Short- and mid-term activity-related variations in the solar acoustic frequencies

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Abstract

The activity-related variations in the solar acoustic frequencies have been known for 30 years. However, the importance of the different contributions is still not well established. With this in mind, we developed an empirical model to estimate the spot-induced frequency shifts. We also propose a new observable to investigate the short- and mid-term variations of the frequency shifts.

Model frequency shifts

Spot-induced frequency shifts, $\delta\nu_{\rm spots}$:

- ⋆ spots affect the propagation of acoustic waves
- ⋆ that perturbation can be expressed by the phase difference, $\Delta\delta$, between the wave solutions inside the spot and outside
- ⋆ we assume that $\Delta\delta$ can be approximated by a characteristic phase difference, $\Delta\delta_{\rm ch}$, equal for all spots
- ⋆ we derived a relation for the frequency shifts, $\delta\nu$, following the approach by Cunha & Gough (2000)

$$\frac{\delta\nu_{lm}}{\nu_{lm}}(t) \propto -\Delta\delta_{\rm ch} \sum_{i=1}^{N(t)} \left[\left(P_l^m(\cos\theta_i)\right)^2 A_i \right]$$

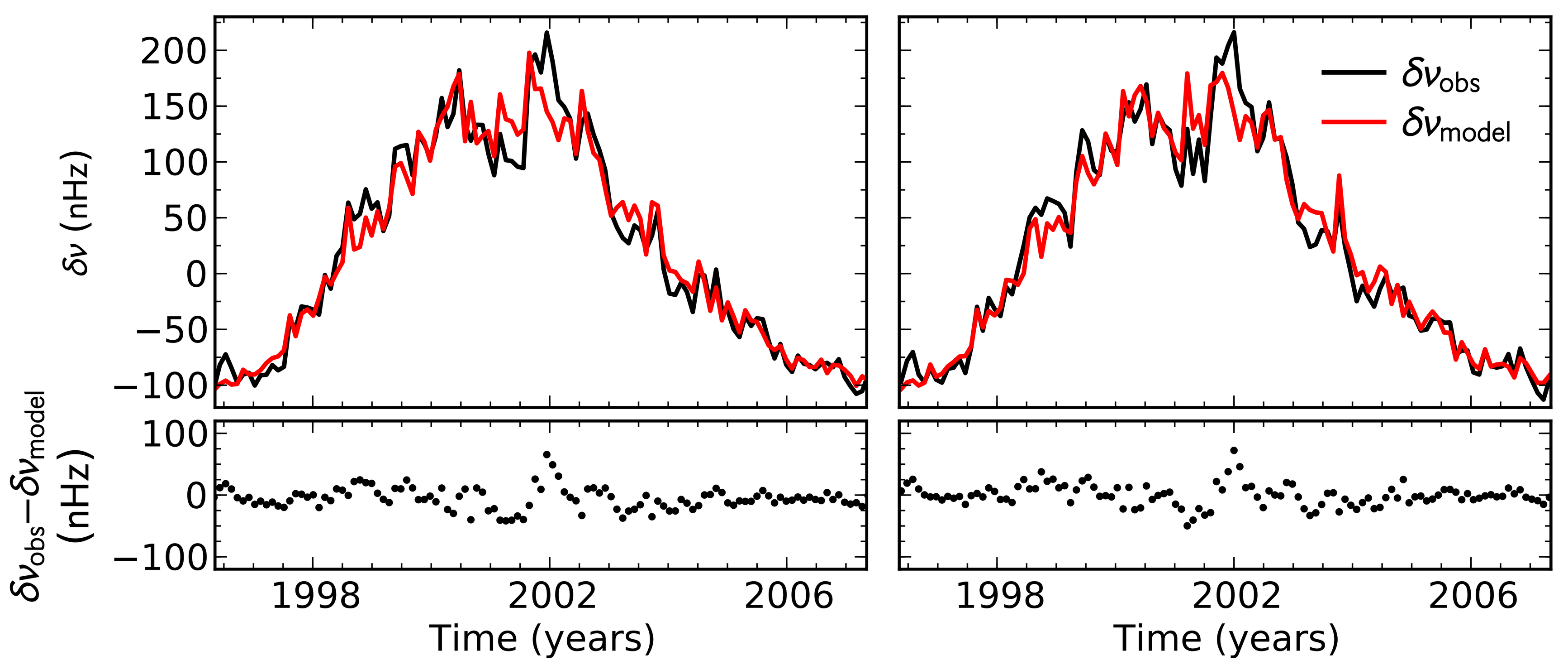
- ∗ l and m: mode angular degree and azimuthal order
- ∗ P_l^m: Legendre polynomials
- ∗ $N(t)$: number of spots at a given time t
- ∗ θ_i and A_i: colatitude and area of a given spot i

$$\delta\nu_{lm} \Rightarrow \delta\nu_l \Rightarrow \delta\nu_{\rm spots}$$

Total model frequency shifts, $\delta\nu_{\rm model}$:

$$\delta\nu_{\rm model} = \delta\nu_{\rm global} + \delta\nu_{\rm spots}$$

$\delta\nu_{\rm global} \equiv$ global component varying on the 11-yr time scale, related to the overall magnetic field



Observed (black; Tripathy et al. 2011) and model (red; using the daily spot records from NGDC/NOAA) frequency shifts for the two independent sets of $\delta\nu$: the observations have a cadence of 36 d and an overlap of 18 d.

Weighted sum of the $\delta\nu$-differences

- ⋆ the area covered by spots, $A_{\rm T}$, varies on a time-scale of days
- ⋆ such short-term variations are expected to be the main source of the 36-d variations seen in $\delta\nu_{\rm obs}$

Weighed sum of the $\delta\nu$-differences, $W_{\rm D}$:

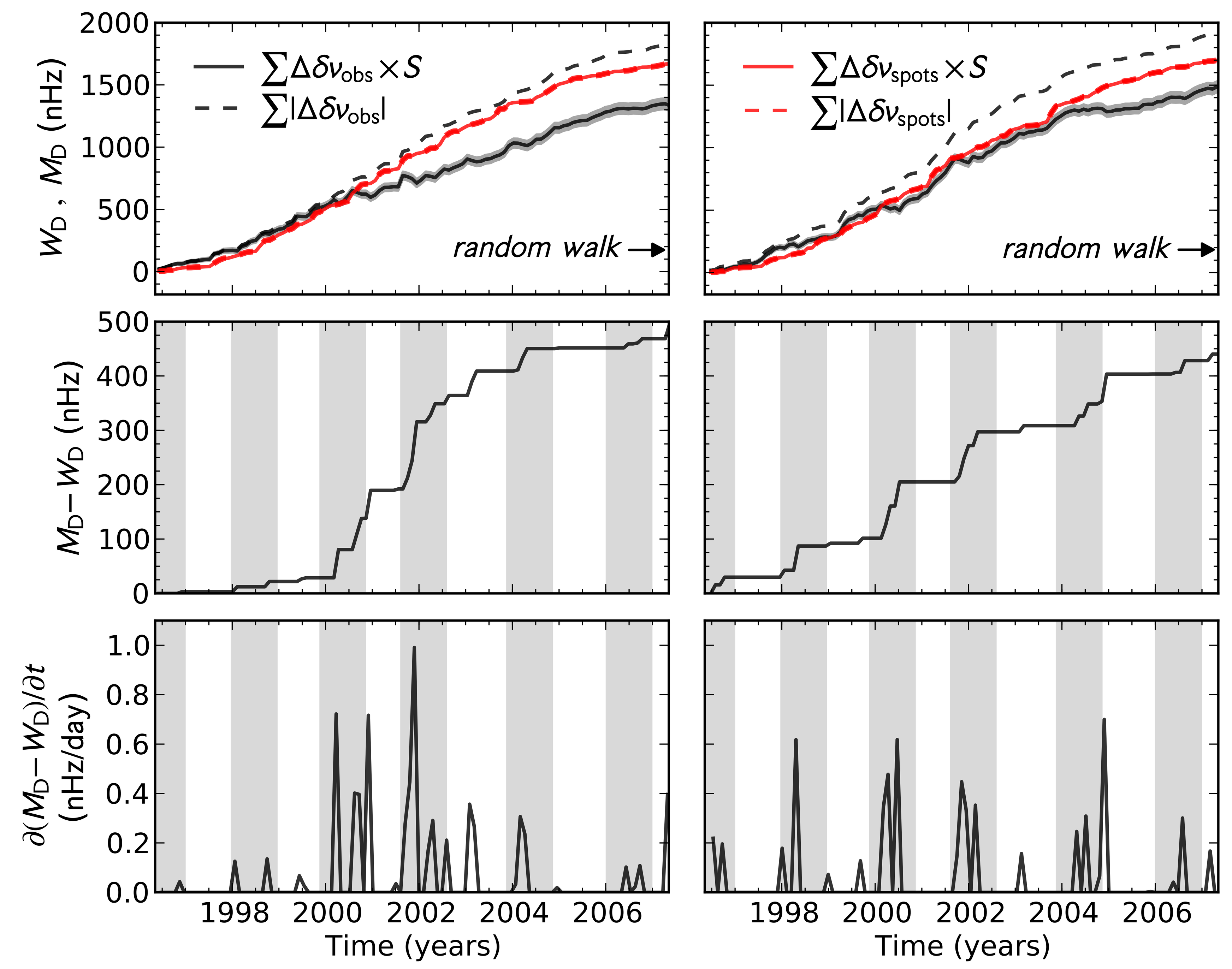
$$W_{\rm D} = \sum_k \Delta\delta\nu_k \times S_k$$

- ∗ $\Delta\delta\nu_k$: $\delta\nu$-difference measured in two consecutive data bins
- ∗ S_k: weight determined by the spot area variations, $\Delta A_{\rm T}$
  - $\Delta A_{\rm T} > 0 \Rightarrow S_k = 1$
  - $\Delta A_{\rm T} < 0 \Rightarrow S_k = -1$
- ∗ insensitive to the long-term variations in the frequency shifts

Sum of the absolute (modulus) $\delta\nu$-differences, $M_{\rm D}$:

$$M_{\rm D} = \sum_k |\Delta\delta\nu_k|$$

- ∗ case of complete correlation between $\Delta\delta$ and $\Delta A_{\rm T}$



__Top:__ $M_{\rm D}$ (dashed) and $W_{\rm D}$ (solid) for $\delta\nu_{\rm obs}$ (black) and $\delta\nu_{\rm model}$ (red). Grey region: 1σ interval resulting from the observational errors. Arrow: standard deviation for a random walk. __Middle:__ Difference between the quantities $M_{\rm D}$ and $W_{\rm D}$ for $\delta\nu_{\rm obs}$. __Bottom:__ Time derivative of the difference shown above. The grey vertical bars mark the maxima of the quasi-biennial signal.

- ⋆ the short-term variations in $\delta\nu_{\rm obs}$ and $A_{\rm T}$ are strongly correlated
- ⋆ $\delta\nu_{\rm obs}$ and $A_{\rm T}$ behave differently around the maxima of the quasi-biennial signal found by Broomhall et al. (2012)
- ⋆ we find that the loss of correlation cannot be fully explained by the errors on $\delta\nu_{\rm obs}$ and the spots on the far-side of the Sun

Conclusions

- ⋆ the sunspot contribution to the observed frequency shifts is roughly 30%
- ⋆ the component responsible for the loss of correlation between $\Delta\delta\nu_{\rm obs}$ and $\Delta A_{\rm T}$ should vary in short time-scales being modulated by the mid-term (quasi-biennial) signal
- ⋆ there is a mid-term contribution to $\delta\nu_{\rm obs}$ that is not accounted in the sunspot data

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