Near-surface effects and solar-age determination

G. Doğan1,∗A. Bonanno2 and J. Christensen-Dalsgaard1

1 Department of Physics and Astronomy, Aarhus University, Ny Munkegade, DK-8000, Aarhus C, Denmark
2 Catania Astrophysical Observatory, Via S.Sofia 78, 95123, Catania, Italy

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The dominant part of the difference between the observed and model frequencies of the Sun can be approximated by a power law. We show that when this empirical law is employed to correct the model frequencies and then the small frequency separations, δνl+2(n), are used for solar age determination, the results are consistent with the meteoritic age (4.563 Gyr < t < 4.576 Gyr). We present the results and compare with those obtained by using the ratios, r02(n), of small to large frequency separations.

1 Introduction

It is known that there is a systematic offset between the observed and model frequencies of the Sun. This offset increases with increasing frequency and is shown (Kjeldsen et al. 2008) to be fitted well with a power law as

$$\nu_{\text{obs}}(n) - \nu_{\text{best}}(n) = a \left[ \frac{\nu_{\text{obs}}(n)}{\nu_0} \right]^b,$$

where the power b is determined to be 4.90 for the Sun. Here νobs(n), and νbest(n), represent the observed, and the best model, frequencies with spherical degree l=0, and radial order n; ν0 is a constant frequency (chosen to be 3100 µHz for the Sun), which corresponds to the frequency for peak power in the spectrum. This difference between the observed and calculated frequencies exists due to improper modelling of the outer turbulent convective layers of the Sun. The outer layers affect the high frequencies most, as the upper turning point of the high-frequency waves are closer to the surface. Since all stellar models are calibrated with respect to the Sun, and since, thanks to the recent developments, we are at a stage to have observations of individual frequencies of stars other than the Sun, it is important to understand the effects of near-surface stellar layers on the oscillation frequencies. These effects also influence the small frequency separations, δνl+2(n) = νnl - νn-1l+2, and hence, for instance, inferences of stellar ages. Here νnl is the frequency of a mode with spherical degree l and radial order n. The use of δνl+2(n) for the purpose of solar-age determination has been presented in earlier works (e.g. Dziembowski et al. 1999; Bonanno et al. 2002). It has also been shown by several authors (e.g. Roxburgh & Vorontsov 2003; Oti Floranes et al. 2005; Christensen-Dalsgaard 2009) that the frequency separation ratios, r1l+2(n) = (νnl - νn-1l+2)/(νnl - νn-1l), are not as sensitive to the near-surface layers. Christensen-Dalsgaard (2009) provides a comparison between the use of δνl+2(n) and r1l+2(n). Here, we present our preliminary results on comparing different ways of using the seismic data for determination of the solar age, including the application of near-surface correction.

2 Tools and methods

We computed a series of standard solar models, using the stellar evolution codes, ASTEC (Christensen-Dalsgaard 2008a) and GARSTEC (Weiss & Schlattl 2008), with different ages while keeping the luminosity, and the surface value of Z/X fixed to 3.846 × 1033 erg s⁻¹, and 0.0245 (Grevesse & Noels 1993), respectively. Here Z is the mass fraction of the elements heavier than helium, and X is that of the hydrogen. Models were computed with the OPAL equation of state (Rogers & Nayfonov 2002), OPAL opacities (Iglesias & Rogers 1996) together with the low-temperature opacities from Alexander & Ferguson 1994, and using the Adelberger et al. (1998) or NACRE (Angulo et al. 1999) nuclear reaction rates. We considered both the commonly used value R1 = 6.9599 × 1010 cm (Auwers 1891) of the solar radius, and the value R2 = 6.9551 × 1010 cm found by Brown & Christensen-Dalsgaard (1998). Models were computed both starting at the zero age main sequence (ZAMS) and including pre-main-sequence (PMS) evolution. We calculated the frequencies of our models using ADIPLS (Christensen-Dalsgaard 2008b), and compared the small frequency separation, δν02(n), and r02(n) of the models with those of the Sun (BISON, Chaplin et al. 2007). We selected the best model minimizing the following χ², adapted for the separation ratios, r02(n), when relevant:
Table 1  Ages of the best models

| Evolution code + Nuc. reaction rates: | Seismic property used in $\chi^2$ | Age\(^a\) (before correction)(Gyr) | Age\(^a\) (after correction)(Gyr) | Age\(^a\) (before correction)(Gyr) | Age\(^a\) (after correction)(Gyr) |
|--------------------------------------|----------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| ASTEC + Angulo et al. (1999)         | $\delta \nu_{02}(n)$             | 4.58±0.05                    | 4.56±0.05                    | 4.60±0.06                    | 4.57±0.06                    |
| Astelberger et al. (1998)            | $r_{02}(n)$                      | 4.55±0.04                    | 4.55±0.04                    | 4.55±0.05                    | 4.55±0.05                    |
| GARSTEC + Angulo et al. (1999)       | $\delta \nu_{02}(n)$             | 4.57±0.05                    | 4.55±0.05                    | 4.59±0.05                    | 4.56±0.06                    |
|                                      | $r_{02}(n)$                      | 4.54±0.05                    | 4.54±0.05                    | 4.54±0.05                    | 4.54±0.05                    |

\(\chi^2(\delta \nu_{02}) = \frac{1}{N - 1} \sum_n \frac{[\delta \nu_{02}^{\text{obs}}(n) - \delta \nu_{02}^{\text{model}}(n)]^2}{\sigma[\delta \nu_{02}(n)]^2},\)

where \(N\) is the number of modes, \(\delta \nu_{02}^{\text{obs}}(n)\), and \(\delta \nu_{02}^{\text{model}}(n)\) are the small frequency separations from the observations and the models; \(\sigma[\delta \nu_{02}(n)]\) represents the uncertainty in the observed \(\delta \nu_{02}(n)\). We repeated this comparison for \(\delta \nu_{02}(n)\) and \(r_{02}(n)\) of the surface-corrected frequencies (cf. Eq. 1).

3 Results and discussion

The results of the age determinations using different input, as described in Section 2, are summarized in Table 1, and one of the cases is illustrated in Fig. 1.

The ages of our best models found using the two different evolution codes are consistent within the error limits, differing by 0.7% at most, and they are also compatible with the values in the literature obtained by employing small frequency separations: 4.57 ± 0.11 Gyr (Bonanno et al. 2002), and 4.66 ± 0.11 Gyr (Dziembowski et al. 1999). Moreover, our two sets of results agree with the meteoritic age, 4.563 Gyr < \(t\) < 4.576 Gyr (Wasserburg, in Bahcall & Pinsonneault 1995), within the uncertainty limits.

In principle we can determine the duration of the PMS evolution, up to the ZAMS, by calibrating the models using PMS evolution to get the meteoritic age of the Sun (see, e.g. Morel et al. 2000, for a discussion on the definition of ZAMS). Our preliminary analysis suggests that the PMS evolution for the Sun is 0.05±0.11 Gyr in order to be consistent with the meteoritic age. A more precise and detailed analysis is obviously needed for defining ZAMS.

The results obtained using separation ratios are consistent with those obtained using the small frequency separation of the corrected frequencies. However, since the application of the surface correction has no significant effect on the age determined by the separation ratios, using these ratios yields a more robust age determination.

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