A fitting LEGACY – modelling *Kepler*'s best stars

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The LEGACY sample

The LEGACY sample represents the best solar-like stars observed in the *Kepler* mission (Lund et al. 2016; in prep., Silva Aguirre et al. 2016; in prep.). The 66 stars in the sample are all on the main sequence or only slightly more evolved. They each have more than one year's observation data in short cadence, allowing for precise extraction of individual frequencies; none of the stars exhibit properties of mixed modes. Here we present model fits using a modified ASTFIT procedure employing two different near-surface effect corrections, one by Christensen-Dalsgaard (2012) and a newer correction proposed by Ball & Gizon (2014). We then compare the results obtained using the different corrections.

Model fitting

We use a model fitting procedure, which combines the Aarhus stellar evolution code (Christensen-Dalsgaard 2008a) with the Aarhus adiabatic oscillation package (Christensen-Dalsgaard 2008b) to fit individual model frequencies within a grid of stellar models. The grid was computed as described for ASTFIT in Silva Aquirre et al. (2015) with the following exceptions: The heavy-element mixture was based on Grevesse & Noels (1993), taking the solar surface ratio between the abundances of heavy elements and hydrogen as $Z_\mathrm{s}/X_\mathrm{s} = 0.0245$. The heavy-element abundance ranged from $Z = 0.0032$ to 0.059, relating Y and Z by $\Delta Y/\Delta Z$ values varying between 1 and 2, in steps of 0.2. Diffusion and settling were not taken into account. Two different surface effect corrections were used:

a: A correction based on a scaled solar fit (see Christensen-Dalsgaard 2012). This works very well for other stars with masses close to $\mathrm{M}_\odot$, but falls increasingly short for heavier, and consequently hotter, stars as seen in Figure 1.

b: A recent correction presented by Ball & Gizon (2014); $\delta\nu = (\alpha(\nu/\nu_\mathrm{ac})^{-1} + \beta(\nu/\nu_\mathrm{ac})^3)/\mathcal{I}$. It is based on calculations by Douglas Gough (1990) to explain solar cycle frequency variations, and includes two terms; one representing a frequency shift due to the increase in pressure scale height that would arise from better modelling of convection and another term correcting for a frequency shift caused by magnetic fields affecting the sound speed without changing the density stratification.

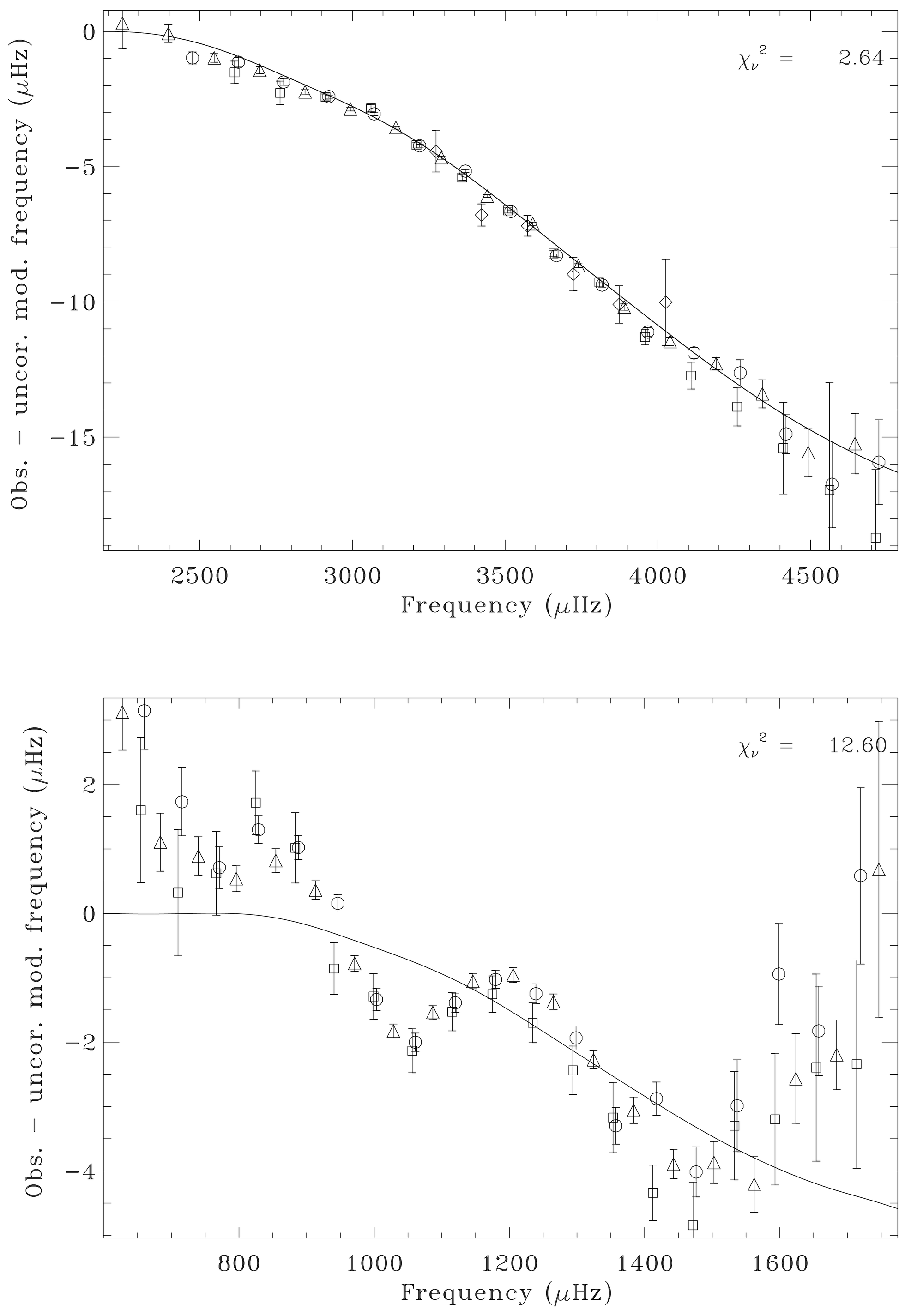

Fig. 1 – *Scaled solar fit applied to models of two different stars. The fits pertain to the models with the lowest combined χ^2. The contribution from the frequency fit χ^2_ν is shown in the upper right corner.* ***Top panel:****. Surface effect correction for a $0.97\mathrm{M}_\odot$ model with $T_\mathrm{eff} = 5465.9\mathrm{K}$.* ***Bottom panel:*** *Surface effect correction for a $1.47\mathrm{M}_\odot$ model with $T_\mathrm{eff} = 6275.8\mathrm{K}$.*

Results

The best fitting model is found by minimizing $\chi^2 = \chi^2_\mathrm{spec} + \chi^2_\nu$, where χ^2_spec indicates the contribution from fitting spectroscopic data (T_eff and $[\mathrm{Fe/H}]$) and χ^2_ν is the contribution from fitting the frequencies. Figures 1 and 2 shows frequency fits for the best fitting models of two LEGACY stars: 8006161 (top) and 7940546 (bottom). Both **a** and **b** work well for the $0.97\mathrm{M}_\odot$ star; in fact the scaled solar fit is slightly better here. For the second star the two approaches yield slightly different masses close to $\sim 1.5\mathrm{M}_\odot$ and effective temperatures of $6275.8\mathrm{K}$ (**a**) and 6313.7 (**b**). The surface effect of this star is very different from the Sun and thus modelled poorly by the scaled solar fit (**a**), whereas the inertia-scaled fit (**b**) captures the overall trends in the curve reflected by a much lower χ^2_ν value.

Figure 3 (top) shows the effect on obtained masses of using either approach for the whole LEGACY sample. This is shown as δM, the mean mass from approach **b** minus the mass from **a** divided by the combined standard deviation σ. For $M \gtrsim 1.4\mathrm{M}_\odot$ there is a significant difference between the two, where **b** consistently yields lower mass models, which are consequently older.

Figure 3 (bottom) shows the χ^2 ratio between the two approaches. Here $\chi^2_\mathrm{min}(\mathrm{a})$ is the best fitting model using the scaled solar fit, and (b) is using the Ball & Gizon (2014) surface effect correction. Except for some cases around $\sim\mathrm{M}_\odot$, model fits using the Ball & Gizon (2014) correction have lower χ^2 values. This is thus preferable to any previous correction formulas – even for stars where the surface term differ significantly from that of the Sun.

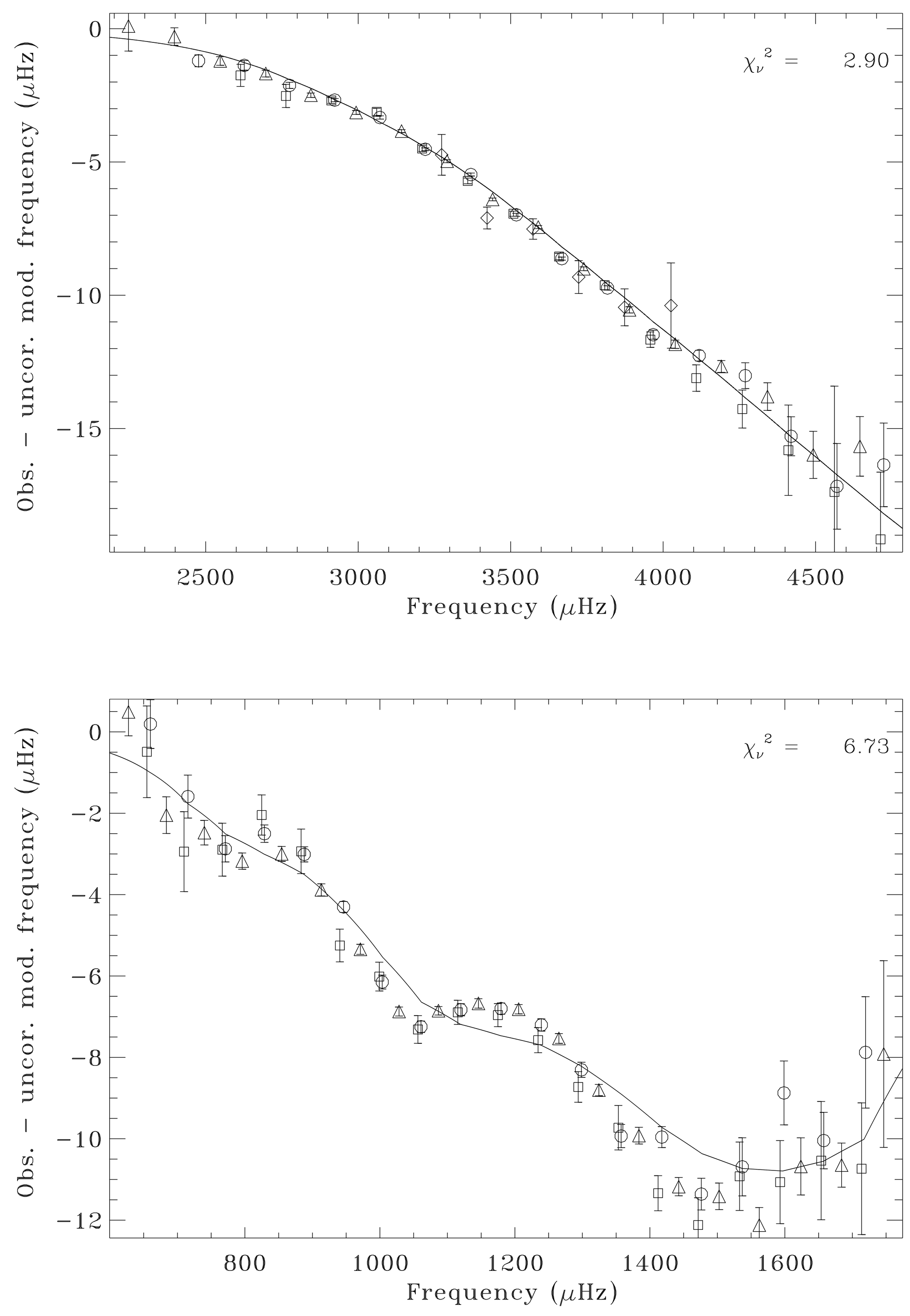

Fig. 2 – *Inertia-scaled two-term fit (**b**) applied to models of the same stars as in Figure 1. Again, the fits shown are from the models with the lowest combined χ^2.* ***Top panel:****. Surface effect correction for a $0.97\mathrm{M}_\odot$ model with $T_\mathrm{eff} = 5465.8\mathrm{K}$.* ***Bottom panel:*** *Surface effect correction for a $1.46\mathrm{M}_\odot$ model with $T_\mathrm{eff} = 6313.7\mathrm{K}$.*

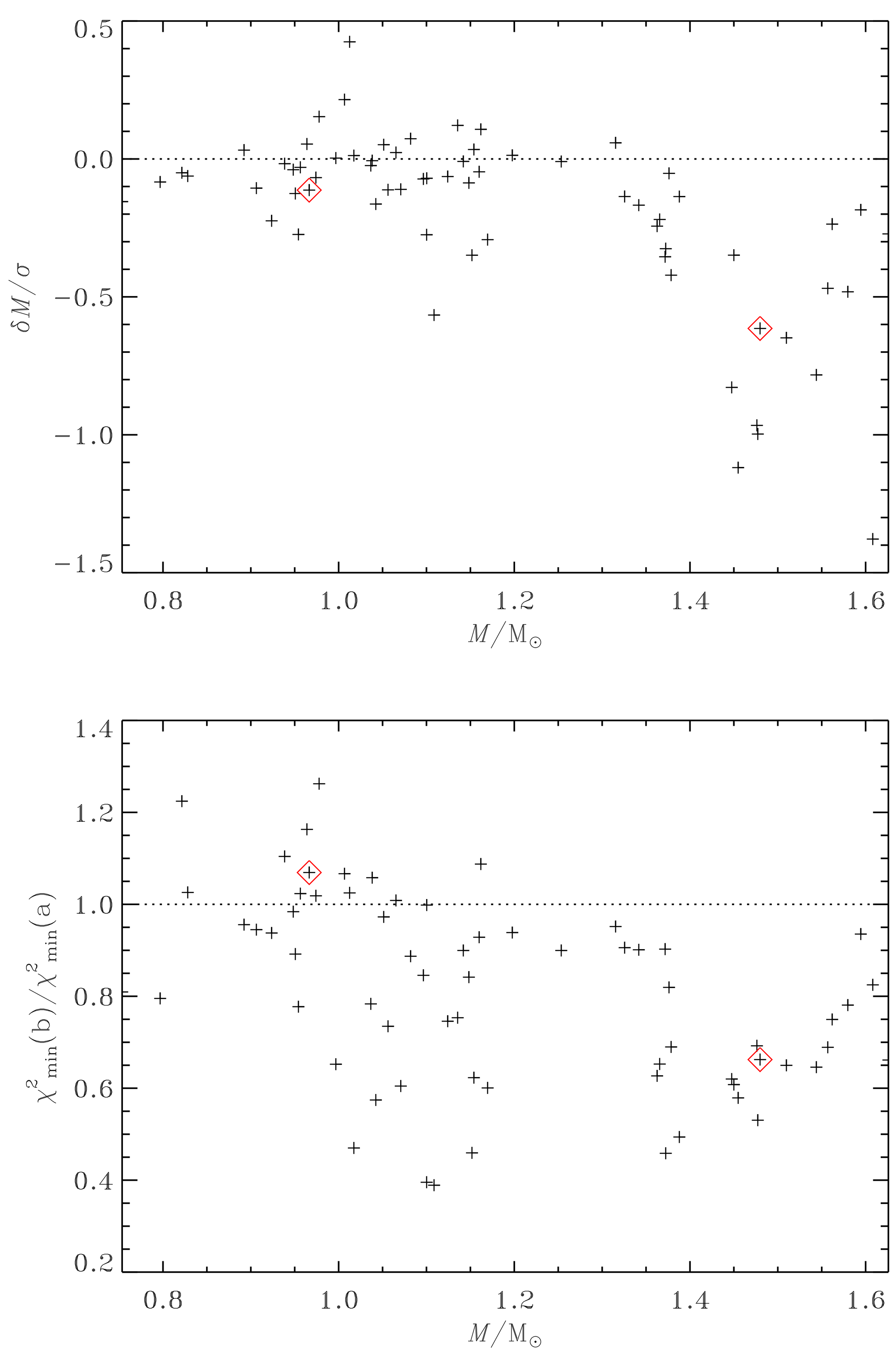

Fig. 3 – ***Top:*** *Difference in mean mass obtained with either surface effect correction for all stars in the LEGACY sample.* ***bottom:*** *Ratio between χ^2 of the best fitting models. Red diamonds highlight the stars in Figures 1 and 2.*

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