Constraining surface-effect corrections for solar-like oscillations using 3D hydrodynamical simulations

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Surface effects on solar-like oscillations

- **Good mode identification of solar-like oscillations is expected to be powerful for seismic inference.**
- **"Surface effects" prevent us from making the best of the high precision.**
  - **Poor modelling (of turbulent pressure) in near-surface regions**
  - **Systematic differences between observed and model frequencies for the Sun**

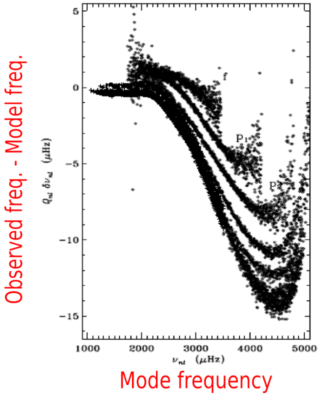

Figure : Solar case (Rosenthal+ 1999)

Empirical correction of model frequencies

- **Kjeldsen+ (2008) proposed an empirical power-law correction,**

$$\nu_{\rm obs} - r\nu_{\rm ref} = a\left(\frac{\nu_{\rm obs}}{\nu_0}\right)^b,$$

with $b = 4.9$ calibrated to the Sun.

- **Many studies adopted this functional and this value of b to correct model frequencies of other stars.**

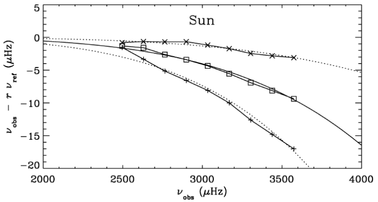

FIG. 1.—Difference between observed and calculated frequencies for radial modes in the Sun. The squares are for model S, with the solid curve showing a fit to eq. (4) with $r = 1$, which gives $b = 4.90$ (see § 3). Also shown are the results of applying the same corrections to model S^- (*crosses*) and model S^+ (*pluses*). The dotted curves show the corrections calculated from eq. (4).

Figure : Kjeldesen+(2008)

Considerations of surface effects for the Sun

- **Effects of modelling of equilibrium structure (e.g. Christensen-Dalsgaard+1997, Rosenthal+1999, Houdek+2010)**
- **Effects of modelling of eigenmodes**
  - **Wave propagation through convective flows (e.g. Bhattacharya+2015)**
  - **Non-adiabatic effects with TDC (e.g. Houdek+2010, Grigahcene+2013)**

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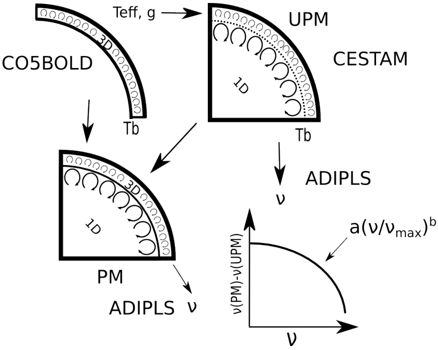
⇒ **Aim of this work**

Constrain surface-effect correction using set of 3D simulations across $T_{\rm eff} - g$ plane

Method

Fit the correction functional to the frequency difference between realistic models (patched models, PMs) and standard models (unpatched models, UPMs).

- **CO^5BOLD (Freytag+2012) with CIFIST grid (Ludwig+2009) for 3D hydrodynamic simulations**
- **CESTAM (Marques+2013) for 1D standard models**



Validity of PM

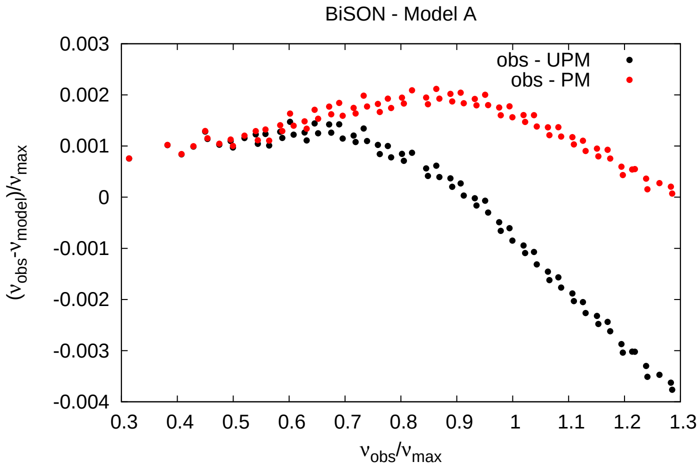


Figure : Frequency differences between BiSON frequencies (Table 3 of Broomhall et al. (2009)) and PM or UPM for model A ($T_{\rm eff} = 5775$ K, $\log g = 4.44$), which is close to the Sun.

Fit to frequency differences between PM and UPM

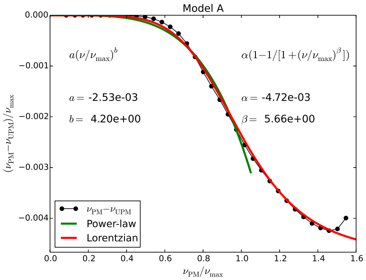


Figure : Model A ($T_{\rm eff} = 5775$ K, $\log g = 4.44$, close to the Sun)

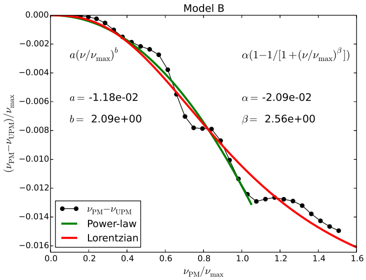


Figure : Model B ($T_{\rm eff} = 6725$ K, $\log g = 4.25$)

- **Power law (Kjeldsen+ 2008)**

$$\frac{\delta\nu}{\nu_{\rm max}} = a\left(\frac{\nu}{\nu_{\rm max}}\right)^b$$

- **Modified Lorentzian function**

$$\frac{\delta\nu}{\nu_{\rm max}} = \alpha\left[1-\frac{1}{1+(\nu/\nu_{\rm max})^\beta}\right] \quad \left[\rightarrow \alpha\left(\frac{\nu}{\nu_{\rm max}}\right)^\beta \quad (\nu \ll \nu_{\rm max})\right]$$

a and α in $T_{\rm eff} - g$ plane

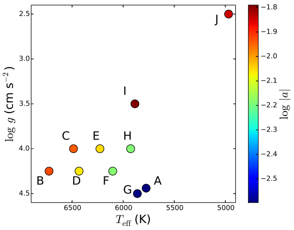


Figure : $a(\nu/\nu_{\rm max})^b$

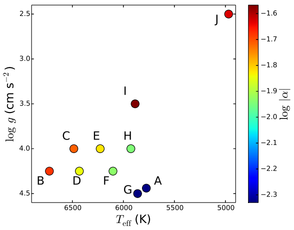
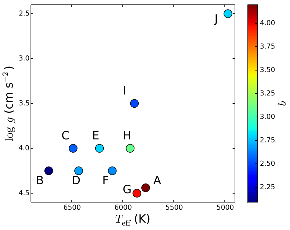


Figure : $\alpha(1 - 1/[1 + (\nu/\nu_{\rm max})^\beta])$

$$\log(-a) = 8.13 \log T_{\rm eff} - 0.670 \log g - 30.2$$

$$\log(-\alpha) = 7.69 \log T_{\rm eff} - 0.629 \log g - 28.5$$

b and β in $T_{\rm eff} - g$ plane



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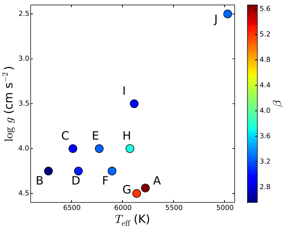


Figure : $\alpha(1 - 1/[1 + (\nu/\nu_{\rm max})^{\beta}])$

$$\log b = -3.16 \log T_{\rm eff} + 0.184 \log g + 11.7$$
$$\log \beta = -3.37 \log T_{\rm eff} + 0.218 \log g + 12.4$$

- **Change by a factor of** $\simeq 2$

$\rightarrow$ **the solar calibrated index should not be used for other stars.**

Lorentzian has smaller deviation than power law not depending on fitting ranges.

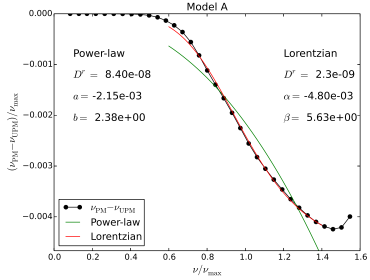


Figure : Fit in range $0.6 < \nu/\nu_{\rm max} < 1.4$

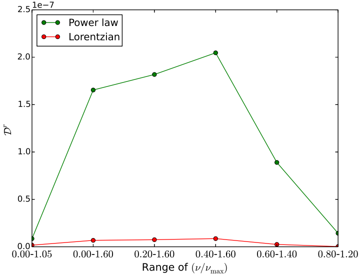


Figure : Deviation of fitting functions

Reduced deviation from the fitting functions $\delta\nu_i$:

$$\mathcal{D}^r = \frac{1}{N}\sum_i^N \left[\frac{\nu_{\mathrm{PM},i} - \nu_{\mathrm{UPM},i} - \delta\nu_i}{\nu_{\max}}\right]^2 \quad (i\text{: label of modes})$$

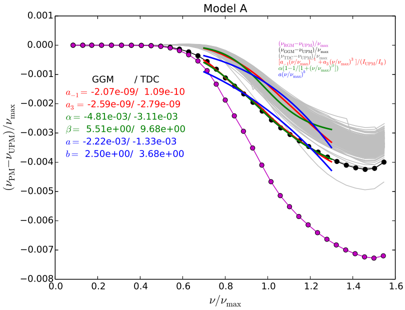
Conclusion

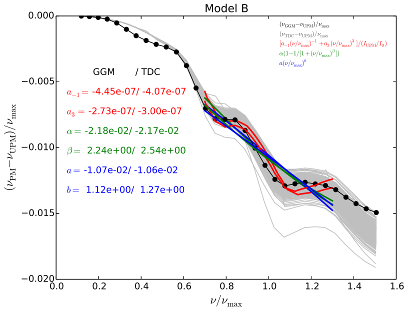
- **The power indices of the frequency corrections certainly depend on $T_{\rm eff}$ and g.**
- **The Lorentzian is nicely fitted to the frequency difference between PM and UPM and is less sensitive to the frequency range than the power law.**

Ongoing work

- **Include perturbation of turbulent pressure and non-adiabatic process with TDC formalism using MAD code.**

[Preliminary] Adiabatic TDC treatment (turbulent pressure perturbation included)





Dependence of *a*, α, *b* and β on fitting range

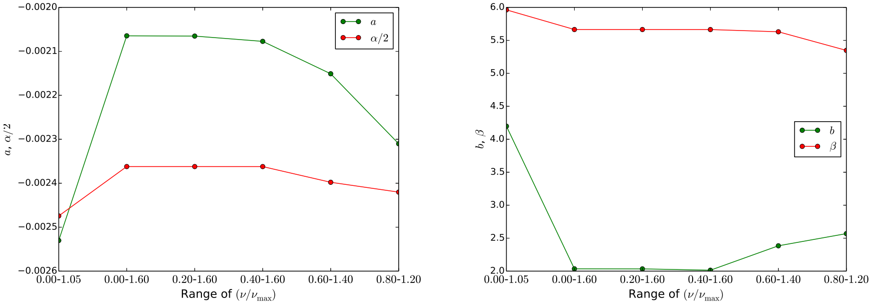
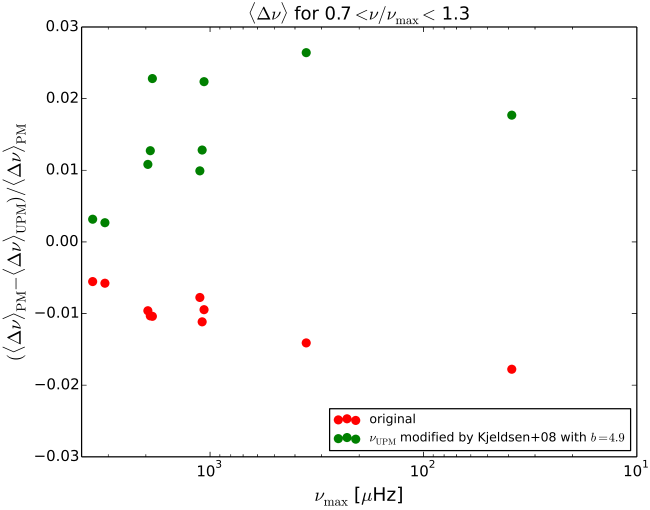
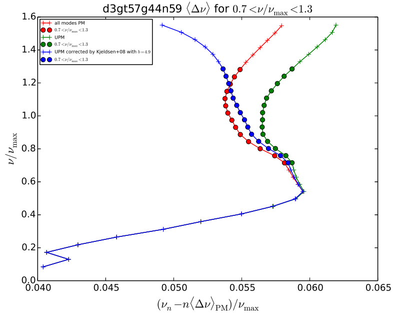


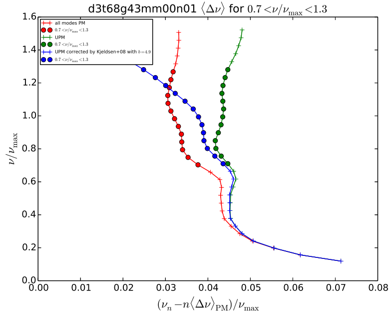
Figure : Model A

Effect of surface-effect correction on difference in large seperation between PM and UPM



Effects of surface-effect correction in Echell diagrams





[Preliminary] Ball & Gizon (2014) fit

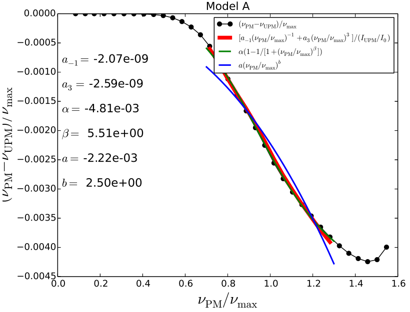


Figure : Model A (the Sun, $T_{\rm eff} = 5775$K, $\log g = 4.44$)

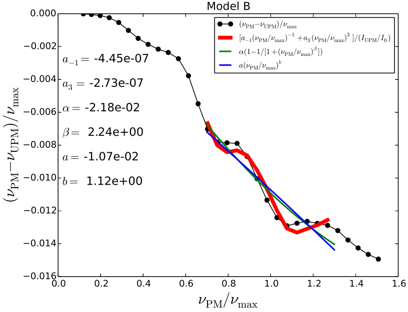
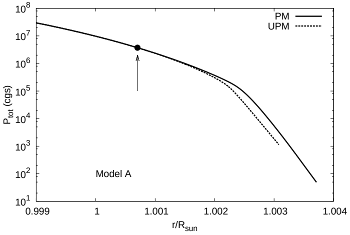
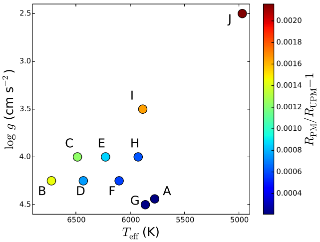


Figure : Model B ($T_{\rm eff} = 6725$K, $\log g = 4.25$)

Elevation of outer layer due to turbulent pressure





Larger elevation with increasing $T_{\rm eff}$ or decreasing g, since

- $T_{\rm eff}\uparrow \Rightarrow$ **superadiabaticity**$\uparrow \Rightarrow v_{\rm conv}\uparrow$
- $g\downarrow \Rightarrow \rho\downarrow \Rightarrow v_{\rm conv}\uparrow$

$\Rightarrow P_{\rm turb}/P_{\rm tot}\uparrow$