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Solar Model with Metal-enhanced Convective Envelope

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Abstract. Solar model with moderate enrichment of heavy elements in the convective envelope is investigated using the up-to-date input physics. It is found that metal enriched model can result in adequate depth of the convection zone and appropriate surface helium abundance, and the agreement between the calculated and observed p-mode frequencies are also improved. The sound speed of our model is worse than SSM and DSM in deep interior, but is better in the base of convection zone.

1. Introduction

A discrepancy has existed between standard solar models predictions of neutrino fluxes and the observed rates for more than three decades(Bahcall 1989). Low Z models are proposed at the beginning to reduce the predicted solar neutrino flux(Bahcall & Ulrich 1971). In contrary to the standard models, low Z models take into account the possibility of chemical stratification of the Sun. A star may capture some interplanetary matter after the Hayashi phase evolution(Joss 1974). For the case of the Sun that has a convection zone just below its photosphere, the falling matter will be mixed into the whole convection zone. As the metal abundance of the interplanetary dust is much higher than that of the solar material, the solar convection zone will be enhanced with heavy elements.

Low-Z models can give rather low neutrino fluxes, but usually result in shallow convection zones and very low initial helium abundance. Moreover, their calculated p-mode oscillation frequencies and sound speed in the solar interior are in bad agreement with the observations(Christensen-Dalsgaard, Gough, & Morgan 1979; Christensen-Dalsgaard & Gough 1980; Bahcall & Ulrich 1988). Therefore, low Z models are thought to be unrealistic in recent years, and more and more authors prefer the standard solar models with elements diffusion(Bahcall & Pinsonneault 1992; Bahcall, Pinsonneault, & Wasserburg 1995; Bahcall, Basu, & Pinsonneault 1998).

However, many evidences confirm that the solar envelope has been contaminated by interplanetary material, even if not as much as demanded by previous low Z models. So we investigate moderate enhancement of the envelope metallicity, using the updated input physics, and focus our attention on not the solar neutrino problem but the structure and p-mode oscillations of the Sun.

2. Properties of Evolution Models

We have calculated three different series of evolution models. SSM and DSM are standard models, without and with helium and heavy element diffusion, respectively. Both of them do not consider the effects of metal enrichment. CSM is a metal enriched model without element diffusion, in order to distinguish the effects of the envelope metal enrichment and element diffusion. We assume for simplicity that the metal enrichment takes place at the zero-age main sequence.

Table 1 gives the basic parameters of the three models. It can be found that $1-f$, which is the mass in unit of $M_\odot$ falling onto the Sun, is about $0.00013 M_\odot$. It is very interesting to notice from table 1 that the surface helium abundance(Y_s) and the base of the convection zone(R_{bc}) for the metal enriched model CSM are in good agreement with recent helioseismic determinations(Basu & Antia 1995; Basu & Antia 1997). This is contrary to the results of previous investigations, in which metal enriched models result in very low surface helium abundance and shallow convection zones. For the standard model with element diffusion, DSM, these two values are also in good agreement with the measured values, as found in many other author's results. We can conclude from table 1 that SSM is in bad agreement with helioseismological analysis. Element diffusion and settling are initial introduced to reduce the envelope helium abundance during the evolution. Now we have another approach to remedy the discrepancy between the calculated and observed solar envelope helium abundance. It can also be noticed from Table 1 that CSM gives lower neutrino fluxes for either Cl or Ga detectors while DSM gives higher fluxes than SSM does.

Table 1. Properties of the Evolution Models

Parameters	SSM	DSM	CSM	Observation
Y_0	0.275	0.272	0.250	
Z_0	0.02	0.02	0.015	
α	1.638	1.726	1.697	
$1-f$			0.000129	
Y_s	0.275	0.242	0.248	0.249 ± 0.003
Z_s	0.02	0.018	0.02	
Y_c	0.632	0.649	0.605	
Z_c	0.02	0.021	0.015	
T_c (10^6K)	15.69	15.79	15.35	
ρ_c (g/cm^3)	153.2	157.7	150.7	
M_{bc} ($M_\odot$)	0.979	0.977	0.979	
R_{bc} ($R_\odot$)	0.724	0.716	0.719	0.713 ± 0.001
T_{bc} (10^6K)	2.122	2.155	2.139	
Φ_{Cl} (SNUs)	7.70	8.52	5.32	2.55 ± 0.25
Φ_{Ga} (SNUs)	127.50	131.52	115.88	73.4 ± 5.7

In Figure 1 we compare the calculated frequencies of $l = 0, 1, 2, 3$ with the observation values(Libbrecht, Woodard, & Kaufman 1990). It is found that the p-mode frequencies of DSM and CSM are in better agreement with the

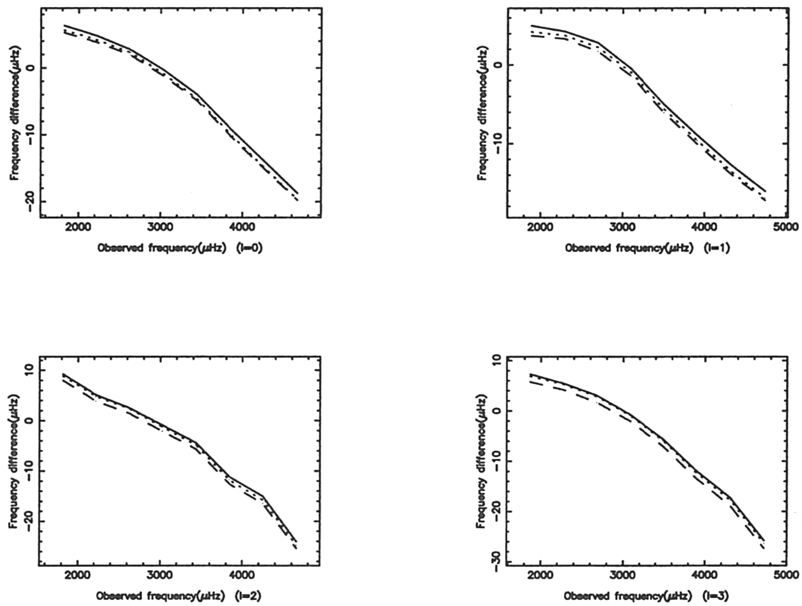

Figure 1. Comparisons of calculated solar p-mode frequencies of $l = 0, 1, 2, 3$ with respect to the observations. Solid line is for SSM, dashed line is for DSM and dotted line is for CSM.

observations than those of SSM. This is an important result, and completely contradicts the conclusions of previous low-Z models.

Figure 2 shows the profiles of sound speed differences of three models with respect to observation values, and those of DSM and CSM with respect to SSM. It can be noticed from left figure that the calculated sound speed is higher in nuclear burning cores and lower in the outer radiative zones than the observed value, and is almost the same as observation in the convection zones for all three models. For the solar interior that $R < 0.6R_{\odot}$, DSM is in better agreement with observation than SSM does, while CSM is worse than SSM, but the maximum difference is less than 1%. In the area just below the base of convection zone, calculated sound speed from CSM is almost the same as observation value, while DSM and SSM give their maximum difference. From right figure we can notice that the diverge of DSM and CSM to SSM is almost opposite.

3. Discussions and Conclusions

From our calculation we find that metal enriched model can result in adequate depths of the convection zone and appropriate surface helium abundance, both of which are in good agreement with the seismic results. The agreement between the p-mode frequencies of our metal enriched model and the observations are also improved, and even better than the standard homogeneous model. The sound speed of our model CSM is worse than SSM and DSM in deep interior. In the base of convective envelope, our model can give the sound speed better than that of DSM and SSM. Further more, our metal enriched model CSM gives

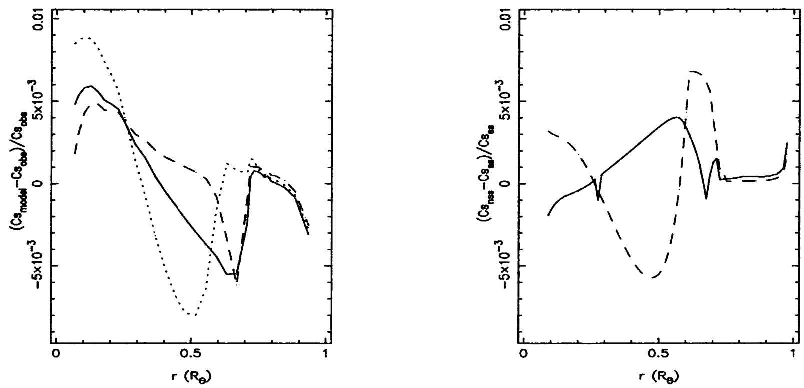

Figure 2. The sound speed differences of models with respect to observation values(left), and those of DSM and CSM with respect to SSM(right). In the left figure, solid line is for SSM, dashed line is for DSM and dotted line is for CSM. In the right figure, solid line is for DSM to SSM, and dashed line is for CSM to SSM.

lower neutrino fluxes for either Cl or Ga detectors than SSM and DSM do, which is helpful to solve the solar neutrino problem.

Upon the improvements discussed above, we conclude that solar models with enhancement of heavy elements exterior to the base of their convection zones are still of vitality, and could be a solution of problems that the present standard solar models cannot solve.

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