Study of the solar opacity using the ATMED code

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Introduction

The opacity of the solar plasma is one of the main governing factors determining the physical state of the Sun. It influences the details of the nuclear reactions, thus the solar neutrino flux, the solar luminosity and several physical details [1]. Particularly, Rosseland mean opacity of stellar material is a key piece in calculations of stellar structure and evolution [2] and it is provided mainly by complex theoretical calculations. In this work we present a study of solar opacity using the LTE code ATMED [3, 4].

ATMED is a code conceived to compute the spectral radiative opacity as well as the Rosseland and Planck means of hot dense plasmas. It can deal with one component plasmas as well as plasma mixtures. The code has been developed in the context of LTE Average Atom Model approximation. The atomic data needed are computed using a New Relativistic Screened Hydrogenic Model [5]. Since the photon-electron scattering has a significant contribution to plasma opacities in the cases where the atoms in the plasma are fully ionized, we have introduced in our scattering opacity model corrections for relativistic effects [6] and electron collective effects [7,8,9,10] that contribute to diminish the plasma opacity.

In this work we have used the model of abundances of Grevesse et al. [11] to compute the opacity and equation of state of the Sun. This model states that the Sun is made of hydrogen, helium and traces of heavier elements up to Z=28, where the abundances of hydrogen and helium depends on the distance to the solar center and heavy metals have a constant mass fraction equal to 0.0195. We compare our results for the Rosseland mean opacity, pressure, sound speed and solar luminosity with the ones published by Rozsnyai [1] computed in the framework of the ion-sphere model with the DCA approach and a quantum mechanical model to compute the plasma opacity.

Description of the model

The total spectral opacity of plasma $\kappa(\nu)$ is the combination of bound-bound, bound-free, free-free and scattering processes. The details of the model are presented in our previous work [3,4]. For a mixture the bound-bound and bound-free cross sections are weighted by the fraction number f_k of the N components of the mixture, in order to obtain the average cross section per ion [12].

$$\sigma_{mix}^{bb/bf} = \sum_k f_k \sigma_k^{bb/bf} \qquad (1)$$

where $\sum f_k = \mathbf{1}$. The bremsstrahlung absorption cross section has been computed with Kramer's formula using the average value of the average ionization of each element in the plasma:

$$\langle \overline{Z} \rangle = \sum_k f_k \overline{Z_k} \qquad (2)$$

The total spectral opacity of the mixture is given by the expression:

$$\kappa'(h\nu) = \frac{n_i}{\rho}\left(\sigma_{mix}^{bb}(h\nu) + \sigma_{mix}^{bf}(h\nu) + \sigma_{mix}^{ff}(h\nu) + \sigma^{scat}(h\nu)\right) \qquad (3)$$

being n_i the average ion number density in the plasma and ρ is the mixture density. The scattering cross section per electron is modified from the Thomson value σ_s by including relativistic and electron collective effects, being given by the expression:

$$\sigma^{scatt}(h\nu) = n_e G(u,T') f(\eta,\delta) \sigma_s \qquad (4)$$

The relativistic effects are taken into account with the factor $G(u,T')$ due to Sampson [6], computed with the expansion:

$$G(u,T') = 1 + 2T' + 5T'^2 + \frac{15}{4}T'^3 - \frac{1}{5}\left(16 + 103T' + 408T'\right)uT' + \left(\frac{21}{2} + \frac{600}{5}T'\right)(uT')^2 - \frac{2203}{70}(uT')^3 \qquad (5)$$

where $u = h\nu/k_B T$ and $T' = k_B T/mc^2$. The collective effect factor $f(\eta,\delta)$ [9] depends on the plasma degeneracy parameter $\eta = \mu_e/k_B T$ and on the parameter $\delta = 2\left(c/\lambda_D \omega\right)^2$, where λ_D is the Debye screening length and ω is the angular frequency of the photon:

$$f(\eta,\delta)=\left(1-\frac{I_{1/2}(\eta)}{2^{3/2}}\right)\left\{1-\frac{3}{8}\delta\left(\frac{\lambda_D}{\lambda_e}\right)^2\left[\left(\delta^3+2\delta^2+2\delta\right)ln\left(\frac{\delta}{2+\delta}\right)+2\delta^2+2\delta+\frac{8}{3}\right]\right\} \qquad (6)$$

where $I_{1/2}(\eta)$ represents the Fermi-Dirac integral and λ_e is the electronic screening length.

Each component of the mixture has its own ion-sphere radius r_{0k}, which determines a volume V_k and a partial density given by $\rho_k = A_k / V_k N_A$. Since the volume of the mixture V is equal to the sum of the volumes occupied by the individual components of the mixture V_k, we have $\frac{1}{\rho}\sum_k m_k = \sum_k \frac{m_k}{\rho_k}$

Furthermore, under the conditions of thermodynamic equilibrium for systems in contact with diffusion, the chemical potentials μ_k should be equal. This condition together with latter equation has been used to obtain the partial densities ρ_k.

Results and Discussion

Table 1 shows our results for Rosseland mean opacity (g/cm^2) in the inner of the Sun computed with (1) and without (2) the corrections to scattering opacity. In the regions near the Sun centre where densities and temperatures are higher the new model diminishes the Rosseland mean opacities in a range between 10% and 20%, while for outer regions the corrections are shorter and decrease with solar radius. The new Rosseland mean opacities values have been used to compute the solar radiative luminosity given by the expression:

Table 1. Rosseland mean opacities computed with ATMED for solar interior without (1) and with (2) corrections to scattering

r/R0	ρ (g/cm³)	kT(eV)	X(H)	κ_R (1)	κ_R (2)
0.0000	157.0200	1362.1000	0.3545	2.3359	1.8067
0.0462	130.0200	1276.2000	0.4171	2.5014	1.9760
0.1131	78.1600	1069.4000	0.5922	3.0006	2.5174
0.1469	59.7000	956.4900	0.6559	3.3852	2.9064
0.2038	33.9600	790.5300	0.7104	3.7827	3.3272
0.2449	22.3300	688.9300	0.7239	4.0800	3.6242
0.3364	8.0350	519.4300	0.7300	4.5341	4.0964
0.5545	0.7656	293.2400	0.7300	9.8973	9.5328
0.7184	0.1803	182.6800	0.7300	24.9270	24.1630
0.8492	0.0558	81.9500	0.7300	108.7800	107.1700
0.9000	0.0246	54.3000	0.7300	141.1400	140.9300
0.9715	0.0027	12.7160	0.7300	9163.2000	9012.6000

$$L(r)=-4\pi r^2\frac{4ca}{3\kappa_R\rho}(k_BT)^3\frac{\partial(k_BT)}{\partial r} \qquad (7)$$

Figure 1 shows the solar radiative luminosity computed with ATMED and compared with the total luminosity including convective luminosity SSM, and with the results by Rozsnyai [1]. In spite of the corrections introduced to the opacity model, luminosity computed with ATMED is far of the SSM luminosity although it reproduces the correct tendency. In Figures 2 and 3 we show the pressure and sound speed versus the solar radius compared with the values from the model of Rozsnyai. Both cases are in good agreement with the reference model.

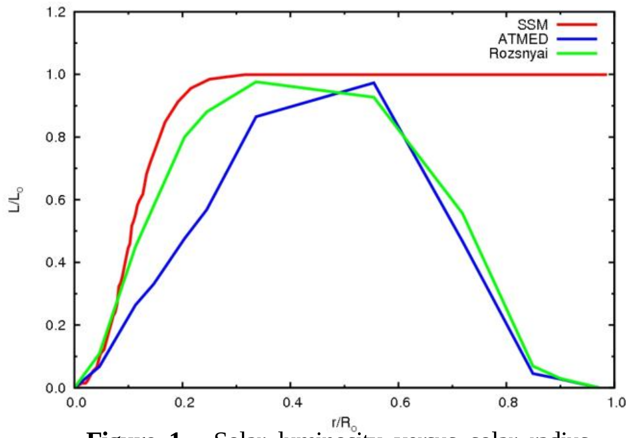

Figure 1. Solar luminosity versus solar radius computed with ATMED.

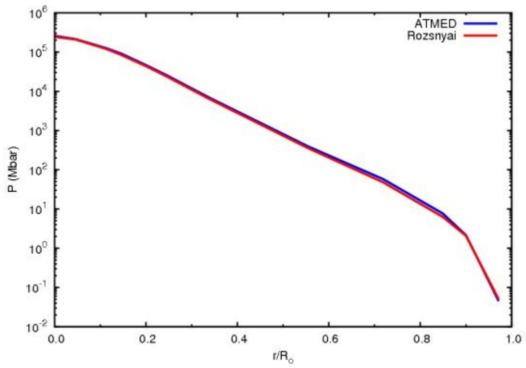

Figure 2. Pressure versus solar radius

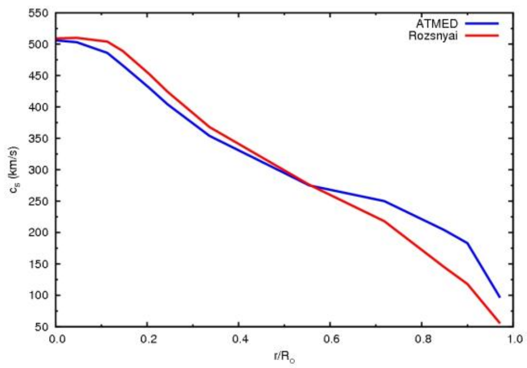

Figure 3. Sound speed versus solar radius

Acknowledgements

This work has been supported by Spanish Ministry of Science and Innovation Grant (ENE2009-11208) and the "Keep in Touch" Project of the European Union.

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