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TITLE: SOLAR MASS LOSS, SOLAR LITHIUM, AND SOLAR OSCILLATIONS

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SOLAR MASS LOSS, SOLAR LITHIUM, AND SOLAR OSCILLATIONS

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ABSTRACT Swenson and Faulkner, and Boothroyd et al. investigated the possibility that early main-sequence mass loss via a stronger early solar wind could be responsible for the observed solar lithium and beryllium depletion. This depletion requires a total mass loss of $\approx 0.1\ M_\odot$, nearly independent of the mass loss timescale. We have calculated the evolution and oscillation frequencies of solar models including helium and heavier element diffusion, and such early solar mass loss. For models with gradual early mass loss (during ≈ 1 Gyr), the early mass loss phase decreases the total amount of helium and heavier elements diffused from the convection zone, and the extent of the diffusion-produced composition gradient just below the convection zone, deteriorating the agreement with observed frequencies for intermediate ℓ modes. The mass loss phase must be confined to ≈ 0.2 Gyr or less to solve simultaneously the solar Li/Be problem and avoid discrepancies with solar oscillation frequencies.

INTRODUCTION AND RESULTS

Swenson and Faulkner (1992) and Boothroyd, Sackmann, and Fowler (1991) investigated the possibility that early main-sequence mass loss could be responsible for the solar Li/Be depletion. They find from evolution calculations that an initial mass of 1.1 $M_\odot$, and an initial mass loss rate 2 x 10^{-10} $M_\odot$/yr, exponentially decreasing with e-folding time 0.45 Gyr depletes Li by a factor of ≈ 50 and Be by a factor of about two. The amount of depletion is more sensitive to the total mass loss than the e-folding time. For example, a higher constant mass loss rate of 5 x 10^{-10} $M_\odot$/yr ending at 0.2 Gyr will deplete about the same amount of Li and Be for initial mass $\approx 1.1\ M_\odot$. In this paper, we compare observed and calculated p-mode oscillation frequencies of three solar models, all including element diffusion: 1) A standard model with no early mass loss; 2) a model with initial mass 1.1 $M_\odot$and gradual early main-sequence mass loss (exponentially-decreasing$\dot{M}$, e-folding time 0.45 Gyr); and 3) a model with initial mass 1.1$M_\odot$and rapid mass loss (constant mass loss rate 5 x 10^{-10} $M_\odot$/yr for 0.2 Gyr). See Guzik and Cox (1992, 1993) and Cox et al. (1989) for a description of the evolution, diffusion, and oscillation frequency calculation procedures. We point out that for all the models, we use the Iben analytical fit calibrated to the OPAL (Rogers and Iglesias, 1992) opacities; the opacities in the 2-5 million K range were adjusted very slightly ($\approx$ 1-2%) to adjust the convection zone depth for each model (to 0.712 $\pm$ 0.001) $R_\odot$; (see Guzik and Cox, 1993) and thereby optimize the agreement between observed and calculated frequencies.

The table summarizes evolution results for the models. We note that the small amount of early mass loss has little effect on the solar central composition gradient. While it does affect the calculated low-degree mode frequencies that sample the solar center (ℓ=0-3), changes are presently comparable to or smaller than the observational uncertainties for these modes (several tenths of a microhertz). Surprisingly, models can be discriminated when element diffusion is included, since early mass loss alters the shape of diffusion-produced composition gradient below the convection zone that is sampled by intermediate-degree p-modes with smaller observational uncertainties ($< 0.1\mu$Hz).

TABLE I   Evolution Parameters

Model	Standard	Gradual	Rapid
Initial Mass ($M_\odot$)	1.0	1.1	1.1
Initial $\dot{M}$($M_\odot$/yr)	-	2 x 10^{-10}	5 x10^{-10}
$\dot{M}$ Timescale (Gyr)	-	0.45 (e-folding)	0.2 (constant $\dot{M}$)
Initial Y,Z	0.263,0.02	0.257,0.02	0.262,0.02
Final Central Y,Z	0.6238,0.0208	0.6316,0.0208	0.6231,0.0208
Final Surface Y,Z	0.2347,0.0189	0.2413,0.0194	0.2365,0.0189
Surface Z/X	0.0253	0.0262	0.0254
Mixing Length/H_p	2.27	2.26	2.26
Convection Base ($R_\odot$)	0.711	0.712	0.712

Figure 1 shows the effect of mass loss on the diffusion-produced helium composition gradient just below the convection zone for each model. Figures 2-4 compare the observed and calculated oscillation frequencies of modes of degree ℓ=5-40 that sample the solar structure in the region of the convection zone base. Note that for the model with gradual mass loss, mass loss reduces significantly the overall amount of diffusion, and the extent of the diffusion-produced composition gradient at the convection zone base at the Sun's present age (4.5 Gyr). This causes the O-C frequencies to increase with increasing degree ℓ for the modes with frequency > 2000μHz that have significant weight just below the convection zone bottom (Fig. 3). This spread in O-C frequencies cannot be removed by adjusting the convection zone bottom radius, or by any other reasonable adjustments in model parameters. Decreasing the mass loss timescale reduces the effect on this diffusion-produced gradient, and such a model is not ruled out by the oscillation frequency comparisons.

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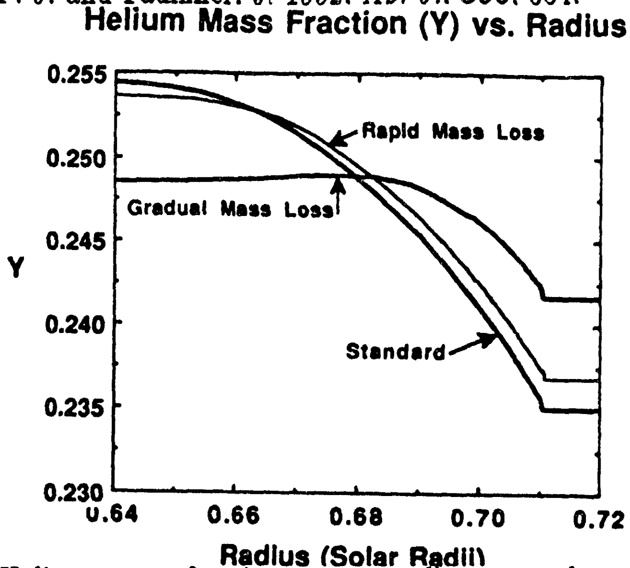

Fig. 1. Helium mass fraction versus radius near the convection zone bottom for standard, gradual mass-losing, and rapid mass-losing models. Gradual early mass loss decreases diffusive settling, and the extent of the diffusion-produced composition gradient below the convection zone.

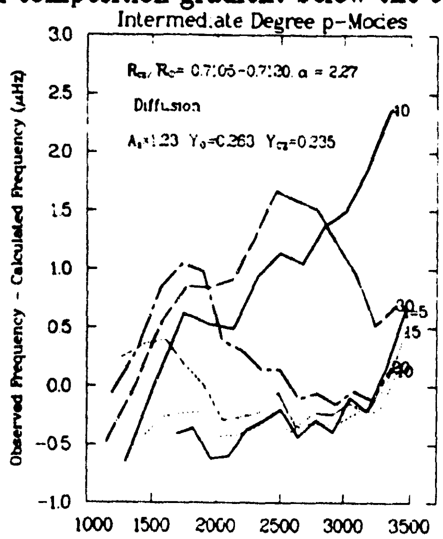

Fig. 2. Observed minus calculated vs. calculated p-mode oscillation frequencies of degree ℓ=5, 10, 15, 20, 30, and 40 for a standard solar model

including diffusive settling of elements. Lines connect discrete modes of the same degree ℓ and different radial order n. Observations are from Libbrecht et al. (1990). Observational uncertainties for these modes are $< 0.1 \mu$Hz.

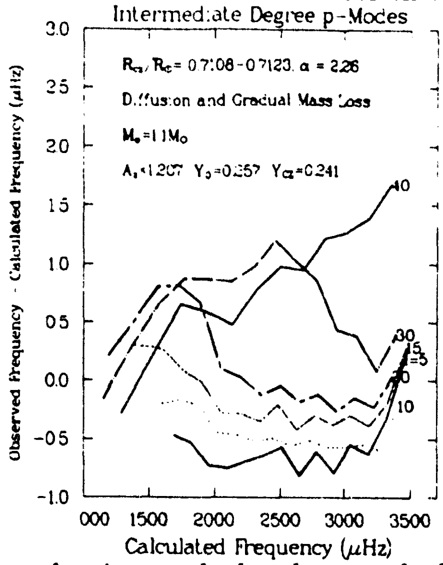

Fig. 3. Observed minus calculated vs. calculated p-mode oscillation frequencies of degree ℓ=5, 10, 15, 20, 30, and 40 for a solar model including both element diffusion and 0.1 $M_\odot$ of gradual early main sequence mass loss (exponentially decreasing mass loss rate with e-folding time 0.45 Gyr). The early mass loss causes a spread in O-C frequencies for ℓ=5-20 modes that probe this region of the Sun.

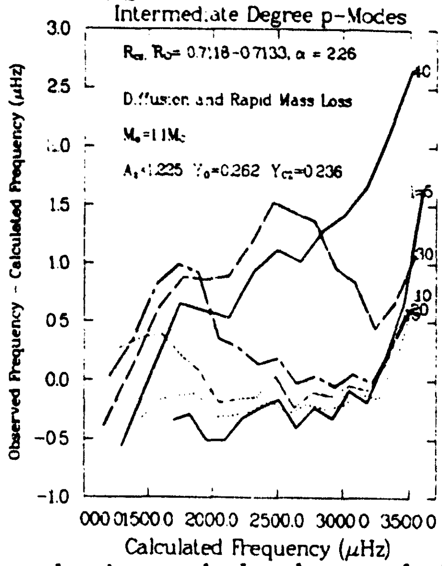

Fig. 4. Observed minus calculated vs. calculated p-mode oscillation frequencies of degree ℓ=5, 10, 15, 20, 30, and 40 for a solar model including both element diffusion and 0.1 $M_\odot$ of rapid early main sequence mass loss (constant mass loss rate 5 x 10^{-10} $M_\odot$/yr for 0.2 Gyr). In this case the mass loss occurs rapidly enough that there is very little effect on the diffusion-produced composition gradient and the O-C frequencies of modes that probe the convection zone base.