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TITLE: EARLY SOLAR MASS LOSS, ELEMENT DIFFUSION, AND SOLAR
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EARLY SOLAR MASS LOSS, ELEMENT DIFFUSION, AND SOLAR OSCILLATION FREQUENCIES

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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 $\sim 0.1 M_{\odot}$, nearly independent of the mass loss timescale. We have calculated the evolution and oscillation frequencies of solar models including helium and element diffusion, and such early solar mass loss. We show that extreme mass loss of $1 M_{\odot}$ is easily ruled out by the low-degree p-modes that probe the solar center and sense the steeper molecular weight gradient produced by the early phase of more rapid hydrogen burning. The effects on central structure are much smaller for models with an initial mass of $1.1 M_{\odot}$, and exponentially-decreasing mass loss rate with e-folding timescale 0.45 Gyr. While such mass loss slightly worsens the agreement between observed and calculated low-degree modes, the observational uncertainties of several tenths of a microhertz weaken this conclusion. Surprisingly, the intermediate-degree modes with much smaller observational uncertainties that probe the convection zone bottom prove to be the key to discriminating between models: 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 these modes. Thus it appears that oscillations can also rule out this smaller amount of gradual early main-sequence mass loss in the young Sun. The mass loss phase must be confined to substantially under a billion years, probably 0.5 Gyr or less, to simultaneously solve the solar Li/Be problem and avoid discrepancies with solar oscillation frequencies.

1. Introduction

Solar evolution modeling^{1,2} indicates that diffusive settling reduces the solar convection zone helium mass fraction by about 0.03 below the initial value of ~ 0.27 required to match the solar luminosity during the Sun's 4.5 billion year lifetime. This helium abundance decrease has been supported by numerous helioseismological studies^{1,2,3,4,5,6,7,8,9}. Although the diffusion calculations for elements heavier than helium are more uncertain, diffusion is also expected to reduce the solar convection zone Z

by 5-10% over the 4.5 Gyr solar lifetime^{10,2}.

Since diffusion velocities are greatest near the solar surface, diffusion produces a steep composition gradient just below the envelope convection zone base. Including this steep gradient in the models improves the agreement between observed and calculated solar p-mode frequencies for intermediate-degree modes that probe the solar convection zone base¹, as well as comparisons of sound speed inversions¹¹. However, the agreement deteriorates if this gradient is smoothed by turbulent mixing below the convection zone in the amount and extent considered¹⁰ to deplete solar lithium by a factor of 25-100 and beryllium by a factor of 2-6 during the Sun's life on the main sequence^{1,11}. It is assumed that Li is depleted by a factor of 2-5 pre-main sequence, for a total depletion of a factor of 200 from the meteoritic, and presumed primordial solar value. Therefore, if the solar convection zone material cannot be mixed to temperatures hot enough to deplete the lithium and beryllium, we must look to some other explanation for the solar Li/Be problem.

Swenson and Faulkner¹² and Boothroyd, Sackmann, and Fowler¹³ 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 $2 \times 10^{-10} M_{\odot}/\text{yr}$, 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 initial mass than the e-folding time. For example, a higher constant mass loss rate of $5 \times 10^{-10} M_{\odot}/\text{year}$ ending at 0.2 Gyr will deplete about the same amount of Li and Be for initial mass $\sim 1.11 M_{\odot}$. Note that this mass loss was originally investigated to explain the classical Hyades G-dwarf lithium problem, but Swenson et al.^{14,15} have since explained this problem by improved input physics and enhanced Hyades O/Fe ratio relative to solar abundances; if the Sun did lose this amount of mass, it would appear to be an anomalous case. However, early solar mass loss with a long timescale is also appealing to solve the faint early Sun problem¹⁶.

In this paper, we compare observed and calculated p-mode oscillation frequencies to test the structure of solar models including early mass loss. First we present the oscillation frequencies of a solar model with extreme early mass loss (initial mass $2 M_{\odot}$) to illustrate that comparisons between observed and calculated low-degree p-mode frequencies can easily rule out such mass loss. Next we compare the evolution and oscillation frequencies of models with helium and element diffusion, and with and without the smaller amount of mass loss ($0.1 M_{\odot}$, exponentially-decreasing M , e-folding time 0.45 Gyr) proposed to explain the Li/Be problem.

2. Evolution and Oscillation Modeling

All models were evolved using the Iben^{17,18} evolution code. Convection is treated using standard mixing-length theory¹⁹, with constant mixing length to pressure scale height ratio α . The initial metallicity $Z=0.02$, and the initial helium abundance and α are adjusted as usual to give the solar luminosity and radius at the present solar age $\sim 4.5 \text{ Gyr}$ ²⁰. The models without mass loss contain ~ 300 -500 zones, and are evolved for ~ 350 timesteps; the models with mass loss and diffusion typically contain ~ 400 -700 zones, and are evolved for ~ 1500 timesteps.

2.1 Diffusion Calculations

The diffusion calculation procedures are discussed in detail by Cox, Guzik and Kidman²¹. Briefly, the treatment of Burgers²² is used to calculate the thermal, gravitational, and chemical diffusion of seven isotopes (H, ³He, ⁴He, ¹²C, ¹⁴N, ¹⁶O, and ¹⁸O) and the electron by solving the equations of diffusion, heat flow, no net mass flow, and no net charge flow. The implementation of these calculations in the Iben stellar evolution code, and the analytical fits to the binary resistance coefficients used in the diffusion equations are discussed by Iben and MacDonald²³ and Cox, Guzik and Kidman²¹. Since the mass fraction of elements heavier than helium that are explicitly diffused is only 62% of the total Z, the calculations may underestimate the amount of Z diffusion. However, Proffitt and Michaud¹⁰ point out that the resistance coefficients used by Cox, Guzik and Kidman²¹ may give up to twice as much gravitational settling of heavy elements than the preferred ones of Paquette et al.²⁴, so our diffusion calculations probably give a reasonable estimate of the Z diffusion. Bahcall and Pinnsoneault²⁵ point out that in diffusion calculations it is important to normalize in comparison to the same final Z/X; Recent determinations of the solar Z/X have varied from²⁶ ~0.02668 to²⁷ ~0.0245. In view of this uncertainty in the absolute value of Z/X, and the very small differences in Z/X between our intercompared models including element diffusion, we did not do the normalization. All of our models with diffusion have Z/X ~0.026.

2.2 Equation of State

The evolution and oscillation calculations for our first set of illustrative models use the older Iben analytical EOS including Coulomb corrections according to Clayton²⁸. The other models use the most recent MHD equation of state tables^{29,30,31}. The MHD tables are only available for Z=0.02, and are used even for the diffusion models with slightly lower envelope Z (~0.018) and higher central Z (~0.021). It is more important to account for this small Z variations in the opacity calculations than in the equation of state.

2.3 Opacities

The solar interior opacities are analytical fits to the Cox-Stewart³² opacity tables as described by Iben³³, calibrated to the Livermore OPAL opacity tables³⁴. Specifically, the κ_{es} term in the Iben analytical fit was multiplied by 1.5-2 to increase the high-temperature opacities, since the iron abundance in the mixture used for the OPAL tables is ten times higher than that of the Cox-Stewart table. For the important opacities in the 2-5 million K region which affect the convection zone depth, the A_z term in the Iben fit was multiplied by a factor of 1.2-1.3 to calibrate to the OPAL tables. As was shown by Guzik and Cox¹, opacity adjustments at the bottom of the convection zone can be used to adjust the convection zone depth and maximize agreement between calculated and observed solar p-mode frequencies. We have opted to use the Iben analytical opacity fit rather than using OPAL tables directly, since we can adjust the A_z factor to easily remove the O-C discrepancies due to convection zone depth, and since it has the Z-dependence built-in that is necessary to take into account opacity changes due to element diffusion. The opacities

between about 1.5 million K and 10,000 K are not critical, as convection carries nearly all of the luminosity at these temperatures in the Sun. For temperatures below 10,000 K, we use the Stellingwerf^{35,36} analytical fit to the Cox-Tabor³⁷ opacity tables, and multiply by a factor of two to account for molecular effects and additional iron lines included in the later Ross-Aller¹³⁸ low-temperature opacity table.

2.4 *p-mode Oscillation Calculations*

From the solar-age models produced by the Iben code, 1700-zone models which incorporate the equation of state and opacities of the Iben code and therefore track almost exactly the evolved structure, are created for input into a linear nonadiabatic pulsation code written by Pesnell³⁹ for calculation of nonadiabatic p-mode oscillation frequencies.

3. Solar Models With Extreme Early Solar Mass Loss

To exaggerate the difference in the central structure and low-degree p-mode oscillation frequencies of solar models with and without mass loss, we first consider solar models with a large amount of early mass loss, and without element diffusion. Extreme early main sequence mass loss, with the Sun initially at 2-3 $M_{\odot}$, and initial mass loss rates of $5 \times 10^{-9} M_{\odot}$ per year was proposed by Willson, Bowen and Struck-Marcell⁴⁰ and investigated by Guzik, Willson and Brunish⁴¹ to explain a number of problems in stellar evolution and solar system formation. Such high rates of mass loss in young A-F stars ($\sim 10^{-9} M_{\odot}/\text{yr}$) have not been verified by observation⁴². For the Sun, the present surface layers would have been deep enough to destroy all of the Li and Be, requiring some explanation for its presence. Also, ^3He processed to higher equilibrium values in the interior is exposed as mass loss proceeds, and the predicted surface ^3He abundance becomes an order of magnitude higher than the observed values⁴¹.

Table 1 summarizes parameters for the models with and without mass loss. The extreme mass losing model has initial mass 2 $M_{\odot}$, and initial mass loss rate $5 \times 10^{-9} M_{\odot}/\text{yr}$, decreasing exponentially with e-folding time 0.2 Gyr. The initial Y abundance of the mass-losing model must be decreased to derive the observed solar luminosity at the current solar age, the mixing length must be decreased to derive the observed solar radius, and the convection zone depth increases for the same opacities. Figure 1 shows the hydrogen abundance versus radius for the standard and mass-losing model; as can be seen, more hydrogen is depleted due to early nuclear burning at high mass. The surface hydrogen abundance is larger, reflecting the higher initial abundance needed to derive the correct solar luminosity. Figure 2 shows the observed minus calculated (O-C) versus calculated low-degree p-mode frequencies of the models, using observed frequencies of Duvall et al.⁴³ Lines connect modes of different radial order n and constant degree l . We have adjusted the A_z factor ($A_z = 1.27$) in the Iben opacity fit to produce the convection zone depth that optimizes the O-C frequency agreement for the mass-losing model, and have used the same A_z factor for both models. As discussed by Guzik and Cox¹, increasing the opacity below the convection zone increases the convection zone depth and decreases the O-C frequencies. Figure 2 shows that for the mass-losing model, the O-C frequencies decrease significantly with increasing degree l ; recall that $l=0$ modes penetrate

Fig. 1. Interior profile of hydrogen mass fraction for a standard solar model (1A) and a model with initial mass $2 M_\odot$ and high early mass loss rate (1B). The mass-losing model depletes more core hydrogen due to early nuclear processing. The initial hydrogen abundance must be increased by 0.02 over the standard model to derive the correct solar luminosity at the current solar age.

Fig. 2. Observed minus calculated vs. calculated p-mode oscillation frequencies of degree $l=0, 1, 2, 3, 5$, and 10 for a standard solar model (1A), and a model with initial mass $2 M_\odot$ and high early mass loss rate (1B). Lines connect discrete modes of the same degree l and different radial order n . The observed frequencies are from Duvall et al.⁴³ The convection zone depth has been adjusted to optimize the agreement between observed and calculated frequencies of the mass-losing model. Nevertheless, the O-C frequencies decrease with increasing degree l , indicating that the central molecular weight gradient of the mass-losing model is too steep.

to the solar center, and the depth of the turning point decreases with increasing l ⁴⁴. Evidently, the frequencies are sensing a molecular weight and sound speed gradient that is too steep. For the standard model, the O-C frequencies are constant at $\sim 6 \mu\text{Hz}$ positive for all l ; this O-C discrepancy could be eliminated by increasing the convection zone depth to $\sim 0.712 R_{\odot}$. Such adjustments cannot improve the agreement for the mass-losing model.

We next examine whether such differences can be detected for models with only $0.1 M_{\odot}$ of gradual early mass loss.

Table 1. Evolution parameters of standard (1A) and extreme mass-losing (1B) models without element diffusion.

Model	1A (Standard)	1B (Mass-Losing)
Initial Mass ($M_{\odot}$)	1.0	2.0
Initial $\dot{M}$ ($M_{\odot}/\text{yr}$)	—	5.0×10^{-9}
Mass-Loss e-folding timescale (Gyr)	—	0.2
Initial Y, Z	0.287, 0.02	0.267, 0.02
Final Central Y	0.6520	0.7069
Mixing Length/ H_p	1.88	2.07
Radius of Convection Zone Base ($R_{\odot}$)	0.720	0.702

4. Solar Models with Element Diffusion and $0.1 M_{\odot}$ of Early Mass Loss

Table 2 summarizes the evolution parameters of the second set of models. Model 2A is a standard model including diffusive settling, without mass loss. For these models, the ϵ_{sk} term in the Iben opacity fit was multiplied by 1.5; the A_z term was multiplied by 1.23 to adjust the convection zone depth to $0.712 \pm 0.001 R_{\odot}$, which gives the best agreement with the O-C oscillation frequencies as discussed in Guzik and Cox ¹. This factor increases the opacity just below the convection zone only 1.8% above the OPAL values.

Table 2. Evolution parameters of standard (2A) and mass-losing (2B) models with element diffusion.

Model	2A (Standard)	2B (Mass-Losing)
Initial Mass ($M_{\odot}$)	1.0	1.1
Initial $\dot{M}$ ($M_{\odot}/\text{yr}$)	—	2.0×10^{-10}
Mass-Loss e-folding timescale (Gyr)	—	0.45
Initial Y, Z	0.263, 0.02	0.257, 0.02
Final Central Y, Z	0.6238, 0.0208	0.6316, 0.0208
Final Surface Y, Z	0.2347, 0.0189	0.2413, 0.0194
Surface Z/X	0.0253	0.0262
Mixing Length/ H_p	2.27	2.26
Radius of Convection Zone Base ($R_{\odot}$)	0.711	0.711

Figure 3 shows the intermediate-degree O-C p-mode frequencies ($l = 5, 10, 15, 20, 30, 40$), with observations from Libbrecht et al. ⁵¹, and observational uncertainties of $< 0.1 \mu\text{Hz}$. Lines connect modes of constant degree l and different radial order n . Frequencies greater than $3500 \mu\text{Hz}$ are omitted, as the pulsation code overestimates the nonadiabatic correction, since the diffusion approximation is inadequate in the optically thin region of the

Sun that is sensed by these modes³. As discussed by Guzik and Cox¹, the $l=5, 10, 15$, and 20 modes have weight functions with increasing weight below the convection zone as frequency (or order n) increases, and thus are excellent probes of the conditions at and just below the bottom of the convection zone. The $l=30$ and 40 modes plotted here have turning points above the convection zone bottom. Note the good agreement between O-C and calculated frequencies for those oscillation modes that have significant weight below the convection zone ($l=5-20$, $\nu \gtrsim 2000 \mu\text{Hz}$), and especially the lack of spread in O-C with increasing degree l . These modes have O-C of about $-0.2 \mu\text{Hz}$, which could be eliminated by a slight decrease in the convection zone depth.

Model 2B is a mass-losing model that includes element diffusion and mass loss. This model has initial mass $1.1 M_{\odot}$, and initial mass loss rate $2 \times 10^{-10} M_{\odot}/\text{yr}$, exponentially decreasing with e-folding time 0.45 Gyr. These parameters result in Li depletion by a factor of ~ 50 and Be depletion by a factor of ~ 2 during the main sequence life of the Sun¹². In this model, the A_z factor in the Iben fit was decreased to 1.207 to decrease the convection zone depth and optimize the agreement between observed and calculated frequencies.

Figure 4 shows the O-C vs. calculated intermediate-degree frequencies of Model 2B. It is evident that the good agreement (lack of spread in l) for the $l=5-20$ modes that probe below the convection zone bottom is destroyed (compare with Fig. 3). The O-C frequencies for these modes now increase with increasing degree l . This can be understood by considering the effects of including mass loss on the amount and extent of the diffusion produced composition gradient at the bottom of the convection zone. Figure 5 shows the helium mass fraction versus radius near the convection zone bottom for Models 2A and 2B. As can be seen in this figure and Table 2, in the mass-losing model the surface Y and Z abundances are not reduced as much by diffusion, as mass loss removes the outer layers depleted initially. Also, since the convection zone of the mass losing model is shallower initially, the extent of the gradient in radius is reduced. Thus it appears that mass loss, by altering the shape and size of the diffusion-produced gradient below the convection zone, worsens the agreement between observed and calculated intermediate-degree p-mode frequencies that probe this region of the Sun.

Figures 6 and 7 show the low-degree p-mode oscillation frequencies ($l=0, 1, 2, 3$), with observed frequencies from Anguera Gubau et al.⁵² for the standard and mass-losing models. For both models, the low-degree modes show a slight decrease in O-C with increasing degree l , with the low- l modes of the standard model showing slightly less spread than those of the mass-losing model. Although the observational uncertainties of these low- l modes are larger (a few tenths of a microhertz), the model without mass loss appears to be preferred for these modes as well.

5. Models With Updated Opacities and Reaction Rates

The models presented above have an initial Y abundance ~ 0.26 , slightly lower than that of recent solar models in the literature^{2,4,12,25,45,53}. Comparisons of our central opacities derived from the Iben fit with the OPAL tables showed that multiplying the esk factor in the Iben fit by 2 instead of 1.5 improves the agreement with OPAL for

Fig. 3. 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 helium and heavier elements (2A). Lines connect discrete modes of the same degree l and different radial order n . Observations are from Libbrecht et al.⁵¹ The observational uncertainties for these modes are $< 0.1 \mu\text{Hz}$. Note the good agreement between observed and calculated frequencies of degree $l=5-20$ and $\nu > 2000 \mu\text{Hz}$ that probe the solar interior just below the convection zone base.

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 early main sequence mass loss (2B). Lines connect discrete modes of the same degree l and different radial order n . The early mass loss decreases the amount of diffusion, and the extent of the diffusion-produced composition gradient below the convection zone, thereby causing a spread in a O-C frequencies (the O-C frequencies increase with increasing degree l) for $l=5-20$ modes that probe this region of the Sun.

Helium Mass Fraction (Y) vs. Radius

Fig. 5. Helium mass fraction versus radius for standard (2A) and mass-losing (2B) models for the region of the Sun just below the convection zone base. Gradual early mass loss (during about 1 Gyr) decreases the overall amount of diffusion, and the extent of the diffusion-produced composition gradient below the convection zone, which is sensed by the oscillation frequencies.

temperatures ≥ 9 million K, and results in initial Y abundances of ~ 0.275 . We also updated the reaction rates from those of Fowler, Caughlan and Zimmerman⁴⁶ to those of Caughlan and Fowler⁴⁷, and updated the solar luminosity to 3.846×10^{33} erg/sec⁴⁸ from 3.826×10^{33} erg/sec used in the previous models. The new models are summarized in Table 3. Model 3A is a new standard model with diffusion and without mass loss. This model requires an A_z factor on the Iben fit of 1.27, to adjust the convection zone depth to $R=0.712 R_\odot$, and maximize agreement between observed and calculated solar oscillation frequencies. Model 3B is a mass-losing model, with $A_z \times 1.25$ to adjust its convection zone to the same depth. Unfortunately, the combination of the increased A_z and esk parameters in the Iben fit increases the opacities over the OPAL values by $\sim 10\%$ at temperatures 4-6 million K, which shows up as a slight deterioration in the agreement between the observed and calculated frequencies of degree $l=5-10$ that are strongly affected by the solar structure in this region. Nevertheless, the low- and intermediate-degree p-mode frequencies for the standard and mass-losing models are qualitatively the same as those of the models in Table 2, with the O-C fits of the standard model preferred to those of the mass-losing model.

Fig. 6. Observed minus calculated vs. calculated p-mode oscillation frequencies of degree $l=0, 1, 2$, and 3 that probe the solar center for a standard solar model including diffusive settling of helium and heavier elements (2A). The convection zone depth has been adjusted to optimize the O-C fit. Observations are from Anguera Gubau et al.⁵² The observational uncertainties of these modes are a few tenths of a μHz .

Figure 7. 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 early main sequence mass loss (2B). The convection zone depth has been adjusted to optimize the O-C fit. The spread in O-C frequencies (decreasing O-C with increasing degree l) is somewhat greater for the mass-losing model than for the standard model (Fig. 6).

Table 3. Evolution parameters of standard (3A) and mass-losing (3B) models with element diffusion, and updated central opacities and reaction rates.

Model	3A (Standard)	3B (Mass-Losing)
Initial Mass ($M_{\odot}$)	1.0	1.1
Initial $\dot{M}$ ($M_{\odot}/\text{yr}$)	—	2.0×10^{-10}
Mass-Loss e-folding timescale (Gyr)	—	0.45
Initial Y, Z	0.277, 0.02	0.272, 0.02
Final Central Y, Z	0.6438, 0.0208	0.6502, 0.0208
Final Surface Y, Z	0.2477, 0.0187	0.2503, 0.0191
Surface Z/X	0.0255	0.0261
Mixing Length/ H_p	2.23	2.22
Radius of Convection Zone Base ($R_{\odot}$)	0.711	0.711
Central Temperature (10^6 K)	15.74	15.76
Estimated ^{37}Cl Neutrino Fluxes	8.3	8.5

6. Conclusions

Gradual early main-sequence mass loss, occurring during about the first billion years of the Sun's lifetime in the amount required to solve the solar Li/Be problem can be ruled out by solar p-mode oscillation frequencies. The evidence is most significant for the intermediate-degree modes that probe the convection zone base; mass loss decreases the amount of helium and Z diffusion, and the shape and extent of the diffusion produced composition gradient at the convection zone base, which is sensed by these oscillation frequencies. It is surprising that solar oscillation frequencies are such a sensitive test of the solar structure that they can so strictly constrain the evolutionary history of the Sun. It is also noteworthy that the discrimination would not have been possible without including diffusive settling in the calculations.

These models have only ruled out somewhat gradual mass loss. As the mass-loss timescale is shortened, the effects of mass loss on solar structure and on the diffusion-produced composition gradient below the solar convection zone decrease. We are currently investigating models with shorter mass loss timescales, to see if an upper limit can be placed on the timescale. However, higher mass loss rates approaching $10^{-9} M_{\odot}/\text{year}$, may not be popular in view of the lack of evidence for such high mass loss rates in young main-sequence G stars. Other explanations for the Li/Be depletion, such as rotational mixing, as investigated by Chaboyer, Demarque and Pinsonneault⁴⁹ in a prescription that does not destroy the steep composition gradient just below the convection zone, or pre-main sequence convective overshoot by 0.3 pressure scale heights as investigated by Ahrens, Stix, and Thorn⁵⁰, should be pursued.

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