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4.8 Sunlight Intensity and Decreasing $\alpha$ ....................................................................................35
4.1 Introduction

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The fine-structure constant, \( \alpha \equiv e^2/(4\pi\varepsilon_0\hbar c) \), is a commonly used dimensionless measure of the strength of the electromagnetic interaction; its value in our universe, which we will designate by \( \alpha_0 \), is \( \sim 1/137 \). This chapter will explicate the ways in which \( \alpha \) is fine-tuned for LTD-optimality. Section 4.2 summarizes some of the published results regarding the way in which the stability of atoms, and hence the existence of life, depends on \( \alpha \) being sufficiently small. Section 4.3 shows that in atomic units, the vast majority of biochemical reactions are not significantly affected by moderate increases in \( \alpha \), and any decrease in \( \alpha \). Sections 4.4 - 4.6 explicate the ways in which \( \alpha \) is fine-tuned for scientific technology and scientific discovery. Specifically, section 4.4 shows that the efficiency of transformers and electric motors rapidly decreases with a decrease in \( \alpha \), with an estimated five-fold decrease in \( \alpha \) rendering most current uses of transformers practically impossible for most applications, and many applications of
motors must more costly; such a decrease would render the universe far less optimal for a highly technological civilization at our stage of development. Section 4.5 shows that any decrease in α would result in a proportionate decrease in the resolving power of light microscopes, with a sufficient decrease making it impossible to use them to see any living cells. Section 4.6 argues that a small increase in α would have likely resulted in it being far less optimal, if not virtually impossible, for carbon-based life forms to harness fire. Because fire is essential for smelting metals (and glass), such an increase would have made the universe far less optimal for development of technology and science for any carbon-based life form. Section 4.7 shows that the intensity of sunlight on a habitable planet (whose atmosphere is sufficiently clear to allow for significant astronomy) is proportional to α²; thus, for example, if α were five times its current value, the intensity of sunlight would be twenty-five times as great. It is then argued that such an increase in intensity would severely negatively impact the ability of plants and forests to grow, which would have severe negative livability and discoverability effects. Conversely, section 4.8 argues that the decrease in the intensity of sunlight on a habitable planet caused by a decrease in α would at some point cause the rate of photosynthesis to decrease to such an extent that it would have a serious impact on livability and the existence of fossil fuels (and hence technology) by the time ECAs arrive. Finally, section 4.9 provides a summary of the livability and discoverability constraints on α along with an attempt to estimate the degree of fine-tuning of α. It is argued throughout those new, positive compensating LTD effects do not occur with the increases and decreases of α being considered.

4.2 α and the Stability of Matter and Stars

It is easiest to understand the effects on the stability of matter of increasing α by using Planck units, in which c = 1, G = 1, and ħ = 1. (G is the gravitational constant.) In these units, the strength of the electric force between protons and electrons in an atom is proportional to α. Thinking classically, since the velocity of an electron in an atom is proportional to the electric force, if α is sufficiently large, or the nucleus has a high enough atomic number, Z, the kinetic energy of the electrons in the lowest orbital would be large enough to create electron/positron pairs. When such a pair is created, the resulting positron is emitted from the atom and the created electron is pulled in closer to the nucleus, effectively reducing the total nuclear charge by one unit, a phenomenon that has been experimentally verified (Greiner and Schramm, 2008, p. 512). For the value of α in our universe, this does not happen until Z > 173, where Z denotes the atomic number (2008, p. 511). Since this effect scales as Zα (p. 511), it follows that more than a two-fold increase of α would undercut the stability elements such as uranium (Z = 92), and a 6- to 7-fold increase would undercut the stability of lighter elements, such as iron (Z = 26). The latter element is essential for hemoglobin, which is by far the most efficient molecule that we know of for the transport of oxygen, and hence for metabolism, of warm blooded creatures (Denton, 1998, p. ____)_. Further, this effect is independent of any compensating changes that
would need to be made in the strength of the strong nuclear force in order to retain nuclear stability.

Other effects come into play upon further increasing $\alpha$. Using the Dirac operator to take into account relativistic effects, Lieb calculates an absolute upper bound on $\alpha$ of \( \frac{128}{15\pi} \approx 2.72 \), after which all matter becomes unstable and collapses in on itself (Lieb, 1988, p. 1696, reference [2].) This upper bound corresponds to a 372-fold increase over $\alpha$'s current value of $\approx 1/137$. Based on his calculations, Lieb estimates that the actual upper bound is probably around $\alpha \approx 1$, though this has not been proven ([2], Lieb, 1988, p. 1696).

### Stability of Stars

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According to calculations by physicist Fred Adams (2008, Fig. 5, p. 18, reference [39]), if $\alpha$ were decreased or increased by more than a 200-fold, no stars could exist. The lower bound is dependent on the strength of gravity, $\alpha_G$, with its decreasing slowly with a decrease in $\alpha_G$. For example, if $\alpha_G$ is decreased by a factor of 100,000, the lower bound is decreased by a little over a factor of 100. On the other hand, the upper bound is very weakly dependent on $\alpha_G$: a $10^{10}$ decrease in $\alpha_G$ results in a two-fold increase in the upper bound of $\alpha$.

### 4.3 Atomic Units, Chemistry, and $\alpha$

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In the remaining sections, we will use atomic units, defined by $m_e = 1$, $e = 1$, $\hbar = 1$, $4\pi\varepsilon_0 = 1$, and $k = 1$, as explained in Chapter 1, section 4.2. Unless otherwise specified, all statements that are made throughout the rest of this chapter are relative to the SI version of atomic units (see Chapter___, section ___). Using atomic units, it is easy to show that the chemistry essential for life remains nearly the same for around a nine-fold increase in $\alpha$ and for any decrease in $\alpha$, assuming that the nuclei of the chemical elements in question remain stable via suitable adjustments in other constants such as the strong nuclear force, $\alpha_s$. The reason for this independence of chemistry on $\alpha$ is that the behavior of outer-shell electrons for the major biochemically active elements is to a high degree of approximation determined by the non-relativistic Schrödinger equation combined with the Pauli Exclusion Principle, and it is these electrons that determine the chemical properties of an element. In atomic units, however, the non-relativistic Schrödinger equation is independent of $\alpha$. Specifically, applied to a single electron in an atom, the non-relativistic Schrödinger equation is:

\[
i\hbar \frac{\partial}{\partial t} \Psi(r, t) = -\frac{\hbar^2}{m} \nabla^2 \Psi(r, t) + V(r) \Psi(r, t)
\]  

(6.1)

where $\Psi(r, t)$ is the wave function, $\frac{\hbar^2}{m} \nabla^2 \Psi(r, t)$ is the kinetic energy operator, $m$ is the mass of the electron, and $V(r)$ is the potential energy at position $r$. $\nabla^2$ is the Laplace operator, which in
three dimensions is \( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \). Since by stipulation, in atomic units \( \hbar = 1 \) and \( m_e = 1 \), the above equation becomes:

\[
(6.2) \quad \frac{i}{\hbar} \frac{\partial}{\partial t} \psi(\vec{r}, t) = -\left( \frac{\hbar^2}{2m} \right) \nabla^2 \psi(\vec{r}, t) + V(\vec{r})\psi(\vec{r}, t)
\]

The only place that \( \alpha \) could enter this equation is via determining the potential \( V(\vec{r}) \). This potential is determined by two factors, the electrostatic forces between the various charges (e.g., between the electron and proton) and the magnetic forces resulting from the intrinsic spin of the electrons and their orbital motion. The electrostatic force between two electric charges, \( q_1 \) and \( q_2 \), is given by Coulomb’s law via the equation \( F = \frac{1}{4\pi\varepsilon_0} \frac{q_1q_2}{r^2} \), where \( r \) is the distance between the charges. Since in atomic units, \( \frac{1}{4\pi\varepsilon_0} = 1 \) and the electric charge, \( e \), of an electron or proton is stipulated to be 1, the Coulomb force between any two charges is simply \( F = \frac{e^2}{r^2} \), and thus is independent of \( \alpha \). Although the magnetic forces are dependent on \( \alpha \), they are tiny compared to the electrostatic forces; in actual atoms the magnetic contribution to the energy of an orbiting electron is around \( 10^{-4} \) to \( 10^{-5} \) less than that resulting from the electrostatic interactions for biochemically active elements, and thus can be neglected.\(^1\) Consequently, the non-relativistic Schrödinger equation can be considered independent of the value of \( \alpha \).\(^2\) This means that insofar as the non-relativistic Schrödinger equation applies to the outer shell electrons in an atom, its chemical properties remain the same for substantial increases in \( \alpha \) and any decrease in \( \alpha \).

According to Neil Bartlett, relativistic effects “become important for elements heavier than the lanthanides” (Bartlett, 1998, p. 2000, reference [3]). Since the lanthanides are elements between atomic number 58 and 71, this means that for the current value of \( \alpha \), relativistic effects on chemistry must be taken into account for elements greater than atomic number 71. For instance, Bartlett points out that some of the important chemical properties of gold (atomic number 79) are the result of these relativistic effects. Since all the elements essential for biochemistry have an atomic number less than 71, this means that to a high degree of approximation the chemistry of all these elements is entirely determined by the non-relativistic Schrödinger equation and the Pauli-Exclusion principle.

Since in SI or Planck units the classical velocity of an electron in a given quantum state of an atom is roughly proportional to \( \alpha \), one would expect that the larger that \( \alpha \) is, the lower the atomic number of the elements for which relativistic effects must be taken into account. In fact, the relativistic corrections to the binding energies of outer-shell, valence electrons scale as \( \alpha^2Z^2 \), where \( Z \) is the atomic number. (Chin, et al., p. 5, reference [23]). Thus, these effects do not become important for the primary elements involved in organic chemistry (hydrogen, carbon,

\(^1\) The correction to the Hamiltonian as a result of the magnetic interactions and relativistic effects is of order \( (Z\alpha)^2 \), with the magnetic correction itself being of the same order (Townsend, 2000, Eqs. 11.118 and 11.111 pp. 328, 331, reference [14]). For the hydrogen atom, \( (Z\alpha)^2 \sim 5.3 \times 10^{-5} \), which is insignificant. (Looking at Townsend’s Eq. 10.34 and comparing it with Eq. 11.118, one sees that correction also varies as \( 1/n \), where \( n \) is the principle quantum number. Thus it is less for the outer orbitals which have higher values for \( n \) – e.g., \( n = 2 \) for carbon and oxygen, whereas \( n = 7 \) for gold.)

\(^2\) Thus, for instance, in atomic units the non-relativistic Schrödinger equation for the hydrogen atom is \( H'\psi=(-1/2 \nabla^2-1/r)\psi \).
nitrogen, and oxygen) unless $\alpha$ is increased by more than around 9-fold.\(^3\) When relativistic effects must be taken into account, one must use a relativistic version of the Schrödinger equation, which explicitly involves the speed of light and hence $\alpha$.\(^4\)

The above considerations mean that for moderate increases in $\alpha$, and any decrease, carbon-based life forms could not tell the difference insofar as they observed the relative chemical (and spatial and temporal) properties of atoms and molecules of moderate to low atomic numbers on their planetary surface, along with the relative sizes and velocities of the objects around them. For instance, suppose $\alpha$ were decreased. Although in Planck units the size of an atom is inversely proportional to $\alpha$, since all atoms less than around atomic number 71 would proportionally change size, the relative size of almost all objects would remain the same. Consequently, since atomic units use the classical radius of the first orbital of hydrogen atom as the basic yardstick, their size would remain the same when measured in atomic units. Similarly, in these units, the relative rates of chemical and atomic processes would remain the same, along with all other chemical properties. Processes involving magnetic fields, or electromagnetic radiation, however, will be affected as explained in the next three subsections.

### 4.4 Magnetism and $\alpha$

The magnetic fields produced by electric currents, and the intrinsic spin of electrons and atomic nuclei, depend on $\alpha$. The magnetic field produced by an electric current is given by the equation

\[
\nabla \times \mathbf{B} = \mu_0 \mathbf{J}
\]

where $\mathbf{J}$ is the current and $\mu_0$ is the magnetic permeability of free space. The latter is related to the speed of light and the electrical permittivity, $\varepsilon_0$, by the equation $\mu_0 = 1/c^2 \varepsilon_0$. Since in atomic units $\varepsilon_0 = 1/4\pi$, it follows that in these units

\[
\mu_0 = \frac{1}{4\pi c^2}.
\]

\(^3\) Since the relativistic effects scale as $\alpha^2 Z^2$ and in our world these effects do not come into play until $Z = 71$, it follows that as long $(\alpha/\alpha_0)^2 (Z/71)^2 < 1$. Because oxygen (atomic number 8) has the highest atomic number of the primary elements in organic chemistry, one would not expect relativistic effects to come into play unless $\alpha$ were increased by a factor of $(71/8) \approx 9$. There is some effect, however, even at a little less than a 9-fold increase. King, et. al. investigated this, concluding that “a sevenfold increase in the fine-structure constant decreases the strength of the O–H bond in the water molecule by 7 kcal mol-1 while reducing its dipole moment by at least 10%.” (King et al., 2010, p. 042523, reference) Since the energy of the O–H bond is approximately 100 kcal per mole, this is around 7% decrease. It is unclear what effect this would have.

\(^4\) For example, one relativistic version of the Schrödinger equation is the Klein-Gordon equation

\[
-\frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} - \nabla^2 \psi + \frac{m^2 c^2}{\hbar^2} \psi - \frac{1}{c} \frac{\partial \psi}{\partial t} = -\nabla^2 \psi + \frac{m^2 c^2}{\hbar^2} \psi.
\]
This means that the strength, $|B|$, of a magnetic field is given by the equation:

$|B| = \mu_0 J \propto \alpha^2$  \hspace{1cm} (6.5)

The magnetic fields of ferromagnetic substances also bear the same relation to $\alpha$. Many atoms have a small magnetic dipole moment due to the intrinsic spin of the electrons and nucleons composing the atom along with the orbital motion of the electrons. Permanent magnets result from the magnetic dipole moments of the atoms in a ferromagnetic substance lining up in the same direction. Most of the dipoles are part of magnetic domains; the magnetic field both causes domains to line up in the same direction and the domains in the direction of the magnetic field to grow. Since as expressed in atomic units, the velocities of all orbital electrons with non-relativistic velocities would remain the same if $\alpha$ were decreased, their total magnetic dipole moment would also remain the same. Further, if they are close to relativistic speeds for the current value of $\alpha$, their velocities will slightly decrease with a decrease in $\alpha$. Consequently, as measured in atomic units, the total magnetic dipole moment created by the orbital motion of the electrons will remain nearly the same.

On the other hand, the “Bohr magnetron” (i.e., the magnetic moment, $\mu_B$, of the lowest orbital in hydrogen) is always $\frac{1}{2}$, with the intrinsic spin magnetic moment of the electrons in an atom $\sim 2\mu_B$. The magnetic field produced by the Bohr magnetron, however, is $B = \mu_0 \mu_B = 2\pi\alpha^2$. So, although in atomic units the value of the dipole moment itself is not dependent on $\alpha$ (at least in the non-relativistic case) the magnetic field produced by the same dipole moment is dependent on $\alpha$. Thus, for instance, a two-fold decrease in $\alpha$ would produce around a fourfold decrease in the magnetic field produced by an atom, which in turn would cause a decrease in the magnetic fields of permanent magnets (which results primarily from the intrinsic spin of the electrons in the atoms composing the magnet).

The above dependence of $B$ on $\alpha$ means that smaller values of $\alpha$ would have made it more difficult and expensive to transform electricity from one voltage to another, which is accomplished by AC electric transformers. A transformer in an electric shaver, for instance, changes the 120/240 AC current coming out of the wall socket into a much lower voltage – such as 3 volts AC – which in turn changed into a DC voltage. Other large transformers are used to change the voltage coming out of generating stations to the very high voltage (often over 100,000 volts) transmitted over high tension wires and then back again to the relatively low voltage used for standard household applications.

Although since the beginning it has been possible to convert voltages using DC converters, historically they were much less efficient and versatile than AC transformers. It is the ease with which AC can be converted from one voltage to another that AC quickly won out in the 1920s over DC for most residential and industrial applications. Because of the development of efficient and cost effective DC converters, efficient AC transformers are not as critical as they once were. Nonetheless, without efficient AC transformers, the technological development of the western world would have been substantially hampered. Further, it is more

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5 More exactly, it is $-g_s\mu_B$, where $g_s = 2$ without very small corrections arising from quantum field theory.
optimal for technology to be able to have both kinds of converters, since each is suited for different applications. As I will now show, a relatively small decrease in \( \alpha \) would have made such transformers far less efficient, if not ineffective for everyday applications.

Transformers consist of a primary coil and a secondary coil. (See Fig. ____ below). Electricity going through the primary coil produces a magnetic field which in turn induces a voltage in the secondary coil. The ratio of voltage, \( V_p \), going through the primary coil to that of the secondary coil, \( V_s \), is the ratio of the number of turns, \( N_p \), in the primary coil to that in the secondary coil, \( N_s \): that is, \( V_p/N_s = N_p/N_s \). The induced voltage is given by Faraday’s law of induction,

\[
(6.6) \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

Since as measured in atomic units, \( B \propto \alpha^2 \) for a given current going through a wire, it follows that \( -\frac{\partial B}{\partial t} \propto \alpha^2 \) if the rate of change of the current remains the same. Hence, Eq. (6.6) implies that the induced voltage will be \( \propto \) to \( \alpha^2 \) for the same rate of change of current.

If a transformer is just sitting idle, as the voltage increases in one direction, current increases in the primary coil producing an increasing magnetic field; the increasing magnetic field in turn induces a counter electromotive force (EMF) against the applied voltage. Because of this counter EMF, energy is expended to create the magnetic field, which is stored in the field itself. The greater the increase in the magnetic field, the stronger the counter EMF will be. Further, the more windings the primary coil has, the stronger will be its magnetic field. The more windings the primary coil has, however, the more distance the current has to travel, and hence the more is lost to resistance. So, there is an efficiency tradeoff between the number of windings and the strength of the magnetic field produced. This is why all transformers have cores made of ferromagnetic substances: the dipoles in these substances amplify the magnetic field produced by the coil a factor of around 1000. This reduces the number of windings needed in the primary coil to produce a sufficient magnetic field.

Now consider decreasing \( \alpha \) by a factor of 2 while keeping the frequency of the AC current the same. (We will address changing the frequency below.) In order for the coil to produce the same magnetic field, four times as many windings would be needed (since \( B \propto \alpha^2 \)). Further, the amplification effect of the ferromagnetic substance would decrease, since each magnetic dipole would be weaker. So, for a given applied magnetic field, to produce the same amplification would require a core that had twice the number of dipoles lined up in the same direction. Further, magnetic cores suffer from what is called core saturation since there are only a finite number of dipoles that can line up. When a large enough proportion of the dipoles have already lined up with the magnetic field, a situation occurs in which further increases in the magnetic field produced by the windings do not result in proportionate increases in the magnetic field going through the core. Core saturation is a major problem in producing efficient transformers since when it occurs, it introduces considerable loss of power. In this lower \( \alpha \) world, the core would have to have four times the cross-sectional area – and thus be four times as large – to prevent core saturation for the same uses of the transformer.

In addition to all this, the loss due to what is called hysteresis -- one of the major losses in transformers -- would be four times as large. This loss occurs when the constantly varying magnetic field causes the magnetic dipoles first to line up in one direction and then in the
opposite direction. This movement of the dipoles back and forth creates molecular friction, which in turn causes energy loss through heat. (Alternating Current Fundamentals, Stephen L. Herman, p. 73). Since more domains would have to move back and forth to create the same magnetic field in the lower \( \alpha \) world, these losses will increase.

Figure 3. From wiki on transformer. See copyright notice.

It is important to stress here that the electric resistance of a wire should not change significantly with a decrease in \( \alpha \). The reason is that the normal resistance of a metal conductor is mostly caused by its free electrons randomly colliding with atomic nuclei and other electrons. This, however, does not involve the magnetic field, since such interactions are determined by the forces between atoms and electrons, which in turn is determined by the non-relativistic Schrödinger equation for most metals (except ones with atomic numbers higher than 71 -- see section above) Except for an insignificant effect of the magnetic field (discussed in section above), the non-relativistic Schrödinger equation is not dependent on \( \alpha \). The same applies to the hysteresis loss due to molecular friction – this should remain the same per dipole.

Could a civilization in this lower \( \alpha \) world compensate for these increased power losses by redesigning transformers? Because transformers can result in substantial losses, scientists have already explored ways of redesigning transformers to reduce losses to resistance and hysteresis. A major way of reducing losses connected with the electrical resistance of the coils is to increase the frequency of the alternating current. The induced voltage (and counter EMF) is proportional to the rate of change of the magnetic field, and this is proportional to the frequency. So, even though the same number of windings in a lower \( \alpha \) world would decrease by a factor of four the magnetic field, one could retain the same amount of inductance by increasing by a factor of four the frequency of the electricity going through the transformer. This, however, would not reduce the loss due to hysteresis. Even though the total magnetic field going through the core would be one fourth as much – thus requiring the same number of dipoles to switch back and forth as in our world – they would be moving back and forth four times as often. Thus, one would still

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\(^6\) As Harold Aspden explains, “The reason for this [hysteresis loss] is that the iron contains domain regions separated by domain boundary walls. As the walls move they increase the size of one domain and reduce the size of the adjacent domain. These domains are fully magnetized in opposite directions and all we see as net flux in the magnetic core is the difference in the flux contribution of all the domains. However, in the passage of those domain walls across inclusions (impurities) in the iron and in the flipping of the flux direction that occurs as the domains adjust to the change of magnetizing conditions, there are instabilities which we can detect as 'Barkhausen' noise. These are the source of hysteresis loss. The loss is a linear function of the number of cycles of magnetization and not a function of how fast we increase the magnetizing current.” (“The Eddy Current Loss Anomaly” Copyright © 1998 Harold Aspden [http://www.aetherscience.org/www-energyscience-org-uk/le/le18.htm](http://www.aetherscience.org/www-energyscience-org-uk/le/le18.htm). [http://www.aetherscience.org/www-energyscience-org-uk/le/le18.htm](http://www.aetherscience.org/www-energyscience-org-uk/le/le18.htm).
expect four times the loss per dipole (see footnote 6). Further, since what is known as 

*capacitance loss* is proportional to the frequency and would not be affected by decreasing $\alpha$ (since it does not involve magnetic effects), this loss would increase in power transmission lines as a result of using a higher frequency, with the losses due to the currents induced by the magnetic field of the wire being the same as in our world. The only other major method of reducing losses is to produce a magnetic core with a higher amplification coefficient or with less hysteresis. In our world, however, such cores are already produced as much as economically feasible for a given application, and thus no real compensation could be accomplished that way.

There is one area in which a lower $\alpha$ could perhaps lead to a significant decrease in energy losses in delivering electricity, namely those losses in electric power transmission resulting from magnetic coupling between wires and eddy losses due to the magnetic field produced by current flowing through the lines. Both of these losses are relatively small, however. As ____ states, “The primary source of losses incurred in a transmission system is in the resistance of the conductors . . . It directly follows that the losses due to the line resistance can be substantially lowered by raising the transmission voltage level, but there is a limit at which the cost of the transformers and insulators will exceed the savings.” (Benedict, et. al., 1992, p. 12, reference [76]) As implied in the above quotation, the cost of transformers is a major limiting factor in decreasing power loss due to electrical resistance.

Using the above analysis, we can estimate that for a decrease in $\alpha$, the efficiency of transformers decreases approximately with the inverse square of $\alpha$.

$$\text{Efficiency of electric transformers} \propto (\alpha_0/\alpha)^2$$

(6.7)

As can be seen by the fact that when a laptop computer is charging, the transformer gets warm if not hot, there is a substantial loss of power in the transformer. Estimates put this loss at around 5% even for the best transformers. (Research assistant: check on this.) Although some of this loss is due to eddy currents, the majority is due to hysteresis. (Research Assistant: check on.) If even 2.5% were a result of hysteresis, a mere five-fold decrease in $\alpha$ would make transformer loss over 50%, which would clearly be unacceptable. It should be noted, however, that the above analysis only applies to AC transformers. There are DC to DC transformers, but these are only now starting to become cost effective.

A decrease in $\alpha$ would also affect the efficiency of electric generators and motors. In the case of generators, it would require that they either spin faster or have more windings to produce the same voltage, both which would tend to decrease efficiency. Although there are electrostatic motors, they are impractical except for certain specialized situations; consequently, almost all electric motors rely on the mutual attraction and repulsion of two or more magnetic fields, at least one of which is produced by an electromagnetic with the other a result of a permanent or electromagnet. This mutual attraction and repulsion produces a torque that causes the motor to turn. Consequently, with a lower $\alpha$, to produce the same torque would require either more permanent magnets or more windings of the electromagnet, or both. Already, electric motors have a large number of windings to produce the required magnetic field, as can be seen by looking inside any motor. Because of the number of windings, one of the major power losses is heating due to electrical resistance. Those motors that use ferromagnetic cores through which the magnetic field varies also encounter significant hysteresis loss. Since these losses are significant,

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7 Capacitance losses become significant when power lines are longer than 100km (60mi). See [http://www.tup.tsinghua.edu.cn/Resource/tsyz/030533-01.pdf](http://www.tup.tsinghua.edu.cn/Resource/tsyz/030533-01.pdf) [Research assistant: find better source.]
motors are already optimized to minimize the some combination of cost and losses. Consequently, it is unlikely that new motor designs could do much to offset the losses associated with a decrease in $\alpha$. A decrease in $\alpha$, therefore, would increase the size, cost, and power losses of such motors in an amount approximately proportional to $(1/\alpha)^2$.

Finally, a decrease in $\alpha$ would also have had detrimental effects on navigation via a compass and paleomagnetic dating. With regard to the compass, the force that a planet’s magnetic field exerts on a compass is the product of the magnetic dipole moment of the compass and the strength of the planet’s magnetic field. Since by relations (6.5) and (6.6) they both are $\propto \alpha^2$ (holding the amount and configuration of currents in the planet constant), it follows that the force is $\propto \alpha^4$. Thus, for instance, a two-fold decrease in $\alpha$ results in a sixteen-fold decrease in the force exerted on a compass. Thus, a decrease in $\alpha$ would have a disproportionate effect on the usability of a compass. As noted in chapter ____, however, the compass allowed for a vast in increase in communication and the flow of goods between cultures, thus making conditions more optimal for the development of technologically advanced civilizations. Further, since the magnetic field of the earth is maintained via by the earth’s magnetic field inducing electric currents in the layers of the core as they undergo convective movement (via the dynamo effect), it is unclear whether a magnetic field could be sustained with a significant decrease in $\alpha$.

With regard to paleomagnetic dating, periodically (around ___ years [research assistant: look up]), the earth’s magnetic field reverses direction, with magnetic north and south switching places. Although not completely regular, once it is determined through some other dating method at one location on earth when these reversals happen, one can then use the magnetization induced by the earth’s magnetic field in newly formed lava as it falls below the Curie point to determine the approximate age of a material. This is the basis of what is called paleomagnetic and archaeomagnetic dating. Since, holding the strength of configuration of electric currents in a planet constant, the force exerted by magnetic field on any given dipole is $\propto \alpha^4$, the ability of the earth’s magnetic field to magnetize the newly formed lava or other material would decrease very rapidly with a decrease in $\alpha$ – e.g., there would be an 81-fold decrease in force with a three-fold decrease in $\alpha$. Thus, a small decrease in $\alpha$ would likely render most paleomagnetic and archaeomagnetic dating impossible. Yet, paleomagnetic dating has played a crucial role in the earth sciences, the most important of which was providing crucial support for continental drift theory, a key theory in our understanding of earth’s history. By using ships to drag a magnetometer over the ocean floor between South America and Africa, scientists were able to determine when the lava at the bottom of the ocean was formed and thus establish the hypothesis of sea-floor spreading, and hence that South America and Africa were moving apart. If $\alpha$ were too small for the earth’s magnetic field to leave a significant magnetic signature in the newly formed lava, it would have been practically impossible to date the time at which each part of the ocean floor was formed. Paleomagnetic dating has also allowed scientists to determine the positions of the earth’s continents millions and hundreds of millions of years ago, since the orientation of the magnetic field changes with the distance one is from the magnetic poles. [Reference, Kastings, ____]. It is hard to see any other method of doing this.

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8 For a historical survey, see Frankel, 2012.
9 Radioactive dating would have been almost impossible to use. For example, the major methods of dating lava flows are potassium-argon dating and rubidium-strontium dating. Potassium-argon would not work because it does not work for lava under the oceans because the argon cannot outgas under the ocean, which is required for an accurate date; Rubidium-Strontium dating requires high temperatures and does not work below around 10 million years.
Above I have listed several major disadvantages resulting from a decrease in the magnetic field produced by a current when \( \alpha \) is decreased. Is there any significant positive effects? One advantage would be decreased skin effect where due to the effects of magnetic induction, the current is forced to flow closer and closer to the surface of a conductor as the frequency of the current increases; this in turn increases resistance. This effect, however, has been overcome even into the gigahertz range. Another potential advantage is the light would travel faster in atomic units, and advantage that might become significant for exploration of other bodies in our solar system by means of space craft. These advantages, however, seem relatively minor compared to the disadvantages listed above— for example, the negative technology effects involving transformers, electric generators, and electric motors are at the base of the technological ladder, and are hence, everything else being equal, they are more important. Further, they are probably offset by other disadvantages— for example, the wavelength of electromagnetic waves is proportional to the speed of light. At present, the wavelength of a 900 MHz device— such as a typical cell phone— is one third of a meter. The optimum size of an antenna is \( \frac{1}{4} \) a wavelength (or an integral multiple of that). Thus, an optimum antenna for such a cell phone is about 8.3 centimeters, or about 3 inches; the shorter an antenna is from this optimum length, the less well it will be able to pick up a transmission. Consequently, as \( \alpha \) is decreased, for the same frequency the size of an antenna would have proportionality to increase to pick up a signal as well.\(^\text{10}\)

4.5 Microscopes and \( \alpha \)

Any decrease in \( \alpha \) will decrease the resolving power of a light microscope by a factor of \( \frac{\alpha}{\alpha_0} \). The reason goes as follows. Visible light can be defined as that region of the electromagnetic spectrum in which the photons have enough energy to power some type of photosynthesis (whether the kind in this world or some other kind) while at the same time not being so energetic as to destroy the organic compounds necessary for carbon-based life. Since in atomic units, for any decrease in \( \alpha \), biochemistry remains the same, the energy required to drive a particular photosynthetic reaction or break a given biochemical bond (such as the carbon-carbon bond) remains the same in these units. What does change, however, is the wavelength, \( \lambda \), of the visible light: since the energy, \( E \), of a photon is related to the frequency, \( f \), via Planck’s relation \( E = hf \), and the \( \lambda \) is related to the frequency by \( c = \lambda f \), it follows that \( \lambda = hc/E \). Since \( c = 1/\alpha \) and \( h = h/2\pi = 1 \), it follows that \( \lambda = 1/(E\alpha) \). Hence, since as \( \alpha \) is decreased, \( E \) must fall into the same narrow range of values to constitute visible light, it follows that the wavelength of each part of the visible spectrum must increase in proportion to \( \alpha \).

The maximum resolving power of a light microscope, however, is about one-half the wavelength of the light being used. For example, with the best light microscopes, light of .50\( \mu \text{m} \) (green light) can resolve images of down to .260\( \mu \text{m} \); and light of .380\( \mu \text{m} \) (the shortest wavelength that the human eye can see) can resolve images of down to .190\( \mu \text{m} \).\(^\text{11}\) This constitutes the maximum resolution of a conventional light microscope. The size of the average

\(^\text{10}\) Using a higher frequencies will run into other problems, as the atmospheric absorption increases very rapidly beyond around 10Ghz.
\(^\text{11}\) See table 2, from reference [24].
animal cell is 10μm, with many cells being less than 5μm in size. Bacteria range in size from ~0.2μm to ~2μm, the lower range coincidentally being right around the maximum resolving power of a light microscope. For example, the width of diphtheria bacteria can be as small as 0.25μm. As is, conventional light microscopes are capable of resolving all cells; if α were any smaller, however, certain bacteria would not be resolvable with a conventional light microscope, though recently Putten, et al. have claimed to have invented a multiple scattering lens that can resolve objects to 0.1μm.

Further, because in atomic units the size and chemistry of the atoms in biochemical compounds remains the same, the range of cell sizes would not change. Consequently, given we are typical ECAs, if α were any smaller, the light microscope could no longer resolve all living cells for typical ECAs. Although changing α would not affect the resolving power of electron microscopes, electron microscopes are far more expensive. Further, electron microscopes cannot be used to see living cells since, among other reasons, samples have to be placed in a vacuum since air scatters electrons. Thus, it is quite amazing that the resolving power of light microscopes goes down to that of the smallest cell (0.2 microns), but no further. If it had less resolving power, these cells could not be observed alive.

4.6 Wood Fires and α

4.6.1A Introduction

[PR#F, Ipad edited.]

Below I will show that increasing α by as little as 10% would make wood burning much more difficult, and by as little as 40% would have made it far more difficult, if not impossible, for ECAs to have harnessed fire. Without being able to burn wood, for any planet with ECAs, it is very unlikely that the ECAs on that planet would have been able to forge metals, something that is crucial for the development of science, technology, and even many aspects of civilization. As we will see, the argument below applies to other forms of biomass, such as peat, that have heat release rates from combustion that are not substantially higher than wood. Although primitive peoples could have fires with biomass that had a substantially higher heat release rate –

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12 For example, according to Robert Blystone, 2004: “Mammalian erythrocytes are generally round with diameters varying from as little as 2.1 μm to as much as 10.8 μm.” (p. 13). (Reference [25]).
15 Further, if light microscopes had significantly less resolving power, conditions would be far less optimal for discovering the nature of this realm, and hence for developing electron microscopes. For example, historically, observations of Brownian motion -- the slight random movements of tiny particles suspended in a liquid -- helped lend support to the atomic hypothesis. Light microscopes also provide an important means of checking the accuracy of electron microscopes: in the realm in which they overlap.
such as oil or pine resin -- in a world with a substantially increased value of $\alpha$, we know from our world that these are nearly as readily available to primitive peoples; thus, it is very unlikely that they would be for typical carbon-based ECAs on other habitable planets. Thus, it could not serve as an adequate substitute; at the very least, if oil or pine resin were the only substitutes, it would have been far less likely for typical carbon-based ECAs to learn to smelt and forge metals. And other than biomass or its products (such as coal), there is no other readily available fuel that is in plentiful supply.

The basic reasoning behind the above claim about open wood fires is straightforward. First, as was shown in section 1.3, up to around a 9-fold increase in $\alpha$ would not substantially affect the chemistry (and hence the heat release rate at a given temperature as measured in atomic units) of the atoms composing wood – namely, oxygen, carbon, and hydrogen. Yet, an increase in $\alpha$ would cause an increase in the amount of heat energy lost to radiation as wood burns. This occurs because a burning wood surface quickly becomes charred, and thus it becomes nearly a blackbody emitter, with an emissivity of ~95% . This means that the radiation coming from the surface is about 95% of what it would be at that temperature if it were a perfect blackbody emitter. (A 5cm wide flame has at most an emissivity ~6%, so once the wood surface producing the flame is heated to a sufficiently high temperature, it will be the primary source of radiation.) Since in atomic units the radiant heat lost by a blackbody source is proportional to $\alpha^2$ (see next subsection), increasing $\alpha$ would increase the radiant heat loss. Because for moderate increases in $\alpha$ the heat release rate of combustion remains the same -- along with the rate of heat loss through smoke and convection -- an increase in radiant heat loss would cause the temperature of the burning wood surface to go down. This would in turn cause the rate of combustion to decrease, thereby further decreasing the temperature. If $\alpha$ were increased too much the rate of radiant heat loss would become so great that the temperature of the wood would fall below the combustion point and the fire would go out.

4.6.1 Quantitative Treatment

To provide a quantitative treatment of the upper limits on $\alpha$ for burning wood in an open fire, we must first consider the physics of wood burning. As the surface of a piece of wood is heated, the material on the surface begins to vaporize, releasing hydrocarbons into the air. For some kinds of wood, this vaporization process can begin at a temperature as low as 523 K (250 °C). If the piece of wood continues to be heated, at some point it will spontaneously ignite. This is called the auto-combustion temperature of wood, and is generally agreed to be about 873 K (600 °C) if the wood is heated by a radiant energy source. It is thus the temperature at which a significant proportion of the hydrocarbon molecules released by the wood and the oxygen molecules in the air have enough kinetic energy to overcome the repulsive forces between them and combine together, thereby releasing energy. The auto-combustion temperature is different from the so-

---

17 Rabash, et al., 2004, pp. 96 – 97, reference [63].
18 Department of Agriculture, 2007, page 17-6, reference [6]. We also could calculate it must be something like this in order for fires to glow red by the blackbody radiation law, which says that . . . ]
called “piloted ignition” temperature, defined as the temperature a surface of wood must have in order for a spark, a match, or some other device to ignite the wood. The latter corresponds to the temperature a surface of wood must have to release enough hydrocarbon vapors to be ignited by a spark or flame. Once the vapors are ignited, a combustion zone with a temperature of 873 K or higher forms above the wood surface. These combusting vapors continue heating the wood surface, thereby causing the release of more vapors and hence maintaining combustion.

Next we must consider the rate, \( Q_{\text{rad}} \), at which radiant energy is emitted by a wood fire. According to the Stefan-Boltzmann law of blackbody radiation, the rate that energy is emitted by a blackbody per unit area at temperature \( T \) is given by

\[
Q_{\text{rad}} = \sigma T^4 \tag{6.8}
\]

where \( \sigma \) is the Stefan-Boltzmann constant; \( \sigma \) is determined by the other constants of physics according to the equation

\[
\sigma = \frac{2\pi^5k^4}{15h^3c^2} \tag{6.9}
\]

Since in atomic units \( k = 1 \), \( h = 2\pi \), and \( c = 1/\alpha \), it follows that

\[
\sigma = \left( \frac{2}{15}\right)\pi^7\alpha^2 \tag{6.10}
\]

Thus,

\[
\sigma \propto \alpha^2 \tag{6.11}
\]

Since all figures I will be citing from the literature are in the SI system of joules, meters, seconds, and kelvin (or degrees centigrade), I will use these units with the appropriate conversion factors between them and atomic units. This can only be done with the proviso that when \( \alpha \neq \alpha_0 \), these “atomic-SI units” are defined by the same conversion factors as discussed in chapter 1, section 4, where we discussed atomic units. Using these atomic-SI units, all the above equations remain the same except that the appropriate conversion factors must be included. For example, including the appropriate conversion factor in Eq. (6.10), it follows that in atomic-SI units

\[
\sigma = 5.670373(21) \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4}(\alpha/\alpha_0)^2 \tag{6.12}
\]

All surfaces and gases are less than perfect blackbody emitters, and thus one must also factor in the emissivity, \( \varepsilon \), of the surface or gas to obtain the total radiant energy emitted:

\[
Q_{\text{rad}} = \varepsilon\sigma T^4 \propto \varepsilon \alpha^2 T^4 \tag{6.13}
\]

For a charred surface of wood, \( \varepsilon \) is around 0.95. It is much less for a flame. A typical 2.5 cm (1 inch) width flame on a wood surface will have an emissivity of between 1.5% – 3.5%, with a 5 cm flame being approximately 3% - 6%. (Rabash, et al., 2004, pp. 96 – 97, reference [63]). Most of this emissivity is due to the heated soot in the flame, since the gas itself has a much lower emissivity. If, for example, the surface were at the same temperature as a 2.5 cm wide flame, it would emit around 20 times as much heat radiation (it is 20 instead of 40 because the

flame emits in two directions whereas the wood surface only emits in one direction.) This means that the flame would have to around twice as hot, on the Kelvin scale, than the surface of the wood to emit the same amount of radiant energy. If, for instance, the wood surface were 800 K, the flame would have to be 1,600 K, far above the maximum temperature a flame can reach in typical circumstances. (See below). In typical open-pit wood fires, therefore, most of the radiant heat loss will be due to the heating of the surface of the wood, not the flame.

Since in order to stay hot the wood surface beneath the combustion zone must be continually heated by the flame, its temperature, $T_s$, will always be less than that of the flame. This means that the temperature, $T_{smoke}$, of the smoke leaving the combustion zone must be greater than the temperature of combustion, 823 K, or $T_s$, whichever is larger. Further, since the combustion zone is over the burning wood surface, only the hot gas in this zone can heat the wood. This means that all the smoke leaving the combustion zone is unavailable to heat the wood surface and thus cannot contribute to the radiant energy loss of the wood surface.

Next, it is important to calculate the minimum rate of energy loss via the smoke leaving the combustion zone. This will allow us to determine the maximum energy of combustion left over for heat radiation. To do this, note that the theoretical maximum adiabatic flame temperature is 2060 K without using pre-heated air or highly oxygenated air. This maximum temperature will be reached when both the hydrocarbons released by the wood combine with the minimum quantity of air required to fully burn the hydrocarbons and there is no heat lost via radiation or some other means. It is calculated by taking the maximum energy released by combustion and assuming all the released energy goes into the air needed for the combustion and the combustion byproducts.

The actual maximum diffusion flame temperature of an open air fire is much less than this, often listed to be around 1300 K. (Schmidt and Symes, 2008, p. 4, reference [8]). This maximum flame temperature will be reached when the heat loss due to radiation is minimized. The primary reason it is less than the theoretical maximum adiabatic flame temperature of 2060 K is a result of two factors: (1) lack of sufficient air at the wood surface for complete combustion to occur; and (2), the air next to the combustion zone almost immediately mixing with the combusting hydrocarbons, causing them to cool. As Randall Noon notes,

Wood usually burns in an air starved condition, because the size of the wood pieces limits the access of air to the reaction which occurs on the surface of the wood . . . . while the reaction itself is air-starved, there is a lot of air near the reaction which soaks up a significant portion of the combustion heat and carries it away without being directly involved in the reaction. (Noon, p. 68).

This implies that

. . . the flame temperature is reduced due to lack of air being able to get to the combustion site, and the flame temperature is also reduced because of excess air which ‘steals’ some of the available combustion energy. Thus, a typical flame temperature of wood in open air burning is often in the range of 550 °C to 900 °C [823 K to 1173 K] As a general rule, the more smoke that is produced in a wood fire, the ‘colder’ the flame temperature of burning.” (Noon, p. 68)


16
An example of fire with a maximal flame temperature and virtually no radiant heat loss is shown in Figure 1. In this fire, the wood was heated from below by flames, causing the wood to release hydrocarbons which then combust above it. A figure of 1300 K is listed for such a fire 0.3 – 0.5 meters above the wood surface and for flame thicknesses of 0.15 meters to 2 meters. (Rabash, et al., 2004, pp. 96 – 97, reference [63]). Since this is the maximum temperature in the center of the flame where there is virtually no radiant heat loss, 1300 K can be reasonably considered the temperature that would be reached under the conditions of no radiant heat loss, whether that loss is direct or indirect (e.g., via heating the wood surface and then being radiated to the surrounding environment from the wood surface). For such a fire, almost all of the energy released by combustion will go into heating the combustion byproducts and the excess air (with a minor amount going to vaporize the hydrocarbons on the wood surface). Since this was at ambient temperature (~300 K), this implies that all the energy of combustion is used up in heating the air and combustion byproducts by 1000 K, and hence that it takes 1/1000 of the heat released by combustion to heat the excess air and combustion byproducts by 1 K.

Now suppose that the same degree of combustion and mixing with excess air occurs in a less than ideal fire, one in which there is radiant energy loss, thus resulting in the flame exiting the combustion zone being less than 1300 K. Thus, assuming that the specific heat of the air and combustion byproducts remains approximately the same over the temperature range under consideration, the fraction of total energy left for radiative heat loss would be (1300 K – $T_{\text{smoke}}$)/1000. For example, if $T_{\text{smoke}}$ were 800 K, then the temperature of the combustion products and excess air would have only increased by 500 K (from a room temperature of 300 K) instead of the maximum of 1000 K. Consequently, only half the energy of combustion would have gone to increasing the temperature of the combustion products and excess air, leaving the other half for radiation: (1300 –800)/1000 = 0.5. Since the flame also radiates some energy away from the fire, the amount of energy left for transference to the wood surface is less than this figure. Thus, in order the temperature of the wood surface not to fall,

\[ Q_{\text{rads}} < Q_{\text{comb}} \frac{(1300 - T_{\text{smoke}})}{1000} \]  

(6.14)

where $Q_{\text{rads}}$ is the rate of heat lost via radiation from the wood surface and $Q_{\text{comb}}$ is the rate of energy released by combustion per unit surface area. Defining $F = \frac{1000}{1300 - T_{\text{smoke}}}$ the above inequality becomes:

\[ Q_{\text{comb}} > Q_{\text{rads}} F \Rightarrow Q_{\text{comb(min)}} = Q_{\text{rads}} F, \]  

(6.15)

where $Q_{\text{comb(min)}}$ represents the minimum heat release rate of combustion needed for a wood surface to sustain a fire with no input of energy other than that from the combustion of the wood surface. If this inequality is not met, there will be a net loss of energy from the fire, and hence its temperature will fall.
Since $Q_{\text{rad}}$ is given by Eq. (6.13) above (with $\varepsilon = 0.95$), the rate of radiant heat loss from the wood surface is

$$Q_{\text{rad}}(\text{min}) = 0.95 \sigma T_s^4$$

Finally, since in order to undergo combustion, the combustion zone must be at least 873 K, it follows that $T_{\text{smoke}}$ must be at least 873$^0$K when it leaves the combustion zone. This means that $F \geq 2.34$ for $T_{\text{smoke}} = 873$ K. Since the smoke leaving the combustion zone must be hotter than the wood surface (otherwise it could not transport heat to the wood surface), when $T_s > 873$ K, $F > 1000/(1300 - T_s)$ – that is, $F(\text{min}) = 1000/(1300 - T_s)$, where $F(\text{min})$ is the minimum value $F$ can have. Using (6.15) and (6.16), Table 1 lists some values of $Q_{\text{rad}}(\text{min})$, $F(\text{min})$, and $Q_{\text{comb}}(\text{min})$ for six different temperatures of the wood surface.

Table 1. Values of $Q_{\text{rad}}(\text{min})$, $F(\text{min})$, and $Q_{\text{comb}}(\text{min})$ for a self-sustaining fire on a wood surface for a variety of surface temperatures, $T_s$. $T_s$ is listed in both Centigrade and Kelvin and $Q_{\text{rad}}$ and $Q_{\text{comb}}$ are in kW/m$^2$.

<table>
<thead>
<tr>
<th>$T_s \degree C$</th>
<th>$T_s$ K</th>
<th>$Q_{\text{rad}}$</th>
<th>$F(\text{min})$</th>
<th>$Q_{\text{comb}}(\text{min})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>573</td>
<td>5.9</td>
<td>2.34</td>
<td>13.8</td>
</tr>
<tr>
<td>400</td>
<td>673</td>
<td>11.2</td>
<td>2.34</td>
<td>26</td>
</tr>
<tr>
<td>500</td>
<td>773</td>
<td>19.6</td>
<td>2.34</td>
<td>45</td>
</tr>
<tr>
<td>600</td>
<td>873</td>
<td>32</td>
<td>2.34</td>
<td>74</td>
</tr>
<tr>
<td>700</td>
<td>973</td>
<td>49</td>
<td>3.1</td>
<td>153</td>
</tr>
<tr>
<td>750</td>
<td>1023</td>
<td>59</td>
<td>3.6</td>
<td>212</td>
</tr>
<tr>
<td>800</td>
<td>1073</td>
<td>73</td>
<td>4.4</td>
<td>317</td>
</tr>
</tbody>
</table>

Next, we must look at the heat release rates of various woods. The heat release rate of wood is virtually always measured by heating a wood surface using a hot electric coil placed some distance above the wood. The radiant energy striking the wood from the coil heats the
surface, causing it to release hydrocarbon vapors. Typically, the vapor is then ignited using an igniter. The experimenter then tabulates the heat release rates of various woods for different values of the incoming flux from the coil. Because of the difficulties involved, the temperature of the wood surface is usually not measured.

For a wide variety of dried wood, Table 2 below lists the incoming flux from the coil, the temperature of the surface \( T_s \), the estimated radiant heat loss \( Q_{\text{rad}} \), the measured heat release rate \( Q_{\text{comb}} \), and the minimum heat release rate, \( Q_{\text{comb}}(\text{min}) \), with (6.15) being used to calculate \( Q_{\text{comb}}(\text{min}) \). As in Table 1, the units are °C and KW/m². Only the first two values for \( T_s \) in row 1 correspond to measured values. For these two cases, \( Q_{\text{rad}} \) is calculated using the Stefan-Boltzmann radiation law, \( Q_{\text{rad}} = \varepsilon \sigma T_s^4 \). For the values of \( T_s \) and \( Q_{\text{rad}} \) in the other rows, the following analysis was used to estimate these quantities. Since the measured surface temperature is 700 °C for a surface heated by 25KW/m² – due to both the energy from the coil and the burning flame above the surface -- it is reasonable to assume that a surface receiving more than 25 KW/m² flux form a coil would have a higher surface temperature. Except for the two measured values for \( T_s \) and the listed cases in which the incoming flux was 50 KW/m², this assumption was used to estimate the minimum values for \( T_s \) and \( Q_{\text{rad}} \) for cases in which incoming flux was greater than 25 KW/m². For the 50 KW/m² cases, the temperature was estimated to be 750 °C, in between the measured values for 25 KW/m² and 65 KW/m² listed in row 1.

For those cases in which the incoming flux was less than 25 KW/m², \( T_s \) was determined based on the assumption that the flux of blackbody radiation emitted by the surface must be greater than the incoming energy from the coil. The reason for this assumption is that the energy leaving the surface via radiation, convection, and vaporization must be equal to the energy coming in from the coil and the flame above the surface. Assuming that the energy from the flame is greater than the energy lost by convection and vaporization, it follows that the energy leaving via radiation must be greater than that coming in from the coil. This assumption is verified by the measured cases of \( T_s \) in the first row: as shown in the table, the incoming radiant energy from the coil is less than the radiant energy emitted by the burning wooded surface.

Table 2. \( Q_{\text{rad}} \), \( T_s \), and \( Q_{\text{comb}} \) for various woods, along with the minimum value of \( Q_{\text{comb}} \) needed to keep a wood surface burning at the temperature \( T_s \) (designated by \( Q_{\text{comb}}(\text{min}) \) in degrees C). Also, \( Q_{\text{comb}}(\text{min}) \) is listed for \( \alpha = 1.5\alpha_0 \).²¹ (Values are in °C and KW/m²).

<table>
<thead>
<tr>
<th>Wood</th>
<th>Incoming Flux</th>
<th>( T_s )</th>
<th>( Q_{\text{rad}} )</th>
<th>( Q_{\text{comb}}(\text{measured}) )</th>
<th>( Q_{\text{comb}}(\text{min}) )</th>
<th>( Q_{\text{comb}}(\text{min}) ) for ( \alpha = 1.5\alpha_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>25, 65, 50</td>
<td>700, 800, ~750</td>
<td>49, ~73, &gt;59</td>
<td>~100, 130, 120</td>
<td>153, 317, &gt;212</td>
<td>344, 713, 477</td>
</tr>
<tr>
<td>set 2</td>
<td>All 40</td>
<td>All &gt;700</td>
<td>All &gt;49</td>
<td>128, 135, 126, 73, 81</td>
<td>All &gt;153</td>
<td>All &gt;344</td>
</tr>
</tbody>
</table>

²¹ The entries for each type of wood are from the following references. Set 1. The first and third entry in the first row are from [7], Babrauskes, 1990, Fig. 9, p. 351, with the second entry for temperature from Urbas, 1992, Fig. 2, p. 207, reference [4] and the entry for heat release rate from [7], Babrauskes, 1990, Fig. 9, p. 351. Set 2 is from [7], Babrauskes, 1990, Table 2, pp. 367 – 68. Set 3 is from [7], Babrauskes, 1990, Table 3, p. 369. Set 4 is from from [6], Encl. wood, p. 17-7, Table 17-2).
Wood set 1 consists of Douglas Fir; wood set 2 consists of Red Oak, Alder, White Pine, Yellow Popular, Redwood, Sugar Maple in that order; set 3 of Hard Maple [oven dried], Hard Maple [Cond.], Southern Pine [Oven Dried], Southern Pine [Cond.], Red Cedar, Spruce; set 4 of Southern Pine, Redwood, Basswood, Red Oak.

Table 2 shows that for $T_S > 700 \, ^0C$, none of the woods have a high enough combustion rate to maintain a self-sustaining fire on a wood surface without some incoming radiant flux. Further, at lower temperatures, those that occur with a radiant influx of 18KW/m$^2$, the situation is not much better. Of the four woods measured in the reference, only two – Basswood and Red Oak-- have a combustion rate above the minimum listed, and this is only for an incoming flux of 18 KW/m$^2$. And this minimum is likely to be substantially lower than the actual minimum since it was calculated for a wood surface temperature of 500 $^0C$, whereas it is probably significantly higher than that given that a 25 KW/m$^2$ flux produces a measured temperature of 700 $^0C$, as listed in row 1. Even given this minimum, if $\alpha$ were raised by a mere 8%, neither of these could support a self-sustaining fire on an exposed wood surface at the temperatures listed.

What about for lower temperatures? I did not find data for the heat release at lower incoming radiance levels (and hence lower temperatures). However, as various authors have discovered, for a given type of wood, the heat release rates are approximately a linear function of incoming flux for the ranges between 18 KW/m$^2$ and 55KW/m$^2$.\textsuperscript{22} Using the heat release rates for the last four entries in the Table 2 above for an incoming flux of 18 KW/m$^2$ and the linear relation given in Fig. 8, p. 202, Reference 2, the heat release rates for lower temperatures can be extrapolated. These are listed in Table 3:

**Table 3.** Extrapolated Heat Release Rates for Lower Flux Levels

<table>
<thead>
<tr>
<th>Tree Type</th>
<th>Incoming Flux (KW/m$^2$)</th>
<th>$Q_{\text{comb}}$(extrapolated; KW/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Pine, Redwood, Basswood, Red Oak</td>
<td>All 10</td>
<td>30, 30, 40, 30</td>
</tr>
</tbody>
</table>

\textsuperscript{22} Tran and White, 204, reference [5].
at least 20KW/m\(^2\) of incoming flux – 10 KW/m\(^2\) from the coil and at least 10 KW/m\(^2\) from the flame – given that the fire would be self-sustaining at T\(^*\). This means that the total heat radiation from the surface is at the very least slightly less than 20KW/m\(^2\) (since some of the heat energy will go to vaporizing the hydrocarbons). If the heat radiation is 20KW/m\(^2\), then by the calculations listed in Table 1, it follows that the minimal heat release rate for combustion is 45KW/m\(^2\) for self-sustaining combustion for an exposed wood surface, which is greater than the measured values for all the different woods. Since 10 KW/m\(^2\) is the minimal irradiance necessary for ignited combustion of any wood – that is, to produce enough hydrocarbon vapors so the wood can be ignited – Table 3 shows that even at the lowest temperature possible for combustion, self-sustaining wood burning is marginal. So, both of the tables taken together show that self-sustaining fires on an exposed surface are marginal for virtually all woods, regardless of the temperature.

So, one might ask, if it is so marginal, how is wood burning even possible? It is possible because of three major factors that help with wood burning:

1. Typically, the heat release rates for wood initially peak in the first one to two minutes of burning, and then they settle down to a lower rate for a considerable period of time. The reason they peak at the beginning is that char quickly forms on the surface and inhibits the ability of the wood to vaporize and, by making it nearly black, at the same time increases the radiant energy loss. For instance, in the case of Douglas Fir with an incoming flux of 25KW/m\(^2\), the heat release rate peaks at 160KW/m\(^2\) immediately after ignition, then drops to 100KW/m\(^2\) in a minute, reaching a low of 60 KW/m\(^2\) in a minute and a half. After that, it slowly rises, in ten minutes reaching 100 KW/m\(^2\), and then in around 15 minutes peaks at 130 KW/m\(^2\), its average being around 100 KW/m\(^2\). [Reference: Barabas?] The slow increase is due to the heating of the materials further and further inside the wood. The above tables listed the average over the steady state burning period of the wood. Because kindling is too small for a significant char layer to build up to inhibit combustion, it will burn faster, combusting at near its peak until it is burned up.

White, et. al. ( pp. 3-7, [10]) lists the highest peak combustion rates for a large variety of wood in California, Colorado, and the Northeast. For a 25 KW/m\(^2\) heat influx, these are ~325 KW/m\(^2\) for over-dried Utah Juniper, with the highest in California being ~285 KW/m\(^2\) for over-dried Olive. Even assuming that one kept a fire going by constantly dumping kindling every minute using the most flammable wood, the maximum increase in \(\alpha\) would be \((325/153)^{1/2} = 1.46\), or a 46\% increase. After that, the kindling would not work anymore.

(2) Once one starts a fire by taking advantage of the high initial heat release rate and the use of kindling, one can keep the fire going by placing the burning wood surfaces face to face with other burning wood surfaces. Since two or more burning wood surfaces of wood can send radiant energy to each other, this allows a moderate decrease in the net radiant heat flow from the wood surface – perhaps as much as a factor 2. One can only take advantage of this effect after a fire is started, which is why kindling is important. Even with a decrease in radiant heat loss by a factor of 2, that would only allow for a 41\% increase in \(\alpha\) before a self-sustaining fire would be impossible with the woods listed above. But, even a much smaller increase in \(\alpha\) would make wood burning much more difficult – e.g., a fire would not be nearly as practical if one had to keep it going by constantly dumping kindling on it and by needing to use the most flammable wood. Further, the above analysis assumed the best possible practically realizable conditions
discussed above: namely, those pertaining to the wood surface receiving oxygen for full combustion and having a minimal amount of excess air. Since most open fires do not occur under these conditions, the allowable increase in $\alpha$ is likely to be significantly less. So, we can conclude that even small changes in $\alpha$ (e.g., 10% -20%) would make the use of fire much less practical, and thus be far less optimal for the development of civilization.

The necessity of placing wood next to each other to reduce the radiant heat loss for a self-sustaining fire is illustrated by Figure 2 of a typical open campfire. Notice that the only places the fire continues to burn are on surfaces that can receive radiant heat from other burning surfaces (such as the underside of the wood), thus reducing their net radiant heat loss; the wood surfaces at the top of the wood are no longer burning since their radiant heat loss is not reduced in this way.

Figure 2. Open wood fire. The piece of wood on top illustrates that typically wood surfaces that have no incoming radiant flux cannot sustain a flame. The major exception is kindling or when a surface first starts on fire: in those cases the charring that occurs in a few minutes is unable significantly to decrease the ability of the vaporized wood molecules to reach the combustion zone.

Finally, as explored more in ____ below, it should be noted that decreasing $\alpha$ would increase the ability of fires to be self-sustaining, and thus likely increase the chance of forest fires, which would reduce the amount of wood available. This would likely occur for any planet that had forests.\textsuperscript{23} Hence, based on these considerations alone, there is good reason to think that the current value of $\alpha$ is near optimal for the use of wood burning.

4.6.2 A Different Atmosphere?

\textsuperscript{23} [Should footnote be moved?] Though, this would be partially compensated for by the ability of fire to spread by radiant energy, since the burning wood would emit less of its energy in radiant heat and more via convection.
Another issue that must be addressed is that the combustibility of wood dramatically increases with an increase in the proportion of oxygen in the atmosphere. Consequently, a larger value of $\alpha$ could still allow for ECAs to forge metals on planets that have atmospheres with sufficiently high concentrations of oxygen. Before going into an analysis of this argument, it is important to note that oxygen is a byproduct of life; without life, it is very unlikely for a planet to have significant amounts of oxygen in the atmosphere, largely because oxygen is highly reactive with various minerals and thus is continually being depleted from the atmosphere (think of iron rusting). Thus, as astrobiologists Peter Ward and Donald Brownlee note, “prior to the appearance of common stromatolites [the earliest form of life], there was no dissolved oxygen in the sea, no gaseous oxygen in the atmosphere . . .” (Ward and Brownlee, 2004, pp. 95-96, reference [12]). Variability in atmospheric oxygen, therefore, is largely due to a balance between the production of oxygen by plants and the depletion by other processes. Nonetheless, it has been estimated that there has been significant variability in the possible level of oxygen in the atmosphere. For example, Wald and Brownlee note that it has been estimated that the level of oxygen was as high as 35% by volume around 400 to 500 million years ago, whereas currently it is 21% (Ward and Brownlee, 2004, pp. 188, reference [12]). Given that this variability is limited to something near Earth’s maximum, however, at most considerations regarding the variability of oxygen can slightly raise the maximum value for $\alpha$ that would allow for open wood fires.

Further, although increasing the content of oxygen would increase the rate of combustion and thus compensate for an increase in $\alpha$, a significant increase in $\alpha$ (e.g., by a factor of two) would make the universe less optimal for using wood to forge metals for the same reasons cited previously with regard to increasing the combustibility of wood. In particular, there would be far more forest fires and wood fires would need to be constantly replenished. One reason for this is that to compensate for a twofold increase in $\alpha$, the combustibility of wood would have to be around four times as large. This would make forest fires much more likely to spread and to spread far more rapidly – for at least three reasons: a significantly higher temperature of the fire (because of the increased proportion of oxygen), around a fourfold increase in the heat released per volume, and around a fourfold increase in the intensity of radiant energy that could catch nearby trees on fire.

An even more critical effect on forest fires would be a significant increase in the ability of lightening to ignite smoldering fires underneath debris and for the smoldering fire to last and spread. Since smoldering fires within debris are subject to very little radiant heat loss (since the fire is not on the surface of the biomass), the chance of them getting started and their ability to keep burning would not be compensated for by changes in $\alpha$. With regard to such fires, Belcher et al. note that

Smoldering fire is a slow, low-temperature, flameless form of combustion, which is the most persistent type of combustion. Biomass capable of sustaining such fires are trunks, litter, duff, humus, peat, coal seams, and soils with a significant organic fraction. Once ignited, such fires are difficult to extinguish (despite extensive rains or weather changes), can persist for long periods of time (years), and can spread over extensive areas of forest subsurface (2010, p. 22448).

Further, they note that “smoldering fires can be initiated with much weaker ignition

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24For a significant discussion of oxygen through time, see National Research Council, 2006. Reference [47].
sources than flaming fires.” (p. 22448). Using a large area covered by such biomass, they calculate (p. 2250) that with a 24% oxygen level almost 100% of the area would be burned; at our current level of 20.9%, they calculate that about 90% of the area would be burned. A mere 3% increase in the proportion of oxygen in our atmosphere, therefore, would dramatically increase the rate and extent of forest fires. They conclude that “If past O₂ levels were higher than the present levels, then vegetation biomass ought to have been drastically reduced by increased fire frequency.” (p. 22448).

[Explain why this is the case here; also, note that the geological record indicates that during ____era O₂ reached 35% -- this is consistent if world were constantly wet, with forests in dry areas burning down.]

The major caveat regarding their claims is that their data is for peat, which has an above average flammability, and it is for a 15% moisture level. So, higher moisture levels would offset this effect, as would less flammable materials. Higher moisture levels in a forest, however, would also make it proportionally more difficult to ignite and maintain an open fire, offsetting the effect of higher concentrations of oxygen. So, if the negative effect on open fires of a larger value of α is exactly offset by a higher O₂ concentration (with the average moisture content remaining the same), the result will be far more forest fires since smoldering fires are not significantly affected by the increase in radiant heat loss resulting from a larger value of α. If, on the other hand, the moisture content of the geographical region in which forests grow is increased to compensate for the increase in fire hazard, it will decrease the combustibility of the wood used in wood fires, thereby making it far more difficult to start and maintain a wood fire. So a dilemma occurs for worlds with both higher values of α and sufficiently higher O₂ concentrations to allow for open fires: either (1), forest fires are much more common because of an increase in smoldering fires, thereby eliminating the wood needed for open fires; or (2), the moisture content of the geographical region is large enough to keep most of the wood from being consumed by forest fires thereby making it harder than in our world to ignite and maintain an open fire. Specifically with regard to (2), by assumption the negative LTD-optimality effect on open fires of a higher value of α is exactly offset by higher O₂ concentrations for dry wood. It therefore follows that for wet wood, it would not be completely offset, so the imagined higher α world is overall less good for starting and maintaining open wood fires.26

Despite the above disadvantages of higher O₂ concentrations, there might be offsetting advantages of higher oxygen levels. Specifically, wood fires could achieve slightly higher temperatures in open air, thus allowing ECAs to melt some metallic ores without a kiln. At most this would be a slight advantage, however. To see why, consider copper, one of the earliest metals to be smelted. Although open fires can only reach a temperature of ~1300 K in our world, a wood-fired kiln can reach a temperature of ~1700 K, significantly higher than the melting point of copper at 1384 K. Finally, one might think that a slight increase in oxygen level could push the maximum temperature of open fires above the melting point of copper and thus allow it to be forged in open fires, eliminating the need for kilns and charcoal, the latter which took large quantities of wood to produce. Before humans learned how to use coal for smelting metals, however, charcoal and kilns were needed to smelt copper because copper, like other metals, is

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26 There is the possibility that the trees would adopt some means of protecting themselves against fires . . .
27 The reason is that higher temperatures could be achieved in wood fires since for every air molecule used in combustion, there would be fewer air molecules to heat that are not used in combustion.
28 For the former figure, see Minogue, Coll and Sanderson, Robert, 20001, p. 11, reference [28].
highly reactive with oxygen, making virtually all metallic ores various forms of oxides – e.g., copper oxide. The charcoal acted as a reducing agent that ripped the oxygen molecule away from the copper, thereby forming elemental copper; the kiln, on the other hand, provided the necessary temperature and the oxygen-starved conditions required for the action of the charcoal. Consequently, since the kiln operates under oxygen-starved conditions, having a higher concentration of O₂ in the atmosphere would not raise the temperature reached in the kiln.

This raises another important point as to why it is critical for the ability to forge metals that O₂ levels be such that they do not significantly increase the likelihood of forest fires: a large amount of wood is needed to produce the charcoal needed for smelting, and thus without extensive forests the ability to produce metals on a wide scale would have been greatly reduced. It wasn’t until the 17th century that coal started replacing charcoal and not until the middle of the 19th century that it became a viable alternative, after more than a century of wide-scale practice at smelting metals. (Reference [49]).

The above analysis of smoldering fires assumed that the increase in the availability of oxygen was the result of changing the proportion of oxygen in the atmosphere. Another possibility is that the atmosphere could have the same proportion of oxygen, but be denser. One might expect a denser atmosphere (with the same proportion of oxygen) to increase the combustion rate since for the same volume of air, more oxygen would be available in the combustion zone. The first thing to note is that whether or not this reasoning is correct depends on how an increase in the density of the atmosphere would affect the volume of air that reaches the combustion zone and the amount of excess air near the combustion zone that sucks energy away from the flame. To analyze this more, first note that at a given temperature, the combustion rate is limited by the mount of hydrocarbons that are vaporized from the wood surface. We noted above that open fires have a maximum temperature of ~1300 K. One would expect that in these fires almost all the hydrocarbons are burnt (as would be indicated by very little smoke). In the case in which all the hydrocarbons are burnt, the rate of combustion is at its maximum for the temperature in question since it is the temperature that determines the rate at which hydrocarbons are vaporized. Consequently, a denser atmosphere will not increase the rate of combustion at a given temperature. What it could affect is the amount of energy taken away by convection. There is no reason to think it would decrease this; however: although a proportionality smaller volume of air would be needed to deliver the air for complete combustion of a unit of fuel and hence presumably a proportionality smaller volume of air will take away the energy released, the volume of air will have a proportionality higher heat capacity. In general, therefore, the net effect should be that the same proportion of heat is carried away by the air for combustion and any excess air. So, there is no reason to think that a denser atmosphere would be able to compensate for the negative effect an increase in α would have on the ability of ECAs to start and maintain an open fire.  

Go through again [Perhaps put this at the end; the only thing it does not apply to is a Darwinian explanation.: Finally, even if a different atmosphere would allow for wood-burning at higher values of α, that just relocates the coincidence at a different place: that the atmosphere on earth is such that, given the value of α in our universe, it allowed for open wood fires when humans arrived. In fact, it seems to have allowed for optimal wood burning – if it had a slightly higher density of air, increasing the proportion of oxygen in the air allows for a unit air mass to create more combustion, decreasing the relative amount of heat taken away by heating the combustion byproducts and excess air. Thus, more is left for radiant heat loss.

30 In contrast to increasing the density of air, increasing the proportion of oxygen in the air allows for a unit air mass to create more combustion, decreasing the relative amount of heat taken away by heating the combustion byproducts and excess air. Thus, more is left for radiant heat loss.
higher proportion of oxygen, many more forest fires (apart from some special adaption) and any lower, open wood fires would have been harder to start and maintain. The coincidence is particularly pronounced when one takes into account that a slightly lower value of $\alpha$ would have also been less optimal, since without some sort of special adaption by trees, it would have resulted in more forest fires and thus less availability of wood. See section ___.

4.6.3 A Darwinian Explanation?

[PR#F, Ipad editing done.]

The above argument assumes that the types of wood that evolved in the universe would remain basically the same if $\alpha$ were greater. Against this, one might claim that the combustibility of wood in higher $\alpha$ universes would be different due to natural selection. One way of attempting to spell this out is by first noting that there would be a selective pressure on individual species of trees not to be so combustible that they would easily burn down in a fire; thus, one would expect the heat release rate of most trees to not be far above the minimum required for open wood fires. This, however, would not itself take away the fact that a small increase in $\alpha$ would cause wood fires to no longer be self-sustaining since an increase in $\alpha$ would even further decrease the chance of a forest fire. So, if this were the only selective pressure operating, one would expect most, if not all, ECA-permitting planets in significantly higher $\alpha$ universes to not be conducive to open wood fires. If, however, one also assumed some independent evolutionary advantage of wood being as flammable as possible while at the same time not being so flammable as to endanger its reproductive success, then one could reasonably expect a universe with a moderately larger value of $\alpha$ to evolve wood that is sufficiently more combustible to be usable for self-sustaining open fires.

There are several problems with this line of reasoning. First, it would lead one to expect much more flammable trees in parts of the world where it is far more moist and hence forest fire are rare – such as in rainforests. Rather, just the opposite appears to be the case. The most flammable woods occur in regions that are very dry – e.g., the Utah Juniper and the California Olive, and the Southern Pine listed above are in arid or semi-arid environments. The evolutionary reasons for this have been debated for over fifteen years.31

Second, such an evolutionary explanation would involve another type of fine-tuning – that of the laws of nature being such that the requirements of natural selection for combustion rates of trees happens to match the requirements for ECAs to harness fire. The reason is that the two seem to be conceptually independent. To see this, consider the so-called fire-line: that is, the line demarcating the combustibility such that a tree with a higher combustibility is likely to be destroyed by a forest fire. Although there is a clear evolutionary advantage of a species of tree being below the fire-line, and so no-fine tuning is required for this, there is no clear evolutionary advantage of its being near the fire-line; thus, if we were told that a some other planet evolved trees, and told that $\alpha$ was 1.5 times higher in the universe it was in, we would be surprised to find that wood from the trees on that planet could be used for open wood fires.

Third, higher flammability seems to be mostly associated with higher resin and other chemicals in wood, which are not the main source of heat energy. Cellulose, hemicellulose, and lignin are by far the major constituents of most woods, with resins and other chemicals composing around 3% - 4% of typical wood. Even if in this higher α universe wood would have more resin and other constituents to increase the combustion rate, it seems highly implausible that it would be much more combustible than Utah Juniper, which is already above the current fire line. Yet, one could not create a self-sustaining fire with a wood as combustible as Utah Juniper if there were much beyond a two-fold increase in α.

Fourth, and most importantly, even if combustion rates were increased to compensate for an increase in α, forest fires would be more intense and spread more easily, for two reasons. One reason is that the rate of energy output of the fire and the intensity of its heat radiation – which helps cause nearby trees to ignite – would be correspondingly higher. For example, for any given wood, if α were doubled, the total combustion rate and the rate of radiate heat output would have to be around four times as great. The second reason is that increasing combustibility to compensate for an increase in α would increase the ability of smoldering fires to spread: since smoldering fires do not lose much heat by radiation, the increase in α would not compensate for the increase in combustibility. This would cause a decrease in forests because of forest fires. Perhaps the only exception to this would be if the trees were sparse – as in some desert regions – and hence not much biomass could accumulate for such fires. Such a world would be far less optimal for forging of metals, however, which as noted above took an enormous amount of wood until about a century ago when the use of coal as a replacement for charcoal was perfected. (And even coal required extensive amounts of biomass to be produced in the earth.)

Finally, even if wood fires could get started in higher α worlds, they would not last as long. Suppose, for instance, that α were twice what it is in our world. Then wood fires would output four times the energy, and consequently they would last ¼ the time. This would likely be less optimal for the fires of primitive ECAs because of the need to constantly replenish the wood. It would be sort of like having to have a fire using only small sticks, which is inconvenient because of their higher combustibility and hence the need to constantly replenish them. Or, to compensate for further increases in α – say by a factor of four – wood would have to have a flammability approaching that of gasoline, which would clearly make it much less suitable for controlled fires.

As a final objection, one might wonder whether some alternative substance to wood – call it X -- might have evolved that had a higher combustibility. Substance X would not only run into the same danger of forests of wood in our world being burned down given the combustibility of wood is increased by too much, but given that hydrogen, carbon, oxygen, and nitrogen are the main elements out of which such a substance could be developed, it would likely not be too much different from cellulose. The above considerations show that there are many reasons to reject a Darwinian explanation for why the combination of the combustibility of wood and α are just right for open fires to exist and such that most of the forests do not burn down.

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4.6.5 A Different Value of $\beta$?
Re-Ipad edit.
Because the mass of the electron is always one in atomic units, in these units the ratio of the mass of the electron to the proton, $\beta$, is $1/m_p$, where $m_p$ is the mass of the proton: $m_p = 1/\beta$. Hence, increasing $\beta$ would decrease the mass of all atoms. The combustion rate is roughly proportional to the number of times atoms collide with each other. This in turn is proportional to the velocity, $v$, of the molecules. At a given temperature, each molecule will have the same kinetic energy, $(1/2)mv^2$, regardless of its mass, $m$. Thus $v \propto (1/m)^{1/2}$, with $m$ in turn being proportional to $m_p = 1/\beta$. Consequently, the combustion rate is proportional to $\beta^{1/2}$. An increase in the combustion rate, however, will increase the upper limit on $\alpha$ for having wood fires; this upper limit, therefore, increases with an increase in $\beta$. As shown in chapter ____, however, for reasons largely independent of $\alpha$, a two-fold increase in $\beta$ would certainly be less LTD-optimal, with probably a much smaller increase being less LTD-optimal. Thus, at most one could increase the combustion rate by $\sqrt{2} = 1.41$ by increasing $\beta$ and still retain overall LTD-optimality of the world. Such an increase in combustion rate would only allow a slight further increase in $\alpha$ before wood fires became impossible. Further, a substantial increase in the combustion rate would also substantially increase the intensity of forest fires, and thus likely have an overall negative affect on the ability to use charcoal for forging metals.

4.6.6 A Lower Wood Burning Bound on $\alpha$

If $\alpha$ were much smaller than its current value, another problem would arise: it would be far less likely for a fire to go out, thus making it very likely that a forest would be decimated by fire. As shown in Figure 2, in our world the fire on a burning wood surface that is not facing other burning wood surfaces will go out because too much radiant heat is lost. If $\alpha$ were lowered by ~$\sqrt{2}$, the radiant energy lost would be $1/2$ as much and hence such wood surfaces would continue to burn. Consequently, once a fire got started by a lightning bolt, it would keep burning until the fuel supply was exhausted; by that time it is highly likely to have spread to other wood surfaces. Not only would a substantial loss of forest due to fire make large scale smelting of metals in the past much less feasible, but it would likely drastically decrease the amount of fossil fuels produced by ancient forests and plant life, thereby also making it far less optimal for industrialization to occur.

One worry with regard to the above argument is the possibility that natural selection . . . Could different atmosphere compensate? Could this be explained by natural selection?

4.6.7 Conclusion

[To be filled in.]

4.7. Sunlight Intensity and Increasing $\alpha$
In this section, we will show how significant increases in $\alpha$ would have an overall negative LTD-optimality effect on the climate and the ability of ECAs to be out in the sun. In the next section, we will consider the potential negative LTD-optimality effects of significantly decreasing $\alpha$.

**Basic Argument:**

For a planet to remain at the same average temperature, the total energy being radiated into outer space must be the same as the amount entering via the solar flux. A planet at a temperature $T$ can roughly be modeled as a blackbody radiator, with a certain fraction of the emitted radiation being absorbed by the atmosphere and re-emitted back to the planet. In presenting the basic argument immediately below, we will assume that the fraction of infrared absorbed by the atmosphere remains the same; as we will see below in the subsection “Detailed Calculations,” the fraction actually increases with an increase in $\alpha$, amplifying certain negative LTD-optimality effects that occur when atmospheric absorption is neglected.

Since the amount of blackbody radiation emitted at a temperature $T$ is proportional to $\alpha^2$ (see Eq. (6.11)) it follows that the energy emitted by a planet into outer space is proportional to $\alpha^2$, given that the fraction of infrared absorbed by the atmosphere remains the same. Since to maintain the same average temperature $T$, the average incoming radiation must be the same as that emitted, the intensity of the incoming radiation must be proportional to $\alpha^2$. This means that increasing $\alpha$ will increase the intensity of sunlight. For example, a two-fold increase in $\alpha$ implies that sunlight be four times as intense to maintain the same average temperature. This will make it more difficult for ECAs to move around in the direct sunlight without getting overheated (unless they evolve a special adaption), and it will pose a problem for plants in the sun. It will also make a much larger difference in total solar flux between those regions of a planet that receive more sun and those that do not: for example, between the latitudes above 45° on September 21 and the equatorial regions on the same day on earth. This implies either that the temperature differences will be much larger between these regions or that there will be a much larger exchange of thermal energy between them, the latter implying much higher winds and larger storms. Either effect would make the planet less LTD-optimal.

**Detailed Analysis**

Let $T_{op}$ designate some average temperature for a planet that falls within the optimal temperature range for complex carbon-based ECAs. Since the average temperature of the earth is \sim 288 K, we will pick $T_{op} = 288$ K, though the exact choice of $T_{op}$ does not affect the overall argument. At equilibrium, the average rate, $Q_{in}$, of energy coming into the planet from solar radiation is equal to the average rate, $Q_{out}$, of radiant energy leaving the planet. We will begin our analysis for the case in which the atmosphere is completely transparent to radiation and the planet is a perfect blackbody absorber, and then add additional complexities as we go along. By Eq. (6.13), $Q_{out} \propto \sigma T_{op}^4 \propto \alpha^2 T_{op}^4$. Holding $T_{op}$ constant, it follows that the $Q_{out} \propto \alpha^2$, and hence $Q_{in} \propto \alpha^2$. This means that the intensity of sunlight, $I_{sun}$, is $\propto \alpha^2$.

Next, consider the case in which the atmosphere absorbs some radiation. Although changing $\alpha$ will increase the absorption coefficients of atmospheric gases, we will neglect this for
now. Neglecting the change in absorption, \( Q_{\text{out}} \propto \alpha^2 \), and hence to retain the same average planetary temperature,

\[
I_{\text{sun}} \propto \alpha^2
\]

To see the effect of increasing \( \alpha \) on LTD-optimality, consider the case in which \( \alpha \) is increased by two-fold. In that case, the sunlight would be four times as intense. First, consider the effects this would have on someone working out in the sun. When people work out in the sunlight, the sun heats their skin, either directly or through their clothes. This heat energy is taken away by radiation, conduction, evaporation, and convection, with the last three processes being roughly proportional to the temperature difference between the heated skin or clothes and the surrounding matter it is in contact with. In light of this, consider the effect of increasing \( \alpha \) by two-fold. We know from experience that the energy from sunlight heats our skin by at most 20°C from the typical ambient temperature of 293 K when it is directly exposed to the sun on a clear day with the sun directly overhead. At this temperature, the total blackbody radiation emitted by heated skin would be \( 5.67 \times 10^{-8} \times (293 + 20)^4 \approx 544 \text{ W/m}^2 \). When the sun is directly overhead, the day is clear, and we are at sea level, the intensity of sunlight is \( \sim 1000 \text{ W/m}^2 \). Thus, \( \sim 460 \text{ W/m}^2 \) is taken away by non-radiative processes, such as convection, conduction, and evaporation. If \( \alpha \) were twice as large, then in atomic units sunlight would be four times as intense, yet none of these processes would be significantly changed. This means that 4000 W/m\(^2\) instead of 1000 W/m\(^2\) would strike the skin under the conditions above. Given that the rate of conduction and convection is proportional to the temperature difference between the skin and its environment, and given that the radiant heat loss is proportional to \( T^4 \), it follows that the temperature of the skin would have to be over the boiling point of water (373 K) in order to eliminate the heat input from the sun. If our skin had a low emissivity, say 0.5, the problem would even be worse.\(^{33}\) Since the temperature difference is already near the margin for humans, increasing \( \alpha \) by very much would make the world less LTD-optimal for beings like us without some special adaptions, such as a thicker or more reflective skin. Such adaptions, however, will most likely have a cost, making the world less optimal for such ECAs in terms of agility and the like in other ways.

Similar problems would arise for plants. Leaves exposed to the direct sunlight would also be overheated, perhaps even to the boiling point – if not for this amount of increase in \( \alpha \), certainly for a slightly larger increase in \( \alpha \): for example, a four-fold increase in \( \alpha \) would result in a 16-fold increase in the intensity of sunlight. Plants would have to form some sort of sophisticated adaption in which the areas directly exposed to the sun were dead and dry cellulose (since any water would be evaporated away). But even this would not work. The temperature of the dry cellulose would conduct heat away less efficiently than skin, and so would reach an even higher temperature. Unless it were extremely thick, the heat would be radiated downward to the plants below; with such an overhead cover, air circulation would be severely reduced, causing the area underneath to become near the temperature of the overhead protection. Deserts with water in them would be virtually impossible, as all the water would quickly evaporate.\(^{33}\)

\[\text{For } (373/313)^4 \cdot 544 \text{ W/m}^2 + 460 \text{ W/m}^2 \cdot (373 - 293)/20 = 1097 + 2300 = 3397 \text{ W/m}^2. \text{ Since in atomic units the relevant chemistry does not change with a moderate increase in } \alpha, \text{ the amount of heat loss per degree Kelvin temperature difference should remain the same for } \alpha = 2\alpha_0. \text{ The calculations assume the black skin (with an emissivity of 1). Skin with lower emissivity would not be affected as much.} \]
example, crops as we know them would be impossible; . . . Further, since already on a clear day with the sun overhead photosynthesis is beyond its saturation point. Finally, although the increased intensity could be offset by increased cloudiness, which could both block incoming radiation and block outgoing infrared radiation, as discussed more below, such increased cloudiness would adversely affect astronomy, thus having a negative effect on discoverability.34

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Another effect would be on the temperature difference between the equatorial regions and the northern and southern latitudes. To obtain a quantitative estimate of this effect, I will first estimate the effect of atmospheric circulation on moderating the temperature difference between equatorial regions and other regions of the earth. And to do this, I will consider what the temperature difference on earth between the equator and 45° latitude would be with the current value of α during the equinox if the atmosphere was transparent to infrared radiation, the earth was a perfect blackbody emitter, and there were no atmospheric circulation. Later I will relax these assumptions.35

Let \( I_{eq} \) denote the intensity of sunlight at the equator during the equinox. Then the intensity, \( I_{45} \) received at 45° latitude is \( I_{45} = I_{eq} \sin \theta - 0.70 I_{eq} \). Hence, without any atmospheric circulation, the intensity, \( I_{45} \), of blackbody radiation emitted at 45° would be \( I_{45} = 0.70 I_{eq} \). Since \( I_{45} \propto (T_{eq})^4 \) and \( I_{eq} \propto (T_{eq})^4 \), it follows that \( T_{45}/T_{eq} = (0.70)^{1/4} = 0.91 \). Assuming that \( T_{eq} = 303 \, \text{K} \) (30 °C or 86 °F), \( T_{45} \) would be ~273 K, the freezing point of water. When atmospheric absorption is taken into account, the temperature difference would likely be considerably greater than this, since warmer air can hold much more water vapor which is a strong greenhouse gas, acting to block outgoing radiation while blocking incoming radiation. In fact, the effect of water vapor is thought to amplify differences in temperature due to solar or other kinds of forcing, even though it also will increase lower level clouds which reflect some of the incoming sunlight back into space. According to Andrew Dressler and Steven Sherwood “the water vapor feedback is virtually certain to be strongly positive, with most evidence supporting a magnitude of 1.5 to 2.0 \( \text{W/m}^2/\text{K} \), sufficient to roughly double the warming that would otherwise occur.” (2009, p. 1021, italics mine, ref [68]). Thus, the temperature difference could be as much as 60 °C. Clearly, the temperature difference is not that great on earth. The tilt of the earth complicates the picture, but we can obtain a rough estimate of what it would be for earth if it was not titled by looking at the average of the mean temperature for the two equinoxes, along with the average annual temperature, for cities far inland that are near 45° latitude. For example, in Chicago, IL – latitude 42° – the mean temperature for March 21 is 35°F, whereas for Sept. 21, it is 65°F, yielding an average of 50°F – which is also the annual mean temperature for Chicago. Or consider Paris, France. It has latitude of 49, with a mean March temperature of 11 C and a September temperature of 15 C, or an average of 13 C. Clearly, oceanic and atmospheric circulation of heat contribute an enormous amount to moderating the temperature differences between the latitudes.

If we let \( \Delta T \) represent the difference in temperature between the equator and 45° latitude, the rate of heat energy that must be transported by this circulation, \( Q_{cir} \), is given by the difference in blackbody emissions is given by the Stephen-Boltzmann blackbody radiation law (Eq. (6.13)),

\[ Q_{cir} = \sigma (T_{eq}^4 - T_{45}^4) \]

\( \sigma \) is the Stefan-Boltzmann constant, \( \sigma = 5.67 \times 10^{-8} \, \text{W/m}^2/\text{K}^4 \).

34 Any planet exposed to direct sunlight would also have to have protective layers to keep the leaves from reaching the boiling point and overheating . . . Also, negative effects on eyes.

35 Decide whether to say something about: Another effect would be on the temperature difference between day and night, desert and non-desert, and different latitudes. For the same rotation rate of a planet, the amount of heat lost overnight would be much larger, unless the planet rotated faster; this, however, would increase intensity of storms due to the Coriolis force.
\[ Q_{\text{circ}} = \sigma (T_{\text{eq}} - \Delta T)^4 - \sigma T_{\text{eq}}^4 = \sigma [(T_{\text{eq}} - \Delta T)^4 - T_{\text{eq}}^4] \propto \alpha^2 [(T_{\text{eq}} - \Delta T)^4 - T_{\text{eq}}^4]. \]

As \( \alpha \) gets larger, either \( Q_{\text{circ}} \) must become larger or \( \Delta T \) must decrease, or both. Keeping the rotation rate and size of the planet constant, if the temperature difference is larger, there will be more atmospheric circulation – since this temperature difference is the primary driver of air and ocean circulation. So, one would expect that both \( Q_{\text{circ}} \) and \( \Delta T \) would become larger; larger \( Q_{\text{circ}} \), however, would result in stronger winds and storms. Of itself, both of these would have a negative effect on livability. So, the overall LTD effect would be negative. [Also, the planet would be in danger of runaway glaciation . . .]

Even temperature differences between regions at the same latitude would be severely increased.

**Effect of \( \alpha \) on atmospheric absorption**

Next, we need to add the effect \( \alpha \) on the absorption coefficients of water and other atmospheric gases. Both water and carbon dioxide absorb in the infrared via molecular and vibrational energy states. The primary gases that absorb outgoing radiation are water vapor and carbon dioxide. As shown in chapter ___, section ___, the absorption cross section is proportional to \( \alpha \). Consequently, doubling \( \alpha \) doubles the absorption coefficient, which in turn is equivalent to increasing by two-fold the total quantity of gases in the atmosphere. Since the absorption of carbon dioxide is almost saturated, it will have a very little effect since the rate of increase is logarithmic. Specifically, a two-fold increase in the amount of carbon dioxide is standardly estimated of itself to raise the temperature of the planet by 1 \(^0\)C. (Kastings, p. 40; Ward and Brownlee, 2002, p. 114, reference [75]). In fact, every ten-fold increase in carbon dioxide in the atmosphere is equivalent to increasing the input of solar radiation (\( Q_{\text{in}} \)) by 10%. (Kastings, 2010, Figure 5.2, p. 88). Thus, for instance, a 100-fold increase in carbon dioxide will increase the temperature by 20%. This is why Kastings notes that it would take a 300-fold (\( 10^{3.5} \)) increase in carbon dioxide to pull the earth out of a situation where the earth absorbed 25% less solar radiation due to its being completely covered in ice (2010, p. 87). Thus, the increase in the infrared absorption by \( \text{CO}_2 \) by a doubling of \( \alpha \) should have a negligible effect.\(^{36}\)

The main effect of this increase in the absorption coefficient will be to increase the overall absorption from water vapor at any given locality, which in many localities is not at saturation. This will make the amplification effect of water worse, leading to even greater temperature differences between those areas that are not saturated but have different levels of water vapor in the atmosphere. The amplification effect of water also tends to make the climate less stable: if some climate forcing causes global temperatures increase, the amount of water vapor in the atmosphere increases, absorbing more infrared radiation, causing the temperature to increase further, and vice versa for some factor that causes global temperatures to decrease – such as the Milankovitch cycles that are thought to be partly responsible for ice ages. In fact, in calculations of climate change from the increasing \( \text{CO}_2 \) in the atmosphere as the result of emissions brought about by human activity, the effect of water vapor is typically taken to amplify the effect of \( \text{CO}_2 \) by a factor of three since the heating caused by \( \text{CO}_2 \) is assumed to result

\(^{36}\)The above means that the temperature increase that directly results from an increase in \( \text{CO}_2 \) concentrations is approximately given by the formula \( T = T_0 + 0.1 \left[ \log \left( \frac{C}{C_0} \right) \right] \), where \( T \) is the temperature with a concentration of \( \text{CO}_2 \) of \( C \), \( T_0 \) is earth’s present average temperature, \( C_0 \) is its present concentration of \( \text{CO}_2 \), and \( \log \) is the logarithm base 10. (Additional Reference?) [Put in somewhere: the overall effect of an increase in \( \alpha \) by even tenfold would be to allow only a 10% decrease in the intensity of sunlight.] So,
in a warmer planet and hence more water vapor in the atmosphere; this additional water vapor in turn is thought to cause a further increase in temperature of around two times the original increase.

**Changing Atmospheric Composition**

Finally, we need to consider the possibility of ECAs evolving in an atmosphere that absorbs much more outgoing infrared radiation. To counteract the effect of a two-fold increase in $\alpha$ on the amount of blackbody radiation emitted at $T_{op}$, one would have to increase the atmospheric absorption to such an extent that it only allows about $\frac{1}{4}$ the amount of infrared radiation to leave the planet as in the case of earth. As noted above, to keep the average temperature of a planet at the same temperature, every 10% decrease in $Q_{in}$ requires approximately a ten-fold increase in carbon dioxide. Thus, in order to keep the intensity of visible light the same with an increase in $\alpha$ by a factor of 1.4, the net energy – which corresponds to a doubling of the blackbody energy emitted by a planet – the amount of carbon dioxide would have to increase by a factor of $10^{10}$. Since the current concentration of carbon dioxide is around 330 parts per million, this would require a the partial pressure of carbon dioxide to be three million bars – that is, three million times the current atmospheric pressure of one atmosphere. This is why it is widely acknowledged that unless some other effect kicks in, higher carbon dioxide concentrations in the atmosphere cannot compensate for substantial decreases in the amount of solar energy hitting a planet.

One such additional effect is the possibility of carbon dioxide clouds. Kastings (210, p. 139 and pp. 177 - 178) estimates that at around 4 to 5 bars of atmospheric carbon dioxide, there is the possibility of carbon dioxide clouds forming that could block considerably more infrared radiation. (A bar is equivalent to the pressure of earth’s atmosphere at sea level.) He claims that his calculations indicate that these clouds could sufficiently insulate a planet so that liquid water could still exist even if the planet received only 0.37 of much solar radiation as earth. This would allow $\alpha$ to be increased by a factor of $\sqrt{0.37} = 0.61$ without the solar radiation needing to be greater than that of earth. These clouds would form as a result of CO$_2$ condensing in the very high atmosphere, where the temperature is at CO$_2$’s condensation point. (At 5bars of pressure, the condensation point of CO$_2$ is -56 $^0$C, whereas at 1bar it is -78 $^0$C.)

There is considerable controversy about whether such clouds could effectively insulate the planet. For instance, unless the clouds have just the right sized particles, the amount of incoming energy that they reflect will be greater than the outgoing energy that they block (reference). Further, Anthony Colaprete and Owen B. Toon have computer simulated whether CO$_2$ clouds can effectively heat the atmosphere. According to them, the effect of these clouds is limited because the warming of the atmosphere caused by the clouds causes them to dissipate. As they state in their abstract, in their model

The surface temperature does not rise above the freezing point of liquid water even for pressures as high as 5 bars, at a solar luminosity of 75% the current value. Our model shows that warming of the surface-atmosphere system by carbon dioxide clouds is self-limiting, since by heating the air the clouds cause themselves to dissipate.

Even if Kastings is correct, however, such a planet would be far less LTD-optimal, for two reasons. First, such high atmospheric pressures would make high-speed travel, such as by plane, more difficult, increasing by five-fold the air resistance. Second, since carbon dioxide is distributed fairly evenly throughout the atmosphere, there would be little local variation in the density of clouds. This means that there would be nowhere one could go to get a clear view of the planets and stars; this would greatly inhibit astronomy. Although the clouds might dissipate during the day due to evaporation of the carbon dioxide by solar radiation, they would return at night when most astronomical observations are performed. (If they did not return at night, then they would not be effective in blocking outgoing radiation, contrary to the assumption of this scenario.) In contrast, even though on earth water vapor acts as a greenhouse gas and forms clouds, it is not distributed evenly throughout the atmosphere, with most of it being in the lower atmosphere and with large local variations. This means that one can go to desert regions and higher elevations to make good astronomical observations. When one considers the key role astronomy played in the scientific revolution, this inhibition of astronomical observations would likely be no small matter, but have major consequences for the development of science.

Another possibility is another atmospheric gas acting as a greenhouse gas. One possibility is methane (CH\textsubscript{4}), the main component in natural gas. Although methane is a powerful greenhouse gas, there is a major limit to how much it can insulate a planet. As Kasting notes, “CH\textsubscript{4} absorption is concentrated in few relatively narrow spectral intervals; hence, it is a good greenhouse gas, but not a great one” (210, p. 75). He then goes on to note that although in our current atmosphere, small increases in CH\textsubscript{4} would produce about 20 times the increase in temperature as CO\textsubscript{2}, this is because, unlike CH\textsubscript{4}, CO\textsubscript{2} is close to saturation; hence, as noted above, increases in it produce only a small effect. In contrast, “when the two gases are present at comparable concentrations, CO\textsubscript{2} is actually a better greenhouse gas because it absorbs more strongly over a wider range of infrared wavelengths.” (210, p. 74). Second, CH\textsubscript{4} is highly reactive with oxygen, making its lifetime in an atmosphere with a comparable concentration to that of earth about 10-12 years, with the ultimate produce of the reaction being water and carbon dioxide (Kastings, 2010, pp. 47-48, 76). By comparison, without oxygen, its life-time is about 1000 times as long (Kastings, 2010, p. 76). This means it would be very difficult for keep both substantial concentrations of oxygen and CH\textsubscript{4} in the atmosphere at the same time. As Ward and Brownlee note, oxygen, is critical for complex life with our levels of intelligence: “Without oxygen, larger animals could never have evolved . . . for a variety of physiological reasons, oxygen is key to the appearance of larger animals; the metabolism of animals requires oxygen” (Ward and Brownlee, 2000, p. 111). Further, as Denton notes, oxygen has many features that make it ideal for life, especially for complex, multicellular organisms. For example, he notes that “oxygen far surpasses any other chemical element except fluorine in the amount of energy released when combining with other elements” (1998, pp. 120 – 121); yet, unlike fluorine it can

Finally, without oxygen, there would be no wood fires, and hence no advanced scientific technology.

Third, significant concentrations of CH\textsubscript{4} produce a haze that reflects and refracts light (Kastings, 210, pp. 77, 27, reference [74]; McKay, Lorenz, and Lunine, 1998, p. 56). This would not only likely cause an antigreenhouse effect by reflecting more sunlight than infrared radiation it would reflect back to the planet ([74]; McKay, Lorenz, and Lunine, 1998, p. 56), but it would definitely make the planet less optimal for astronomy and astrophysics. Thus, for multiple reasons, a much higher CH\textsubscript{4} atmosphere would make the planet less LTD-optimal. Similar problems exist for ammonia, NH\textsubscript{3}, which the other major gas that has been considered as
a potential greenhouse gas for warming the early earth. For example, in an atmosphere containing only small amounts of oxygen, ammonia is rapidly broken apart by ultraviolet radiation. (Kastings, 2010, p. 48).

**Effect of Changing β**

The above argument depends on heat conduction and convection rates remaining constant. As shown in the appendix of chapter ___, in gases and liquids these rates are approximately proportional to $\beta^{1/2}$, where $\beta$ is the electron to proton mass ratio. [Include convection and conduction in the beta chapter appendix.] Thus the effect of an increase in $\alpha$ could be offset by an increase in $\beta$. Specifically, suppose that for the intensity of sunlight to be livability optimal, when $\beta$ is held constant $(\alpha/\alpha_0)^2 \leq C$, where $C$ is some number greater than 1 – e.g., 2. If $\beta$ is allowed to vary, then $(\alpha/\alpha_0)^2 \leq C \beta^{1/2} \rightarrow (\alpha/\alpha_0)^2 \beta^{1/2} \leq C$. We will discuss how to deal with this ability for changes in $\beta$ to compensate for changes in $\alpha$ in the concluding section of this chapter.

**Conclusion**

These factors would certainly make the world less ideal world. Two potential factors that could potentially offset these negative LTD-optimality effects are (1) increased photosynthesis, and (2) increased ability to utilize solar energy. . . .

### 4.8 Sunlight Intensity and Decreasing $\alpha$

Decreasing $\alpha$ would decrease the solar flux by $\sim (\alpha/\alpha_0)^2$ for the reasons stated in the last section and thus have just the opposite effect on temperature differences on the planetary surface. By decreasing the absorptivity of water vapor by $\sim \alpha/\alpha_0$, it would also make the climate more stable in the short run. Since the infrared absorptivity of CO$_2$ would be decreased by $\sim \alpha/\alpha_0$, however, CO$_2$ would not be as good a negative feedback mechanism for preventing global glaciation; so, for example, if $\alpha$ were $\frac{1}{2}$ its value, to reverse a global icebox scenario would take require that CO$_2$ rise by ____ instead of the ____ estimated for our world by ____ Kastings. Further, by decreasing the temperature difference between various latitudes of the earth, it would decrease the global circulation of air in the atmosphere and the oceans, which is driven by these differences. This means there would likely be more desert and semi-desert regions, at some point making the planet less LTD-optimal, everything else being equal.

The main negative LTD-optimality effect of a decrease in $\alpha$ would be a decrease in the rate of photosynthesis. For example, consider the oceans. Although at the surface on a clear day with the sun overhead photosynthesis appears to be saturated, when the entire zone over which photoplankton can function – the euphotic zone – is taken into account.$^{38}$ The results of their study shows that the average rate of photosynthesis on the surface for a typical sample of marine photoplankton at the same latitude as Newport, Rhode Island peaks out at about $\frac{1}{4}$ to $\frac{1}{3}$ of the maximum intensity of sunlight on June 17. (Figures 2 and 3), with it decreasing considerably beyond that. Hence, the surface is saturated for much of the day. However, when integrated over the entire euphotic zone (that is, the zone from surface to the depth that receives just enough sunlight for plants to survive) the relationship between photosynthetic activity and amount of sunlight is nearly linear, as shown in the figure below.

$^{38}$ [Reference: “Photosynthesis in the Ocean as a Function of Light Intensity”JOHN H. RYThER. Contribution No. 819 from the Woods Hole Oceanographic Institution. Fig. 6].
According to them, even taking into account nutrient depletion, which limits the growth of natural plankton, light is always the limiting factor: “Thus light is always limiting to the photosynthesis of natural plankton populations and the effect of nutrient depletion is at most additive to the light factor. (p. 70).

According to them (p. 70), the reason is that as nutrient deficiency sets in, the rate of photosynthesis decreases, thus making light even more important for significant amount of photosynthesis to take place. Further, the rate of respiration is a constant of 11.04 relative units (p. 69). Thus, only when the light intensity is above approximately 200 g. Cal/cm\(^2\)/day can photosynthesis contribute increase the oxygen concentration in the atmosphere for photoplankton.

Presumably, at least some species of photoplankton have evolved to be as efficient as possible in absorbing light, since this would be a selective advantage. Consequently, one would expect that a significant decrease in the intensity of sunlight would decrease the amount of oxygen produced by photoplanckton, consequently decreasing the amount of available oxygen in the atmosphere on a planet with a similar composition to earth.

A substantial decrease in \(\alpha\) would also significantly decrease the amount of photosynthesis on land. In our world, because of saturation, on a clear day with the sun overhead the photosynthesis is saturated. However, on a cloudy day, or when the sun is lower in the sky, it is not saturated. Yet, ____ of days are cloudy, and most of the year . . . So, the average amount of sunlight that strikes earth is ____ of what it would be when the sun is overhead on a clear day. Further, the leaves of almost all plants are at random angles to the sun, and most plants have many more leaves that are partially shaded; in forests, many plants grow in the shade of other plants, as in a forest. So, even on a clear day with the sun overhead, one would expect photosynthesis to decline with a decrease in the intensity of sunlight. Given these considerations, there is no question that a substantial decrease in \(\alpha\) would make the amount of photosynthesis on land much
less. For example, a five-fold decrease in $\alpha$ would decrease the amount of sunlight by a factor of 25.  

One likely negative LTD-optimality effect of a substantial decrease in photosynthesis would be on oxygen levels. According to Donald Brownlee and Peter Ward (2002, reference [75]) high levels of oxygen are crucial for the evolution of complex, warm-blooded land mammals. Thus, a significant decrease in oxygen would make the evolution of ECAs more difficult, if not impossible. In equilibrium, however, oxygen is also taken out the atmosphere at the same rate it is produced. Conceivably, therefore, a planet with much less photosynthesis could have enough oxygen for ECAs to evolve. One of the major ways in which oxygen is taken out of the atmosphere is through combining with un-oxidized elements, especially iron, brought to the surface by the action of plate tectonics. Such a world, therefore, would have to have either considerably less plate tectonics or considerably less iron, presenting problems its own problems for life, technology and discoverability: as shown in chapter ____, section ____, if plate tectonics were much less than on earth, there would be no continents, and hence no terrestrial ECAs; if substantially less iron, then there would be less material available for steel and other metals made of steel. This would most likely have had a negative impact on technology. Further, it is unlikely that the planet would have a magnetic field, as this requires a substantial iron core in which electric fields can occur. As elaborated in chapter ____, the absence of a planetary magnetic field would have negative effects on the development of civilization (which was greatly aided by the compass) and would eliminate paleomagnetic dating, which plays an irreplaceable role in certain kinds of dating.

Another negative LTD effect would be on the availability of plant food, which would inhibit the evolution of ECAs. Further, there would be substantially less fossil fuels, such as oil and coal. Such fuels have played a crucial role in the development of an industrial, highly technological civilization. If there were considerably less fossil fuels, the development of a highly technological civilization would have been substantially inhibited. Since such fossil fuels are produced by the burial of plant and animal life, if there were considerably less plant and animal life, there would be considerably less oil and coal. In fact, if the level of photosynthesis were to fall below a certain point, one would not expect there to be any fossil fuels, since the rate of plant and animal burial must exceed the rate of oxidation of the buried material.

A less intense sunlight would also severely hamper the hydrologic cycle, since the movement of air is driven by temperature differences. These differences are caused by differential heating of the earth’s surface, and hence are proportional to the intensity of sunlight. Thus in a substantially decreased $\alpha$ world, there would be far less rain, and hence far less land vegetation. Further, phytoplankton require high levels of nutrients. They obtain these nutrients either by water entering the ocean through rivers or the upwelling of water from deep in the ocean. [Research assistant: find reference for this.] The two factors driving the latter are temperature differences in the ocean and evaporation of the ocean (which makes it more salty, increasing its density). With a less intense sunlight, the former would be directly decreased, and the latter would be indirectly decreased by decreased winds as a result of smaller temperature differences in the air. These effects on the hydrologic cycle and ocean circulation would further

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39 Since the proportion of light in the visible spectrum does not significantly change for planets orbiting stars with higher surface temperatures (see chapter ____), even planets orbiting higher temperature stars would suffer around a 25-fold loss in visible light. As shown in chapter ____, those at lower temperatures have a considerably smaller proportion in the visible region (versus the infrared), and hence the decrease would be greater than 25-fold.
amplify the negative optimality effects cited above: for example, less water would mean fewer plants, with each of the plant engaging in less photosynthesis. [To be completed]

Effect of changes in $\beta$
[To be completed.]
Just as an increase in $\beta$ can compensate for an increase in $\alpha$, a decrease in $\beta$ could compensate for a decrease in $\alpha$. As shown in Chapter ___, not only would one expect the rate of conduction and convection in gases and solids to be proportional to be $\beta^{1/2}$, but one would also expect the rate of diffusion and chemical reactions to be proportional to $\beta^{1/2}$. Thus, a decrease in $\beta$ would cause the time for . . . .

4.9 Summary

PR#3

To summarize, when the other constants are held fixed, the requirements of livability and discoverability provide around eight major constraints, along with several others the importance of which is difficult to determine. The eight major and one moderate (navigation by compass and paleomagnetic dating) are given in the table below.

Summary Table of Major DL Constraints on $\alpha$ Discussed in this Chapter.

<table>
<thead>
<tr>
<th>Fine-Tuned Constraint</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stability of nuclei</td>
<td>$\alpha &lt; 6\alpha_0$</td>
</tr>
<tr>
<td>2. Stability of matter against collapse</td>
<td>$\alpha &lt; 2.72$</td>
</tr>
<tr>
<td>3. Stability of Stars</td>
<td>$\alpha_0/200 &lt; \alpha &lt; \sim 200\alpha_0$</td>
</tr>
<tr>
<td>4. Transformers, generators, and motors</td>
<td>$\alpha &gt; \alpha_0/3$</td>
</tr>
<tr>
<td>5. Light microscope</td>
<td>$\alpha \geq -\alpha_0$ (to see all living cells); $&gt; \alpha_0/50$ to see most living cells.</td>
</tr>
<tr>
<td>6. Wood Fires</td>
<td>$\alpha &lt; \sim 1.4\alpha_0$</td>
</tr>
<tr>
<td>7. Sunlight not too harsh</td>
<td>$\alpha &lt; 2\alpha_0$</td>
</tr>
<tr>
<td>8. Optimal Photosynthesis</td>
<td>$\alpha &gt; \alpha_0/2$</td>
</tr>
<tr>
<td>9. Navigation by Compass + paleomagnetic dating</td>
<td>$\alpha &gt; ___$</td>
</tr>
</tbody>
</table>

Summary Table of Minor, or Difficult to Determine DL Constraints on $\alpha$. 

38
1. Discovery of wave nature of light not greatly inhibited \( \alpha < \alpha_0 \)
2. Ice-core for atmosphere \( \alpha < \alpha_0 \)
3. Temperature difference between latitudes \( \alpha < \alpha_0 \)
4. Wood in forests not being subject to burning down without special adaptions by trees. \( \alpha_0/2 < \alpha \)

Summary Diagram of Major and Moderate Constraints

![Diagram of constraints on \( \alpha \). The thick lines are constraints that provide an upper bound on \( \alpha \) and the thin lines are those that provide a lower bound, with the solid lines being livability constraints and the dashed lines being discoverability (and technology) constraints. The star marks the current value of \( \alpha \), which is \( \sim 1/137 \). The three minor or indefinite constraints listed in the second table above are not shown. Notice that for an optimally livable and discoverable world, all the thick lines must be above the star and all the thin ones below the star. Since the underlying laws determine the position of the constraints, they must be fine-tuned so that optimal discoverability can occur.]

Livability Constraints (Solid Lines)
- **Upper Livability**: Sunlight not too harsh; Stability of biochemically important elements; stability of matter; stability of stars.
- **Lower Livability**: Optimal photosynthesis

Usability Constraint Bounds:
- **Upper Discoverability** (thick dashed): wood fires; CMB as useful as in our universe.
- **Lower Usability** (thin dashed lines): light microscopes; electric transformers; Compass and Paleomagnetic Dating; CMB as useful as in our world.

REFERENCES


Ritchie, S. J.; Steckler, K. D.; Hamins, A.; Cleary, T. G.; Yang, J. C.; Kashiwagi, T.
White, Robert. “Cone Calorimeter Testing of Vegetation: An Update,” USDA Forest Service, Forest Products Laboratory, Madison, WI 53726-2398
David R. Weise
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Frank Pilar ((Elementary quantum chemistry, p. 156)


http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/hydfin.html#c2;
http://hyperphysics.phy-astr.gsu.edu/hbase/spin.html;

Acze, Amir. [The Riddle of the Compass: The Invention that Changed the World, Amir D. Acze, Mariner Books (May 2, 2002).]

Day, Clive. Also, Clive Day, History of Commerce, page 73 says something similar


http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/hydfin.html#c2;
http://hyperphysics.phy-astr.gsu.edu/hbase/spin.html;

Chin, et. al. “Ultracold molecules: new probes on the variation of


[35] [35]


[37] Williams, Darren M. et. al. note, James F. Kasting, & Richard A.,Habitable moons around extrasolar giant planets, NATURE
Insect Physiology, Vincent Wigglesworth, 1972, pp. 146 - 147.


Also see A Brief History of Iron and Steel Production

by

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References

Citing Articles (1)

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[55] Living in the Multiverse

[56] All Universes Great and Small

[57] Do we Live in a “Small Universe”?
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D. Rasbash (Author), G. Ramachandran (Author), B. Kandola (Author), J. Watts (Author), M. Law (Author)

[64] Liddle and Lyth, 2000,

[65] G. J. Withrow (1955) British journal for the philosophy of science, 6,


The constants of nature: from Alpha to Omega--the numbers that encode the, By John D. Barrow, Pantheon, 2003.

Analytic Solutions for the Antigreenhouse Effect: Titan and the Early Earth Christopher P. McKay Space Science Division, NASA Ames Research Center, Moffett Field, California 94035 Email: cmckay@mail.arc.nasa.gov and Ralph D. Lorenz and Jonathan I. Lunine Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721 Received April 27, 1998; revised September 14, 1998


Henry R. Frankel, The Continental Drift Controversy: