# Higher Flux from the Young Sun as an Explanation for Warm Temperatures for Early Earth and Mars

## FINAL REPORT

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## 1. Motivation and Goals

Observations indicate that the Earth was at least warm enough for liquid water to exist as far back as 4 Gyr ago, namely, as early as half a billion years after the formation of the Earth (Cogley & Henderson-Sellers 1984; Mojzsis et al. 1996; Eiler, Mojzsis, & Arrhenius 1997; Eriksson 1982; Bowring, Williams, & Compston 1989; Nutman et al. 1984); in fact, there is evidence suggesting that Earth may have been even warmer then than it is now (Kasting 1989; Oberbeck, Marshall, & Aggarwal 1993; Woese 1987; Ohmotu & Felder 1987; Knauth & Epstein 1976; Karhu & Epstein 1986). These relatively warm temperatures required on early Earth are in apparent contradiction to the dimness of the early Sun predicted by the standard solar models. This problem has generally been explained by assuming that Earth's early atmosphere contained huge amounts of carbon dioxide ($CO_2$), resulting in a large enough greenhouse effect to counteract the effect of a dimmer Sun. However, the recent work of Rye, Kuo, & Holland (1995) places an upper limit of 0.04 bar on the partial pressure of $CO_2$ in the period from 2.75 to 2.2 Gyr ago, based on the absence of siderite in paleosols; this casts doubt on the viability of a strong $CO_2$ greenhouse effect on early Earth. The existence of liquid water on early Mars has been even more of a puzzle; even the maximum possible $CO_2$ greenhouse effect cannot yield warm enough Martian surface temperatures (Kasting 1991; Kasting, Whitmire, & Reynolds 1993). These problems can be resolved simultaneously for both Earth and Mars, if the early Sun was brighter than predicted by the standard solar models. This could be accomplished if the early Sun was slightly more massive than it is now, i.e., if the solar wind was considerably stronger in the past than at present. Lunar rock observations suggest a solar wind over the past $\sim 3$ Gyr averaging an order of magnitude higher than the present observed value (Geiss 1973; Geiss & Bochsler 1991; Kerridge et al. 1991). If an even stronger solar wind existed at still earlier times, the young Sun could have been a few percent more massive than at present. However, there is an upper limit: the young Sun could not have been more than 7% more massive than it is now, or the early Earth would have lost its water via a moist greenhouse effect (Kasting 1988).

A slightly more massive young Sun would have left fingerprints on the internal structure of the present Sun. Today, helioseismic observations exist that can measure the internal structure of the Sun with very high precision. The task undertaken here was to compute solar models with the highest precision possible at this time, starting with slightly greater initial masses. These were evolved to the present solar age, where comparisons with the helioseismic observations could be made. Our computations also yielded the time evolution of the solar flux at the planets — a key input to the climates of early Earth and Mars.

Early solar mass loss is not the only influence that can alter the internal structure of the present Sun. There are minor uncertainties in the physics of the solar models and in the key observed solar parameters that also affect the present Sun's internal structure. These other uncertain quantities include the observed solar composition, age, luminosity, and radius, as well as the physics uncertainties in the equation of state, opacities, nuclear reactions, and rates of gravitational settling (diffusion) of helium and the heavier elements. It was therefore imperative to obtain an understanding of the effects of these other uncertainties, in order to disentangle them from the fingerprints that might be left by early solar mass loss.

From these considerations, our work was divided into two parts. (i) We first computed the evolution of standard (non-mass-losing) solar models with input parameters varied within their uncertainties, to determine their effect on the observable helioseismic quantities. We discuss the results of this part of the investigation in § 2; details can be found in our attached preprint "Our Sun IV. The Standard Solar Model and Helioseismology: Consequences of Uncertainties in Input Physics and in Observed Solar Parameters." (ii) We then computed non-standard solar models with higher initial masses to test against the helioseismological observations. We discuss the results of this investigation in § 3; details of the comparison, and a presentation of the variation of the solar flux as a function of time, are given in the attached preprint "Our Sun V. A Bright Young Sun Consistent with Helioseismology and Warm Temperatures on Ancient Earth and Mars."

## 2. Helioseismological Observations and Solar Interior Structure

Helioseismic frequency observations from the Michaelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory (SOHO) spacecraft were used; these enable the adiabatic sound speed $c$ and adiabatic index $\Gamma_1$ as a function of the radial position $r$ in the solar interior to be inferred with an accuracy of a few parts in $10^4$, and the density $\rho$ as a function of $r$ with an accuracy of a few parts in $10^3$ (Basu, Pinsonneault, & Bahcall 2000). An accurate value for the position of the base of solar envelope convection can also be obtained from the helioseismic observations, namely, $R_{ce} = 0.713 \pm 0.001\ R_\odot$ (Basu & Antia 1997), and bounds can be placed on the helium fraction by mass in the Sun's envelope of $0.24 \lesssim Y_e \lesssim 0.25$ (Pérez Hernández & Christensen-Dalsgaard 1994; Basu & Antia 1995; Kosovichev 1997; Basu 1998; Richard et al. 1998). Theoretical models also allow one to compute the above quantities. Comparison of these theoretical values with those inferred from helioseismic observations provides a test of the theory.

### 2.1. Effects of Uncertainties in Input Parameters

We found that the largest effects on the sound speed profiles in theoretical solar models arise from the observational uncertainties in the photospheric abundances of the elements. The key elements C, N, O, and Ne together represent the major portion of the Sun's metallicity $Z$,[1] but their solar abundances are uncertain by 15% (Grevesse & Sauval 1998); this leads to an uncertainty of order 10% in the solar $Z/X$ ratio. We determined that this uncertainty affects the sound speed profile at the level of 3 parts in $10^3$. There is an estimated 4% uncertainty in the OPAL opacities (Iglesias & Rogers 1996), a $\sim 5\%$ uncertainty in the basic *pp* nuclear reaction rate (Angulo et al. 1999), and a $\sim 15\%$ uncertainty in the diffusion constants for the gravitational settling of helium (Proffitt 1994); we found that each of these could lead to effects of 1 part in $10^3$. The $\sim 50\%$ uncertainties in diffusion constants for the heavier elements (Proffitt 1994) would have nearly as large an effect. Different observational methods for determining the solar radius yield results differing by as much as 7 parts in $10^4$ (Ulrich & Rhodes 1983; Guenther et al. 1992; Antia 1998; Brown & Christensen-Dalsgaard 1998); we found that this leads to uncertainties of a few parts in $10^3$ in the sound speed in the solar convective envelope, but has negligible effect on the interior. (We did not explicitly consider the effects of rotational mixing or uncertainties in the interior equation of state, which other investigators have found to yield uncertainties in the sound speed of order 1 part in $10^3$: see Morel, Provost, & Berthomieu 1997; Guzik & Swenson 1997; Elliot & Kosovichev 1998.) We found that other current uncertainties, namely, in the solar age and luminosity, in nuclear rates other than the *pp* reaction, in the low-temperature molecular opacities, and in the low-density equation of state, have no significant effect on the quantities that can be

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[1] The metallicity $Z$ refers to the sum of the fractional abundances by mass of all elements heavier than hydrogen and helium. The fractional abundances by mass of hydrogen and helium are referred to as $X$ and $Y$, respectively.

inferred from the helioseismic observations.

Our reference standard solar model (with $Z/X = 0.0245$) yielded a convective envelope position $R_{ce} = 0.7135\ R_\odot$, in excellent agreement with the observed value of $0.713 \pm 0.001\ R_\odot$ Basu & Antia (1997), and was significantly affected ($\pm 0.003\ R_\odot$) only by $Z/X$, the *pp* rate, and the uncertainties in helium diffusion constants. Our reference model yielded envelope helium abundance $Y_e = 0.2424$, in good agreement with the range $0.24 \lesssim Y_e \lesssim 0.25$ inferred from helioseismic observations (Pérez Hernández & Christensen-Dalsgaard 1994; Basu & Antia 1995; Kosovichev 1997; Basu 1998; Richard et al. 1998): values of $Y_e$ outside this range were found only for extreme $Z/X$ cases (i.e., $Z/X$ values near the boundary of what is allowed by the uncertainties in observed solar abundances).

We found that the predicted pre-main-sequence lithium depletion is uncertain by a factor of 2. Not including uncertainties in the capture cross sections, the predicted neutrino capture rate is uncertain by as much as $\sim 30\%$ for the $^{37}$Cl experiment (which is sensitive to $^8$B and $^7$Be neutrino fluxes) and by $\sim 3\%$ for the $^{71}$Ga experiments (sensitive largely to the *pp* neutrino flux); there is an uncertainty of $\sim 30\%$ in the $^8$B neutrino flux, which is observed by the Kamiokande water-Cerenkov experiment and by the Sudbury Neutrino Observatory (SNO).

For our standard solar models, the sound speed profiles favor (i) a $Z/X$ ratio of $\sim 0.026$ (slightly higher than the recommended observational value of $Z/X \approx 0.023$), or (ii) slightly higher opacities than the current 1995 OPAL opacities, or (iii) a *pp* rate slightly higher than the recommended rate from the NACRE compilation (but close to the last value given by Caughlan & Fowler, in 1988); on the other hand, such changes would lead to $R_{ce} \approx 0.7115$, a poorer match to the observed value of $R_{ce} = 0.713 \pm 0.001\ R_\odot$.

## 3. Ancient Earth and Mars, and a Brighter Young Sun

As discussed in § 1, it is not clear whether a strong enough greenhouse effect existed to produce the relatively warm temperatures on the early Earth. The existence of liquid water on early Mars has been even more of a puzzle; even the maximum possible $CO_2$ greenhouse effect cannot yield warm enough Martian surface temperatures (Kasting 1991; Kasting et al. 1993). We therefore considered the case of a bright young Sun, resulting from a slightly increased initial solar mass. The relatively modest early mass loss that is required remains consistent with observational stellar mass loss limits (Brown et al. 1990; Gaidos, Güdel, & Blake 2000) and with the estimates of the past solar wind from lunar rock measurements (Geiss 1973; Geiss & Bochsler 1991; Kerridge et al. 1991). We considered seven initial solar mass cases, from $M_i = 1.01$ to $1.07\ M_\odot$ –– the latter being the maximum permitted by the constraint that the early Earth not lose its water via a moist greenhouse effect (Kasting 1988). We considered three types of mass loss: (i) a reasonable choice of a simple exponential decline in the mass loss rate (which is consistent with all available mass loss observations), (ii) an extreme step-function case that gives the maximum effect consistent with the mass loss observations, and (iii) the radical case of a linear decline (which leads to considerably higher mass loss rates over the past 3 Gyr than are allowed by the lunar rock measurements). We have computed the evolution of highly detailed mass-losing solar models up to the present solar age, and tested them against the high-precision helioseismic observations of the present Sun via the method described in § 2.

Our computations demonstrated that all of the mass-losing solar models led to interior structures at the present solar age that were consistent with the helioseismic observations; in fact, our preferred mass-losing cases were in slightly better agreement with the helioseismology than the standard solar model was. The sound speed profiles in the mass-losing cases differed from that of the standard solar model by amounts smaller than those resulting from the other uncertainties in the input physics and in the solar composition discussed in § 2 (e.g., solar metallicity, opacities, *pp* nuclear reaction rate, equation of state, and diffusion constants). Mass loss produced negligible effects on the predicted depth of the solar convective envelope and on the predicted solar surface helium abundance. The mass loss had only a relatively minor effect on the predicted lithium depletion, smaller even than the uncertainty in pre-main-sequence lithium depletion; the major portion of the solar lithium depletion must still be due to rotational mixing. Thus the modest mass loss cases considered here cannot be ruled out by observed lithium depletions.

For the three mass loss types considered, the preferred initial masses were $1.07\ M_\odot$ for the exponential case and $1.04\ M_\odot$ for the step-function and linear cases; all of these provided high enough solar fluxes at Mars 3.8 Gyr ago to be consistent with the existence of liquid water on the Martian surface. With mass loss, the early history of the Sun would have been significantly different from that of the standard (non-mass-losing) model: the young Sun would have been considerably brighter, and would have had a slightly hotter surface temperature, than the standard model has indicated. The early behavior would be opposite to the standard model: the mass-losing models initially grow dimmer and slightly redder (instead of growing brighter and slightly bluer). For a more massive early Sun, the planets would have had to be closer to the young Sun in order to end up in their present orbits — e.g., all the planets would have been 7% closer at birth for our preferred "exponential" case, or 4% closer for our preferred "step-function" case; during subsequent epochs, the orbital radii of the planets would have varied as the inverse of the solar mass. Both the higher solar luminosity and the closer planetary orbits contribute to the fact that the early solar flux at the planets would have been significantly higher than that from the standard solar model at that period.

Figure 1 illustrates the solar flux at the planets (relative to the present flux) as a function of time for our preferred initial masses for each type of mass loss that we considered. Our preferred "exponential" case predicts a solar flux at the planets about 5% higher at birth than at present, considerably higher than that indicated by the standard solar model (which

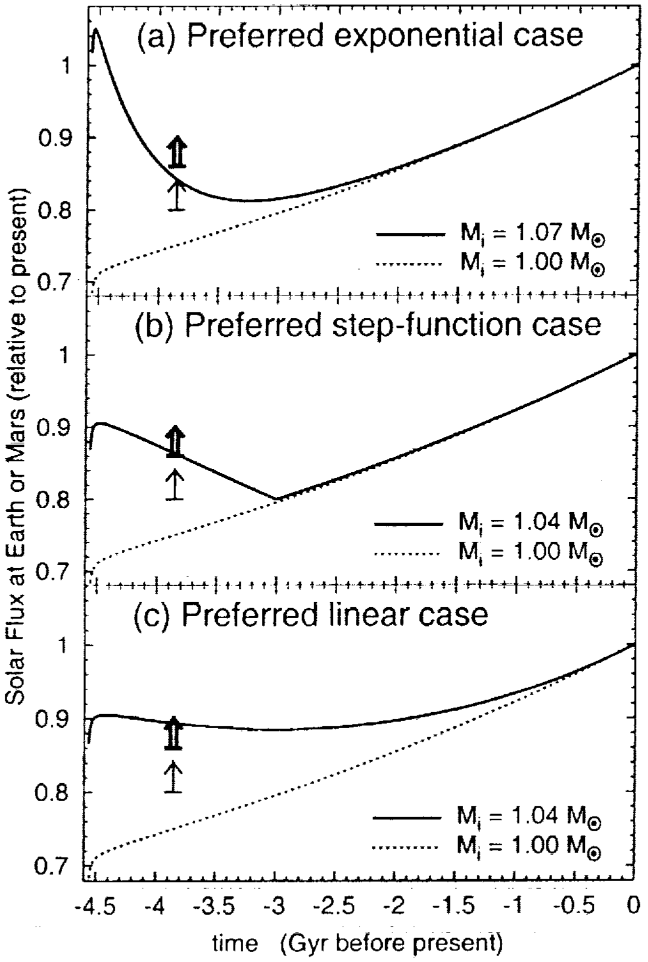

Fig. 1.— Solar flux at the planets (relative to the present flux) as a function of time for our preferred initial masses, for each type of mass loss that we considered. Heavy double arrows give the lower flux limit of Kasting (1991) for the presence of water on early Mars; light single arrows give his extreme lower flux limit (for a model with an unrealistically low Martian surface albedo).

predicts a flux 29% lower than at present). At 3.8 Gyr ago, the flux for our "exponential" case would have been only 16% lower than at present (cf. 25% for the standard model). For our preferred "step-function" case, the flux at the planets would have been only 10% lower at birth than at present (cf. 29% for the standard model); at 3.8 Gyr ago, the flux would have been only 14% lower than at present (cf. 25% for the standard model). For these "exponential" and "step-function" cases, the flux at the planets for the past 3 billion years would be essentially the same as that predicted by the standard solar model. Our radical "linear" case would have had an almost constant solar flux at the planets for the first 3 Gyr, namely, only 11% lower than at present (cf. 29% to 12% lower for the standard model); for this case, the flux would be close to that predicted by the standard solar model only during the last billion years.

## 4. Conclusions

A slightly higher initial solar mass, producing a brighter young Sun, turns out to be a viable explanation for warm temperatures on ancient Earth and Mars. For approximately the first billion years, the mass-losing Sun would grow dimmer, a behavior opposite to that predicted for the standard case. For the last 3 billion years, the mass-losing Sun would be behave very similarly to the standard case, both growing brighter. (For the radical, least probable "linear" mass loss case, these timescales are reversed, to ~ 3 and ~ 1 billion years, respectively.) Such a higher initial solar mass leaves a fingerprint on the Sun's present internal structure that is large enough to be detectable via helioseismic observations. Our computations demonstrated that all 21 of the mass-losing solar models that we considered were consistent with the helioseismic observations; in fact, our preferred mass-losing cases were in marginally better agreement with the helioseismology than the standard solar model was. However, there are still significant uncertainties in the observed solar composition and in the input physics on which the solar models are based; these uncertainties have a slightly larger effect on the Sun's present internal structure than the fingerprint left from early solar mass loss. Future improvements in the accuracy of these input parameters could reduce the size of the uncertainties below the level of the fingerprints left by a more massive, brighter young Sun, allowing one to determine whether early solar mass loss took place or not. Also urgently needed are more measurements of mass loss rates from other young stars similar to the young Sun, and more measurements from our solar system that can be used to estimate the solar wind in the past.

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