EVALUATING THE MASSIVE YOUNG SUN HYPOTHESIS TO SOLVE THE WARM YOUNG EARTH PUZZLE.

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Introduction: The contradiction between the cold ancient terrestrial and martian climates predicted by the lower solar luminosity and the warm ancient terrestrial and martian climates derived from geological evidence has been called the faint early Sun paradox, and most attempts to resolve the paradox involve models of the early atmospheres of Earth and Mars containing enhancements of atmospheric greenhouse gases [1–6]. An alternative solution to the faint early Sun paradox involves a non-standard solar model in which the Sun has lost significant mass over time. A more massive early Sun will have two effects. First, it will have a correspondingly larger solar energy output. Second, the planets would have orbited closer to the Sun and consequently have received higher solar fluxes.

Effect of Solar Mass on Climate History: We use a simple climate model to explore the dependence on the mass of the Sun of the mean surface temperature of the Earth [7]. The steady state mean surface temperature of a terrestrial planet is given by the following energy balance equation:

\[ (1 - A) \sigma \varepsilon T^4 \pi R^2 = \frac{2}{5} \left( 1 - t / t_\odot \right) \]

(1)

where \( A \) is the average planetary albedo, \( S \) is the solar flux at the top of the atmosphere, \( R \) is the planetary radius, \( \varepsilon \) is the atmospheric IR emissivity, and \( \sigma \) is the Stefan-Boltzmann constant [2]. Values for the Earth used here are \( A = 0.34 \) and \( \varepsilon = 0.6 \). The rate of increase in luminosity of the Sun with time can be represented as

\[ L(t) = \left[ 1 + \frac{2}{5} \left( 1 - t / t_\odot \right) \right]^{-1} L_\odot, \]

(2)

where \( t_\odot \) is the current age of the Sun, and \( L_\odot \) is the current solar luminosity [5].

The main sequence stellar luminosity is quite sensitive to stellar mass, \( L \propto M^4 \), where \( P = 4.75 \) for solar mass stars [8]. If the solar mass loss is slow compared with the orbital motion of the planets, then adiabatic invariance of orbital action integrals provides

\[ [M(t) + M_i] a_i(t) = \text{constant}, \]

(3)

where \( M_i \) and \( a_i \) are the mass and orbital semimajor axis of a planet (or minor planet) in the solar system, and \( M(t) \) is the time-varying solar mass. The solar radiation flux at Earth, \( S \), is related to the Sun’s luminosity \( L \) and Earth’s semi-major axis \( a \) by \( S \propto L a^{-2} \). Using these relations we obtain the time dependence of the terrestrial surface temperature:

\[ T_s(t) = \left[ \frac{S_0 (1 - A)}{4 \pi \varepsilon \left[ 1 + \frac{2}{5} (1 - t / t_\odot) \right]} \right]^{1/4} \left( \frac{M(t)}{M_\odot} \right)^{1.69}. \]

(4)

The “minimum mass-loss” history, \( M(t) \), for the Sun that keeps the terrestrial surface temperature \( T_s(t) \) above 273 K for all time, and is also consistent with the current solar mass loss rate, \( M_\odot = 10^{-7} M_\odot \text{ yr}^{-1} \) requires the initial solar mass, \( M(0) = 0.92 M_\odot \). Also by using Equation (4) and by demanding continuity of the solar mass time variation and consistency with the present solar mass loss rate, we obtain the solar mass as a function of time:

\[ M(t) = \begin{cases} 
0.974 M_\odot \left[ 1 + \frac{2}{5} (1 - t / t_\odot) \right]^{0.15} & t \leq 2.39 \text{ Gy}, \\
M_\odot + \dot{M}_\odot (t - t_\odot) & t > 2.39 \text{ Gy},
\end{cases} \]

(5)

We also consider a solar mass loss rate that has decreased exponentially with time. This implies a solar mass as a function of time as follows:

\[ M(t) = M_\odot + C(t - t_\odot) + D(e^{-\alpha t} - e^{-\alpha t_\odot}). \]

(6)

If we denote the initial solar mass, \( M(0) = m_f M_\odot \), then the constants \( C \) and \( D \) are as follows:

\[ C = \dot{M}_\odot + \alpha D e^{-\alpha t_\odot}, \]

\[ D = \frac{(m_f - 1) M_\odot + \dot{M}_\odot t_\odot}{1 - e^{-\alpha t_\odot}}. \]

The time constant, \( \alpha = 1.32 \times 10^{-9} \text{ yr}^{-1} \), is found by considering the requirement that the mean surface temperature of Earth remained above the freezing point of water during all of Earth’s history. In order to avoid a runaway greenhouse on Earth, we also have an upper limit on the initial mass factor of \( m_f = 1.07 \). With this value, we have \( C \simeq -9.2 \times 10^{-11} M_\odot \text{ yr}^{-1} \) and \( D \simeq 0.070 \).

Considering Mars, Kasting calculated the required solar luminosities to keep Mars above the freezing point of water with a massive CO\(_2\) atmosphere, and he found that the ratio of the solar radiation flux to the current solar radiation flux (\( S/S_0 \)) had to be greater than 0.80–0.86 [9]. We see in Fig. 1 that the solar radiation flux ratio as a function of time for the solar mass loss models considered above for Earth also satisfy Kasting’s requirement for keeping Mars warm.

Dynamical Effects of Higher Mass Sun: For an initial mass of the Sun greater than present by a factor \( m_f \), the net expansion of all planetary orbits has been a factor \( m_f \) relative to the initial orbits, and the orbital periods \( T_i \) have increased by a factor \( m_f^2 \). Thus considering the mass loss histories described above, the year would have been shorter by 2–6% during the early Archean. The rates of secular precession of apsides and of orbit poles would have been faster by a factor \( m_f \).

For minor planets, locations of mean motion resonances depend on the ratios of the semimajor axes between the planets and a test particle. It follows from Equation (3) that the relative locations of mean motion resonances of the major planets remain nearly unchanged as the solar mass changes, however the fractional amplitude of resonant perturbations is proportional...
to \( \sim m_f^{1/2} \), so that resonance widths \( \Delta a \), scale as \( \sim m_f^{-3/2} \).

For the Kirkwood Gaps, asteroids from near the edges of the resonances would be destabilized, but this would not leave a trace of the original boundaries of the gaps in the present asteroid orbital distribution. For the surviving Hilda asteroids, the result would be a more compact final orbital element distribution; the net changes estimated are small, not inconsistent with the observed population, but also consistent with other dynamical processes in the early solar system [10]. We also find that the free precession rates of minor planets as well as the secular frequencies of the major planets are both proportional to \( m_f \), therefore the locations of secular resonances are invariant relative to the orbits of the major planets.

If the solar mass were higher in the past by a factor \( m_f \), then the Hill radius of each planet would have been

\[
\frac{r_H'}{r_H} = m_f^{-4/3}
\]

where \( r_H \) is the present value. Thus, a mass losing Sun causes the Hill sphere of each planet to expand; this offers a novel way for the giant planets to capture satellites. The long timescale of this process is an attractive means for evolving irregular satellites into secular resonances.

Astronomical evidence suggests that both the cumulative mass loss and the timescale for the mass loss of sun-like stars is significantly short of what is required to resolve the faint early sun paradox (see Fig. 2) [11].

Of course, the astronomical data does not directly rule out the possibility that the Sun had a different time history of mass loss than that indicated by the compilation of stellar wind flux estimates of an ensemble sun-like stars of various ages. We therefore examined the effects of a solar mass loss history on the orbital dynamics in the planetary system. Most effects are found to be too small to provide unambiguous tests of the early-massive-sun hypothesis.

\[ S(\text{yr}) = \begin{cases} 0.75 & \text{minimum mass loss} \\ 0.85 & \text{exponential mass loss} \\ 0.80 & \text{Wood et al. power law mass loss} \end{cases} \]

Figure 2: Mass loss rates due to stellar wind of the G-K main sequence stars from Wood et al. [11] are plotted as black circles along with the three different solar mass history models considered. The vertical error bars are calculated assuming the measured stellar wind mass loss are known to within a factor of two.

**Conclusions:** We have calculated that the minimal cumulative mass loss of the Sun that would resolve the faint early Sun paradox is \( \sim 0.026 \, M_\odot \) [7]. Models with a Sun which is up to \( \sim 7\% \) more massive than present are also consistent with helioseimological constraints on solar interior evolution and with geological constraints. However, another important conclusion of our study is that the solar mass loss history that would resolve the faint early Sun paradox requires the Sun to remain moderately more massive than present for 1–2 Gy in its early history.

**Acknowledgments:** We thank Alex Pavlov for helpful discussions on Mars climate issues. RM thanks Jack W. Szostak for inspiring her interest in this problem. We are grateful for research support from NASA’s Origins of Solar Systems Research Program and from the NASA Astrobiology Institute.

**References:**