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Main-sequence oscillators as a test of stellar opacities

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Abstract. The last decade has given rise to several tensions between calculated and (sometimes indirectly) measured stellar opacities. I discuss the current and future capacity for the asteroseismology of B-type oscillators (slowly-pulsating B-type stars and β Cepheids) and main-sequence solar-like oscillators to test stellar opacities. I briefly highlight two methods by which the B-type oscillators already constrain opacities, though they do not yet identify a superior set of tables. I then consider how the main-sequence solar-like oscillators might also test opacities, using the 16 Cygni system as an example. There are currently greater uncertainties than the opacities (in this example, the atmospheric structure) but many of these will be separately constrained in the near future.

Keywords. radiative transfer, stars: oscillations

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1. Introduction

Opacity, given as a function of density and temperature, is one of several physical properties that is not computed a priori in stellar evolution models and must therefore be provided separately. Different sources give different opacities, which thus affect the predictions of stellar structure models. Though the effect is relatively small for many purposes, some stellar oscillators are sufficiently sensitive to the opacities to constrain them. In this article, I review and speculate on the contribution of main-sequence oscillators to this goal.

Before discussing the role of the oscillators in testing opacities, it is worth noting the recent measurement by Bailey *et al.* (2015) of iron's opacity at conditions very similar to those at the base of the solar convection zone. Curiously, they measured higher opacities across the continuum, with an enhancement of about 60% relative to a number of opacity models. These measurements are being complemented by results from the OPAC collaboration, which is conducting both extensive experiments and code comparisons (e.g. Turck-Chièze & Gilles 2013, see also Le Pennec *et al.*, these proceedings). While it will take some time to digest these experimental and numerical results, such detailed re-assessment is clearly warranted.

This article is divided into two halves, each of which discusses a different class of main-sequence oscillator and can be read separately from the other. The first half covers B-type oscillators: the slowly-pulsating B-stars (SPBs) and β Cepheids. I focus on specific methods by which these stars test opacities. The second half considers main-sequence solar-like oscillators, including a brief summary of the solar abundance problem and its connection to opacities. Solar-like oscillators have not yet been used to constrain opacities, so I instead demonstrate how this might be done.

2. B-type oscillators

The B-type oscillators cover two separate classes: the slowly-pulsating B-stars (SPBs) and the β Cepheids (β Ceps). The SPBs undergo high-order g-mode oscillations with periods roughly between 0.5 and 5 d, whereas the β Ceps undergo low-order p- and g-mode oscillations with periods roughly on the order of hours and days, respectively. In both cases, the modes are excited by the κ mechanism through an opacity bump mostly due to iron-group elements at temperatures between about 100 000 K and 200 000K. Thus these stars are not just sensitive to the opacity through their oscillation frequencies but also through the excitation of the modes. That is, the opacities determine whether or not a particular mode is intrinsically unstable.

The β Ceps already have a history with opacities. Simon (1982) pleaded for a re-examination of heavy element opacities on the basis that it would resolve problems in modelling both classical Cepheids and the β Ceps. The plea was met with updated opacity tables, which Dziembowski & Pamiatnykh (1993) used to compute stellar models that broadly matched the observed properties of β Ceps. At the same time, Dziembowski *et al.* (1993) found a second sequence of lower-mass stars in which high-order g-modes were unstable. These are now recognized as the SPBs, then still recently-discovered by Waelkens (1991). Thus, the new opacities provided the basis of our understanding of these stars.

Though the basic picture is established, newer techniques and observations have placed tighter constraints on the opacities. I briefly highlight here just two types of result by which the B-type oscillators test opacities, though there has been broader progress than I have time or space to describe.

2.1. *Complex asteroseismology*

Daszyńska-Daszkiewicz *et al.* (2003) introduced a novel model constraint for coherent pulsators observed in both multi-colour photometry and radial velocity. They showed that, for a given mode, one can measure the complex-valued parameter f, related to the relative amplitude of the oscillation in photometry and radial velocity, which can be compared with predictions from non-adiabatic oscillation codes. They originally applied the method to δ Scuti stars but could not find models that matched the observed values. However, they subsequently applied the method to β Ceps successfully (Daszyńska-Daszkiewicz *et al.* 2005).

The method has now been applied to a number of stars. Walczak & Daszyńska-Daszkiewicz (2014) presented results for four stars, from which I have chosen the example of θ Ophiuci. The masses and ages of stellar models with different metallicities Z, overshooting parameters $\alpha_{\rm ov}$ and opacity tables were fitted using the frequencies of the radial and dipole p_1 modes. Fig. 1 shows these models, with the lines indicating models of a given mass, for each of the three opacity tables considered. In addition, Fig. 1 shows the constraints from the luminosity and effective temperature (grey shading), from the instability boundaries of the radial and dipole modes (thick black and dashed red lines) and from the complex parameter f measured for the radial p_1 mode.

For the different opacity tables, matching models are found in different regions of the Z–$\alpha_{\rm ov}$ plane, with the complex parameter f playing a decisive role. Notably, with the OP tables, suitable models are only found with very large values of $\alpha_{\rm ov}$. This would suggest that the OP tables are somehow unreliable but the best-fitting or excluded opacity tables vary from star to star and no table is consistently better than any other. Thus, though the method is powerful, it remains to find an opacity table that simultaneously produces matching models for all the β Ceps studied in this way.

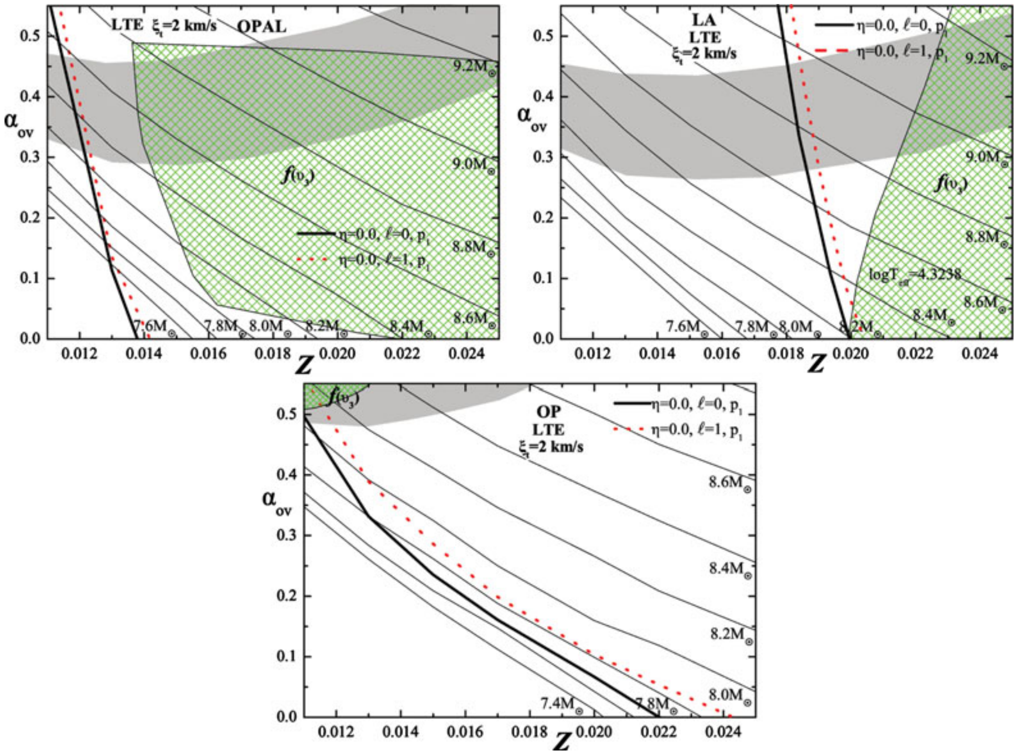

Figure 1. Plots showing observational constraints on models of θ Ophiuci in the plane of metallicity Z and convective overshooting parameter $\alpha_{\rm ov}$ for each of the three opacity tables considered. The solid lines show the masses of models fit to the radial and dipole p_1 mode frequencies. The grey region indicates models falling within the luminosity and effective temperature uncertainties. The thick black and dashed red curves show the instability boundaries of the fitted radial and dipole modes, respectively. The hatched green region shows where models match the complex parameter f measured for the radial p_1 mode. (From Walczak & Daszyńska-Daszkiewicz 2014.)

2.2. *Instability strips in the Magellanic Clouds*

Dozens of candidate SPBs and β Ceps have been discovered in the Large and Small Magellanic Clouds (Kołaczkowski *et al.* 2006; Sarro *et al.* 2009, see also Engelbrecht *et al.*, these proceedings). At such low metallicities, many research groups have struggled to produce stellar models with unstable modes. The modes' stability hinges on the opacities and an appropriate correction to the opacity data has (as before) been suggested as way to resolve this problem (e.g. Salmon *et al.* 2012).

I highlight here just one recent result along these lines. Walczak *et al.* (2015) recomputed the instability strips in the Magellanic Clouds with updated opacities from Los Alamos. While they found some broadening of the instability strips, it is still not enough to explain the existence of B-type oscillators.

2.3. *Outlook*

This brief overview has covered just two means by which B-type oscillators test stellar opacities. As new, high-quality observational data continues to stream in, advances have been made along other lines. First, the interpretation of the power spectra of classical oscillators is improving (e.g. Kurtz *et al.* 2015). Second, it is becoming more routine to fit stellar models directly to the observed frequencies (e.g. Ostrowski *et al.*, these proceedings). Such advances test the opacities, and other stellar physics, further still. The B-type oscillators therefore already constrain to constrain stellar opacities, with the result generally being that no opacity table is consistently superior to any other. But when such a table appears, techniques will be ready to put it to the test.

3. Solar-like oscillators

We now turn to the solar-like oscillators. These are stars that, like the Sun, have a surface convection zone in which global oscillation modes are continuously excited and damped over a broad frequency range. On the main sequence, these oscillations peak in power at frequencies from about 4 mHz in K-type dwarfs down to about 1 mHz in F-type dwarfs. In the Sun, they peak around 3 mHz and are sometimes referred to as the 5-minute oscillations. Solar-like oscillations also occur in subgiants and red giants, peaking at much lower frequencies, but I am restricted here to the main-sequence oscillators.

The study of these stars has recently undergone something of a revolution owing to space-based missions, notably CoRoT and then *Kepler*. Such oscillations have very low amplitudes: 10ppm in intensity and a few $\mathrm{cm \cdot s^{-1}}$ in velocity. A handful of measurements were made using carefully co-ordinated ground-based campaigns but the long duty cycles and high sensitivity of space telescopes led to detections in hundreds of stars and the robust identification of individual frequencies in dozens thereof.

3.1. *The solar abundance problem*

The canonical solar-like oscillator is, of course, the Sun, which is also our main motivator for carefully assessing opacities in these stars. *Science* dedicated a special issue to helioseismology in 1996 and this serves as a useful snapshot of the state of the field at the time. Therein, Christensen-Dalsgaard *et al.* (1996) presented a calibrated solar model, dubbed Model S, that has become fairly standard in the field. Gough *et al.* (1996) combined this model with frequencies observed by the Global Oscillation Network Group (GONG) to perform a seismic inversion of the density and sound speed in the Sun. In short, an inversion is a calculation of the precise perturbation to the sound speed and density of the stellar model that would cause it to exactly reproduce the observed mode frequencies. This calculation showed discrepancies of roughly less than 0.1%, which demonstrated that our understanding of most of the physics in the Sun was correct.

The situation changed somewhat when Asplund *et al.* (2005) presented the first results from a new calculation of the solar abundance, made using synthetic spectra from detailed hydrodynamic simulations of the Sun's surface layers. The original result was a significant decrease of the solar metallicity, though the revision by Asplund *et al.* (2009) brought the number a bit closer to its pre-2005 levels. When solar models were re-calibrated using the new abundances, the inferred structural differences became much larger, chiefly in the radiative zone. The greatest change is near the base of the convection zone and gradually decreases towards the core. This discrepancy has not yet been resolved and is known as the *solar abundance problem*.

The structural changes can be evaluated in terms of opacity differences. Two example calculations are shown in Fig. 2. From the computed structural differences, Christensen-Dalsgaard & Houdek (2010) inferred the change to the opacity that would best eliminate the structural difference. The relative change is shown by the dashed curve in Fig. 2. The maximum difference, reached just below the base of the convection zone, is nearly 25%. Gough (2004) instead took a helioseismically-calibrated solar model and, taking the luminosity as given, used the equation of radiative diffusion to compute the opacity. The solid curve in Fig. 2 shows the difference between the opacity in Model S

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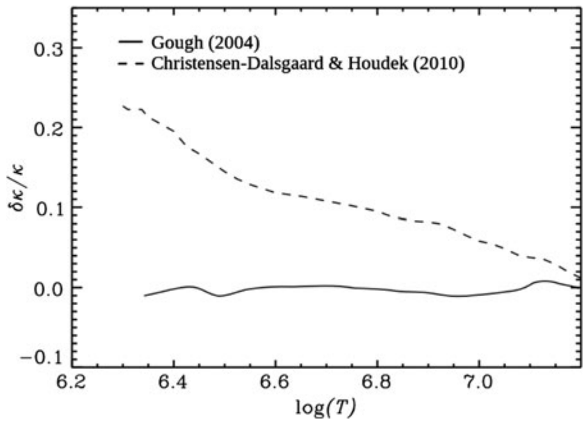

Figure 2. Fractional differences between opacities for various solar models and the Sun. The dashed curve shows the estimate by Christensen-Dalsgaard & Houdek (2010) of the opacity change necessary to reconcile helioseismic inferences with a solar model with the Asplund *et al.* (2009) abundances. The solid curve shows the calculation by Gough (2004) of the opacity difference between a helioseismically-calibrated model and Model S. Assuming that the opacities are the sole cause of the solar abundance problem, these show that a substantial increase of the opacity would be necessary and that Model S in essence has the correct opacity, even if not the correct abundance. (Adapted from Gough 2013.)

and computed as just described. They are nearly the same, showing that although Model S has the incorrect abundances, it appears to have the correct opacity.

This discussion demonstrates that solar-like oscillators are sensitive to opacities in a region where they might be in error. However, bear in mind that the observational data for the Sun is vastly superior to data for other stars. We can resolve the surface (and therefore observe modes with high angular degree) and have been doing so for decades.

3.2. *How can solar-like oscillators constrain opacities? An example*

Though solar-like oscillators have been used to study other physical processes of stellar models (e.g. core convective overshoot, Silva Aguirre *et al.* 2013), they have not yet been used to study microphysics data like opacities. A reasonable approach to constrain opacities might be to fit stellar models with different tables, all else being equal, and compare the quality of the fits. The fit metric would then indicate if one table is preferred and this would accumulate over many stars.

To demonstrate this approach, I fit models to the two components of 16 Cygni. Both are quite similar to the Sun, eliminating other uncertainties in stellar models. For example, neither star is massive enough to have a convective core, so reasonable fits can be expected without including convective overshooting. The two stars are also among the brightest and best-characterized solar-like oscillators in the nominal *Kepler* field, with many $\ell = 3$ modes reliably detected.

Specifically, fits were made to the spectroscopic data reported by Ramírez *et al.* (2009), the luminosities derived by Metcalfe *et al.* (2012) and the mode frequencies measured by Davies *et al.* (2015). Stellar models were fit using the Modules for Experiments in Stellar Astrophysics (MESA†, Paxton *et al.* 2011, 2013). We took as constitutive physics the "old" solar mixture of Grevesse & Sauval (1998), MESA's default equation of state (Rogers & Nayfonov 2002, based principally on the OPAL tables), nuclear reactions rates from the NACRE collaboration Angulo *et al.* (1999) or, when those were not

† `http://mesa.sourceforge.net/`

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Table 1. Best-fitting values of χ^2 for the six fits to 16 Cygni A and B. In each cell, the upper and lower values are for component A and B, respectively. The opacity tables are found to make little difference, whereas the solar-calibrated atmospheres lead to slightly better-fitting models.

	OPAL	OP
Eddington	103.2 79.9	101.1 79.3
Krishna Swamy (1966)	96.1 71.4	98.4 73.2
Solar Hopf (VAL-C)	96.7 71.4	93.6 71.7

available, Caughlan & Fowler (1988). Convection was described using mixing-length theory (Böhm-Vitense 1958). Oscillation frequencies were computed using ADIPLS (Christensen-Dalsgaard 2008) and corrected using the two-term (or "combined") fit by Ball & Gizon (2014). Initial guesses were determined by comparing the non-seismic data and global seismic parameters to a grid of models, after which the current 1σ-error region was randomly resampled, about 20 parameter sets at a time, until the total χ^2 was no longer improving by more than about 0.5. Errors were determined by finding the smallest bounding ellipsoids around the $\chi^2_{\rm min} + 1$ surface.

I performed separate fits using opacities from the OPAL collaboration (Iglesias & Rogers 1996) and from the Opacity Project (OP Seaton 2005), both complemented at low temperatures by values from Ferguson *et al.* (2005). However, opacities are not the only uncertain input to stellar models so, as an example, I also varied the atmospheric temperature–optical depth relation ($T(\tau)$-relation), which is integrated from the photosphere to an optical depth of 10^{-4} to determine the model structure in the atmosphere. I used the three options available in MESA: a standard Eddington grey atmosphere, the solar-calibrated model by Krishna Swamy (1966) and a fit to the VAL-C solar atmosphere Vernazza *et al.* (1981, as used in Model S).

The best total χ^2 values for each of the six different fits (two opacity tables and three atmosphere models) are shown in Table 1. It is clear that the choice of opacity table makes nearly no difference to the quality of the fit. The atmosphere matters more. Though the two solar-calibrated relations give similar quality of fit, both are somewhat better than the widely-used Eddington grey atmosphere. In all cases, however, we found that the model parameters are mutually consistent and also consistent with the recent results by Metcalfe & Creevey (these proceedings).

Better constraints could be obtained by exploiting the binarity of the system. We expect that both components formed at the same time from the same well-mixed material, so we could constrain the ages and initial compositions to be the same. Though we have not done so here, we can get some idea of the improved constraints by comparing our results for the two stars. Fig. 3 shows the 1σ-error ellipses in the initial metallicity and initial helium abundance. Ideally, the error ellipses would overlap substantially, though the disunion here is small. Moreover, we would hope that different choices of opacity table would place the ellipses either closer together or further apart, indicating that those models are more or less likely, respectively. Unfortunately, this does not appear to be the case. The locations of the ellipses follow the major axes of the ellipses themselves and therefore still do not prefer either opacity table.

3.3. *Outlook*

It appears that there are other uncertainties in the stellar models that currently affect our predicted mode frequencies more than the choice of opacity table. Here, we have

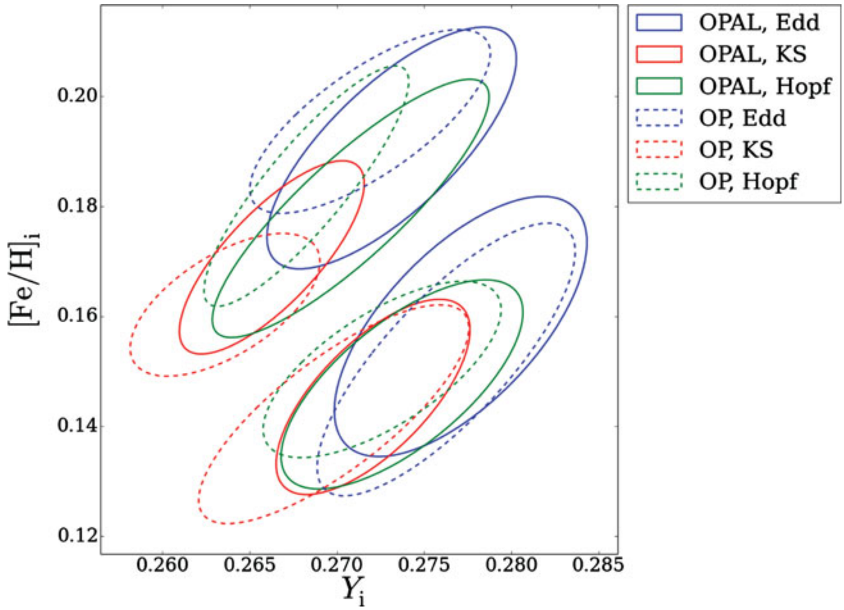

Figure 3. Error ellipses (1σ) for the six fits to the two stars for initial helium and initial metallicity. The solid and dashed styles correspond to fits using the OPAL and OP opacity tables, respectively, and the red, blue and green colours correspond to fits using the Eddington, Krishna Swamy (1966) or VAL-C $T(\tau)$ relations.

shown that the atmospheric model is one such uncertainty but there has recently been a great deal of work in computing realistic simulations of the surfaces and near-surface layers of solar-like oscillators (e.g. Kitiashvili *et al.*, these proceedings). Trampedach *et al.* (2014) published a series of $T(\tau)$ relations based on such simulations, which Salaris & Cassisi (2015) already incorporated into their stellar models. As more such simulations are computed and tested, we will be able to reduce the uncertainty in the atmospheric models.

Despite these uncertainties, the study of main-sequence solar-like oscillators carries the advantages that the interpretation of their power spectra is now relatively routine, and free of the problem of mode identification. In addition, we have a large and growing number of high-quality observations from past, present and future space missions. We will ultimately be able to fit stellar models to all such stars in these populations using different tables, and thereby determine which (if any) opacity table fits better. Many marginal results still add up to a significant one!

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