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ASSESSING THE MASSIVE YOUNG SUN HYPOTHESIS TO SOLVE THE WARM YOUNG EARTH PUZZLE

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ABSTRACT

A moderately massive young Sun has been proposed to resolve the so-called faint young Sun paradox. We calculate the time evolution of the solar mass that would be required by this hypothesis using a simple parameterized energy-balance model for Earth's climate. Our calculations show that the solar mass-loss rate would need to have been 2–3 orders of magnitude higher than at present for a time on the order of ~2 Gyr. Such a mass-loss history is significantly at variance (both in the timescale and in the magnitude of the mass-loss rates) with that inferred from astronomical observations of mass loss in younger solar analogs. While suggestive, the astronomical data cannot completely rule out the possibility that the Sun had the required mass-loss history; therefore, we also examine the effects of the hypothetical historical solar mass loss on orbital dynamics in the solar system, with a view to identifying additional tests of the hypothesis. We find that ratios of planetary orbital spacings remain unchanged, relative locations of planetary mean motion and secular resonances remain unchanged, but resonance widths and the sizes of the Hill spheres of all planets increase as the Sun loses mass. The populations and dynamics of objects near resonances with the planets, as well as those of distant irregular satellites of the giant planets, may contain the signature of a more massive young Sun. Planetary and satellite orbits provide a few tests, but these are weak or non-unique.

Subject headings: Earth — solar system: general — solar-terrestrial relations — stars: mass loss — Sun: evolution

1. INTRODUCTION

It has been well established in models of solar evolution that solar luminosity has increased over the lifetime of the Sun due to the increase in the mean density of the solar core as hydrogen is converted into helium (Gough 1981). This process has led to a ~30% increase in the solar luminosity during the past 4.56 Gyr. Because the Sun's luminosity was significantly lower in the past, calculations of Earth's ancient climate based on contemporary values of terrestrial albedo and atmospheric composition suggest that the mean surface temperature of Earth would have been below the freezing point of seawater until roughly 2 Gyr ago (Sagan & Mullen 1972). However, there is abundant geological evidence that Earth had surface liquid water in the early Archean epoch, 3.8 Gyr ago (Kasting 1989), and possibly even during the Hadean epoch, 4.3 Gyr ago (Mojzsis et al. 2001). Geological evidence also suggests that Earth's climate may even have been warmer on average than the contemporary climate, with the exception of the relatively brief *snowball Earth* epochs at ~2.2 Gyr, ~760 Myr, and ~620 Myr ago (Hyde et al. 2000; Hoffman et al. 1998; Kirschvink 1992; Evans et al. 1997). The problem is even more pronounced for Mars, where even at the current levels of solar luminosity, the mean surface temperature of Mars is far too cold for liquid water to exist, and yet there is abundant evidence that Mars was warm enough for surface liquid water, and that surface liquid water was present at around 3.8 Gyr ago (Goldspiel & Squyres 1991; Jakosky & Phillips 2001).

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 young Sun paradox*. Most attempts to resolve the paradox involve models of the early atmospheres of Earth and Mars containing enhancements of atmospheric greenhouse gases. Sagan & Mullen (1972) proposed an early atmosphere of Earth that contained small amounts of ammonia (NH_3) to provide enough of a greenhouse effect to offset the lower solar luminosity. However, it has been shown that NH_3 would have been rapidly dissociated by solar UV radiation and was unlikely to be a major constituent of the early atmosphere of Earth (Kuhn & Atreya 1979; Kasting 1982; Pavlov et al. 2001).

Carbon dioxide (CO_2) has also been proposed as a greenhouse gas capable of resolving the paradox. A CO_2 concentration of at least 100 × the present atmospheric level (PAL) would have to have been present to prevent the Archean Earth from freezing over (Kasting 1987). According to Rye et al. (1995) this abundance of CO_2 in the atmosphere should have led to the common presence the mineral siderite ($FeCO_3$) in Archean paleosoils, but the absence of siderite from known soils older than 2.2 Gyr suggests that CO_2 could not have been present in the Earth's atmosphere in the required amount. Analysis of the weathering rinds of river gravels dated to 3.2 Gyr ago suggest that the presence of Fe (II)-rich carbonate in the rinds sets a lower limit of CO_2 partial pressure in the atmosphere to only several times the present value, which is 2 orders of magnitude below what is required to keep the surface temperature of the Earth above freezing (Hessler et al. 2004). More recently, Ohmoto et al. (2004) have challenged the interpretation of Rye et al. regarding the lack of siderite in paleosoils, arguing that if even a very small amount of oxygen was present in the Archean Earth's atmosphere, siderite (or any other ferrous-rich mineral) would have been unstable, and a concentration of CO_2 that was 100 × the PAL in the Archean atmosphere could be consistent with the geological evidence.

Methane (CH_4) has also been proposed as a possible greenhouse gas responsible for keeping the Archean Earth warm (Hart 1978; Kiehl & Dickinson 1987). Although CH_4, like NH_3, is susceptible to photodissociation by solar UV, it can remain in the atmosphere for much longer, and methanogenic bacteria could maintain the required atmospheric levels (Pavlov et al. 2000). Were there adequate populations of methanogenic bacteria available in the early Archean epoch? With only trace amounts of evidence of life even existing prior to about 3.6 Gyr ago, it is difficult to support the evidence of a warm young Earth throughout the Hadean and early Archean epochs, with methanogenic bacteria replenishing atmospheric CH_4.

For Mars, one longstanding problem with solving the faint young Sun paradox with a dense CO_2 atmosphere is that models predict that the CO_2 will begin to condense out as a cloud layer at the required atmospheric pressures, thereby increasing the global albedo and offsetting the warming greenhouse effect (Kasting 1991). Pierrehumbert & Erlick (1998) proposed a model of the early Martian atmosphere in which CO_2 cloud particles of a certain size could cause a scattering greenhouse effect, requiring an atmospheric pressure of less than 1 bar CO_2 to keep young Mars above the freezing point of water. However, laboratory studies of CO_2 cloud formation under Martian conditions seem to suggest that the types of clouds that could form on Mars, even with a CO_2 atmosphere with pressures as high as 5 bars, would not warm the planet above the freezing point of water (Glandorf et al. 2002; Colaprete & Toon 2003).

An alternative solution to the faint young Sun paradox involves a nonstandard solar model in which the Sun has lost significant mass over time. A more massive young Sun will have two effects. First, since stellar luminosity is mass dependent, a larger solar mass implies a correspondingly larger solar energy output. Second, owing to the existence of adiabatic invariants of the Keplerian orbits, the planets would have orbited closer to the Sun had the solar mass been higher. Willson et al. (1987) explored the hypothesis that the Sun may have lost as much as $\sim 1-2\ M_\odot$ early in its history. Such an extreme mass loss offered a solution to the warm young Earth and Mars problems, as well as several other outstanding problems in early solar system history, including the relatively massive iron core of Mercury, the slow rotation rate of Venus, and the Late Heavy Bombardment (Bowen & Willson 1986). It also could provide plausible mechanisms for the formation of chondrules and calcium-aluminum-rich inclusions (CAIs) in meteorites, and iron meteorite parent bodies (Kracher & Bowen 1986). Solar evolution models incorporating extreme early mass loss also held promise for explaining photospheric abundances of Li, Be, and B (Guzik et al. 1987).

Kasting (1988) found, however, that there is an upper limit to how much more massive the Sun could have been in the past based on the constraint that if the solar flux at Earth had been $\gtrsim$10% higher at any time in the past then the Earth would have lost its water due to a moist greenhouse atmosphere in which water reaches the stratosphere and is lost due to UV dissociation and escape of hydrogen. Such a process is thought to have occurred on Venus (Kasting & Pollack 1983). Guzik & Cox (1995) investigated a solar model with an initial mass of 1.1 $M_\odot$ and found that the mass loss would have to be confined to a duration of 0.2 Gyr, with an average mass-loss rate of $5 \times 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, in order to fully explain the photospheric Li and Be abundances. Whitmire et al. (1995) suggested that a young Sun 3%–7% more massive would be able to explain the evidence of liquid water on the surface of Mars at 3.8 Gyr ago. Sackmann & Boothroyd (2003) tested solar models in which the Sun first entered the main sequence with an initial mass of up to 1.07 $M_\odot$. They used various mass-loss rate functions that were constrained such that after 4.56 Gyr on the main sequence the solar models had the currently observed solar wind mass-loss rate and the current mass for the Sun. They then compared the resulting solar interiors of their models against solar interior profiles (adiabatic sound speed and density) based on contemporary helioseismic measurements. They concluded that the mass-losing Sun models were consistent with helioseismic measurements, with the 7% more massive Sun case marginally more consistent than the standard solar model. While promising, the technique used by Sackmann & Boothroyd can neither support nor rule out a solar model with a mass loss of about 7% until improvements are made in both helioseismic observational sensitivity and models of solar input physics.

The Sun currently loses a small amount of mass due to coronal mass ejections, $\sim 10^{-15}\ M_\odot\ \mathrm{yr}^{-1}$ (Jackson & Howard 1993), the solar wind, $\sim 2-3 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$ (Feldman et al. 1977), and radiation, $\sim 7 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$, the latter due to conversion of matter into energy through thermonuclear fusion at the core (Shu 1982). Assuming that each of these rates have remained constant over time, the total amount of mass lost by the Sun over its 4.56 Gyr history is only about 0.05% of the total solar mass. However, the physical processes that set the rate of mass loss due to solar wind and coronal mass ejections are poorly understood, and it is not unreasonable to explore solar models in which the rates of mass loss were larger in the past by orders of magnitude. Astronomical observations indicate generally larger mass-loss rates by stellar winds for younger solar analogs (Wood et al. 2002, 2005). There is some evidence in lunar regolith samples of a long-term secular decrease in solar wind flux during the past 3 Gyr (Kerridge et al. 1991). There is also evidence in the meteoritic record of enhanced solar activity during the solar system's early history, although this has been interpreted as evidence of the Sun's very active but brief T Tauri phase, rather than an extended period of enhanced solar wind (Caffee et al. 1987).

In this paper we examine anew the hypothesis of a mass-losing Sun. First we constrain the solar mass-loss rate time history that would be required to solve the faint young Sun paradox by requiring that Earth's mean surface temperature remain above 273 K for all of its history (§ 2). We then compare the resulting mass-loss functions with estimates in the literature for the stellar wind mass-loss rates of younger Sunlike stars (§ 3). The comparison is discouraging: the astronomical data do not support a solar mass-loss history that would resolve the faint young Sun paradox. However, astronomical data cannot rule out the hypothesis either. Therefore, with a view toward identifying other tests of the hypothesis, we explore the effects of a mass-losing Sun on the orbital dynamics of the solar system, including how a 7% more massive Sun would affect mean motion and secular resonances, the irregular satellites of the Jovian planets, and other small bodies in the solar system (§ 4). We summarize our results and conclusions in § 5.

2. EFFECT OF SOLAR MASS ON CLIMATE HISTORY

A very simple climate model can be used to explore the dependence on the mass of the Sun of the mean surface temperature of the Earth, while keeping all other factors constant. The steady state mean surface temperature of the Earth (or any other terrestrial planet) is given by the following energy balance equation (Pollack 1979):

$$(1 - A)S\pi R^2 = \sigma\varepsilon T_s^4 4\pi R^2, \tag{1}$$

where A is the average planetary albedo, S is the solar flux at the top of the atmosphere, R is the planetary radius, ε is the atmospheric IR emissivity, and σ is the Stefan-Boltzmann constant. Typical values for the Earth are $A = 0.34$ and $\varepsilon = 0.6$ (Pollack 1979; Hartmann 1994). For the purposes of this paper, we make the minimalist assumption that these parameters are time-independent, and we take the current typical values to be constant over all of geologic time. This is not necessarily the most accurate way to model the Earth's atmosphere, since changes in atmospheric greenhouse gas composition can vary the emissivity parameter ε, and changes to surface composition and cloud cover can change the planetary albedo parameter A; this parameterization may also be criticized as insufficient to represent the variety of greenhouse effects that may be possible. However, our purpose is to identify solar mass histories that simply and completely resolve the faint young Sun paradox without the need to invoke other effects. Thus, for our purposes equation (1) provides an adequate representation and can be rearranged to give the terrestrial surface temperature as a function of solar flux

$$T_s = \left[\frac{S(1-A)}{4\varepsilon\sigma}\right]^{1/4}. \qquad (2)$$

Gough (1981) reports that, based on stellar nucleosynthesis and stellar evolution models, the rate of increase in luminosity of the Sun with time, assuming the solar mass is constant, can be represented as

$$L(t) = \left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{-1} L_\odot, \qquad (3)$$

where $t_\odot = 4.56$ Gyr is the current age of the Sun (Dearborn 1991), and $L_\odot \approx 3.9 \times 10^{33}$ erg s^{-1} is the current solar luminosity (Shu 1982). We will assume that the Earth's orbital eccentricity can be neglected, and that the Earth's orbital radius is equal to its semimajor axis, a.

A mass-losing Sun will affect the Earth's climate in two ways. First, the main-sequence stellar luminosity is quite sensitive to stellar mass, $L \propto M^P$, where P is in the range of 3–5 depending on sources of opacity (Iben 1967); for the young Sun we adopt $P = 4.75$, following Whitmire et al. (1995). Second, if the solar mass loss is slow compared with the orbital motion of the planets, then it follows from the adiabatic invariance of the actions for a Keplerian orbit that

$$[M(t) + M_i]a_i(t) = \text{constant}, \qquad (4)$$

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. In the solar system, $M_i \ll M_\odot$, therefore a planet's semimajor axis will be smaller for a more massive Sun by $a_i \propto M^{-1}$. The solar radiation flux at Earth, S, is related to the Sun's luminosity L and Earth's semimajor axis a by $S \propto La^{-2}$. Therefore, the time variation of the solar flux at Earth is given by

$$S(t) = S_0\left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{-1}\left[\frac{M(t)}{M_\odot}\right]^{6.75}, \qquad (5)$$

where S_0 is the current solar radiation flux at the top of Earth's atmosphere, $S_0 = 1.37 \times 10^6$ erg cm^{-2} s^{-1}. Using equation (5) in equation (2), we obtain the time dependence of the terrestrial surface temperature

$$T_s(t) = \left\{\frac{S_0(1-A)}{4\varepsilon\sigma[1 + (2/5)(1 - t/t_\odot)]}\right\}^{1/4}\left[\frac{M(t)}{M_\odot}\right]^{1.69}. \qquad (6)$$

Note that equation (6) is obtained from a straightforward energy balance model. We now use it to construct the "minimum mass-loss" history 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 of $\dot{M}_\odot \approx -2 \times 10^{-14}$ $M_\odot$ yr^{-1}.

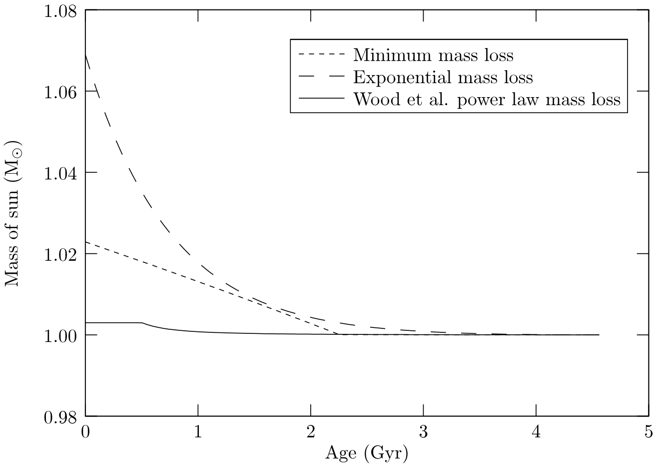

FIG. 1.—Solar mass over time for the three different solar mass history models considered.

We do this as follows. We assume that the current solar mass-loss rate has remained constant for the past 2.3 Gyr, the time span over which the standard solar model yields terrestrial surface temperature above 273 K (Sagan & Mullen 1972). For times prior to 2.3 Gyr, we calculate the solar mass that would be required to just keep the terrestrial surface temperature at 273 K. Therefore, we specify the terrestrial surface temperature at $t = 0$, $T_s(0) = 273$ K. Equation (6) then yields the initial solar mass, $M(0) = 1.026$ $M_\odot$. Also from equation (6) we obtain the solar mass as a function of time that keeps the terrestrial surface temperature constant, $T_s(t) = T_s(0) = 273$ K,

$$M(t) = 0.973\ M_\odot\left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{0.148}; \qquad (7)$$

the corresponding mass-loss rate is given by

$$\dot{M}(t) = -1.26 \times 10^{-11}\left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{-0.852} M_\odot\ \text{yr}^{-1}. \qquad (8)$$

In equations (6) and (8) we have adopted the numerical values of A and ε typical of Earth mentioned above, and $t_\odot = 4.56 \times 10^9$ yr. By demanding continuity of the solar mass time variation and consistency with the present solar mass-loss rate, we obtain the piecewise "minimum solar mass-loss" model:

$$M(t) = \begin{cases} 0.974\ M_\odot\left[1 + \frac{2}{5}\left(1 - \frac{t}{t_\odot}\right)\right]^{0.15} & \text{for } t \le 2.39 \text{ Gyr}, \\ M_\odot + \dot{M}_\odot(t - t_\odot) & \text{for } t > 2.39 \text{ Gyr}. \end{cases} \qquad (9)$$

This function is shown by the short-dashed curve in Figure 1.

Beyond the minimum solar mass-loss history, we consider a solar mass-loss rate that has decreased exponentially with time. We construct this with parameters constrained to keep the mean surface temperature of Earth above the freezing point of water for all of the planet's history. A functional form of this mass-loss rate can be specified as $\dot{M}(t) \sim c + d(e^{-\alpha t} - e^{-\alpha t_\odot})$, which implies solar mass as a function of time as

$$M(t) = M_\odot + C(t - t_\odot) + D(e^{-\alpha t} - e^{-\alpha t_\odot}). \qquad (10)$$

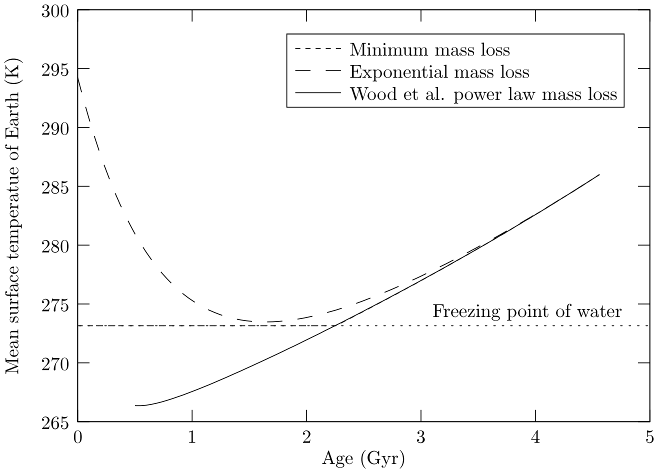

FIG. 2.—Estimated mean surface temperature of the Earth calculated using eq. (6) for the three different solar mass history models considered.

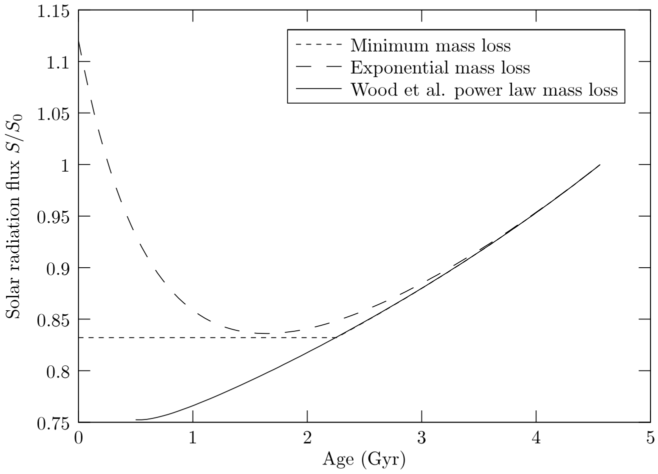

FIG. 3.—Solar radiation flux, $S(t)$, for any planet relative to the current solar radiation flux, S_0.

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

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

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

where $\dot{M}_\odot = \dot{M}(t_\odot) \simeq -2 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$ is the present solar wind mass-loss rate (at $t = t_\odot$). The time constant, α, 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: $T(t < t_\odot) > 273$ K. This yields $\alpha = 1.32 \times 10^{-9}\ \mathrm{yr}^{-1}$. The parameter m_f is a free parameter, except that, as discussed above, Kasting (1988) argues that the solar flux cannot have been more than 10% higher at any point in the past, since Earth has not lost its oceans due to a runaway moist greenhouse atmosphere. This provides an upper limit on the initial mass factor of $m_f = 1.07$, and Sackmann & Boothroyd (2003) calculate that this value is consistent with helioseismology. With this value we have $C \simeq -9.2 \times 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ and $D \simeq 0.070$. The resulting solar mass function $M(t)$ is shown in Figure 1.

For the mass-loss functions considered above, the corresponding mean surface temperature of Earth as a function of time is plotted in Figure 2. Note that although the cumulative mass loss of the Sun required to resolve the faint early Sun paradox is modest, the timescale required for this mass loss is quite long, $\mathcal{O}(10^9)$ yr.

We briefly consider Mars. With the standard solar model, in order to keep the global surface temperature on Mars above 273 K prior to 3.5 Gyr ago, the effective atmospheric emissivity would need to be $\varepsilon = 0.29$ (assuming its present albedo, $A = 0.16$), or $\varepsilon = 0.23$ (assuming an earthlike albedo, $A = 0.34$). For the mass-losing solar models considered here and for the minimum required $\dot{M}$ that solves the faint early Sun problem for Earth, in order to solve the problem for Mars the effective emissivity of Mars would need to be $\varepsilon = 0.33$ (assuming its present albedo of $A = 0.16$) or $\varepsilon = 0.26$ (assuming an Earth-like albedo, $A = 0.34$).

Kasting (1991) calculated the solar luminosity required to have kept ancient Mars above the freezing point of water with a massive CO_2 atmosphere, considering the effects of CO_2 condensation. He found that in order to keep young Mars warm enough for liquid water with a massive CO_2 atmosphere, 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, or at least 12%–20% higher than that predicted by standard solar models. If the solar flux ratio was lower than this value, then the decrease in the convective lapse rate in the troposphere of Mars due to the condensation of CO_2 clouds would have offset the greenhouse warming enough that the surface could never have been above the freezing point of water, no matter how high the CO_2 pressure was. Figure 3 shows the solar radiation flux ratio as a function of time for the solar mass-loss models considered here. Both the models considered here that solve the warm young Earth problem are also capable of satisfying Kasting's criteria for keeping young Mars warm.

3. STELLAR WINDS OF SUN-LIKE STARS

Since the Sun is thought to be a typical G-type dwarf star, it would be informative to measure the stellar wind mass outflows of other Sunlike stars at various stages of their evolution on the main sequence. Stellar winds from G- and K-type dwarf stars are very difficult to observe directly owing to their low optical depth. Recently however, indirect measurements of the stellar winds of a small number of nearby Sun-like stars have been made using the *Hubble Space Telescope*. These measurements exploit the charge exchange that occurs when the ionized stellar wind collides with the neutral interstellar medium, which is detectable in a H I Lyα absorption feature (Zank 1999; Wood et al. 2002). By measuring amount of Lyα absorption in a star and fitting the observed absorption feature to a model astrosphere interacting with its local interstellar medium, the mass-loss rate of the star due to stellar winds can be estimated. The density and relative velocity of the local interstellar medium with respect to the star must also be known.

Using this method, Wood et al. (2005) have estimated the stellar wind fluxes of several nearby solar-type main-sequence stars. For each star, Wood et al. reported a mass-loss rate due to stellar winds relative to the currently measured solar wind mass-loss rate. They also reported the stellar X-ray luminosity and the stellar surface area. They then used a power-law relationship between the stellar X-ray flux and the age as reported by Ayers (1997),

$$F_X \propto t^{-1.74 \pm 0.34}. \tag{11}$$

We use equation (11), together with the Sun's age as a reference point, to obtain an age estimate for each of the stars in Wood et al.'s sample. We also calculated the errors in the stellar ages using the error in the power-law relationship between stellar X-ray flux and age. In addition, we also searched the literature

TABLE 1

Estimated Stellar Wind Mass-Loss Rates of Sunlike Stars with Measured Astrospheres

Name	X-Ray Age[a] ($\times 10^9$ yr)	Independent Age ($\times 10^9$ yr)	Stellar Wind $\dot{M}$ [a] ($\times 10^{-14}$ $M_\odot$ yr^{-1})
Sun	...	4.56 ± 0.1[b]	2.5 ± 1.5
α Cen	3.4 ± 0.2	6.52 ± 0.3[c]	5.0 ± 3
ϵ Eri	0.72 ± 0.3	...	75 ± 45
61 Cyg A	1.9 ± 0.3	...	1.3 ± 0.8
ϵ Ind	2.3 ± 0.3	1.3 ± 0.3[d]	1.3 ± 0.8
36 Oph	0.88 ± 0.3	...	38 ± 23
λ And	0.36 ± 0.2	...	13 ± 8
70 Oph	0.90 ± 0.3	0.50 ± 0.22[e]	250 ± 150
ξ Boo	0.44 ± 0.2	0.06 ± 0.03[e]	13 ± 8
61 Vir	6.5 ± 0.6	6.6 ± 3[d]	0.75 ± 0.45
δ Eri	2.0 ± 0.3	...	10.0 ± 6
DK UMa	0.36 ± 0.2	...	0.38 ± 0.23

[a] Wood et al. (2005).
[b] Dearborn (1991) .
[c] Eggenberger et al. (2004).
[d] Lachaume et al. (1999).
[e] Barry (1988).

for independent measurements of stellar ages, if available. The ages estimated from equation (11) do not always agree with the ages found by other methods, and some are well outside the error bars of the X-ray flux ages. We consider here a subset of Wood et al.'s stars, i.e., only the 11 G and K stars for which mass-loss rates were obtained. These data are listed in Table 1 and plotted in Figure 4. Mass-loss functions that fit to the data of Wood et al. with a power law are also plotted in Figure 4, along with the two solar mass-loss history models described in § 2.

It is clear that the mass-loss rate functions that we derived in § 2 to solve the faint young Sun paradox are inconsistent with the astronomical data on the mass-loss rates of Sun-like stars as found by Wood et al. The required solar mass-loss rates at early times (0–2 Gyr) are about 1–2 orders of magnitude higher than that for the observed solar analogs. The cumulative stellar mass loss inferred from the Wood et al. data is $\lesssim 0.003$ $M_\odot$, in contrast with the required 0.03–0.07 $M_\odot$. The data also indicates a timescale of $\mathcal{O}(10^8)$ yr for the decrease of stellar wind flux at early times, whereas our hypothesis requires a slower decay, on a timescale of $\sim 10^9$ yr.

To summarize, the faint young Sun paradox requires cumulative solar mass-loss and early solar mass-loss rates that are about 1–2 orders of magnitude and about 1 order of magnitude, respectively, higher than the astronomical data have revealed. The caveat is that the stellar wind flux estimates of the younger solar analogs are model dependent. Wood et al. (2002) estimate that there may be a factor of 2 uncertainty in their estimated mass-loss rates due to the uncertainty in the stellar wind velocity.

4. DYNAMICAL EFFECTS OF HIGHER MASS SUN

In the above analysis we have shown that in order for a mass-losing Sun to solve the faint young Sun paradox, the Sun's mass had to be significantly higher for a period of time on the order of 2 Gyr. In this section, we explore what effects such a higher mass Sun might have had on the dynamics of the solar system, and whether some signatures of the early massive Sun may remain imprinted on the orbital dynamics of the present planetary system. A nonexclusive list of dynamical effects is discussed below.

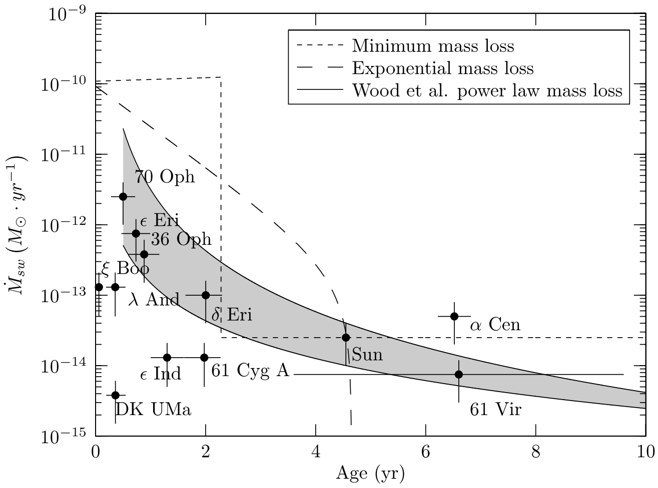

Fig. 4.—Mass-loss rates due to stellar wind of the G–K main-sequence stars from Wood et al. (2005) are plotted as black circles along with the three different solar mass history models considered. The vertical error bars are calculated assuming the measured stellar wind mass loss are known to within a factor of 2.

4.1. *Planetary Orbits*

A slow solar mass loss conserves all the three actions of a Keplerian orbit. Therefore, orbital eccentricities and inclinations of all planetary orbits are unchanged by a solar mass loss, and it was shown above that the semimajor axes of each of the planets are related to the time-varying mass of the Sun through equation (4). This means that, for an initial mass of the Sun greater than at 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, for $m_f \approx 1.07$, and considering the mass-loss histories described in § 2, the length of the year on Earth would have been shorter by 2%–6% during the Archean epoch (Earth age 0.5–2.5 Gyr; see Fig. 1). Indicators of the length of the year in the geological record (tidal rhythmites, banded iron formations) provide poor precision for pre-Cambrian epochs (Williams 2000; Eriksson & Simpson 2000) and are unlikely to provide a test of a shorter year.

The slightly more compact ancient planetary system would have experienced relatively stronger orbital perturbations arising from the mutual gravitational interactions of the planets. The rates of secular precession of apsides and of orbit poles, which are proportional to $M_j/(T_i M_\odot)$, where planet j is perturbing planet i, would have been faster by a factor m_f. Although these precessional motions have been linked to climate cycles on timescales of $\mathcal{O}(10^5–10^6)$ yr in recent Earth history (Hinnov 2000), the much lower resolution of the very ancient climate record (Erwin 2006) makes it unlikely that it could be useful in testing these implications of the higher ancient solar mass.

4.2. *Minor Planet Resonance Locations*

Locations of mean motion resonances depend on the ratios of the semimajor axes between the planets and a test particle. It was previously shown that the semimajor axes of the planets are related to the time varying mass of the Sun through equation (4). For a Sun with a higher mass given by the factor m_f, the change in the ratio of the semimajor axis of Jupiter to a massless particle, p, can be found by

$$\frac{a_p/a_{\rm J}}{a'_p/a'_{\rm J}} = \frac{m_f(M_\odot + M_{\rm J})}{m_f M_\odot + M_{\rm J}}, \qquad (12)$$

where the primed values refer to the pre–mass-loss semimajor axes. For a mass loss of 7%, this gives a change in the ratio of semimajor axes of

$$\frac{a_p/a_{\rm J}}{a'_p/a'_{\rm J}} = 1.00006.$$

The assumption that $a_i \propto M_\odot^{-1}$ is therefore a good one when considering the locations of mean motion resonances. It follows that the relative locations of mean motion resonances of the major planets remain nearly unchanged as the solar mass changes; however, the strengths of resonant perturbations are not invariant: the fractional amplitude of resonant perturbations is proportional to $\sim(M_i/M_\odot)^{1/2}$, so that resonance widths (measured as a range in semimajor axis), Δa, scale as $\sim m_f^{-3/2}$. The Kirkwood Gaps and the Hilda group of asteroids in the main asteroid belt may have been subjected to the effects of an expanding resonance width due to solar mass loss. 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 compared to their initial orbits; the net changes estimated are small, not inconsistent with the observed population, but also consistent with other dynamical processes in the early solar system (e.g., resonance sweeping that accompanied the orbital migration of the planets; Franklin et al. 2004).

One of the strongest resonant perturbations on asteroids is the ν_6 secular resonance, which defines the inner edge of the present-day asteroid belt. Considering the effects of the time varying solar mass, we 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. Thus, we expect no signature of the solar mass loss in the inner boundary of the asteroid belt.

4.3. *Irregular Satellites of the Outer Planets*

The irregular satellites of the outer giant planets are small objects having semimajor axes, eccentricities, and inclinations much higher than the regular satellites; the majority of them are on retrograde orbits. They are thought to be objects that formed in heliocentric orbits, which were subsequently captured into stable orbits around the giant planets.

The irregular satellites all orbit well within their planet's Hill sphere. In the restricted three-body problem, the Hill sphere is defined by the radius

$$r_{\rm H} = a_2\left(\frac{Gm_2}{3m_c}\right)^{1/3}, \tag{13}$$

where m_c is the central mass, and m_2 is the large primary mass. If the solar mass were higher in the past by a factor m_f, then the Hill radius of each planet would have been

$$r'_{\rm H} = m_f^{-4/3} r_{\rm H}, \tag{14}$$

where $r_{\rm H}$ 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. This mechanism is similar to the pull-down capture mechanism proposed by Heppenheimer & Porco (1977), which invokes the expansion of the planet's Hill sphere during the gas accretion phase; however, the gas accretion phase is very short lived, whereas the solar mass loss would occur over a much longer timescale. As the Sun loses mass, its Hill's radius increases as shown in equation (14). Objects that are weakly bound to a planet, or are unbound but near the weak stability boundary of the planet may become permanently captured as the Sun's mass decreases (cf. Astakhov & Farrelly 2004).

The efficiency of this mechanism is only weakly dependent on planet mass. We speculate that it may offer an explanation for the observed similarity in the irregular satellite populations of Jupiter, Saturn, Uranus, and Neptune (Jewitt & Sheppard 2005; Sheppard 2006). The long timescale of this process is also an attractive means for evolving irregular satellites into secular resonances (cf. Saha & Tremaine 1993; Nesvorný et al. 2003). A detailed examination of these possibilities is beyond the scope of the present paper, but we hope to address them in future work.

We note briefly that the growth of the giant planets as they accreted large amounts of gas during their formation also causes an expansion of the Hill sphere. This has been invoked in the "pull-down" mechanism proposed by Heppenheimer & Porco (1977) for the capture of irregular satellites. In this mechanism, the planetary Hill sphere expands by a much larger magnitude and over a much shorter period of time compared to the solar mass-loss mechanism. Another mechanism for changing planetary Hill spheres is the late orbital migration of the giant planets (Hahn & Malhotra 1999; Tsiganis et al. 2005), which could also have facilitated the capture of irregular satellites (Brunini & Conicet 1995).

5. CONCLUSION

We have calculated that the minimal cumulative mass loss of the Sun that would resolve the faint young Sun paradox is $\sim$0.026 $M_\odot$. Models with a Sun that is up to $\sim$7% more massive than at present are also consistent with helioseimological constraints on solar interior evolution and with geological constraints. However, an important conclusion of our study is that the solar mass-loss history that would resolve the faint young Sun paradox requires the Sun to remain moderately more massive than present for 1–2 Gyr in its early history (Figs. 1 and 4).

Astronomical evidence (also shown in Fig. 4) suggests that both the cumulative mass loss and the timescale for the mass loss (by means of stellar winds) of Sun-like stars is significantly short of what is required to resolve the faint early Sun paradox. The cumulative mass loss of solar age Sun-like stars on the main sequence, based on the power-law mass-loss rate time history given by Wood et al. (2005) is $\lesssim$0.3%, and the mass-loss rate declines rapidly in $\sim$1 Gyr.

Of course, the astronomical data do 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 a relatively small ensemble of 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, including possible signatures in the geological and climate record. Most effects are found to be too small to provide unambiguous tests of the early massive Sun hypothesis. This hypothesis may offer a novel explanation for the capture of irregular satellites of the outer planets, including the capture into secular resonance for some Jovian irregular satellites. However, even if the current satellites of the giant planets preserved the signature of a more massive Sun, other dynamical events in the early solar system, such as the accretion and orbital migration of the giant planets, may also provide viable explanations. With the recent accumulation of considerable data on the properties of irregular satellites, it may be possible to test the viability of these alternative mechanisms for the capture of irregular satellites. This requires more detailed theoretical development of the alternative scenarios for comparison with observations.

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