SOURCES OF AMPLITUDE MODULATION OF SOLAR P-MODES

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ABSTRACT

We study the amplitude modulation of low degree solar p-modes using time–frequency methods. Previous results, showing a clear rotational modulation for selected modes, are confirmed. The modulation is clearly connected to the level of solar activity and the frequency of the modulation is confirmed to be close to the siderial rotation frequency of the latitude of the dominant activity. The dominant rotational modulation is seen in the l=*0* modes with radial orders 13, 16, 21 and 22. The modulation is nearly identical for the same modes as observed in irradiance and radiance with VIRGO and observed in radial velocity with MDI. No other clear and persistent peaks of similar amplitude are seen in the l=*1-2* modes.

1. INTRODUCTION

For some time there has been a debate on whether the solar acoustic modes are correlated or not. A widely accepted picture is that the excitation of p–modes are caused by turbulent motions close to the solar surface (Woodard 1984). In this case the individual modes should be excited independently and therefore be uncorrelated (Chang 1996). Baudin et al. (1996) analyzed 160 days of IPHIR data and concluded that the modes were likely to be correlated. Gavryusev and Gavryuseva (1997) claim that there is an anti-correlation between the mean solar magnetic field and the p–mode power from IPHIR data. Analysis of GOLF data show very little correlation between the modes (Baudin et al. 1997, Foglizzo et al. 1998).

Time-frequency methods (see Hanssen et al. 1994 or Baudin et al. 1994) clearly show the stochastic nature of the modes. The mode amplitude vary strongly in power (Baudin et al. 1994, Leifsen et al. 1995) and on a large range of time–scales from a few hours to several months as a large number relatively short lived, independent events interact. This is also consistent with a large number of stochastic excitations (Chang 1996).

Leifsen et al. (1997) discovered that the mode amplitude of the l=*0* modes averaged over radial modes 16-26 as observed in irradiance in VIRGO/SPM data show a strong modulation close to the solar rotation frequency. As longer SPM datasets became available it became clear that the modes were modulated at the solar siderial rotation frequency while the solar irradiance is modulated by the solar synodic rotation frequency as one would expect as active regions rotate on the solar disk (Leifsen et al. 1998). This frequency difference indicates strongly that the amplitude of the symmetric l=*0* modes themselves somehow are modulated by activity. The frequency difference also makes a correlation analysis difficult. However, if the mode amplitudes were resampled to a synodic frequency, a much better correlation with the Stanford magnetic index was found and the two signals were in phase.

Here we investigate the connection between the modulation of the l=*0* modes and solar activity further.

2. DATA AND METHOD

The data used in this study are the VIRGO/SPM blue channel data from 29-01-96 to 15-02-98, the VIRGO/LOI data from 27-03-96 to 15-02-98 and SOI/MDI velocity data from 01-05-96 to 31-12-97.

In this study the l=*0,1* and *2* modes with radial orders 12-32 have been investigated.

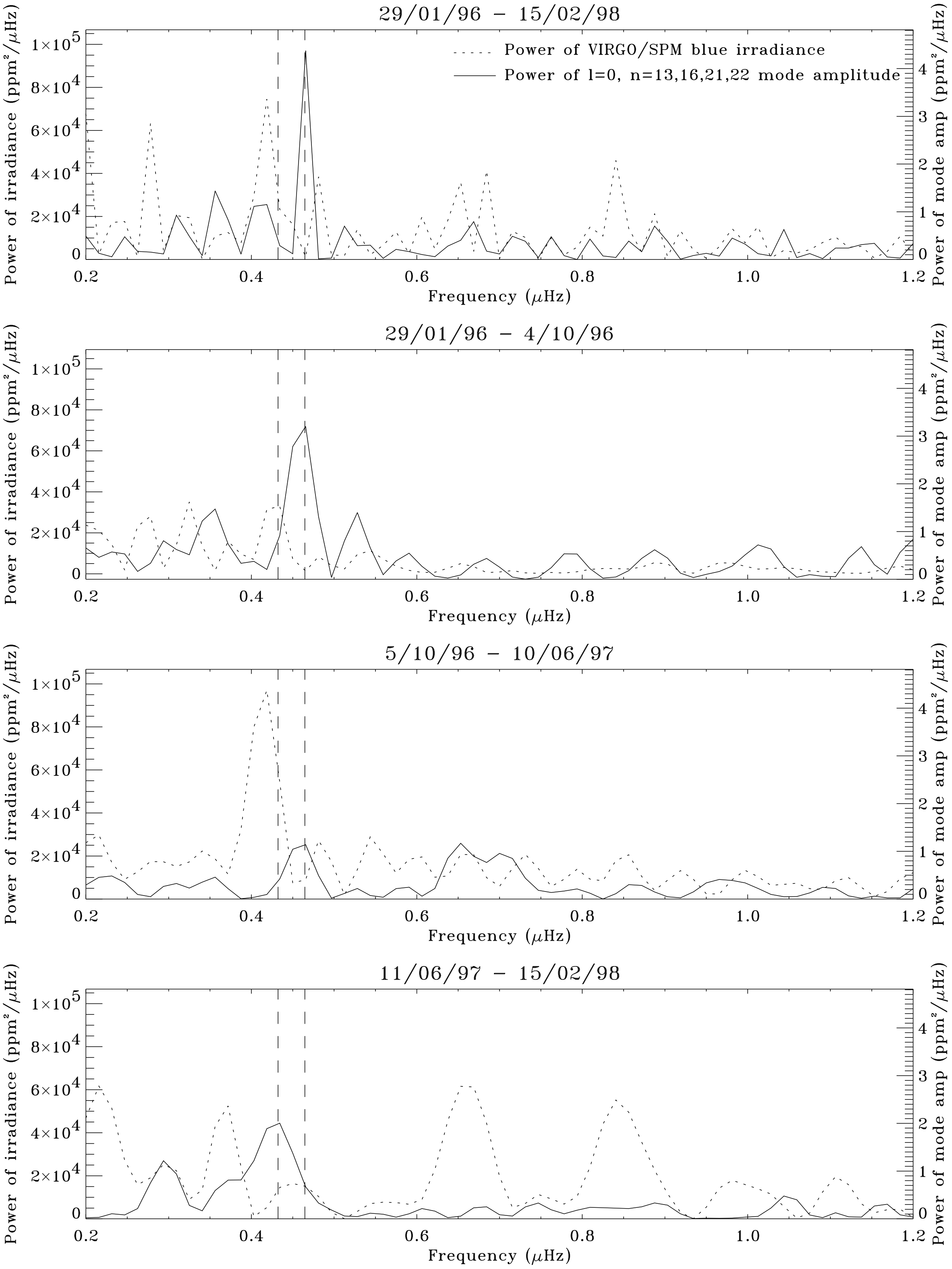

Figure 1. Power of mode amplitude for l=0, n=13,16,21 and 22 (averaged) is showed in solid lines. Power of VIRGO/SPM blue irradiance is shown in dotted lines. The upper panel shows the whole timeseries. Panel 2-4 shows the same timeseries divided in three. The solar siderial rotation frequency at equator (right dashed line) and the solar synodic rotation frequency at equator (left dashed line) is marked.

A spatial filtering technique (Appourchaux and Andersen 1990) was used to separate the various m modes for $l > 0$. The use of a covariance matrix method greatly reduced the spatial crosstalk for the $\pm m$ (Appourchaux et al. 1998). The SOI/MDI Doppler shift data used are the so called LOI–proxy data. This implies that the pixels are averaged to resemble the configuration of the 12 LOI pixels.

The amplitude modulation for the individual modes were calculated using a Hilbert transform of a 5 μHz band around each mode. The method consists of calculating the product of the Hilbert transform of the bandpassed timeseries with the timeseries itself. This produces an envelope or amplitude function that is used in the further analysis. The selection of the bandwidth determines the time–resolution. As in all time–frequency analysis this restricts how small the time–resolution can be. As the bandwidth is increased (resulting in a better time–resolution) more solar nose is smeared into the signal. Influence from nearby modes may also increase. For rotationally split modes this is a serious restriction for single pixel detectors, but this is overcome by using the spatial filtering and cleaning techniques on the LOI and MDI data, isolating the components prior to the time–frequency analysis. This allows us to study the amplitude modulation of the rotationally split components with a reasonable time–resolution.

Several bandwidths in the range 2-10 μHz was used, but they all produce consistent results. The noise level in the power spectra increases significantly for the broadest bandpass.

The Hilbert transform method has been compared in detail with the wavelet methods described earlier (see Hanssen et al. 1994). For the current type of study they are equivalent. However, the Hilbert method is much less computer intensive and was therefore preferred.

3. RESULTS

In this study a more detailed analysis of the time variation of individual *l=0* modes have been performed for radial order in the range *n=12,32*. An unexpected result is that only some of the modes show an amplitude modulation at the solar siderial rotation frequency. More specifically this is *l=0, n=13,16,21* and *22*. The other modes in the range *n=12,32* show no such rotational modulation.

Fig. 1, upper panel, shows the low frequency part of the power spectrum of the mode amplitudes averaged for *l=0, n=13,16,21,22* (solid line) and the power spectrum of the SPM blue channel irradiance (dotted line). As expected the latter show a peak near and below the solar equatorial synodic rotation frequency (Fig. 1, left vertical dashed line). However, the dominant peak in the power spectrum of the mode amplitudes is at the solar equatorial siderial rotation frequency (Fig. 1, right vertical dashed line).

To study the possible influence of solar activity on the modulation we have divided the dataset in three (Fig. 1, panels 2–4). In the irradiance we clearly see the shift in frequency as one would expect as the dominant region of activity shifts to higher latitude. A surprising result is that the modulation frequency of the mode amplitudes show a similar shift, indicating that the modulation of the modes is connected to the solar activity. However, due to the difference in dominant frequency there is no correlation between the rotation of activity over the visible solar hemisphere and the degree of modulation. The observed modulation effect does not depend on whether the active region is visible on the disk or is on the backside of the Sun, but rather upon the latitude (that is rotation frequency) of the activity.

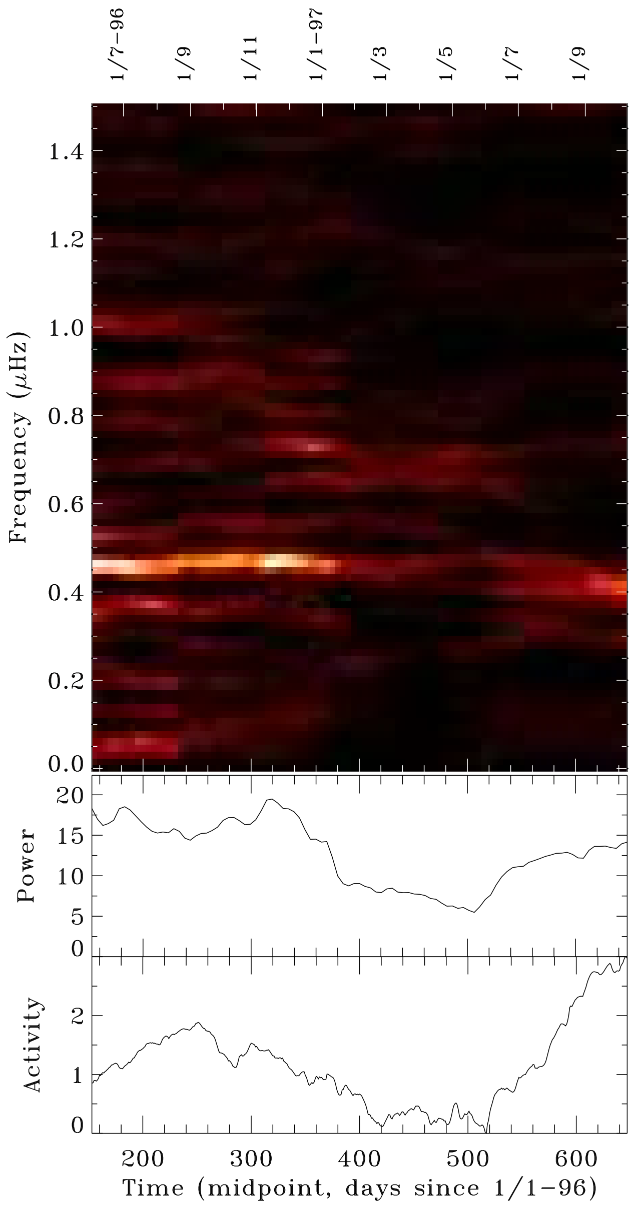

Figure 2 The powerspectrum as function of time for the l=0, n=13,16,21 and 22 mode amplitudes (upper panel). A 127 day sliding window was used to show the time development. The midpoints of the windows was used on the time–axis. The integrated power in the 0.4 to 0.5 μHz frequency range is shown in the middle panel (arbitrary power units). A 127 day running average of the absolute value of the Stanford magnetic index is plotted (lower panel) as an indicator of solar activity.

In Fig. 2, upper panel, we show the powerspectrum of the *l=0, n=13,16,21,22* modes (averaged) as function of time. A 127 day sliding window was used. The middle panel shows the integrated power in the 0.4 to 0.5 μHz frequency range as function of time. As an indicator of solar activity we have also plotted the 127 day running average of the absolute value of the Stanford magnetic index (lower panel). One can clearly see how the modulation vary with the solar activity. In the fall of 1997 a prominent shift in frequency is seen as the new solar cycle sets in and the dominant region of activity shifts towards higher latitudes.

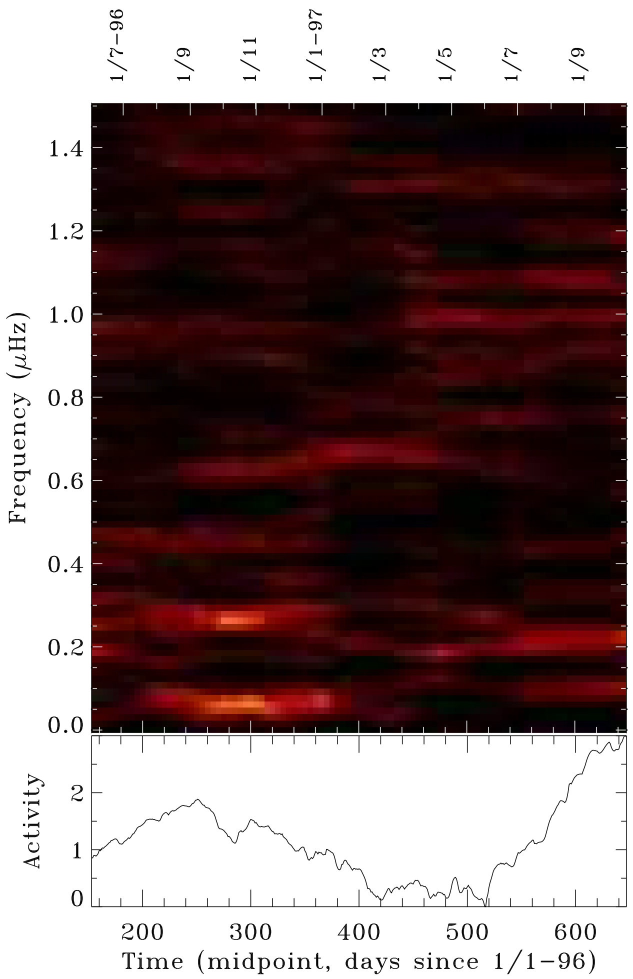

Figure 3. The powerspectrum as function of time for the l=0, n=12,14,15,17, 18 and 19 mode amplitudes (upper panel). The gray scale is the same as in Fig. 2. Other parameters are described in the caption of Fig. 2.

In contrast, Fig. 3 shows a similar powerspectrum for *l=0, n=12,14,15,17,18,19* (averaged). These modes do not show peaks at or close to the solar rotation frequency. The same applies for the remaining modes we have investigated closely *l=0, n=23-32*.

We have also applied the same analysis to MDI/SOI velocity data (LOI proxy). We see the same modulation of *l=0, n=21-22*, but the effect is not so apparent at *n=13* and *n=16*. For *l=0, n=21,22* there is a striking similarly between the mode amplitude as observed in irradiance and velocity. Fig. 4 shows a portion of the mode amplitude timeseries for *l=0, n=22*. The mode amplitude as observed in irradiance with VIRGO/SPM is shown in solid line and the mode amplitude as observed in SOI/MDI velocity is shown in dashed line. In the plot the two timeseries have been scaled to the RMS of the signal.

The fact that we observe very similar modulation in the mode amplitude as observed in irradiance and in velocity strengthens the conclusion that the observed modulation is not an effect of irradiance fluctuations due to active regions passing the solar disk, but rather a modulation of the modes themselves.

The cross-correlation of the amplitude modulation of the modes between the north and south pixels of LOI have been computed in order to check the possible direct influence of active regions in the field of view on the mode amplitude modulation. As shown in Fig. 5 the correlation is very high, and this clearly shows the global nature of the observed rotational modulation.

The *l=1-2* modes have been studied in a similar fashion in both LOI radiance and MDI velocity data. We do not find significant peaks at the solar rotation frequency for these modes.

4. CONCLUSIONS

The amplitudes of the *l=0, n=13,16,21,22* modes show a strong modulation at the solar siderial rotation frequency representative of the latitude of the dominant activity. The amplitude of the modulation changes with the solar activity and the frequency shifts as the dominant region of activity shifts to higher latitudes. The effect is shown to be global in nature and is seen in both irradiance and velocity. The amplitude modulation of the modes observed with VIRGO and MDI are astoundingly similar.

The amplitude of the rotational modulation is correlated to the global activity level as described by the global solar magnetic field.

A rotational modulation of *l=0* modes is rather surprising as these modes should be insensitive to rotation. The fact that we observe the solar siderial rotation frequency rather than the synodic rotation frequency strongly indicates that the observed amplitude modulation of the modes is a real modulation of the modes by solar activity and not an observational effect. This is also strongly supported by the nearly identical modulation observed in the VIRGO and MDI data. The visibility effect of an active region rotating over the visible hemisphere is distinctively different in intensity and Doppler shift measurements.

If the symmetric *l=0* modes are modulated by activity the view–angle will not be important. In contrast when we observe the modulation of the solar irradiance as solar activity rotates on the solar disk, the Earth's (and thereby SOHO's) position will modify the observed frequency and we see the synodic rotation frequency.

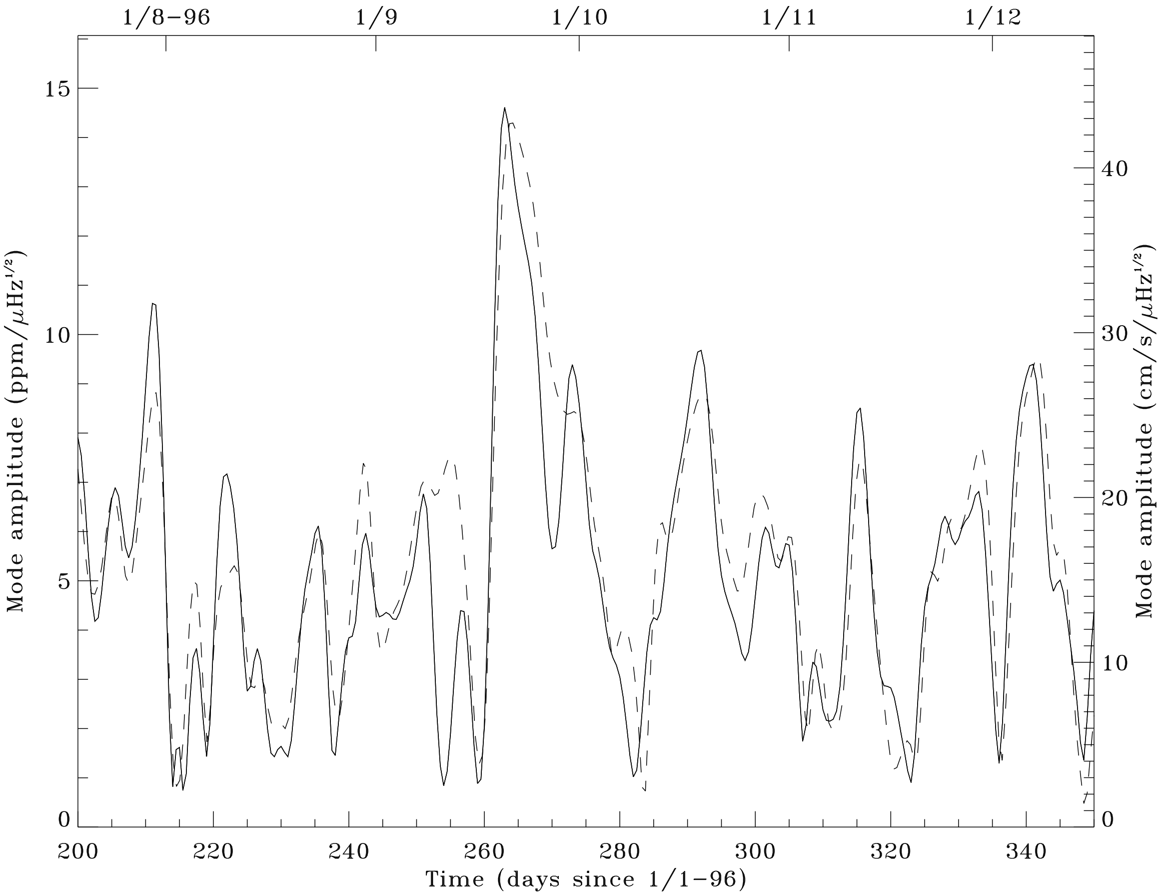

Figure 4. The mode amplitude as function of time for the l=0, n=22 mode as observed in VIRGO/SPM blue channel irradiance (solid line) and SOI/MDI velocity (dashed line) The two timeseries have been scaled to the RMS values. The difference between the signals at days 251-255 is due to a gap in the VIRGO observations.

The mechanism behind this observed rotational modulation and clear connection to solar activity of certain *l=0* modes is so far unknown. One should bear in mind that the modes are not observed directly, but rather the response of the solar atmosphere to the modes. How this should effect only some of the *l=0* modes is hard to see, and we suspect that the explanation lies elsewhere.

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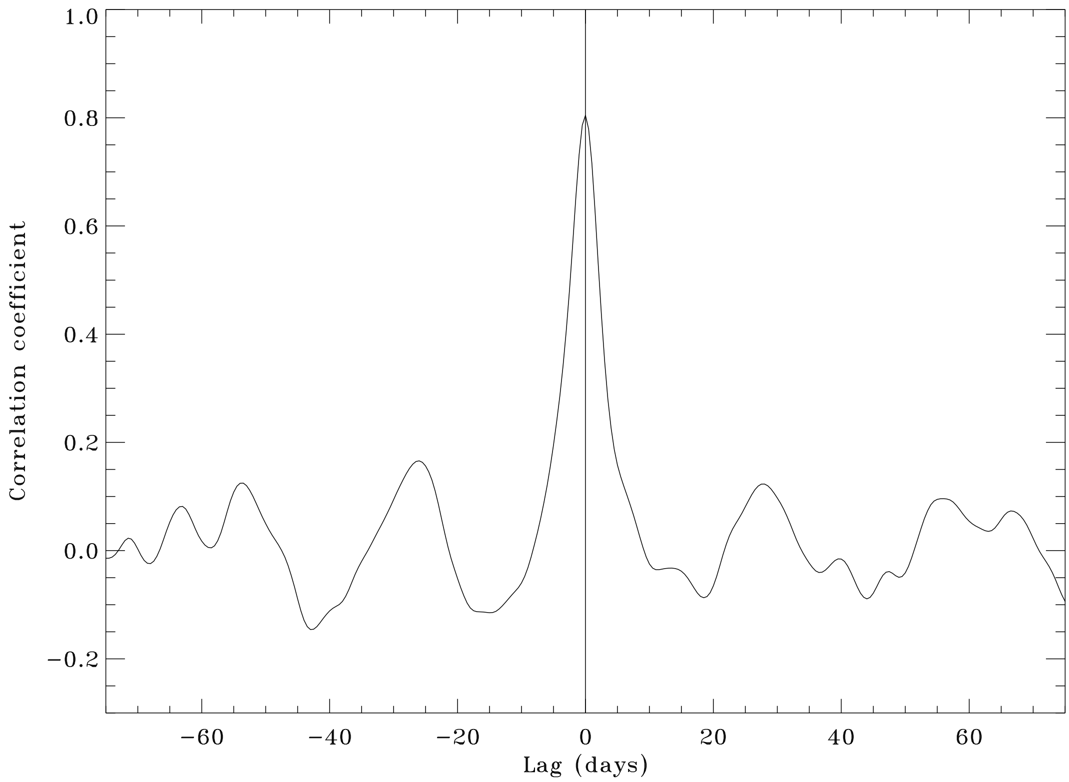

Figure 5. The cross-correlation function of the amplitude modulation for the l=0, n=22, mode observed for the north and south halves of the solar disk.

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