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Probing 5-minute oscillations in the solar wind with comet Hale-Bopp (C/1995 O1)

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Abstract. This study aims at short-period fluctuations of the solar wind by using comet Hale-Bopp (C/1995 O1) as a probe. The comet's intensity fluctuations due to changes in the reflectivity and emission of molecular lines are investigated both in the coma and the tails at about 1 AU heliocentric distance. The existence of oscillations with periods of a few minutes as an already suggested by Isserstedt & Schlosser (1975) on the basis of observations of comet 1973f (Kohoutek). We focus here on the time scale of the solar p-modes (5 min.); Thomson et al. (1995) have recently claimed to observe these periods in the flux density of the solar wind.

Both in the comet's coma and in the ion tail we found oscillations on the time scale of minutes if mainly the stimulated emission of the C_3 line was observed through a 'narrow-band' filter. No comparable oscillations were seen through a 'broad band' filter where reflected sunlight dominates the intensity. We show that the observed fluctuations are neither induced by the earth's atmosphere nor due to genuine comet activity.

Key words: solar wind – Sun: oscillations – comets: individual: Hale Bopp

1. Introduction

Most of the work on oscillations of the interplanetary medium deals with the interaction between the solar wind and the interplanetary magnetic field (see e.g. Nakariakov et al. 1996 and Orlando et al. 1997 for recent theoretical work as well as Tu & Marsch 1995 for a comprehensive review). Magnetic field changes induced by the interaction of comet Giacobini-Zinner with the solar wind were extensively studied with the International Cometary Explorer (e.g. Smith et al. 1986, Scarf et al. 1986, Moses et al. 1992).

Analysing in situ measurements from Ulysses and Voyager 2, Thomson et al. (1995) found the particle flux of the solar wind oscillating in the frequency range of the solar g and p modes, but the solar origin of the g mode signal was subject to some doubts (Kumar et al. 1996). While the determination of g modes requires observations of a very long duration[1], p-mode periods are short enough to allow the use of *the* classical solar-wind probe: a comet (see Flammer et al. 1997 for a summary of the interaction processes of Hale-Bopp with the solar wind). With changes on the time scale of a few minutes, p-mode like oscillations are clearly separated from the time scale of typical cometarian effects like rotation, evaporation, etc. (see Rodriguez et al. 1997 for Hale-Bopp's variability). The report of such oscillations, already given by Isserstedt & Schlosser (1975) on the basis of observations of comet 1973f (Kohoutek) encouraged us to verify p-mode like oscillations in the solar wind by observing comet Hale-Bopp (C/1995 O1). While Isserstedt & Schlosser (1975) had more (11) nights under acceptable weather conditions, our Hale-Bopp data sets – taking advantage of a CCD camera – are improved with respect to their one-channel photometer observations in two ways: a posteriori corrections for tracking errors of the telescope are possible, and the two-dimensional

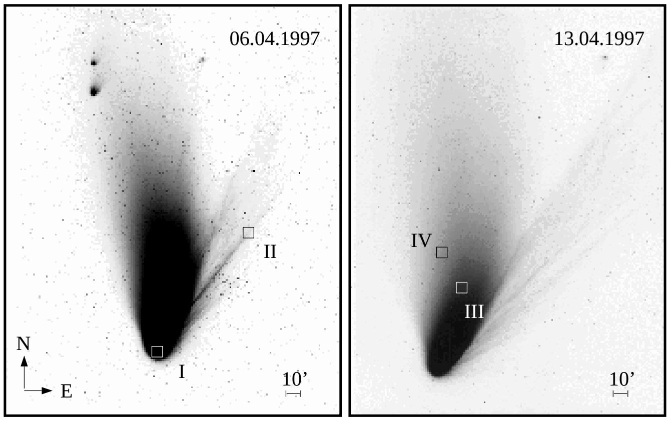

Fig. 1. Schmidt plate images ($4\overset{\circ}{.}4 \times 5\overset{\circ}{.}3$) of comet Hale-Bopp with $8' \times 8'$ fields of view (indicated by squares) as observed in different nights. Coma (I) and ion tail (II) were observed through either filter in subsequent nights. Transition region (III) and dust tail (IV) were only observed in the 'broad band' filter. Plates were taken by K. Birkle on Calar Alto.

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[1] As currently performed by various earth- and space-based campaigns continuously observing the sun for months or even years — so far without clear evidence for g-modes (e.g. Toner & Jefferies 1998, Martin Mateos & Pallé 1998).

Table 1. Overview on the obtained data sets

position	date 04/97	time (UT)	filter	frames [min^{-1}]
I coma	04	19:15 - 21:10	Gunn g	3
I coma	05	19:15 - 21:10	Strömgr. v	2
II ion tail	06	20:00 - 21:25	Gunn g	2
II ion tail	07	20:30 - 21:25	Strömgr. v	2
III coma-tail transition	12	20:00 - 21:15	Gunn g	2
IV dust tail	13	19:50 - 21:15	Gunn g	2

field of view gives the opportunity to track the spatial evolution of conspicuous events. Apart from the enhanced accuracy, we do not only present data from the comet's coma but also analyse both ion and dust tail.

2. Observations and data reduction

The observations were performed with the 1.23 m telescope on Calar Alto Observatory, Spain between the 3rd and 14th of April 1997, comprising 6 days with acceptable observational conditions. We recorded time series with a duration of at least one hour and a temporal resolution of 20 and 30 seconds using a Gunn g and a Strömgren v filter. A total field of view of $8' \times 8'$ was observed with a spatial resolution of 2 arcsec. Each night the filter and/or pointing position was changed tracking either coma, dust tail or ion tail. Fig. 1 displays the observed positions, Table 1 summarizes the relevant information.

Two different sources contribute to the observed intensity signal: reflected sunlight and stimulated emission by resonant fluorescence. Thus the signal might be influenced by an oscillating solar wind (changes of density and of the magnetic field) but also by genuine activity of the comet (like changes in evaporation, and by effects of rotation). In addition, the signal might be affected by changes in the earth's atmosphere, by straylight, and by instrumental effects. For the distinction of different processes, we alternated between two different filters in subsequent nights. Both filters transmit photons from stimulated emission *and* reflected sunlight, but with different contributions. We used a broad filter (Gunn g) to detect reflected sunlight and a narrow filter (Strömgren v) centered on a molecular spectral line (namely C_3 at 4100 Å). Fig. 2 shows the corresponding transmission curves. Unfortunately, all hitherto published spectra of Hale-Bopp taken in the appropriate frequency band were observed at rather large heliocentric distance (e.g. Fig. 2 in Fitzsimmons & Cartwright 1996 at 6.82 AU and Fig. 1 in Cartwright 1997 at 4.2 AU). Instead we use here a spectrum of comet Hyakutake (ESO Press Photo 22/96) taken at a heliocentric distance of about 1 AU. This spectrum was used to prepare the observations of Hale-Bopp, assuming a general similarity of the spectra of both comets.

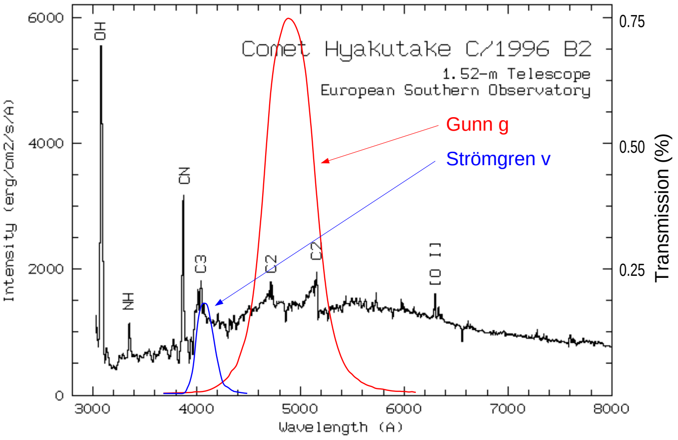

Fig. 2. Transmission curves of both filters used in these observations plotted over the spectrum of comet Hyakutake (ESO Press Photo 22/96). Two different contributions were observed: stimulated emission in the C_3 line dominating the Strömgren v filter as well as a mixture of reflected sunlight and emission from C_2 with the Gunn g filter.

3. Data analysis

After applying the usual procedures of dark current subtraction, flat fielding and cosmic event corrections, the inaccuracy of the telescope guiding was compensated by shifting the frames: For the time series of coma images, the maxima of the $n \rightarrow n+1$ crosscorrelation functions were used; for the tail positions, we recorded coma pictures with a fixed distance from the tail position before and after the observing run, correcting their drift with a linear interpolation. Thus we obtained movies at a fixed position relative to the comet's nucleus. Fig. 3 displays typical single frames of these movies both taken from the coma with the Strömgren v and the Gunn g filter.

In a first step we binned 20×20 pixels — i.e. $40'' \times 40''$ — to derive fields of view comparable to those presented two decades ago by Isserstedt & Schlosser (1975). These authors obtained light curves with a photometer aperture of 45 arcsec when observing comet Kohoutek at about the same heliocentric distance as Hale-Bopp had during our observations in April 1997, namely between 0.92 and 0.94 AU (1.38 - 1.48 AU geocentric distance).

Sample light curves from 40" × 40" subfields of the comet's coma are shown in Fig. 4. These unprocessed light curves are dominated by long term trends due to changes in the brightness of the sky, the airmass, and the comet's activity during the observations. In order to concentrate on the periods adressed in this study and again, to allow for comparison with the measurements of comet Kohoutek's oscillations, we applied in our data sets the same reduction procedure which was used by Isserstedt & Schlosser, i.e. we subtracted a 5.5 minutes running mean from a 1.5 minutes running mean, reducing the high frequency noise and suppressing all changes on long time scales. Obvi-

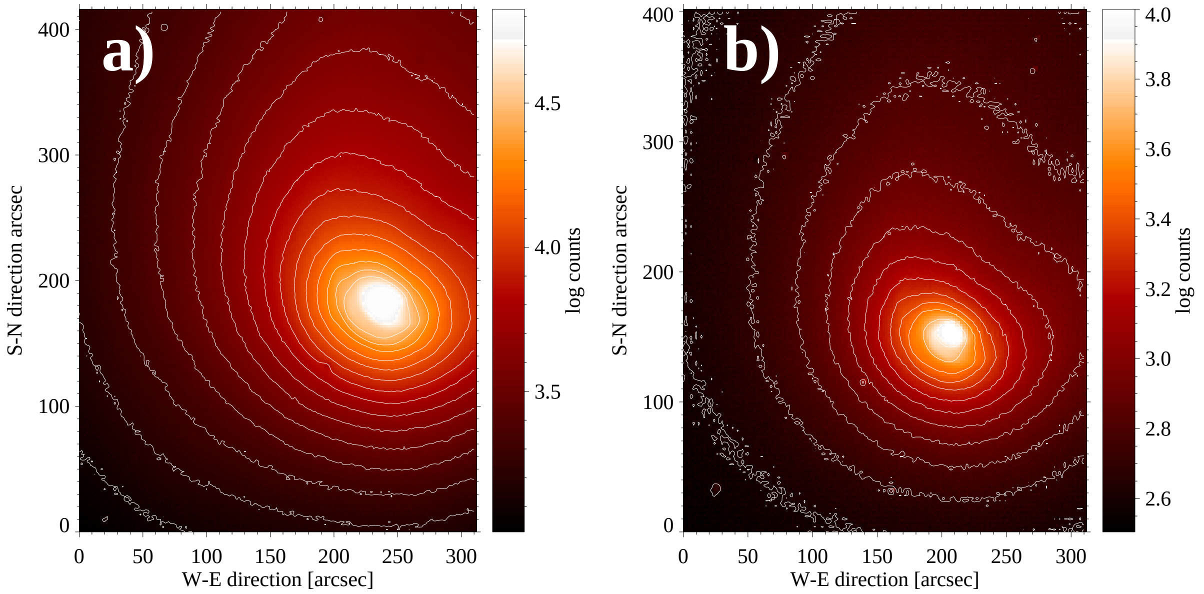

Fig. 3. Intensity maps of the comet's coma seen through the Gunn g filter (**a**) and the Strömgren v filter (**b**). Each contourline marks an increase of the count rate by 25 %, beginning at 1000 counts (**a**) and 316 counts (**b**). The brightness of the night sky contributes with about 10 counts. At the comet's geocentric distance of about 1.4 AU, 1 arcsec corresponds to about 1000 km. Compare with Figs. 6 and 8.

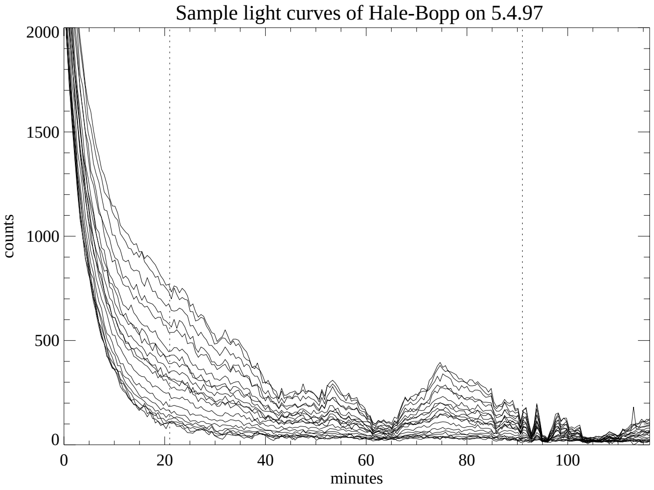

Fig. 4. Light curves of the comet's coma. In these unprocessed light curves (see also Fig. 5 below) changes on long time scales dominate. Nevertheless, some fluctuations on the time scale of minutes can also be seen. For further processing we have used only the data within the time interval, marked by dotted lines, when the observations were neither contaminated too much by daylight nor by strong irregular variations due to large zenith distance.

ously, the processed data has to be treated carefully to avoid misinterpretations due to reduction effects. Some of the processed lightcurves are shown in Fig. 5. The reader should compare these curves with those in Fig. 3 of Isserstedt & Schlosser (1975) which are indeed remarkably similar both in period and amplitude. A first guess to explain this similarity might be to assume that the signal is an artefact either due to the similarity of the applied frequency filter or due to the earth's atmosphere. We will argue below, that neither explanation is satisfactory.

In the next step we calculated the power spectrum for each recorded pixel. In Fig. 6 we display the power corresponding to the lightcurves oscillating with a notable amplitude in Fig. 5, i.e. those observed through the Strömgren v filter and thus representing C_3 emission. Both the power of the unprocessed lightcurves and the power of the filtered lightcurves — as shown in Fig. 5 — is displayed. The power around 5 mHz — corresponding to a period of about 3 minutes — is well enhanced by the filter method in particular with respect to lower frequency contributions. The similarity of the peaks in the processed and unprocessed data shows that they are not due to the filter transmission. This excludes the first potential artefact mentioned above.

At any given frequency, one can rearrange the power values taken from all power spectra to form a *power map* in the spatial domain (Fig. 7). These maps are a tool quite helpful in discussing the power spectra. For calculating the power, the intensity fluctuations were normalized to the mean intensity of the corresponding pixel. Consequently, the noise signal will be reduced with the square root of the intensity. On the left side of Fig. 7(a and c) we show a power map derived from data taken with the Gunn g filter together with a map of the average *gradient* of the intensity in the same data set. Here, the power is generally reduced with enhanced intensity (see Fig. 3a) and only at the loci of high intensity gradients the power rises again in the inner coma. One can argue straightforward from such a powermap that noise and image motion are the dominant contributors to the oscillations seen through the Gunn g filter[2].

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[2] The stripes in the power map result from the relative motion of field stars with respect to the comet-fixed coordinate system; no steep *gradient* is seen around the comet's nucleus because this area was saturated on the CCD.

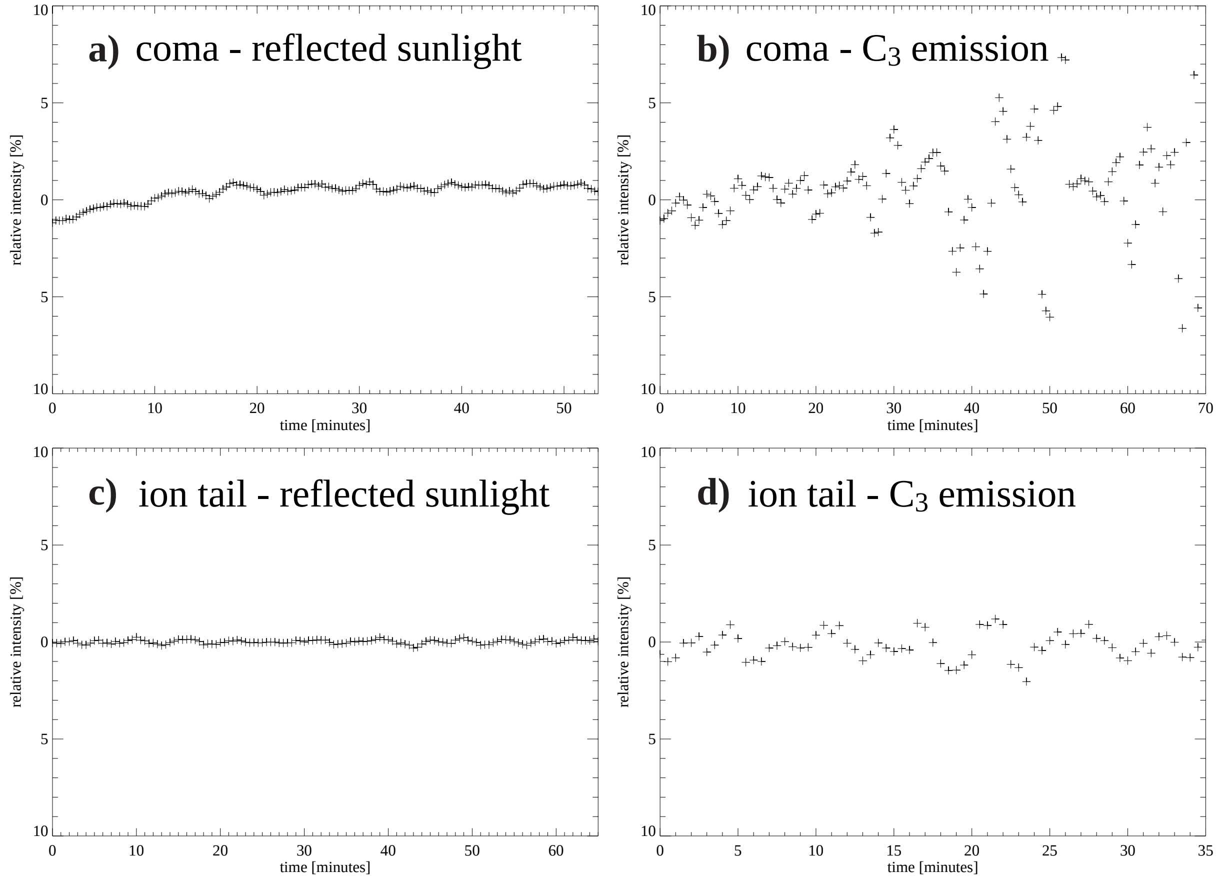

Fig. 5. Selected light curves derived from the original data sets (like the one shown in Fig. 4) by smoothing and subtracting the long-time trend (see the text for further explanation). Each curve represents the intensity averaged over 40 x 40 arcsec corresponding to the aperture of the photometer used by Isserstedt & Schlosser (1975). Both in coma and ion tail one can see an oscillation in C_3 (**b**, **d**) with an amplitude distinctly higher than fluctuations in the reflected sunlight (**a**, **c**).

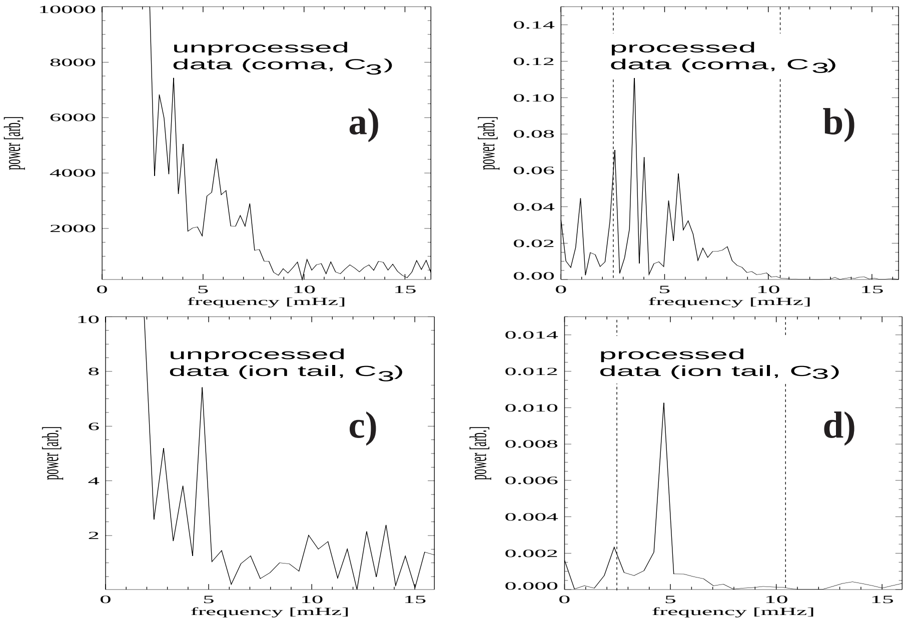

Fig. 6. Power spectra of the C_3 emission both in the coma and ion tail. The power was averaged over an area equal to that used for the light curves in Figs. 4 and 5. Displayed are power spectra of the original data (**a**, **c**) and of the data after applying the procedure adapted from Isserstedt & Schlosser (**b**, **d**). The dotted lines indicate the smoothing frequencies (see the text). Apart from the power at lower frequencies which is not our subject, there are two prominent peaks in the coma's power spectrum: a double-peak at about 3.7 mHz and one at 5.5 mHz, corresponding to periods of 4.5 and 3.0 min, respectively. The signal from the tail has a distinct power peak at about 4.8 mHz (3.5 min). We note that both positions were observed in different nights.

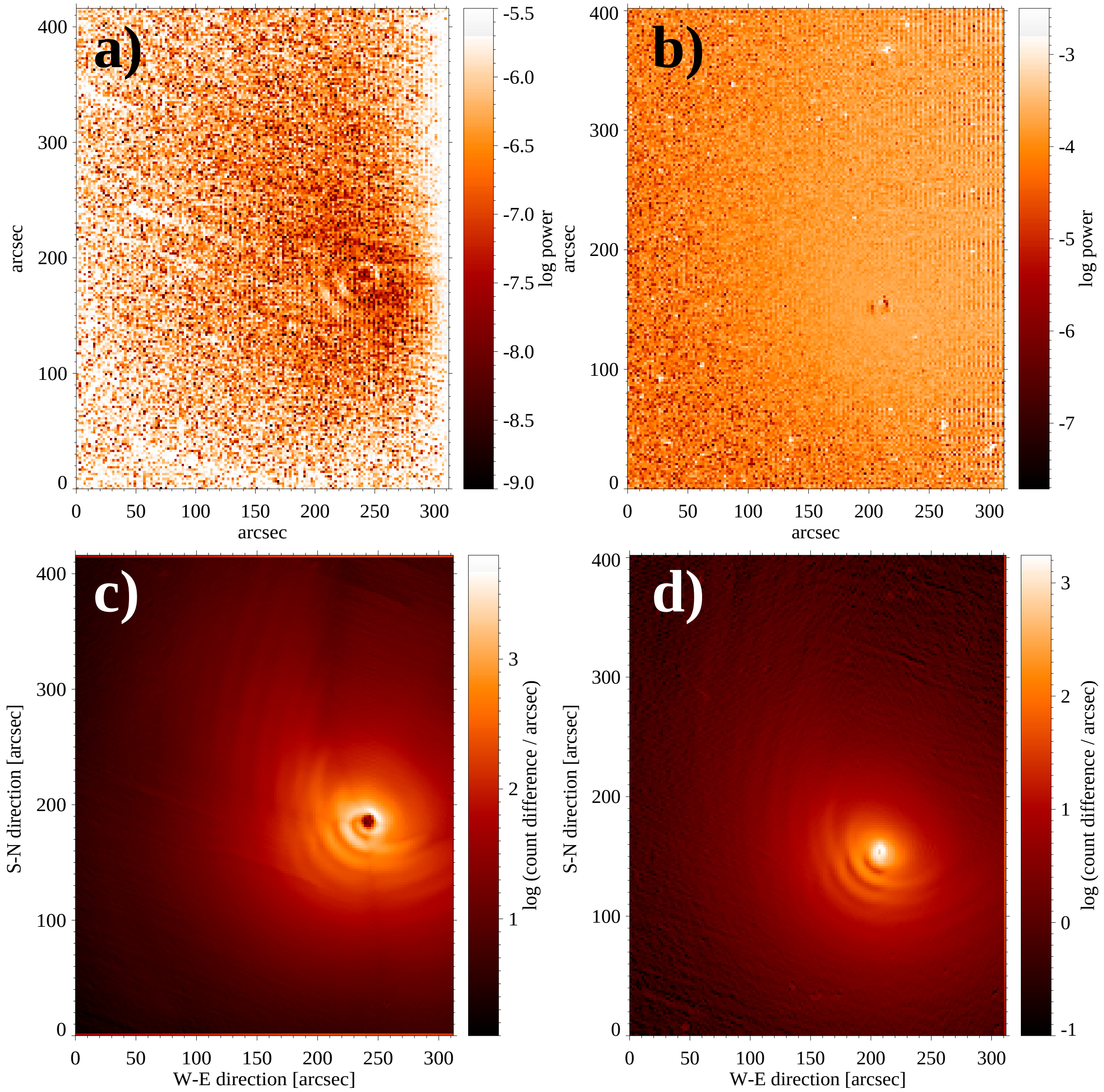

Fig. 7a–d. Power maps of the comet's coma seen through the Gunn g filter (**a**) and the Strömgren v filter (**b**) together with corresponding maps (**c**, **d**) of the *gradient* of the local intensity (see Fig. 3). For the power calculation the intensity fluctuations were normalized to a 5.5 minutes running mean per pixel. Both maps display power on a logarithmic scale around 3.5 mHz in an interval corresponding to the frequency resolution. In **a** the power is concentrated mostly at loci of high intensity gradients (**c**), which means that this power signal is probably produced by image motion. In contrast, we see in **b** a (higher) power signal that spreads smoothly over the coma of the comet with no distinct connection to local intensity gradients (**d**). Compare panel **b** also with Fig. 8. Note that 1 arcsec corresponds to about 1000 km at the comet's geocentric distance of about 1.4 AU.

In contrast, the right side of Fig. 7(b and d) shows a power signal that spreads smoothly over the inner coma, gaining amplitude with intensity (see Fig. 3b and Fig. 8), and which apparently is hardly at all influenced by local intensity gradients resulting from the well-known onion peel structure of the coma. Comparing panels b and d with a and c we find that the artefacts made responsible for the power in a will not be the main contributers in b. This excludes the second potential artefact with respect to the oscillations shown in Fig. 5.

4. Results and discussion

While low-amplitude oscillations seen through the broad Gunn g filter can be explained with artefacts, a genuine oscillation can be observed in the stimulated emission of the C_3 molecular line (using a Strömgren v filter). The relative amplitude of this fluctuation is about 3 % (peak to peak) and its range of periods lies on the time scale of minutes. It can be observed in the ion tail as well as in the comet's coma where the increase of power in the vicinity of the comet's nucleus is steeper than

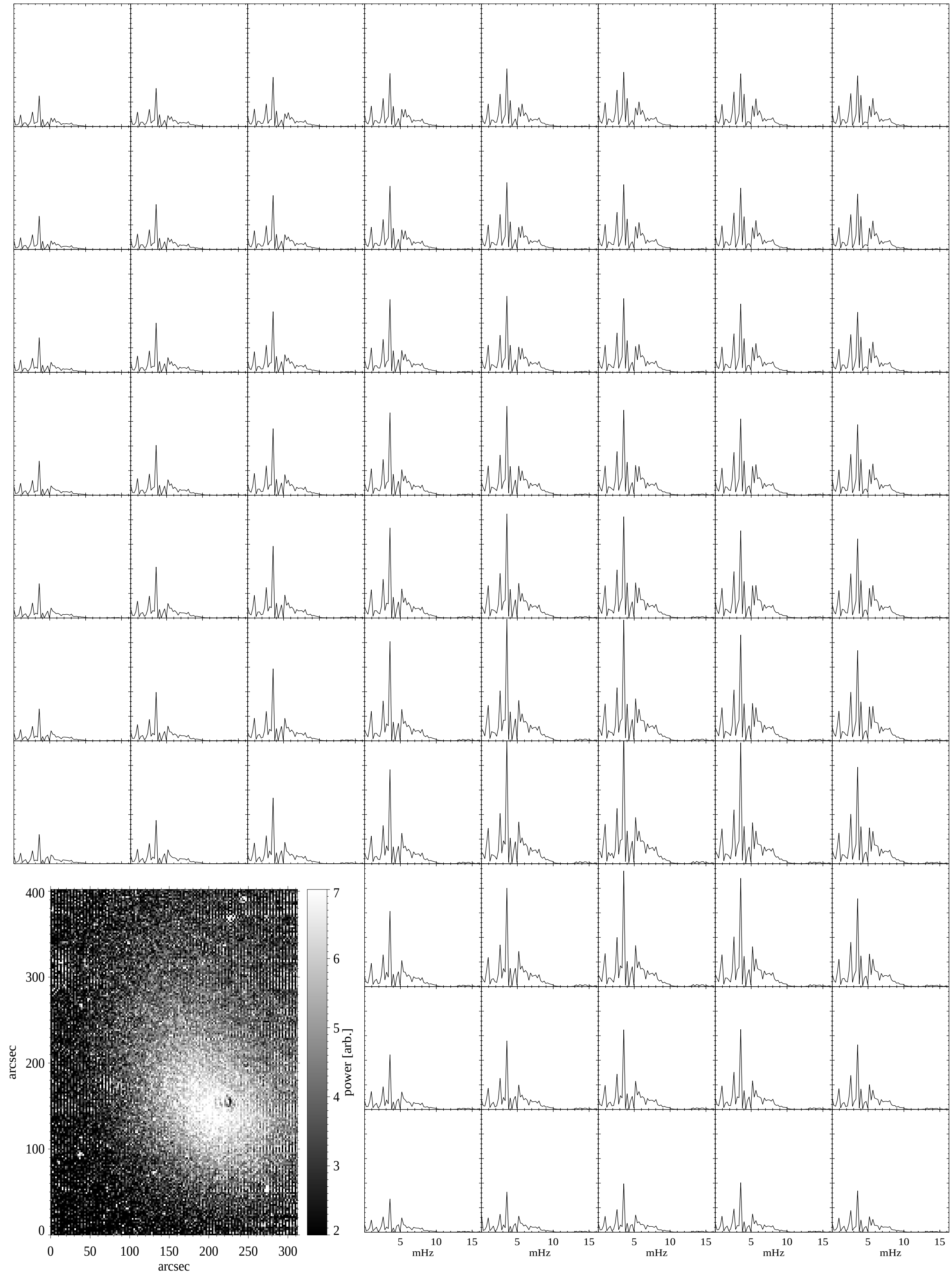

Fig. 8. Power spectra of the coma intensity fluctuations arranged in correspondence to Figs. 3b and 7b. Each spectrum represents an independent 40” x 40” bin. The scaling of the power axis is the same for all positions. These diagrams demonstrate the similarity of the peak frequencies over a wide field of view. Since the intensity signals were normalized, the fact that the power signal increases near the comet’s nucleus demonstrates that its dependence from the intensity is stronger than linear. See the greyscale panel where the power at the peak frequency is displayed at full resolution on a linear scale for direct comparison with the logarithmical scaled panel b in Fig. 7.

the local intensity gradient. Both in period and amplitude this signal is remarkably similar to the one obtained with different methods from the head of comet 1973f (Kohoutek) by Isserstedt & Schlosser (1975). This similarity seen in signals from two different comets' comae suggests that the oscillations have a common origin and are thus probably induced by the solar wind. Nevertheless, the frequencies of the power peaks apparently differ between coma and tail of Hale-Bopp (Fig. 6). In contrast, this might indicate that we see the comet's response to the trigger rather than the trigger frequency itself. However, we should remember that we deal with data sets from different days which are certainly subject to severe statistical effects. Although we note that the peak frequencies are stable over the whole field of view (Fig. 8), it is known from solar observations that even the rather sharp p-mode peaks broaden and display power spectra like those in Fig. 6 when observed only over a short duration.

Thomson et al. (1995) have claimed to observe frequencies *equal* to those of the solar p-modes on the basis of in situ measurements of the flux density in the solar wind. The data sets presented here display oscillations up to 8 mHz (2 minutes period). This confirms the existence of solar wind fluctuations in that frequency range. On the other hand, several results – the differences between the signal from coma and tail, the frequency values of the very peaks of the power signal, and their relative sharpness with respect to the broad power band of the solar p-modes – seem to indicate that the solar p-mode signal is not the source of this fluctuation. Taking into account the limited duration of the data sets – and thus the limited resolution in the frequency domain –, one might attribute these apparent deficiencies of the observational evidence to statistical effects, though. For a discussion on the appearence of peaks at different frequencies also refer to the arguments given by Roberts et al. (1996) and Thomson et al. (1996). However, it would be useful to observe fluctuations in the coma and the ion tail of a comet simultaneously and over a longer period.

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