SF2A 2014
J. Ballet, F. Bournaud, F. Martins, R. Monier and C. Reylé (eds)

STELLAR OPACITY VALIDATIONS

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Abstract.
This paper focuses on the radiative transfer in stars where opacities seem to raise problems : β-Cephei and solar-type stars. We first concentrate on the iron bump (log T = 5.25), responsible for β-Cephei pulsations through the κ-mechanism. To discriminate between the different opacity calculations used to predict their oscillations, new well-qualified calculations are used and compared to OP calculations. In parallel with this theoretical work, an experiment has been conducted at LULI 2000 in 2011 on iron and nickel. We show that this extended study pushes for the revision of the tables in the conditions corresponding to the iron bump region, at least for nickel. We will then deal with the Sun case for which we are preparing an opacity experiment on a high-energy laser, in some conditions of the radiative zone (T = [2 - 15 $\times 10^6$ K] and ρ = [0.2 - 150 g/cm^3]). To reach these high temperatures and densities at LTE and validate or not plasma effects and line widths, we are exploring an approach called the Double Ablation Front, driven by plasma radiative effects. The 1D simulations performed with the code CHIC show that with this technique, we could reach conditions equivalent to the conditions of half of the solar radiative zone.

Keywords: opacity, sun, massive stars, plasma physics

1 Introduction

Helioseismology and asteroseismology measurements provide very accurate diagnostics of the stellar structure by using the acoustic modes propagating into stellar interiors. If oscillation spectra are correctly interpreted, then a substantial amount of information can be extracted concerning the star. However, in some cases, the comparison between the seismic observations and the predictions coming from stellar models show discrepancies. We focus in this paper on two cases where these discrepancies are observed and could be attributed to the description of the microscopic physics: the envelopes of β-Cephei and the solar interior.

2 β-Cephei

β-Cephei are pulsating stars, progenitor of type II supernovae. They pulsate through the κ-mechanism, due in this case to M-shell transitions for the elements of the iron group (principally iron and nickel) which induce an opacity bump. This bump is very sensitive to the mass, the metallicity and the age of the considered star (Le Pennec & Turck-Chièze 2014), showing that a very precise determination of these three parameters as well as the proper knowledge of the opacities are needed to understand the structure and evolution of the star.
The first difficulty to interpret their oscillation spectrum comes from the fact that some modes are observed but not predicted by stellar models. Indeed, one observes modes which were calculated to be stable in theoretical predictions using OP or OPAL opacity tables (Pamyatnykh 1999; Zdravkov & Pamyatnykh 2009). Furthermore, depending on the mass of the star, some of the modes seem better predicted using OP (Seaton 2005) or OPAL (Rogers & Iglesias 1992; Iglesias & Rogers 1996) tables. This fact suggests that some of these opacities could be inaccurately determined for both tables (Salmon et al. 2012) or that some hydrodynamic process plays an important role not yet understood.

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To understand the limitations of OP and OPAL, new codes have been developed, with different physical approaches. The comparison of these new calculations with the tables currently used in astrophysics shows large discrepancies for iron and nickel. If the quality of the calculations strongly depends on the quality of the atomic data, we see with this study that the number of levels taken into account in the opacity calculation is evidently crucial (Turck-Chièze et al. 2014). One could then be tempted to consider all the detailed radiative transitions with their configuration interaction to get a good determination of this quantity but this is presently limited by the computer capability. So, one has to find a compromise between detailed and statistical approaches and the execution time of such a process.

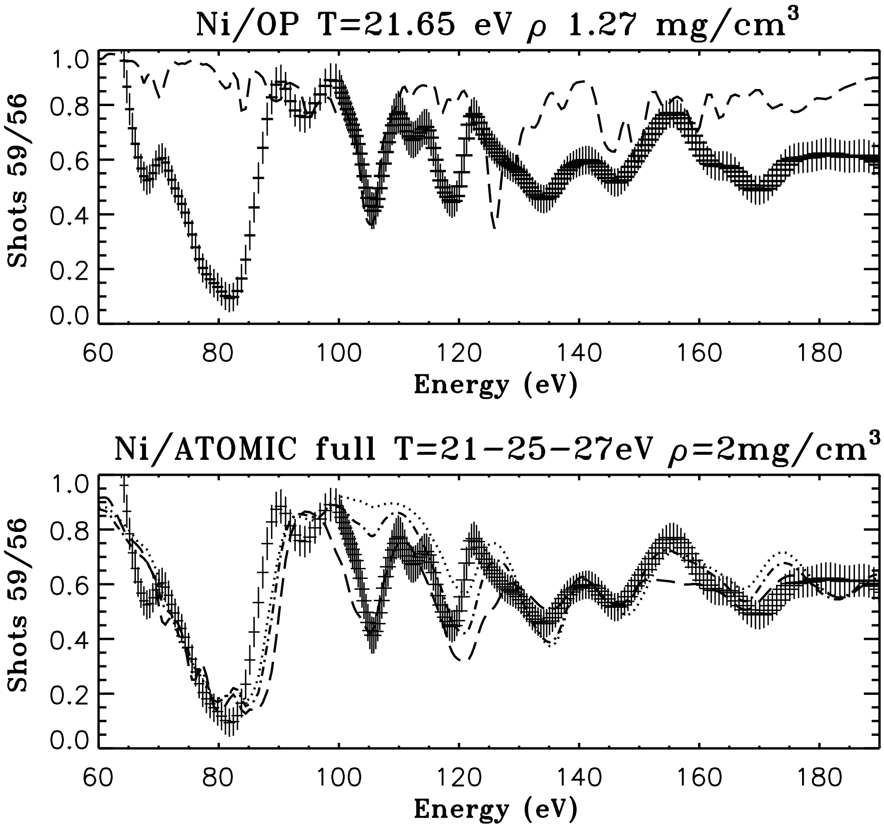

Fig. 1. Comparison of the nickel experimental spectrum (including an analysing error) with (up) the theoretical spectrum given by OP at the nearest node in the tables compared to the experimental conditions and with (bottom) ATOMIC calculations (Colgan et al. 2013) at 2 mg/cm^3 and several temperatures to show how calculations vary in the range where one can find gradient in the nickel foil. 1 eV = 11 604 K. From Turck-Chièze et al. (2014).

In parallel, an experiment has been performed on iron and nickel on LULI 2000 facility (Thais et al. 2014). As it is not possible to perform an experiment at the very low densities of these envelopes, equivalent conditions of plasma have been determined, where the degree of ionization is similar. In the case of nickel, the comparison of the experimental spectrum with previous calculations shows that both are not satisfactory. New calculations show better agreement with the experiment than OP calculations which were derived from iron calculations as shown on Figure 1. In the case of iron, new calculations are interesting to compare (Turck-Chièze et al. 2014). We will try to confirm these conclusions by analyzing two other elements contributing to the iron bump, which were measured during the same experimental campaign: copper and chromium.
New opacity tables for astrophysical use are in preparation in the range of density and temperature corresponding to the iron peak.

3 Solar radiative zone

The Sun is our closest star and thus used as a benchmark to study other stars. Its radius, luminosity and mass are known with great accuracy, that allows to make very precise models of the Sun. However, some doubts are raised on the accuracy of the used microscopic physics. Indeed, a discrepancy between helioseismic observations and predictions by SSM appeared in the solar sound speed profile. This discrepancy, of about 20 times the vertical error bar, put some questions on the solar radiative transfer (Turck-Chièze et al. 2011). Indeed, there exists several hypotheses to explain this difference. Among them:

- it could be due to macroscopic processes in the radiative zone not taken into account in the energetic balance of the Sun
- the radiative transfer calculations are not accurately estimated, either in the Rosseland mean value that could be underestimated or in the treatment of the radiative acceleration which limits the gravitational settling and could lead to incorrect internal abundances.

It could also be due to all these effects simultaneously. Determining where this discrepancy originates would be an important step toward our understanding of the Sun and solar-like stars.

The heavy elements significantly contribute to opacity even if they are present only at few percents in mass fraction in the solar mixture which is principally constituted of hydrogen and helium (Turck-Chièze et al. 2010). The most important contributors are:

- iron, which contributes to the total opacity (including H and He) at a level of 20% in most of the radiative zone because always partially ionized;
- oxygen, which becomes partially ionized at 0.6 $R_\odot$ and plays a major role at the basis of the convective zone. The increase of its opacity contribution triggers the convection;
- silicon, which plays a role at the level of 10% below 10 millions of degrees.

Hydrogen and helium are fully ionized in the radiative zone. The contributions to the opacity of iron, oxygen and silicon, when they are partially ionized, are more complex to calculate depending on the number of bound electrons. So, it could be useful to confirm the existing calculations by experiments, regarding the difficulty to compute the opacity of these elements.
Reproducing the solar interior conditions is a real challenge because one tries to reproduce the charge state distribution of the different elements together with the free-electron density (N_e) at the targeted conditions, that means density greater than solid and high temperature. Table 1 presents some values of the temperature and the free-electron density at different solar depths.

Solar radius ($r/R_\odot$)	T(eV)	N_e (cm^{-3})
0.5	340	8 x 10^{23}
0.6	270	2.5 x 10^{23}
0.7	200	1x 10^{23}

Table 1. Temperature and free-electron density at different depths of the Standard Solar Model computed with the MESA code for the Asplund et al. (2009) composition.

Bailey et al. (2007) have already measured on the Z-pinch facility the iron transmission at conditions lower than those at the basis of the convective zone at 156 eV. This first measurement agrees reasonably well with the compared theoretical calculations. Then, they have increased the temperature up to 196 eV and reached free-electron densities of several 10^{21} - 10^{22} cm^{-3} (Bailey et al. 2009; Nagayama et al. 2014). However, for this last measurement, an unexplained gap exists between the measurement and the theoretical calculations coming from different codes. It has already been shown that this difference is not attributed to the bound-bound transitions.

So we propose to use the Double Ablation Front (DAF) to reach conditions of Table 1 with high energy laser facilities and check the energy spectra of iron and other elements. This approach is based on the use of a moderated Z material (Si, SiO_2...) as target ablator, that increases the conversion of the laser energy in X rays compared to low Z ones. The energetic photons emitted by the corona* are absorbed in the more opaque region at the basis of the thermal wave, creating an additional ablation front (Sanz et al. 2009; Drean et al. 2010). The two ablation fronts (radiative and electronic) are separated by a density and temperature plateaux as shown on Figure 2 that are used to limit the gradient inside the sample (temperature and density). This multi-ablation structure was put in evidence experimentally on the GEKKO laser (Fujioka et al. 2004) and was produced recently at the OMEGA laser (Smalyuk et al. 2010).

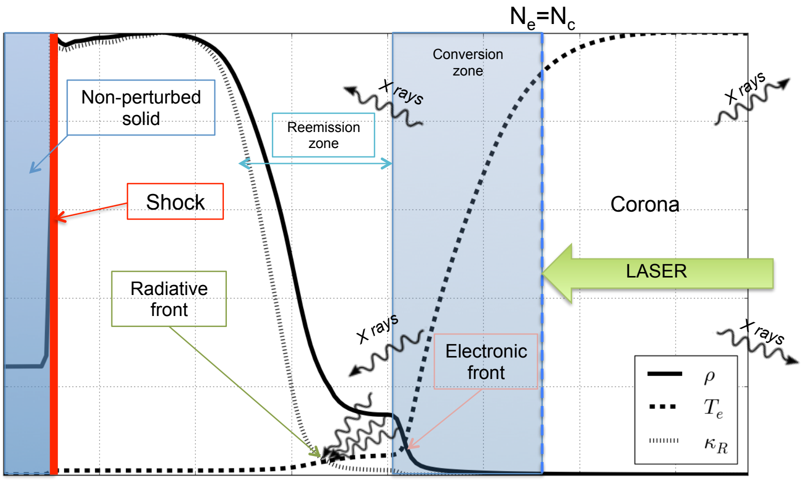

Fig. 2. Schematic structure of a Double Ablation Front: profiles of temperature, density and opacity at a give time in a layer of SiO_2 (Z=10). One can see two ablation fronts: one due to electrons (electronic front), the other due to photons (radiative front). Between the two fronts, there is a plateau region, that extends with time.

This approach could use planar targets composed by three layers of material. The sample of interest is tampered by two other layers, which depend on the chosen irradiation: one-side or symmetrical irradiation. We perform 1D simulations with these targets thanks to the CHIC code (Breil & Maire 2007) with various laser intensities and various widths of the target.
Some of our results are summarized in Table 2. We performed in this case simulations with iron as sample of interest and we used silicon as the ablator, to create the DAF structure. What is interesting to note is that with a moderate laser intensity, we seem to be able to reach thermodynamical conditions close to the conditions of half the solar radiative zone, near LTE conditions. Moreover, these conditions are reached with very low gradients in the target: around 8% in the simple irradiation case, lower than 6% in the symmetrical irradiation case (Le Pennec et al. submitted).

4 Conclusions

Discrepancies between seismic observations and models predictions require to check the opacity calculations. The study of the iron bump in the envelope of the β-Cephei shows the limitations of the astrophysical used tables. The development of new calculations and experiments have allowed to understand the limitations of the previous calculations and leads to the construction of new tables at the conditions of density and temperature of the iron peak. We are also presently adopting the same approach for the solar case by suggesting a new experimental scheme for opacity measurements. We hope to have the opportunity to validate experimentally this new concept with the LMJ-PETAL facility at Bordeaux.

*The corona is the heated plasma at keV temperature and free-electron density lower than the critical density defined by $N_c = \frac{1.1 \times 10^{21}}{(\lambda[\mu m])^2}$ [cm^{-3}].

Target	Irradiation type	I $_{laser}$ (10^{15} W/cm^2)	T$_{e\ mean}$ (eV)	ρ $_{mean}$ (g/cm^3)	N$_{e\ mean}$ (10^{23} cm^{-3})
Si / Fe / CH 8 μm / 0.1 μm / 7 μm	One-side	1.5	160 - 180	0.75 - 1	1.1 - 1.5
Si / Fe / Si 7 μm / 0.1 μm / 7 μm	Sym.	1.5	200 - 230	1.2 - 1.5	2.2 - 2.5
Si / Fe / Si 7 μm / 0.1 μm / 7 μm	Sym.	4.0	260 - 290	2.0 - 2.3	3.7 - 4.1

Table 2. Conditions obtained in the iron sample for the simulations of the proposed experimental scheme.

The authors thanks the SF2A organizing committee and the editors of the proceedings. Part of this work was supported by the ANR OPACITY. We would like to thank Y. Ralchenko for providing access to the FLYCHK code and CELIA for providing access to the CHIC code.

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