CHAPTER 2

THEORY OF SOLAR OSCILLATIONS

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SENSITIVITY OF SOLAR P-MODES TO SOLAR ENVELOPE STRUCTURE

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ABSTRACT. We present a study of the effects of diffusion of helium and heavy elements from the convection zone into the radiative layer immediately below the convection zone, on the structure of the solar envelope. A comparison is made of the p-mode oscillation spectrum and the run of the speed of sound in a model with diffusion, in a standard model, and with observation.

1. APPROACH

Diffusion in the solar envelope has two main consequences:

(1) The helium abundance at the surface and in the convection zone decreases slowly with time during the evolution of the sun (Michaud, Fontaine and Beaudet 1984).

(2) Similarly, the heavy element content also decreases at the surface and in the convection zone. As a result the value of Z throughout the rest of the solar interior, which contains most of the mass, is higher than the value of Z determined spectroscopically in the stellar photosphere (about 0.02).

In order to explore the importance of these effects on the solar internal structure, we have constructed a solar model with high initial Z and in which progressive helium diffusion from the convection zone takes place during its evolution from the main sequence, and we have compared this model's oscillation characteristics to those of a standard model and to observation.

We emphasize that in each case, special care was taken to match accurately the luminosity, radius and age of the sun. This is essential for a meaningful comparison of the oscillation characteristics of the models.

Our model parameters are summarized in Table 1. We note that in the model with helium diffusion, in which the surface abundance of helium decreases by about 25 per cent during evolution, the predicted present helium surface abundance is nearly the same as in the standard model. This is because a higher Z in the interior implies a higher initial helium abundance in order to match the current solar luminosity at the same age. The main parameters of our two models are given in Table 1.

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Table 1.

Standard	High Z with diffusion
$Z = 0.02$	$Z = 0.04$
$X_{Center} = 0.399$ $X_{Surface} = 0.743$	$X_{Center} = 0.339$ $X_{Surface} = 0.701$ (initial) $X_{Surface} = 0.727$ (evolved)
Radius at base of convection zone = 5.0×10^{10} cm	Radius at base of convection zone = 4.7×10^{10} cm
$\alpha = 1.37$	$\alpha = 1.47$
Neutrino Flux (Davis Cl detector) = 4 SNU's	Neutrino Flux (Davis Cl detector) = 7 SNU's

2. THE P-MODE SPECTRUM

Figure 1 shows the difference between the observed and calculated p-mode frequencies as a function of frequency for the standard model (○ for $l = 1,\ldots,4$ and ✕ for $l = 9, 10, 14, 20$), and the high-Z model with diffusion (□ for $l = 1,\ldots,4$ and ✚ for $l = 9, 10, 14, 20$). We see that for the standard model, smaller l modes agree better with observation than larger l modes at all frequencies. For the high Z model with diffusion, the overall agreement is much improved. However, we note that small l modes agree better than large l modes at higher frequencies, but less well at lower frequencies. For the highest frequencies plotted here, larger errors in the calculated modes are accounted for by the shell-grid resolution.

Figures 2 and 3 are ν-l diagrams for the standard and high-Z with diffusion models respectively. In both figures, the solid lines represent the observations, taken from Harvey and Duvall (1984), the dashed lines represent the theoretical data.

3. THE SOUND SPEED

Figure 4 is a plot of the sound speed vs radius in the standard and high-Z with diffusion models. The following comments summarize our main results:

(1) The sound speed is insensitive to differences in helium abundances within the convection zone for models which are constrained to fit the observed solar radius and luminosity.

(2) A break in slope is noticeable at radii 5.0×10^{10} and 4.7×10^{10} cm respectively for the standard and high-Z with diffusion models. This indicates the position of the base of the C.Z.

(3) The differences in sound speed near the center can be understood in terms of differences in central hydrogen abundances between the two models.

(4) Between 2×10^{10} and 5×10^{10} cm, the excess sound speed of the high-Z model with diffusion is explained by the change in structure due to higher opacities.

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Figure 1.

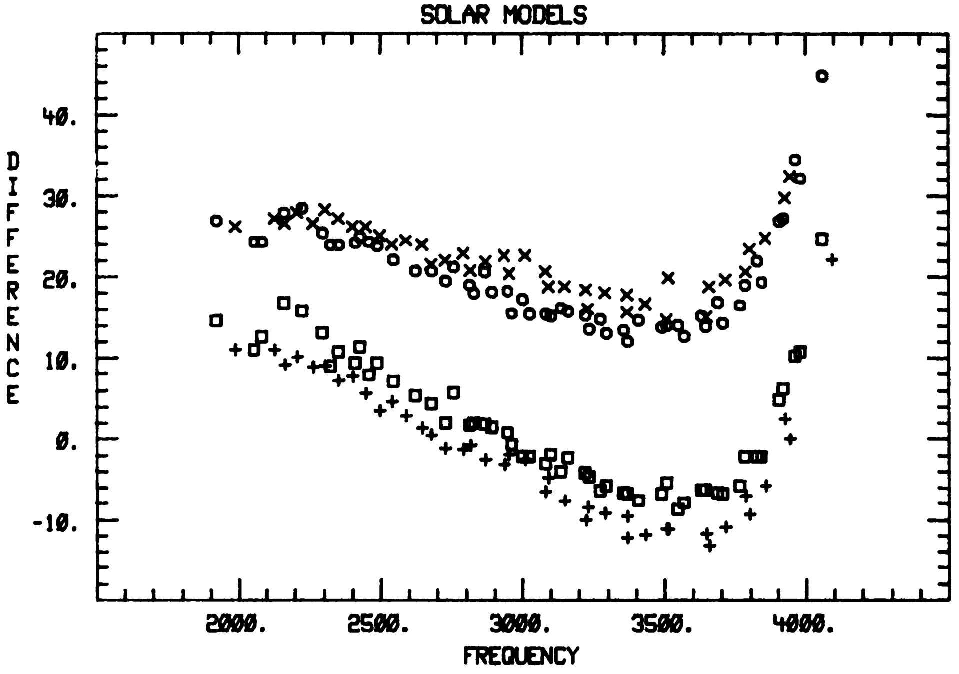

Figure 2.

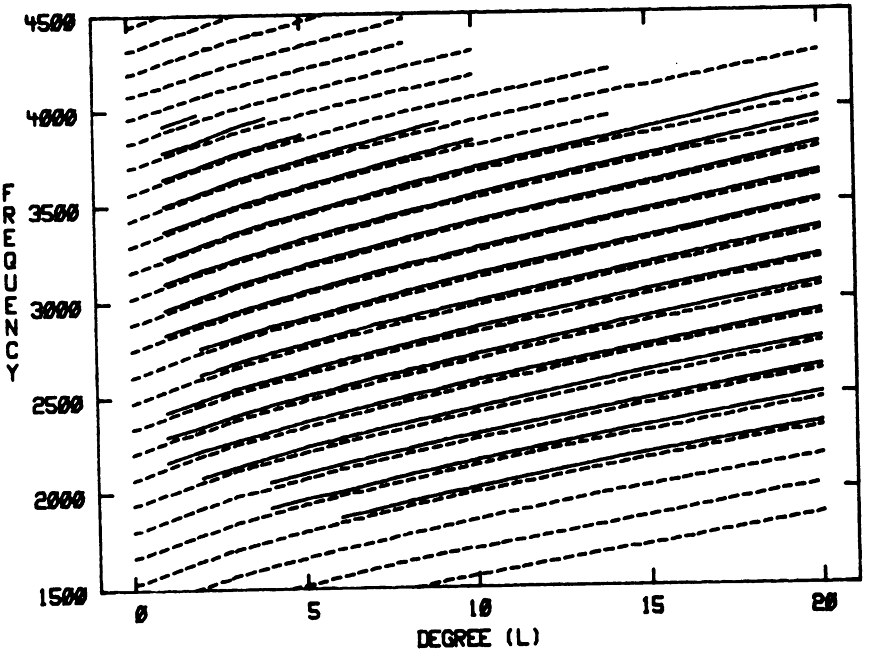

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Figure 3.

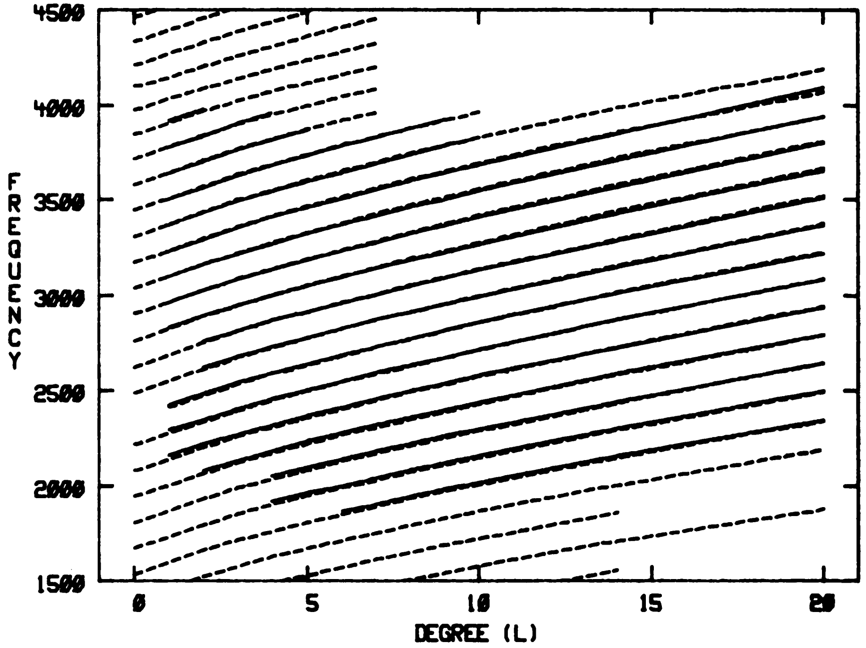

Figure 4.