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News from the opacity consortium OPAC

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Abstract. The international OPAC consortium (see list below) was formed three years ago. It is composed of astrophysicists, plasma physicists and experimentalists from different laboratories[b]. This consortium examines specific opacity calculations used in stellar physics. They contribute to solve the problems suggested by the astrophysical community in performing new calculations and new experiments with laser installation. We show here the specific example of the iron opacity peak that plays an important role in the envelope of intermediate-mass and massive stars and we present our first conclusions on iron and nickel.

1. OPEN PROBLEMS COMING FROM SEISMIC OBSERVATIONS

The stellar community hopes to progress on the internal dynamics of stars thanks to the space-borne seismic missions SoHO, CoRoT and *Kepler*. But good identification and interpretation of acoustic frequencies are based on a proper microscopic physics. Along the last decade, some questions on energy transfer, linked to plasma opacities, have arisen and two cases have retained our attention.

1. The extraction of the solar internal sound speed and density has revealed clear discrepancies with the Standard Solar Model predictions [1–3]. These discrepancies are not explained by the transport of momentum by rotation during the main sequence evolution [4]. So the energy balance and (or) energy transfer stay clearly under suspicion. In parallel, the recent OPAS calculations [5] have revealed large differences in individual element spectra with previous calculations and in particular with OP [6, 7]. OPAS calculations also show some compensation effects between low Z nuclei and the iron group contributions in the Rosseland mean opacity values. All these facts encourage further works and experimental verifications.
2. The second case concerns massive stars. SPB and β Cephei stars are interesting pulsators that might put important constraints on rotation and magnetic fields, two key actors for massive stars. Presently, the 40 stars observed by *Kepler* show acoustic and gravity modes probably up to $\ell = 20$ (deformed stars) that are difficult to identify [8]. The first difficulty comes from the iron group opacities, which drive their pulsations. The observed modes do not agree with the stability of modes deduced from the OP or OPAL tables [9], which suggests that those opacities are underestimated [10, 11].

Up to now, our effort is dedicated to the second case. The first analysis of the OPAC consortium confirms an underestimate of these opacities through comparison with more recent opacity calculations based on old and new measurements [12–15]. We shall here present our first conclusions and new orientations for the coming years.

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Table 1. Comparison of Rosseland and Planck mean values for different codes of the consortium in the case of iron and nickel, for three temperatures T = 15.3 eV, 27.3 eV and 38.5 eV and a density of 3.4 10^{-3} g/cm^3.

Codes	K_R Fe 15.3	K_R Fe 27.3	K_R Fe 38.5	K_P Fe 15.3	K_P Fe 27.3	K_P Fe 38.5
STA	19330	20500	7020	58650	33380	16100
OP	8160	14642	5978	23400	28000	14289
Cassandra	27650	20250	7545	56770	31250	16280
OPAS	18906	23323	8854	59441	36438	18156
SCO-RCG	18209	19335	6423	54652	30331	13167
LEDCOP	18578	18790	7359	55533	29263	15573
Codes	K_R Ni 15.3	K_R Ni 27.3	K_R Ni 38.5	K_P Ni 15.3	K_P Ni 27.3	K_P Ni 38.5
STA	11910	20180	9012	43340	34870	20080
OP	5910	5990	6620	12900	21000	16100
Cassandra	19370	19110	8448	43910	32330	19210
SCO-RCG	11695	19737	8252	38162	33629	17731

2. LABORATORY CONDITIONS AND NEW CALCULATIONS OF THE CONSORTIUM

The iron opacity bump was at the center of attention in the nineties to solve the Cepheids problem [16, 17], but large differences are still present between the two types of calculations used by astrophysicists: OPAL [9] and OP [7], as mentioned, e.g., by [18]. These differences are clearly visible in Figures 1 and 2 of [13] and have stimulated our interest when the asteroseismic community has shown that this fact complicates their understanding of SPB and β Cephei stars. So our consortium has decided to do new calculations and to perform new measurements.

As a laboratory experiment cannot be performed at the very low density of these stellar envelopes, we have first calculated some equivalent plasma conditions, that one can reach in laboratory. We choose conditions for which the distribution of ionization state is rather similar to the astrophysical state. Figure 1 shows, for the case of iron, the opacity spectra and the distribution of ion charge at T = 27 eV, $\rho = 3.4\ 10^{-3}$ g/cm^3. These laboratory conditions are equivalent to T = 15 eV and $\rho = 3.4\ 10^{-6}$ g/cm^3 that one meets in the envelope of 12 $M_\odot$ stars. In a laboratory, one does not measure directly the opacity spectrum j(ν), but rather the transmission spectrum T(ν) of the photons through a foil of thickness r and density ρ:

$$T(\nu) = \exp^{-\kappa(\nu)\,\rho\, r}.$$

Our consortium has proposed to compare the existing tables OPAL and OP with new calculations for cases that are accessible to experimentation. In parallel, our experimental team (subgroup of the OPAC consortium) has performed specific laser experiments at LULI 2000 (Ecole Polytechnique, France) for chromium, iron, nickel and copper elements in the XUV domain that corresponds to the range useful for the calculation of the mean Rosseland values. In this range of energy, a streak camera is placed behind a specifically designed XUV-ray spectrometer [19] (see [12] for a short description of the experiment done at LULI 2000).

Table 1 and Fig. 2 summarize the comparison of different calculations performed inside our OPAC consortium (a short description of the different calculations can be found in [13]). Table 1 puts clearly in evidence a large dispersion of the Rosseland and Planck values for the three studied temperatures. The differences are more important at low temperatures and for Rosseland than for Planck mean values but they appear at the level of 30% at the equivalent laboratory conditions for iron and goes up to a factor ∼4 for nickel. Figure 2 reveals the regions where the differences are the largest and puts in evidence the two kinds of calculations. STA [20], OPAS, SCO-RCG [21], LEDCOP [22] are similar. OP calculations

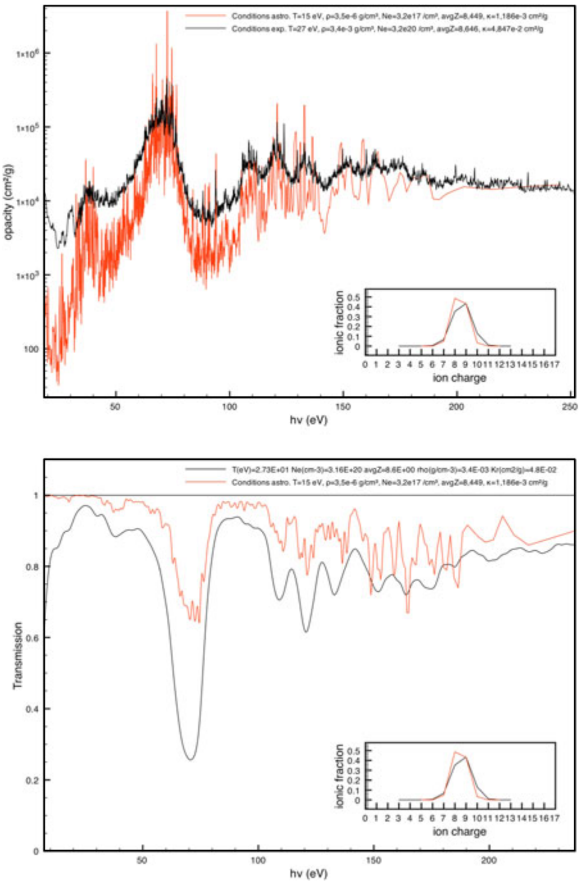

Figure 1. Comparison of OP iron opacity spectrum and its distribution of ionization in the stellar conditions: 15 eV (178000 K) and 3.4 10^{-6} g/cm^3, and in the equivalent laboratory conditions of 27 eV (319000K) and 3.4 10^{-3} g/cm^3.

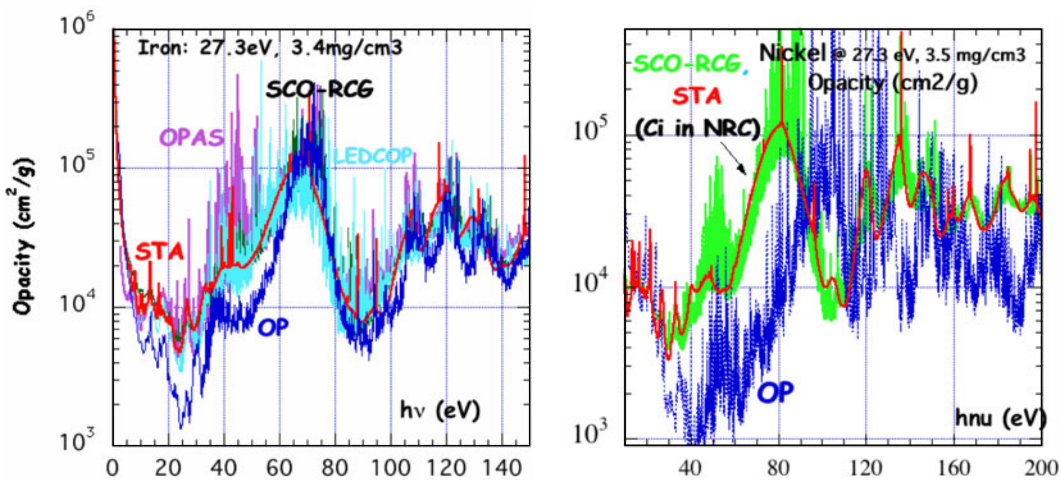

Figure 2. Comparison between opacity spectra for Fe (left) and Ni (right) obtained by different groups in the laboratory conditions.

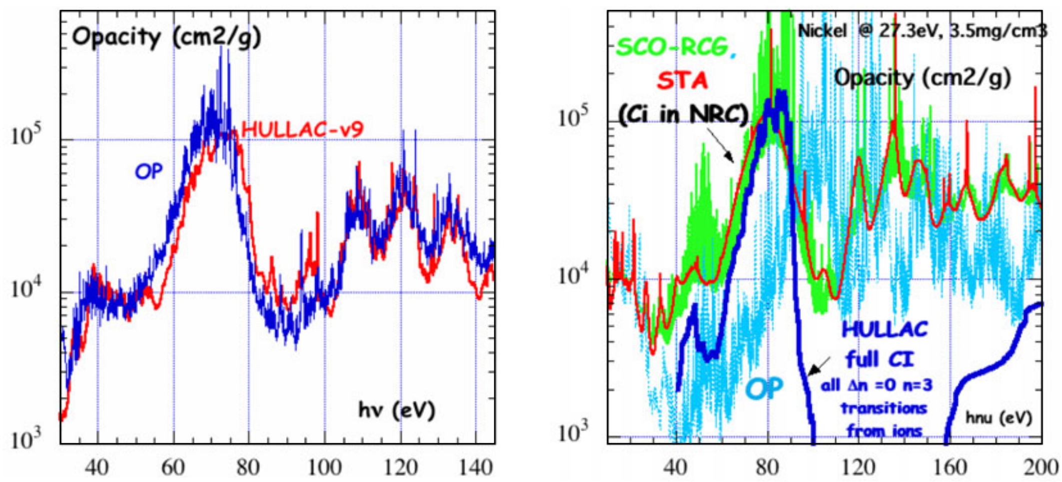

Figure 3. Comparison between calculated opacity spectra for Fe (left) and Ni (right). See also [14, 15].

appear strongly different from the others both for iron and nickel. So the next step is to understand the origins of such differences and to try to determine which are the most adapted for astrophysical calculations.

3. THE ROLE OF THE INTERACTION OF CONFIGURATION

Another detailed code called HULLAC [23, 24] has been used to estimate the origin of the differences. This code is well adapted to check the role of the Configuration Interaction (CI) which is not present in all the codes used. Its action on spectral opacities is no more to be demonstrated and several approaches have been developed to take this effect into account [25, 26]. Full CI inclusion supposes that the diagonalization of the Hamiltonian is performed taking into account all atomic levels. The effect of CI on spectral opacities is mainly to shift the energy level toward higher energies and possibly to change the intensity distribution. When the number of levels is so large that full CI treatment becomes impossible because of computational difficulties appearing for such complex systems, it is also possible to diagonalize the Hamiltonian only for blocks of levels (sub- CI modes). Among them, the most commonly used submodes are CI in a non-relativistic configuration, i.e. the CIinNRC submode and the CIinLAYZER submode. In the OPAC collaboration, two opacity codes offer the possibility to include full CI treatment: OP [6, 7] and HULLAC [24]. Other codes (SCO-RCG, LEDCOP, OPAS) include only partial CI (CI in NRC). In the HULLAC-v9 version it is possible to select the CI mode (no CI, CI in NRC, CI in LAYZER, full CI) and this helps us to compare to other opacity code results.

The transitions $n = 3$, $\Delta n = 0$ and $n = 3$, $\Delta n = 1$ are the dominant contributions of the iron and nickel spectra around the Rosseland mean value maximum (typically $4h\nu/kT = 100\,eV$). These transitions are very sensitive to CI effects, with larger effect on iron. On the left panel of Figure 3, we present a comparison, for iron at a temperature of 27.3 eV and a density of 3.4 mg/cm^3, between results obtained with OP and HULLAC full CI codes. The agreement is very good and significantly differs from results obtained with the other codes SCO-RCG, LEDCOP and OPAS. We can note two families of results corresponding to full CI treatment (HULLAC and OP) and CI in NRC treatment. In that case CI effects are notable and play a large role in the differences on Rosseland mean coefficients shown in Table 1. Surprisingly, in the nickel case (Figure 3, right), HULLAC and OP opacities do not agree. Only the $n = 3$, $\Delta n = 0$, are reported in HULLAC calculations and we can note that CI effects are quantitatively large enough to fill the opacity peaks between 60 and 90 eV, as confirmed by other

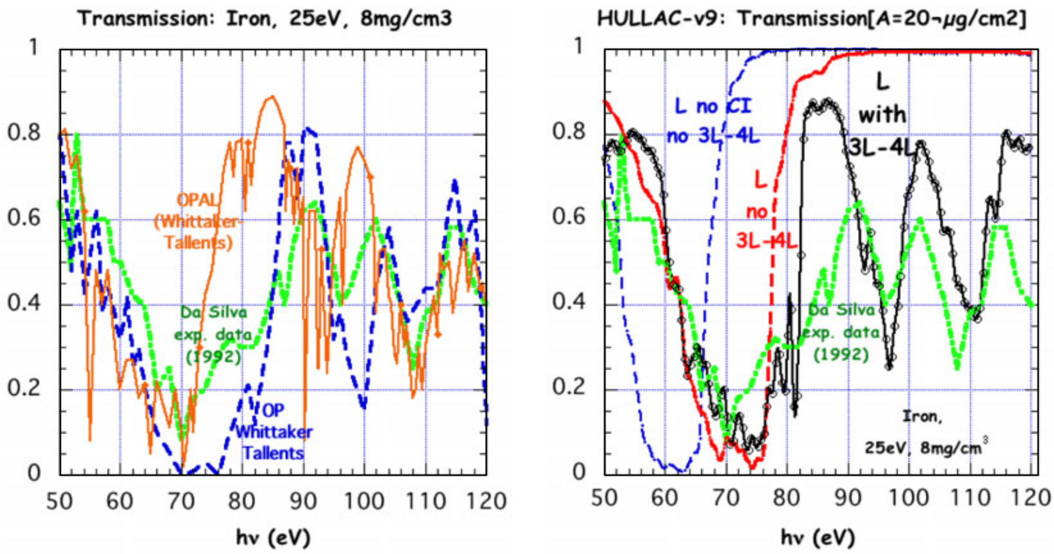

Figure 4. *Left*: Comparison between experimental opacity spectrum of [28] and OP and OPAL, extracted from [27]. *Right*: comparison with different options of the HULLAC calculations [15].

codes. As OP opacities are smaller than all the other results, it may be due to an insufficient number of excited levels in OP or to some extrapolation from iron not done properly. The influence of the atomic description, i.e. the number of configurations taken into account in the CI groups, is very important. However, in full CI treatment, there remains the difficulty to take into account all the excited levels.

4. COMPARISON WITH EXPERIMENTAL SPECTRA

The left panel of Figure 4, coming from [27], shows the transmission spectrum of iron obtained with OPAL and OP, and also with an experiment done by [28] twenty years ago. In this figure, one sees clearly the effect of CI between OPAL and OP (displacement of the spectrum toward higher energy). It is visible that OP reproduces better the experiment than OPAL, even if the calculation is not in total agreement with the experiment. On the right panel of Figure 4, one sees different options of the HULLAC code and their impact on the theoretical spectrum.

The measurements require to form a plasma in LTE with ionization conditions equivalent to stellar conditions. Such a goal depends upon a good simulation of the whole experiment, to probe the foil at the best moment to get the appropriate temperature and density without pollution due to the emission of the gold of the cavity. The rapid expansion of the foil during the heating is limited by placing it between two thin samples of a low Z material, playing the role of inertial confinement to prevent a dramatic decrease of the density (see previous experiment [29]). In the experiments done at LULI 2000, we measure the radiative temperature of the X radiation in the cavity thanks to a multi channel spectrometer which measures X-rays energy [30]. We limit the temperature gradient below 10% inside the foil in separating the incident beam in two parts, and we then insert the foil between two cavities that are both heated by a similar flux. The streak camera gives the time dependence of the phenomenon, in order to discriminate between backlight signal and self-emission of the cavity. A preliminary comparison of the obtained spectra confirms some aspect of [28] experiment but shows also some extended spectrum up to 200 eV. The new calculations show also a high sensitivity to the foil temperature and density so the exact conditions of the experiment need to be carefully determined. The results of the two campaigns performed in 2010 and 2011 are still being discussed, but it seems that we get interesting spectra for chromium, iron, and nickel which are promising to give complementary information on the quality of the calculations.

5. FIRST CONCLUSIONS

Asteroseismology will largely improve stellar evolution in the next decade. Consequently the required accuracy on the predicted stellar models will increase with time, and new benchmarks are useful with new calculations and laser experiments to validate the microscopic physics used in stellar evolution: ionic distribution of each species, equation of state, and opacity. The international consortium OPAC performs theoretical and experimental studies to improve absorption spectra of photons in stellar plasma.

The present report is dedicated to radiative envelopes of stars. We show, in the case of iron, that the OP calculations appear clearly better than the OPAL ones, unlike from what emerges from Z pinch experiments for higher temperatures and densities [31]. In the present study, we show, thank to the HULLAC code, that full relativistic calculations including interaction of configurations are required. Of course our present analysis does not yet exclude a final small change of the iron Rosseland mean values but probably smaller than 30%. On the other side, OP calculations for nickel do not agree with HULLAC calculations, and the potential increase could be of the order of a factor 2 up to 4. The measurements on nickel, chrome and iron elements performed in LULI 2000 will soon confirm these first conclusions.

A strategy of progress is defined in our consortium to improve as quickly as possible our understanding of different kinds of stars and will be discussed in the second international meeting on astrophysical opacities which will be held in Bordeaux on 27-28 February 2013.

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