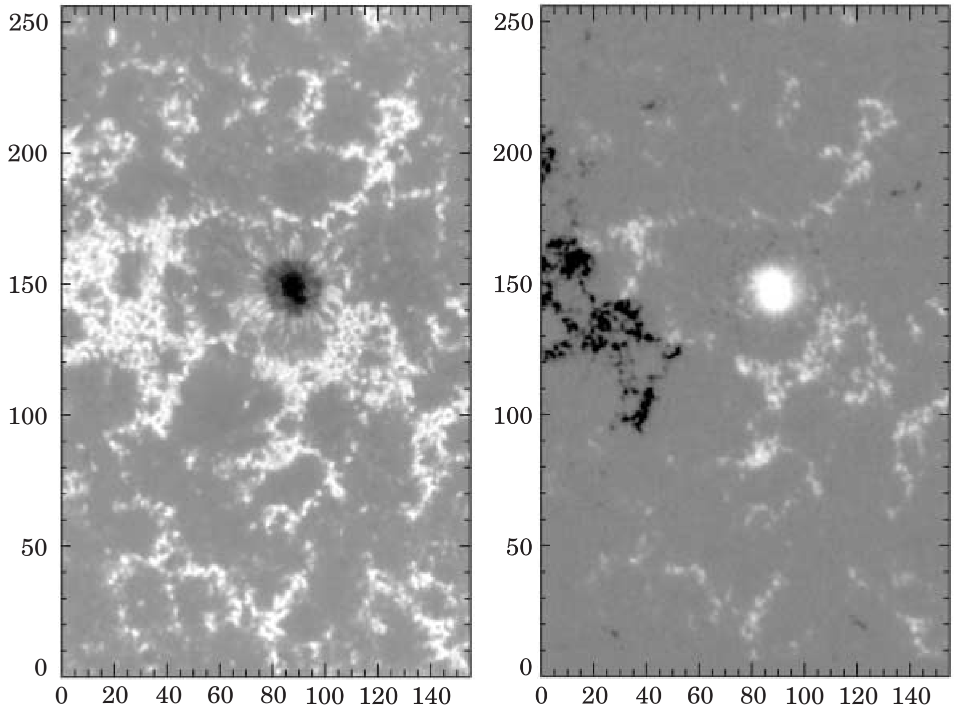

Fig. 1. – Left: temporal average image of the TRACE 1700 Å; right: MDI magnetogram; the numbers on the axes are arcseconds.

3. – Results and discussion

Figure 1 (left) shows a temporal average of the 4 hours of co-aligned 1700 Å images and next to it a magnetogram taken by MDI, giving the distribution of magnetic flux of the same area (fig. 1, right). The dark structure in the center of the 1700 Å image is the sunspot (with umbra and penumbra well recognizable), the bright structures around it, is plage and further away chromospheric network. All these structures harbour strong (kG) magnetic fields in the photospheric layers of the solar atmosphere. The dark-cell–like structures are the internetwork cells, which are free of kG fields. As can be seen in the magnetogram, the AR is bipolar, with the inversion line of the two polarities running diagonal to the left of the sunspot. Along this inversion line a filament was located as could be seen in an Hα image of the same day.

Figures 2 and 3 show maps of the integrated power in the five (left) and three (right) minute range. Each image is linearly scaled, the brighter the region, the higher the power, black means that there is no power. In fig. 2 the power maps include all power in the selected frequency range, while in fig. 3 only the power after the randomisation test is used (all frequencies with a probability of less than 95% are set to zero).

In the following we concentrate on the area outside the actual sunspot (plage, network and internetwork). It is well known from ground-based observations of, *e.g.*, the Ca II H and K line that there is a distinct difference in wave frequencies between quiet-sun network and internetwork: the network is dominated by oscillations with periods of 5 min and longer, while the internetwork also displays power in the 3 min range (*e.g.*, [8]). This

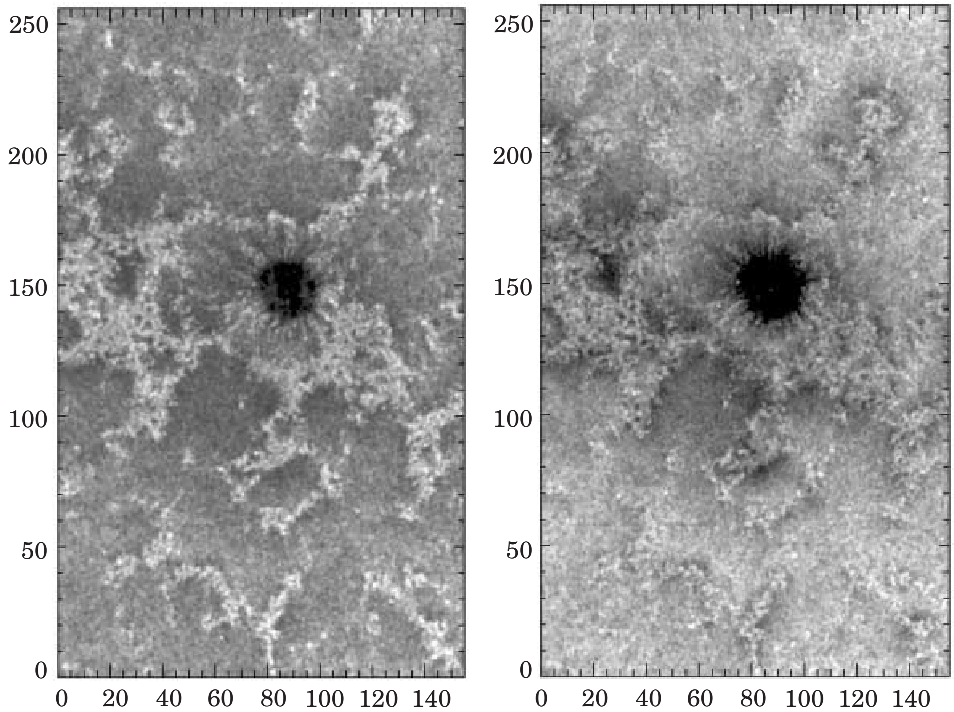

Fig. 2. – TRACE 1700 Å 5 min (left) and 3 min (right) power maps (all frequencies are included), the numbers on the axes are arcseconds.

is confirmed in figs. 2 and 3. The brightest patches in the 5 min map can be found at the locations of the network and plage, when comparing fig. 1 with 2 and 3. Applying the randomisation test, plage and network are even completely black in the 3 min map, indicating that the power there has a probability of less than 95% to be due to a real period in the data. The nature of the network oscillations is still not known, although the fact that the network (and plage) consists of small-scale strong-field magnetic elements hints at a connection to these fluxtubes. The 3 min internetwork oscillations (as observed in the Ca II H line) have been successfully reproduced by acoustic waves that travel into the chromosphere and form shocks in the higher layers [9].

Figures 2 and 3 show another interesting and new feature, especially in the 3 min map: in the immediate surroundings of the network and the plage the 3 min power is considerably lower than in the internetwork away from the AR. This is quite a large-scale effect and produces a dark ring around the AR. The field-free region in the plage area around $x = 30''$ and $y = 150''$ even completely disappears in the 3 min map of fig. 3, which means that there is not significant power at all. When comparing this region with the regions in the magnetogram one finds that it lies exactly at the magnetic neutral line (between the black and white of the two polarities). The same is true for a large internetwork cell at $x = 60''$ and $y = 100''$, which shows a gradient of power radially away from the sunspot. The network regions show a darkening immediately around them as well.

I want to suggest the following explanation of this effect: at the lower photospheric

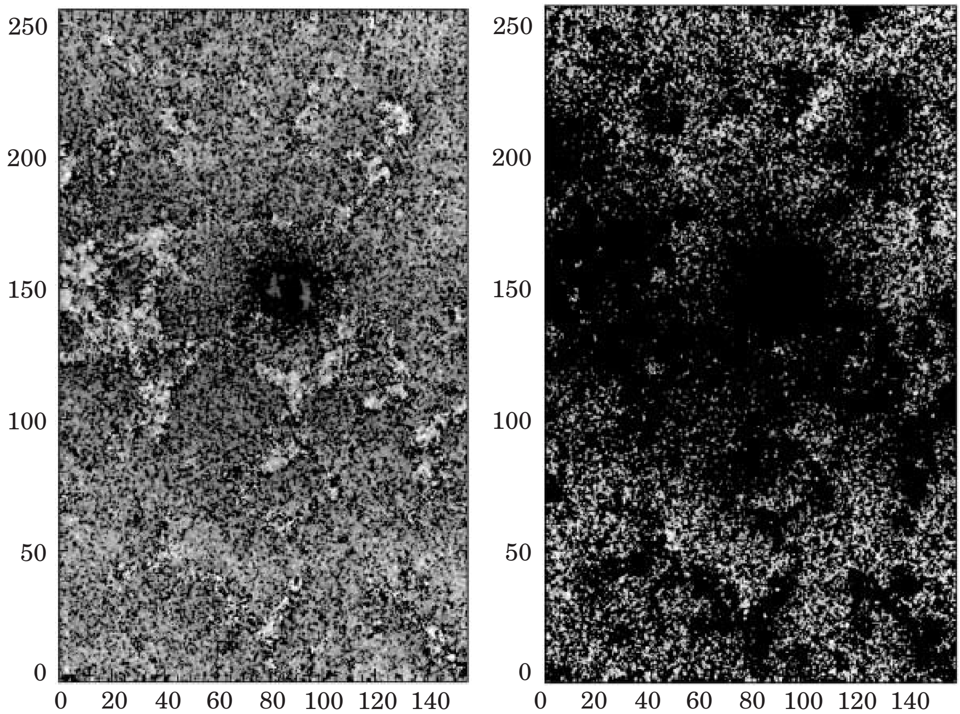

Fig. 3. – TRACE 1700 Å 5 min (left) and 3 min (right) power maps, now including the result of the randomisation test: all frequencies with a probability less than 95% are set to zero.

level there are acoustic waves in the internetwork (the global p-modes). These waves can travel upward (especially those at frequencies above the acoustic cut-off frequency of 5.5 mHz) and in higher layers they interact with the expanding magnetic field of the sunspot and the magnetic elements that make up the network and plage. The increase of the diameter of magnetic fluxtubes is a standard feature of all fluxtube models. As the fluxtubes expand with height, their field lines get more and more inclined until they either become horizontal or encounter fieldlines from other fluxtubes. Thus, they form a so-called magnetic canopy above the field-free region below. As mentioned in the beginning, the filtergrams probe the quiet solar atmosphere at a height of about 400–500 km above the zero level in the photosphere. If the inclined or horizontal magnetic field is below this height, then the acoustic waves interact with the canopy boundary before they reach the height we can probe. This is the case in the field-free region in the plage area around $x = 30''$ and $y = 150''$, which is supported by that fact that this is also the location of the magnetic neutral line. Considering the expansion rate of a large fluxtube (sunspot) and a small one (magnetic element), then one finds that it scales with size and thus the effect is much larger in the sunspot than in the network.

What might be the nature of the interaction of the acoustic waves with the overlying magnetic field? There has been theoretical work which studies these effects in [10] and [11]. They find that the waves can be reflected or there can be a mode conversion.

Finally, let us compare our observations with previous investigations on chromospheric dynamics. There are a number of active region studies that were carried out from ground using Ca II K filtergrams [12-14]. Interestingly, they find an enhancement of 3 min acoustic power in the surroundings of an active region, although in [15] it is concluded that at least part of the patterns seen in acoustic power maps obtained from ground can be due to the effect of seeing. These enhancements were also investigated using photospheric data from ground and from MDI [14, 16-19]. In this case the intensity power maps show neither enhancement nor darkening around the sunspot, but in power maps of Doppler velocity they also find an enhancement of 3 min power.

A detailed comparison of our TRACE data and simultaneous MDI data is currently in progress and will be published elsewhere.

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This research is part of the TMR-ESMN (European Solar Magnetometry Network) supported by the European Commission. I would like to thank the TRACE instrument team and planners for their support during this observing campagne. The magnetogram in fig. 1 is courtesy of SOHO/MDI consortium. SOHO is a project of international cooperation between ESA and NASA.

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