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OSCILLATIONS OF SOLAR MODELS WITH INTERNAL ELEMENT DIFFUSION

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Two precision solar models have been constructed with the Iben evolution program, one with no diffusion of the internal atomic nuclei, and another that includes the effects of gravitational settling, thermal diffusion, and concentration gradient diffusion on the element abundances. Our pressure and energy equation of state and opacity have been specially fit to the latest theoretical data. Then the opacity at the bottom of the convection zone was increased 15 percent (within its theoretical uncertainty) to allow a better agreement with the observed solar p-mode frequencies. The theoretical p-mode frequencies are still too small by about 10-20 microhertz. The solar mass, radius, luminosity, and age of 4.6±0.1 billion years were matched for both evolution runs so that the theoretical error of the predicted oscillation frequencies was less than one microhertz. Parameters that were adjusted to match with the $M_\odot$, the observed $R_\odot$, and $L_\odot$ were the initial helium abundance and the ratio of the mixing length to the pressure scale height in the normal convection theory. The original helium mass fractions of the mixture were 0.300 and 0.298 for the no-diffusion and diffusion models, respectively. The diffusion model evolved to a surface Y=0.263 at the solar age, and the original Z value of 0.0200 decreased to 0.0179 by diffusive settling. Our equation of state gives pressures that average a few percent too large throughout the sun, and therefore more helium, with its lower pressure per gram than hydrogen, is needed to compensate for this error. We estimate that the true helium mass fraction is about 0.02 smaller than what we use. The bottom of our convection zone is hotter than for most previous models because we have tried to match the p-mode frequencies better, but it is probably not hot enough to deplete the surface lithium abundance to the observed value unless there is overshooting below the bottom of the convection zone by about half a pressure scale height. It is possible that theoretical uncertainties in the pressure equation of state will always prevent matching the helium abundance (Y) and the p-mode frequencies to better than 0.02 and 10 microhertz, respectively. A discussion is given of the agreement of asymptotic theory p-mode frequency separations and those directly calculated with nonadiabatic theory. Calculation of g-mode

solutions shows that they do not have equal spacings in period until very high radial order. Nonadiabatic solutions for these modes enable us to predict the relative visibility of them, and for l=1-5, the highest order modes seem to be more detectable. We find that the f-mode is pulsationally unstable for high l at the solar granulation space and time scales. The high helium needed to match the p-mode frequencies results in high central temperatures that give 13 SNUs from the ^8B and 2 SNUs from the ^7Be reactions.

Table 1
Solar Evolution Results

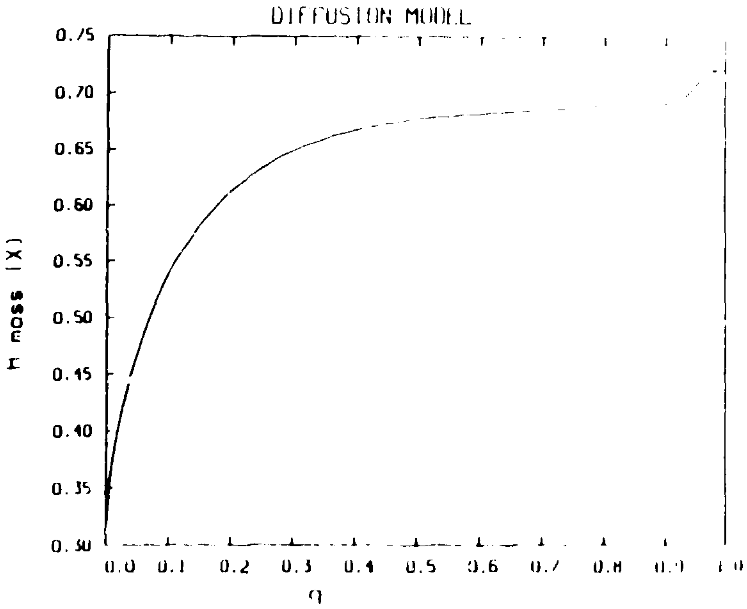
Parameter	Without Diffusion	With Diffusion
Initial Y	0.300	0.298
Initial Z	0.020	0.020
Mixing Length Ratio	1.876	1.919
T_{eff} (K)	5771.2	5770.4

Table 2
Solar Interior Results

Parameter	Without Diffusion	With Diffusion
Central Y	0.6664	0.6672
Central Z	0.0206	0.0214
Central T (10^6K)	15.77	15.82
Central Density (g/cm^3)	165.4	165.6
B^8 Neutrinos (SNU)	12.6	13.0
Be^7 Neutrinos (SNU)	1.9	2.0

Table 3
Solar Envelope Results

Parameter	Without Diffusion	With Diffusion
Surface Y	0.3003	0.2620
Surface Z	0.0200	0.0179
Convection Zone T (10^6K)	2.236	2.123
Convection Zone R ($R_\odot$)	0.717	0.721
Convection Zone M ($M_\odot$)	0.977	0.978



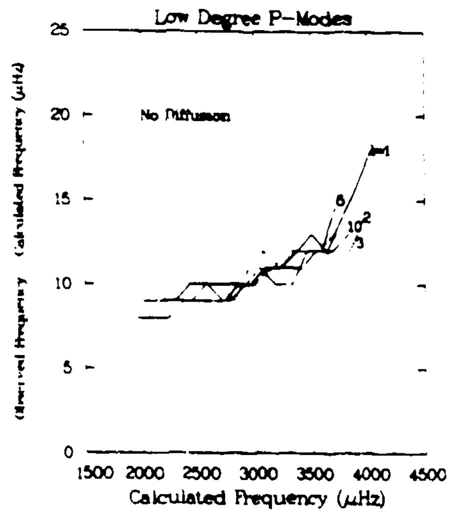
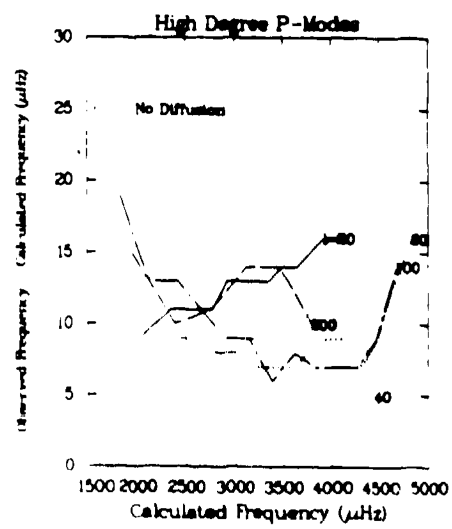


Figure 1. The hydrogen mass fraction in the mixture is plotted versus the internal mass fraction for the diffusion solar model.

Figure 2. Observed minus calculated p-mode frequencies are plotted versus the frequency for the no-diffusion model. These modes sample the model region below the convection zone.



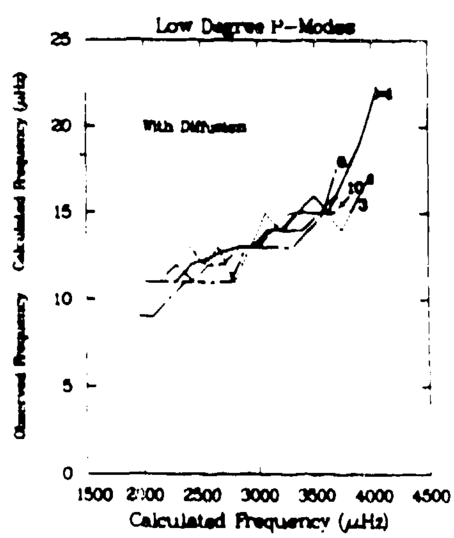
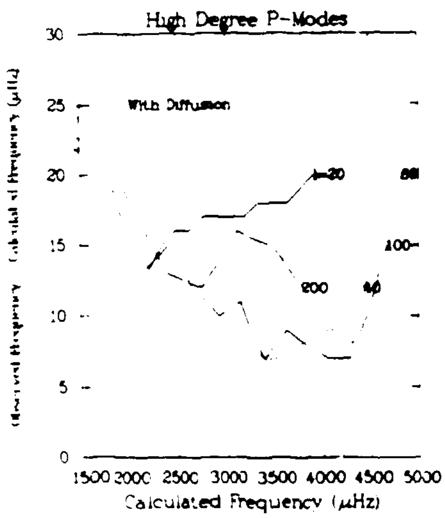


Figure 3. Observed minus calculated p-mode frequencies are plotted versus the frequency for the no-diffusion model. These modes sample the convection zone.

Figure 4. Observed minus calculated p-mode frequencies are plotted versus the frequency for the diffusion model. These frequencies run a few microhertz above the similar plot for the no-diffusion model.



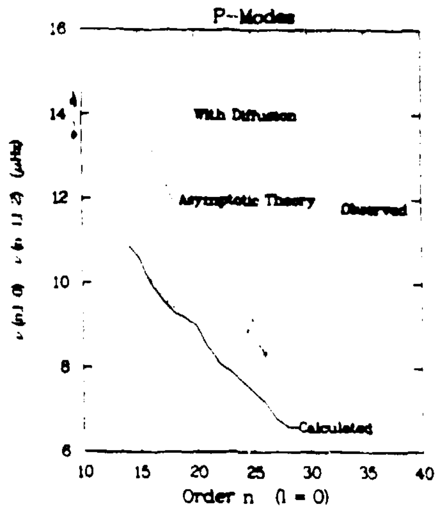
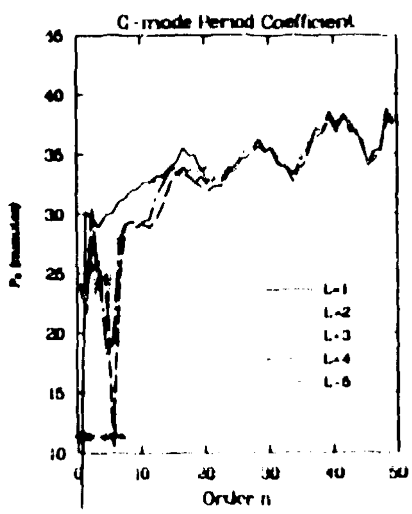


Figure 5. Observed minus calculated p-mode frequencies are plotted versus the frequency for the diffusion model. These modes sample the convection zone.

Figure 6. The δ nonadiabatic frequency difference between the radial and quadrupole modes for radial orders 12 to 28 is plotted versus radial mode order for the diffusion model.



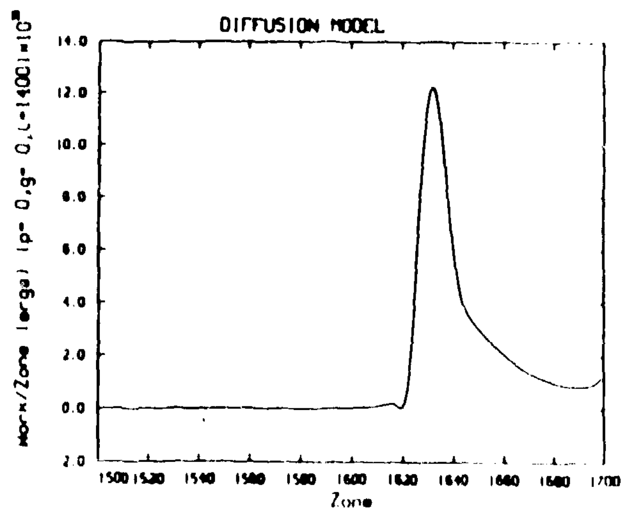


Figure 7. The period spacing between mode periods multiplied by $\sqrt{l(l+1)}$ is plotted versus g-mode order. Fluctuations are due to our nonsmooth Brunt Väisälä frequency.

Figure 8. The work per zone over each pulsation cycle for the photospheric zones is plotted versus zone for the f mode with l=1400, near the solar granulation scale. The mode is pulsationally unstable because of the κ and γ effects. The work integral predicts an e-folding time to be about 7700 cycles, which, at the f mode period of 268 seconds, is only 25 days.