Helioseismic Diagnostics of Solar Flares

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- Helioseismology: Are flares efficient exciters of helioseismic modes? For which modes? How are the modes damped?

- Flare physics: Is this mechanism efficient? For which modes? How much energy is deposited, when and where?

- Wave physics: How are the helioseismic modes excited by coherent, large-scale events (compared to the stochastic excitation due to high-velocity downflows and entropy fluctuations below the surface)?

Flares and Low Spatial-Degree Modes (1)

Several authors have investigated a possible correlation between solar activity and solar *p*-mode amplitudes: Gavryuseva & Gavryusev, Baudin & Finidori, Richardson *et al.*, Karoff & Kjeldsen (ApJ, 2008). This latter work shows apparently convincing evidence:

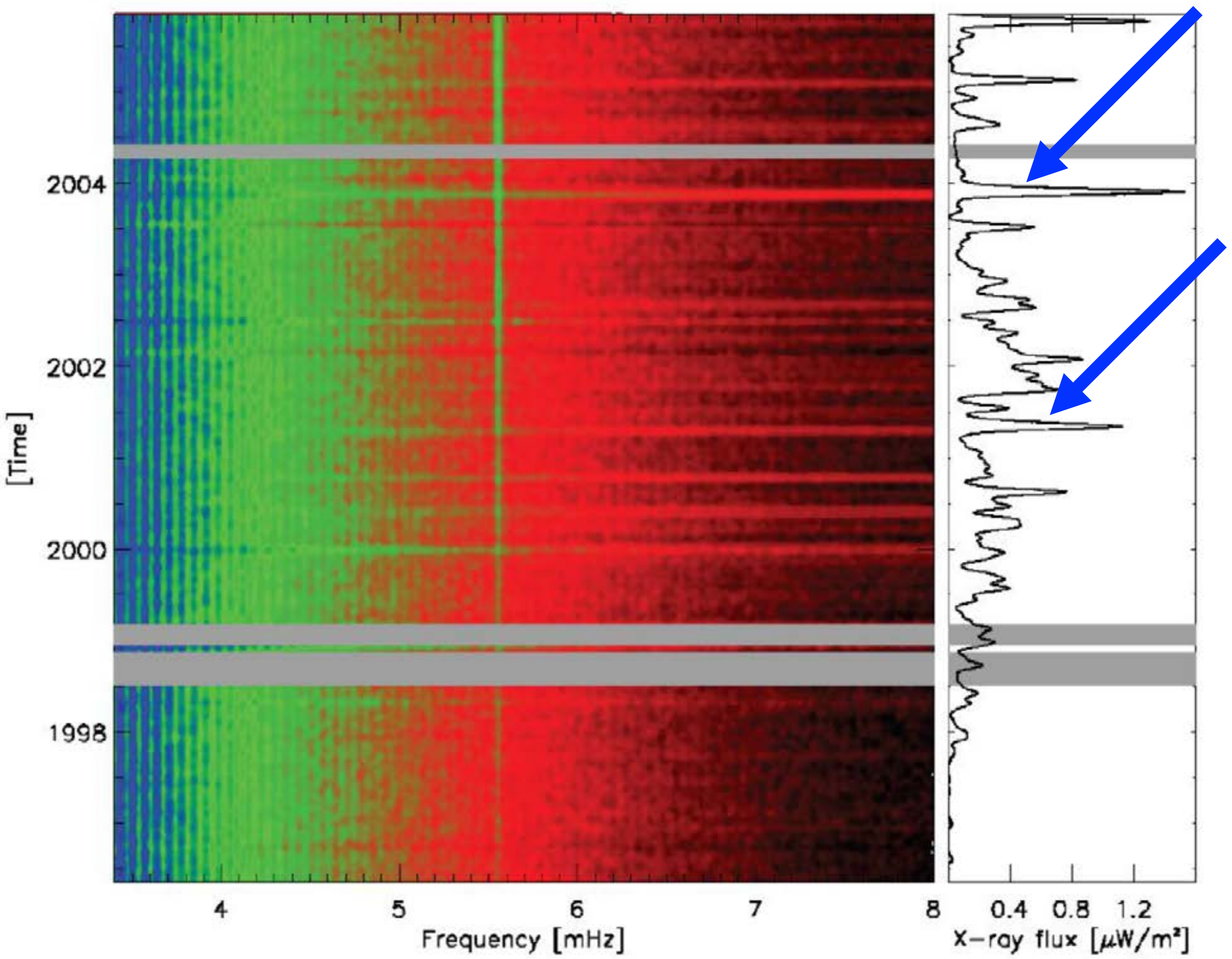

Fig.1: Fig.2 of Karoff & Kjeldsen, showing a 2D spectrum of the intensity variations (SOHO/VIRGO) and on the right the X-ray flux variations (GOES). Two examples (blue arrows) exhibit localized maximum of power in the 2D spectrum <u>and</u> the X-ray flux.

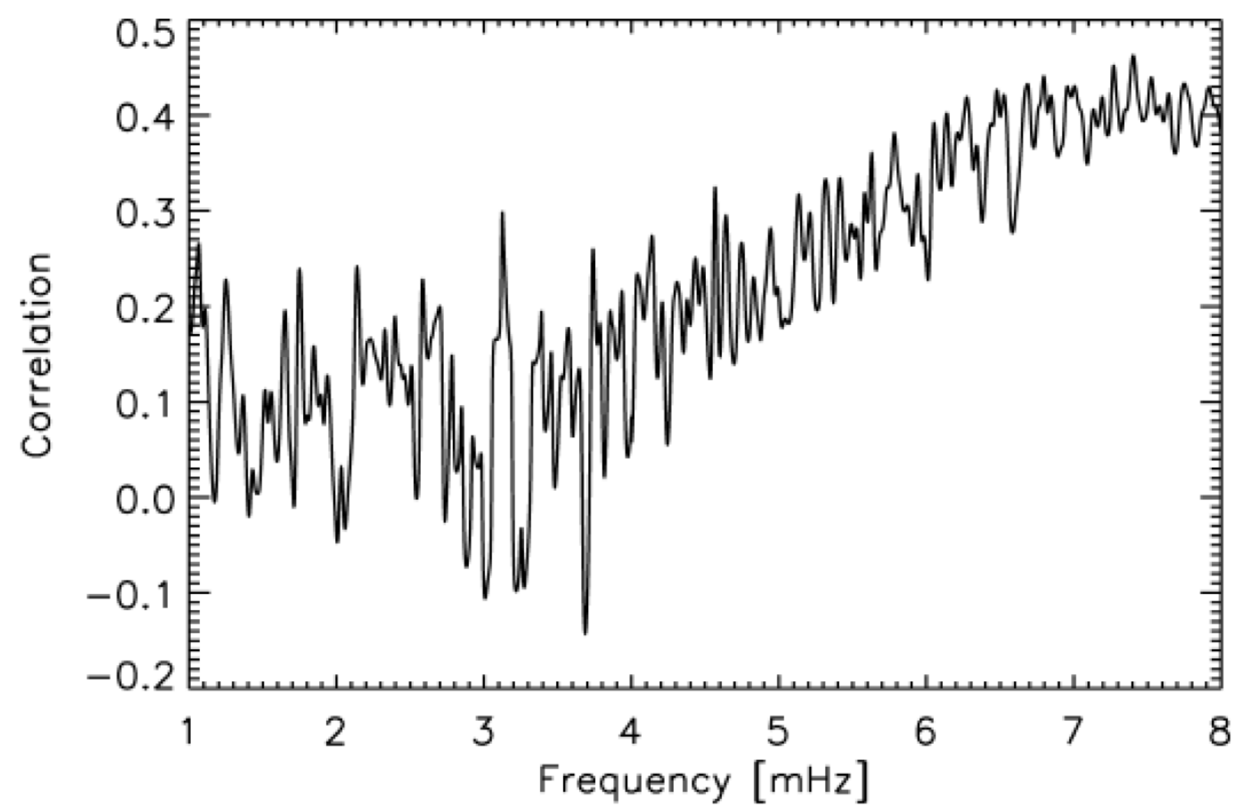

Fig.2: Fig.5 of Karoff & Kjeldsen showing the variation with frequency of the correlation between intensity variation power and X-ray flux, with a clear increase toward higher frequencies.

Flares and Low Spatial-Degree Modes (2)

However, excluding the two most powerful flaring events (Fig.3), the correlation decreases very notably. Moreover, when filtering the long-term trends (way below the *p*-mode frequency range) in the intensity signal, the correlation disappears completely (Fig.4).

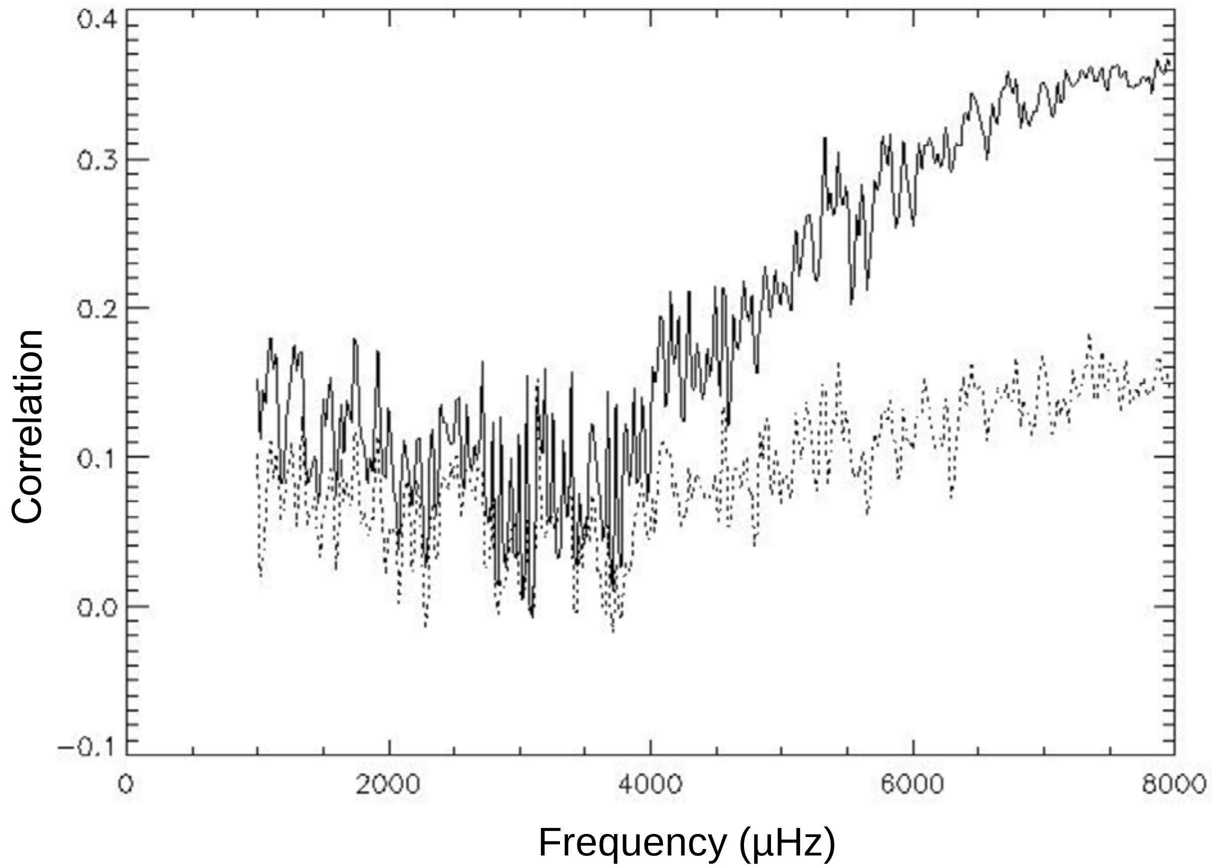

Fig.3: similar to Fig.5 of Karoff & Kjeldsen (solid line) with the same correlation computed when excluding the two most powerful events (dotted line)

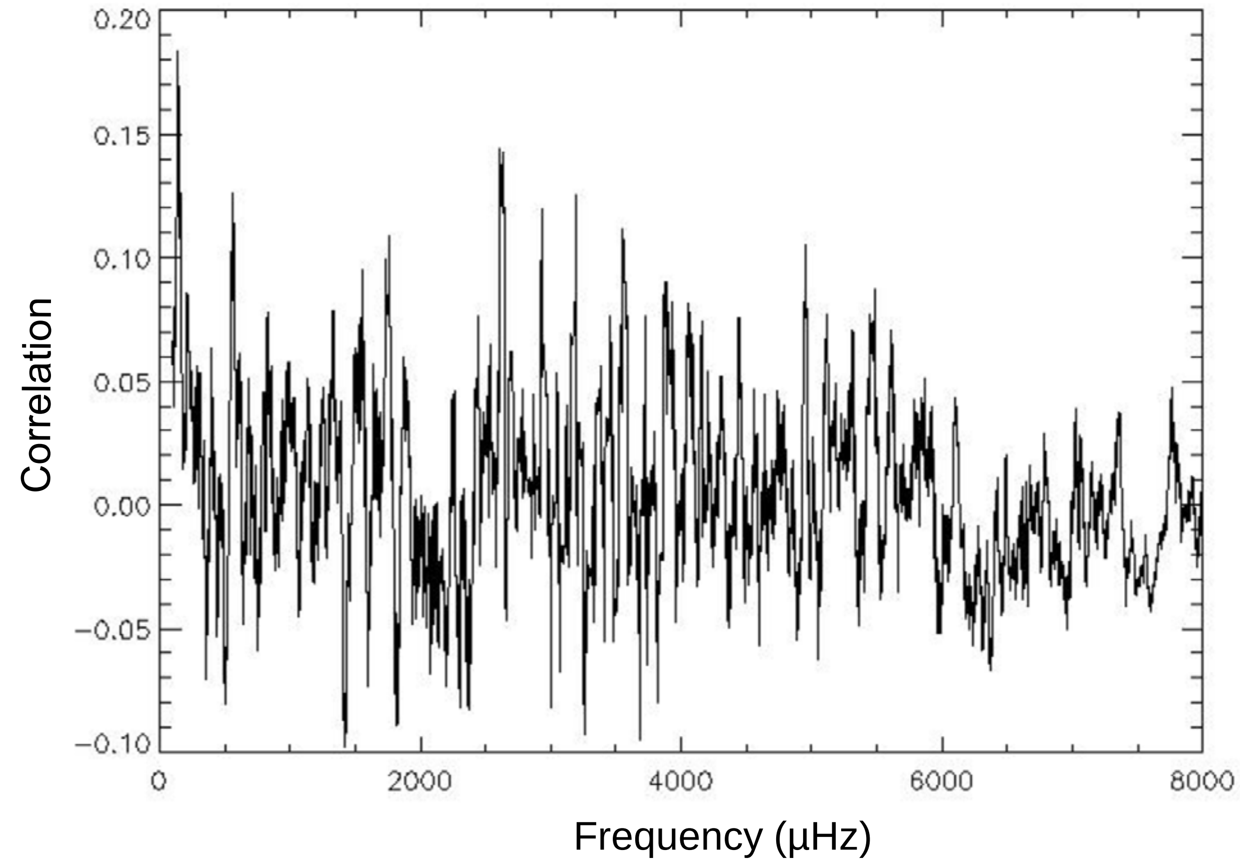

Fig.4: similar to Fig.3 but using a high-pass filtered intensity signal

In conclusion, it seems that the observed correlation is not robust against some simple filtering that suggests that the origin of the correlation lies in the long-term trends of the signal and not the *p*-mode signal.

Flares and Higher Spatial-Degree Modes (1)

Many authors have searched for a flare signature in *p*-mode amplitudes. The famous Halloween event was particularly studied. For example, Maurya *et al.* (*ApJ*, 2009) used mode fitting to show an increase of amplitude after the 28 October flare. However, fitting of data acquired during flares can be difficult (perturbed spectrum). We confirm the amplitude increase by using simple ℓ--ν diagrams from GONG data:

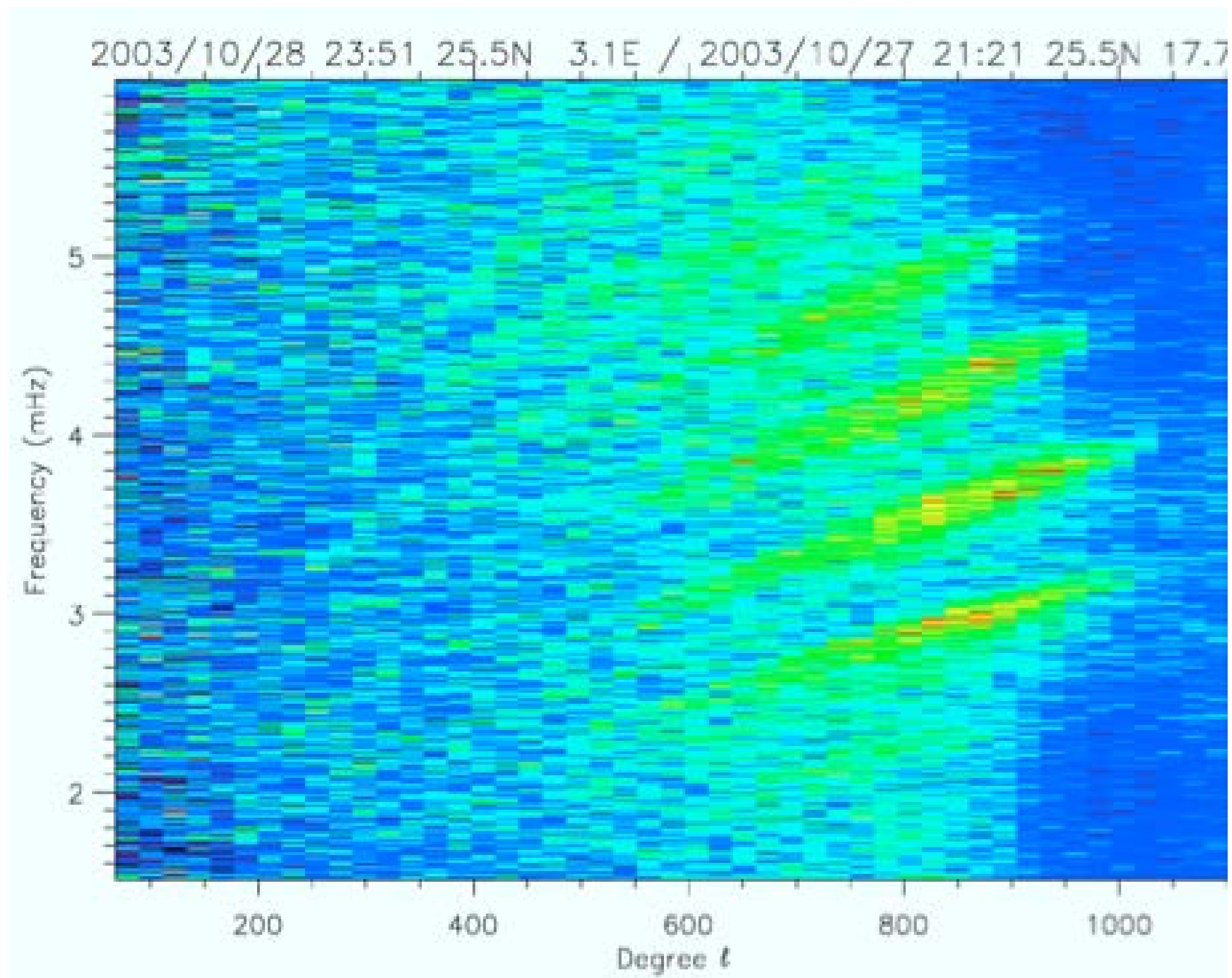

Fig.5: ratio of ℓ–ν diagrams from before and after the flare, showing a clear increase for higher-ℓ modes.

Flares and Higher Spatial-Degree Modes (2)

The amplitude enhancement can be seen for a given value of ℓ (450 in the figure below). For this ℓ value, the enhancement is about 30% and shows no mode structures.

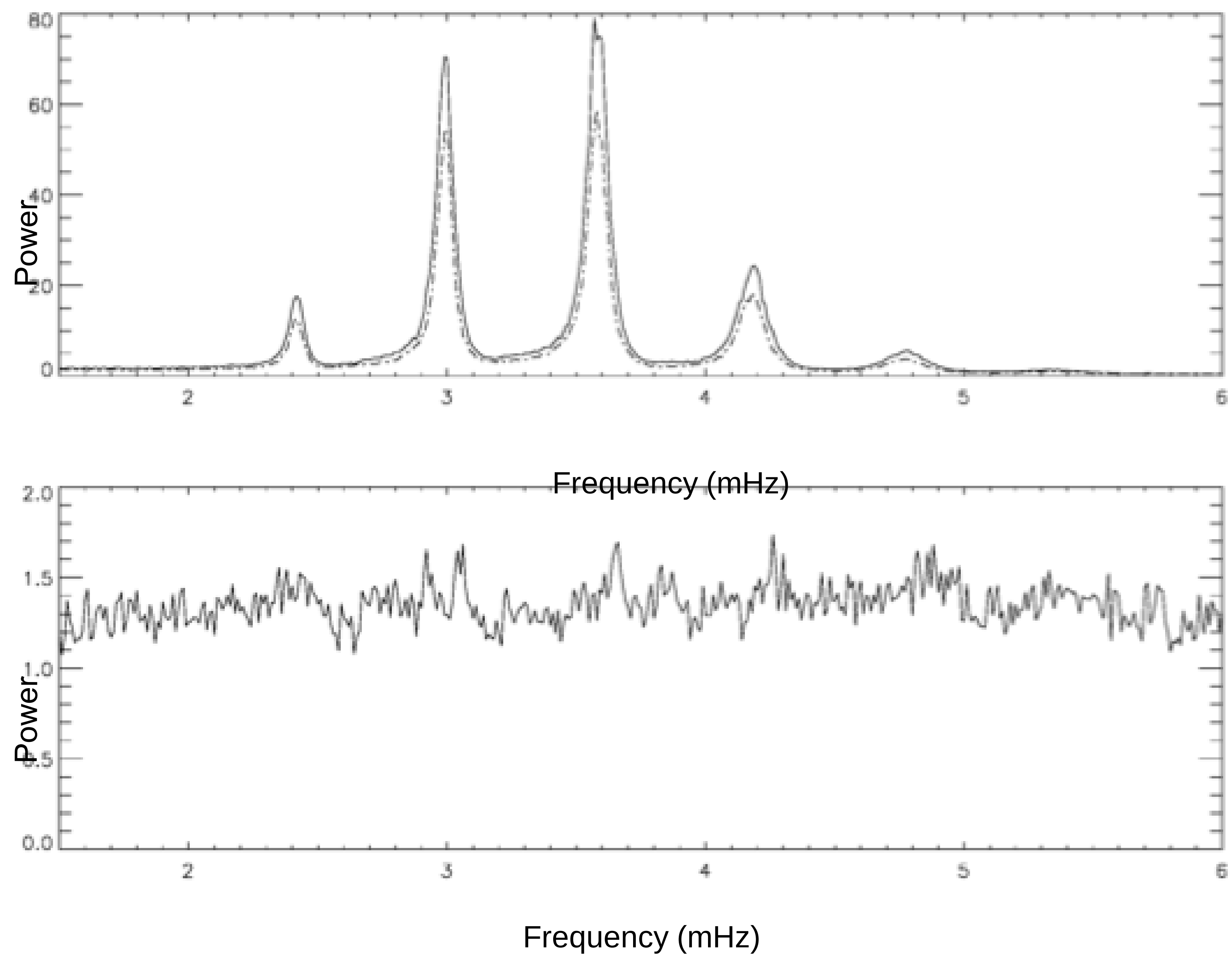

Fig.6: Above: cuts in the ℓ–υ diagrams before (dash-dotted line) and after (solid) the flare; Below: ratio of the two profiles.

Flares and Higher Spatial-Degree Modes (3)

The amplitude enhancement is not always simple and regular at all frequencies: it can present important variations in the mode profile as seen in Fig.7.

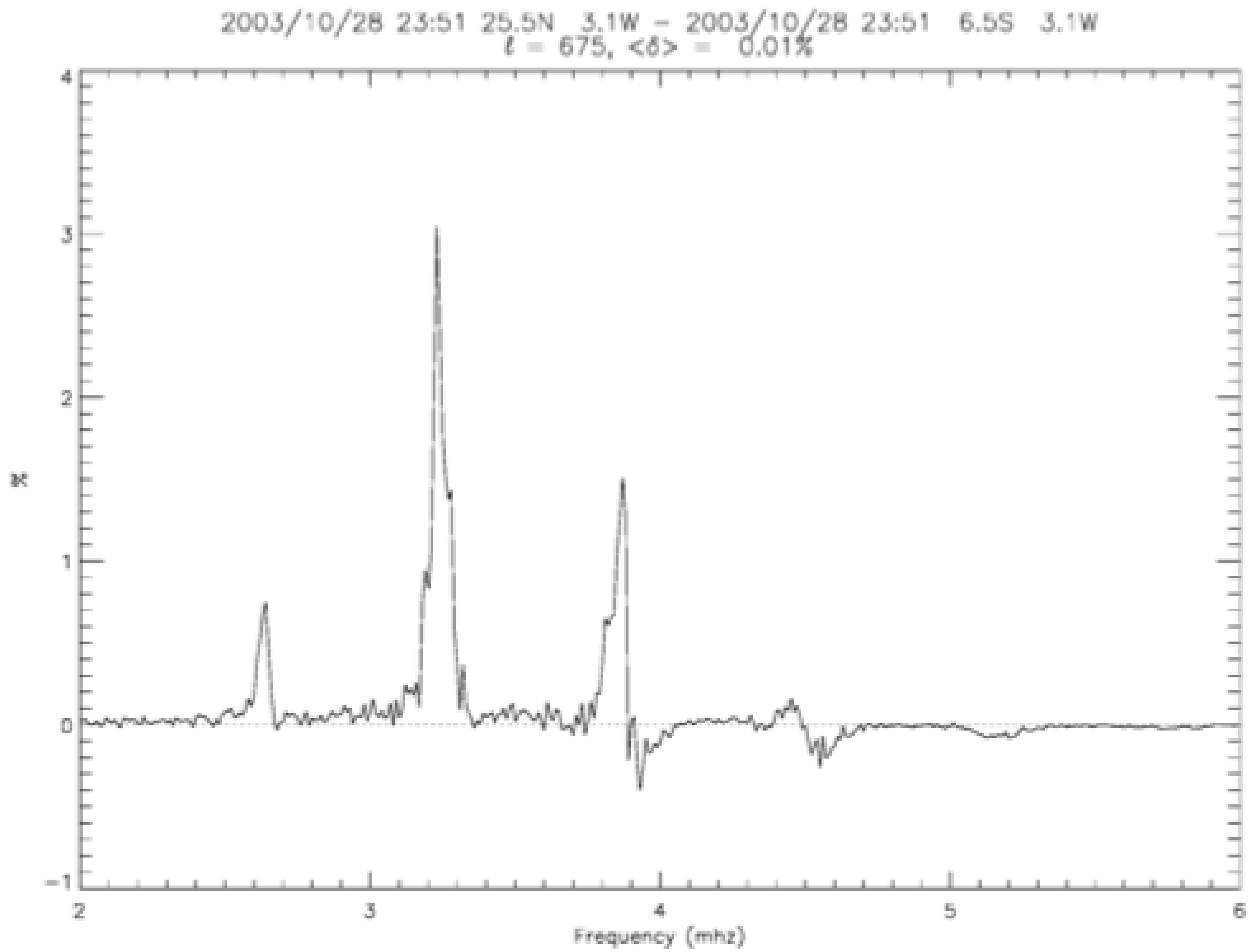

Fig.7: Relative amplitude variation for ℓ = 675 showing more complicated patterns.

Conclusion and Perspectives

• Looking for correlation between seismic oscillations and indexes related to solar activity can be tricky, which leads us to consider an artifact origin for some observed correlation for low spatial degree modes ($\ell \leq 2$).

• We confirm that high-ℓ modes show amplitude enhancement as a signature of flare (in the case of the famous Halloween flare of October 2003 but other cases not shown here exhibit a similar enhancement).

• These results have to be extended/confirmed with MDI and/or HMI data, studying a larger spatial and temporal extent in order to improve spatial and temporal flare signature description.

• Physical understanding of this enhancement will be investigated, in particular by checking the influence of mode inertia and altitude of the upper turning point of the mode cavity.

Acknowledgments

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