Issues on Barry Setterfield's Claims of a Recently Decaying Speed of Light,

2nd Edition[1]

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ABSTRACT

One of the primary problems for Young-Universe Creationists (YUCs) is the question of how light could have travelled from galaxies millions and billions of light years away in the less than 10,000 year old Universe required in their cosmology. One solution proposed by Barry Setterfield is that the speed of light was much higher in the not-so-distant past. In this paper, I will examine this hypothesis and demonstrate that it does not match up with many cosmological observations as well as observations in our own galaxy and even here on Earth.

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1. Introduction

The notion that fundamental physical constants have changed over cosmic history is not a new hypothesis - P.A.M. Dirac (Dirac 1937, 1938) and others (Brans and Dicke 1961) have suggested it on various grounds. Along with the theoretical interest, there have been a number of experimental searches for evidence that some physical parameters which we consider as constant, might in fact vary over the history of the cosmos. Taylor and Weisberg (1989) used changes in the orbits of binary pulsars (due to gravitational radiation losses) to search for changes in G, placing a limit on $|\dot{G}/G| < (1.2 \pm 1.3) \times 10^{-11} yr^{-1}$. There have been reports of a possible variation in the Fine Structure constant, α, through observations of spectral lines in high-z quasars(Webb et al. 1998). Shlyakhter (1976) used the fission reaction created in the Oklo uranium deposits to place limits on the variation of the Fine Structure constant ($|\dot{\alpha}/\alpha| < 10^{-17} yr^{-1}$), the weak nuclear coupling constant ($|\dot{g_w}/g_w| <$

$2 \times 10^{-12} yr^{-1}$) and the strong nuclear coupling constant ($|\dot{g}_s/g_s| < 5 \times 10^{-19} yr^{-1}$). Damour and Dyson (1996) re-analyzed this data in more detail and revised the estimate of variation in the Fine Structure constant to $-6.7 \times 10^{-17} yr^{-1} < \dot{\alpha}^{averaged}/\alpha < 5.0 \times 10^{-17} yr^{-1}$. A number of similar tests are described and summarized in Sisterna and Vucetich (1990). Even the speculation that the extragalactic redshifts could be due to a changing speed of light is not new, having been suggested by Wold (1935). The possibility that the cosmological redshift was due to light losing energy, the 'Tired Light' hypothesis, was also suggested by Stewart (1931).

Since one goal of this document is to provide a resource for teachers (particularly in physics, astronomy and perhaps mathematics), the treatment herein will be very pedagogical. Problems are available at the end for students and those who wish to explore the issue further. This document will be subject to periodic additions and revisions. The derivations within are my own work based on descriptions by others in the talk.origins newsgroup and other sources. I'd appreciate information on original work on some of these topics so they can be properly cited.

1.1. An Introduction to the Setterfield Hypothesis

Setterfield based his initial hypothesis on trends he claimed existed in early measurements of the speed of light. Setterfield has made much of this material available online (Setterfield a). Another site which seems to mirror some of Setterfield's site is Dolphin (2001). Many rebuttals deal with Setterfield's interpretation of the measured values for the speed of light over the past 250 years and these rebuttals are dealt with in other sources.

- Strahler (1999, pp. 116-118) summarizes and describes a number of problems with how Setterfield collected his data.
- Excellent online resources on the fallacies in Setterfield's theory can be found on TalkOrigins(Day 1997).

We can summarize the main points of Setterfield's hypothesis:

1. Accept the cosmic distance estimates as valid.
2. The speed of light varies universally at the same time. This means that only time can appear explicitly in the functional form for the speed of light.
3. Dynamical time, which we will designate with the letter τ, is synchronized to gravitational phenomena. Orbital periods are constant in this timescale. This is the 'true' timescale, or what Setterfield might call the 'Biblical Timescale'.
4. Atomic time, which we will designate with the letter t, is synchronized to atomic phenomena. Atomic and nuclear processes are keyed to this timescale.

5. In the (not so distant) past, the atomic timescale was much faster than the dynamical timescale. This allows radioisotopes to appear to have taken millions to billions of years to decay when really only a few thousand years in dynamical time have passed. The ratio of a unit of the atomic time to the dynamical time we'll designate by ζ, so $dt/d\tau \propto c$ or $dt/d\tau = \zeta(\tau)$.
6. Today, a second of atomic time is indistinguishable from a second of gravitational time ($\zeta(\tau) = 1$ and ζ no longer changes, so $d\,\zeta/d\,\tau = 0.$). Setterfield claims this phase begin in 1967.5.
7. Other physical quantities are allowed to vary so that certain other quantities remain constant with time: $E = mc^2 = constant$, $Gm = constant$ (this is strange because Setterfield initially claims that G is the constant), and $hc = constant$. See Section 4.
8. The speed of light is *linearly* proportional to the observed redshift, or

$$c \;=\; k\;z \tag{1-1}$$

where k is a constant of proportionality whose actual value is strangely difficult to discern from Setterfield's writing(Setterfield 2001, Equation 109).

In this work, I will address implications of Setterfield's claims that don't seem to get much treatment in the literature but which are just as, if not more, important in determining if the value of the speed of light has changed substantially in historical times. Legitimate science *builds* on the work done before and there are strong observational arguments for why the speed of light has *not* undergone significant change (within a factor of 2?) in the past approximately 14 billion years of the Universe's history. In addition to direct measurement of the speed of light (which Setterfield uses), there are numerous other predictions which can be made by this hypothesis alone. It is often complained by Creationists that quantities such as the speed of light are *assumed* constant over the history of the cosmos. However, just because it is an assumption does not mean that it is an *untested* assumption, as the number of references in Section 1 attest. This constancy is just the simplest assumption that fits the available data. This exercise also enables us to see just how science can actually test these assumptions.

2. Kinematic Implications of a Changing Speed of Light

While Setterfield goes into great detail on alleged quantum mechanical issues with his hypothesis (see Section 5.5), he fails to consider the fatal flaws in his arguments on *kinematic* considerations alone that can be addressed by anyone with a competent background in calculus-based physics, a course which is occasionally taught at the high-school level. These arguments are based on one of the oldest physical principles, that distance traveled is velocity multiplied by the travel time, or in calculus terms, that distance is the integral of velocity over time:

$$s = \int_{t_1}^{t_2} v(t)\;dt \tag{2-1}$$

or, inversely,

$$v(t) \;=\; \frac{ds(t)}{dt} \tag{2-2}$$

This is one of the founding equations of kinematics to compute the distance, s, travelled by an object moving at a non-constant velocity $v(t)$ at time t during the interval t_1 to t_2. It is basically the *definition* of velocity. In this section, I'll address many predictions about c-decay based on this concept alone.

We'll start this description with a simple, down-to-Earth example. Consider drivers in two cars want to travel from Springfield to Palmdale, two (fictitious) towns 100 miles apart. Driver A leaves Springfield at noon, travelling at an average speed of 50 miles per hour (MPH). Note this is his *a*verage speed - they start out travelling 51 mph and uniformly decelerate during the trip, arriving in Palmdale at a speed 49 MPH, so that their average speed is 50 MPH. Driver B leaves at 1PM, one hour later than Driver A, and starts out travelling at 50 MPH, uniformly decelerating during the trip so that two hours later, they are travelling at 48 MPH. While Driver B left Springfield an hour after Driver A, Driver B will arrive in Palmdale *o*ver an hour after Driver B. Knowing the velocity as a function of time along the trip, and some integral calculus, we can determine precisely what this time difference is. This holds true in all cases where velocity is defined, whether the objects making the trip are two cars, two aircraft, two groups of electrons or photons, or the wavecrests of photons. This is the fundamental exercise that is covered in this section.

Next, let's establish a few conventions to ensure we develop the concepts in a self-consistent fashion. One of Setterfield's base assumptions is that there are two timescales: an atomic time scale that is synchronized to atomic interactions, and a dynamical time scale that is synchronized with gravitational phenomena. According to Setterfield's hypothesis, in our modern day, a second of atomic time is indistinguishable from a second of dynamical time, but just a few thousand years ago, a second of dynamical time could correspond to several months of atomic time. This allegedly enables radioisotopes to appear to have taken millions or billions of years to decay in modern measurements while only a few thousand years have passed in the dynamical time scale. It also lets the speed of light appear constant when measured against the atomic time scale but varies when measured against the gravitational time scale.

For the purpose of our analysis and to ensure consistency throughout, we'll use t to designate measurements on the atomic time scale and τ to designate measurements made on the dynamical time scale. Setterfield claims the dynamical time scale is the 'true' or uniform time so we'll perform our analyses using this time tag and translate to the atomic time scale when necessary. The key component of Setterfield's theory is that the aforementioned changing time scales are linked to changes in the speed of light (measured in a vacuum). To guarantee consistency, we'll separate our equation for the speed of light into a dimensional component, $\bar{c}$, which will be equal to the speed of light in the modern era ($2.99792458 \times 10^{10} cm/sec$), and a dimensionless component, ζ, which will contain all the time variability (measured in dynamical time, τ). This separation makes it easier to identify just how the time varying component affects other observables. Changing the c to $\bar{c}$ when we mean the constant speed of light helps keep track of which speed of light is being used in our equations. So our equation for the time variable speed of light becomes

$$c(\tau) = \bar{c}\,\zeta(\tau) \tag{2-3}$$

where τ is time from the instant of creation measured on the dynamical time scale. Therefore, Setterfield's hypothesis can be reduced to the idea that $\zeta(\tau)$ is much greater than one in the distant past and generally decreases towards a value of unity in the modern age.

2.1. Physical Model of Photon Propagation

Over the past 300 years of the development of physics, from the discovery of the wave nature of light in the 17th century, to the discovery of light's wave/particle duality nature in the 20th century, a physical model of photon propagation has been developed. This model is well established experimentally and is an integral component of all technologies relying on radio wave, photon and light travel time, including technologies such as radar, LIDAR, and the GPS (Global Positioning System). This propagation model consists of three components:

1. Photons are emitted from some source at a location (x_e, y_e, z_e) at some time t_e and some wave speed, c_e, and wavelength, such that $\nu_e = c_e/\lambda_e$.
2. The photon travels through some medium or geometry that can alter the photon's characteristics as it travels.
3. The photons are detected at the observer at a location (x_o, y_o, z_o) at some time t_o and some wave speed, c_o, and wavelength, such that $\nu_o = c_o/\lambda_o$.

Examples of implementing this model for the Doppler effect and the Hubble expansion are given in Appendix A.

2.2. First-Order Implications on Dynamical Periodic Phenomenon if c is Changing

The universe is full of convenient 'clocks': spectral lines, binary stars, pulsars and variable stars which provide ready methods for measuring cosmological changes. Since Setterfield defines two different timescales in his hypothesis, we'll want to examine phenomena which would be constant in both of these timescales. We'll first examine the case of phenomena which would be periodic in Setterfield's dynamical timescale.

Consider an object at some distance, s, that emits pulses of light at regular intervals, P (measured in dynamical time). In Figure 1 we use a binary star system. When the blue companion

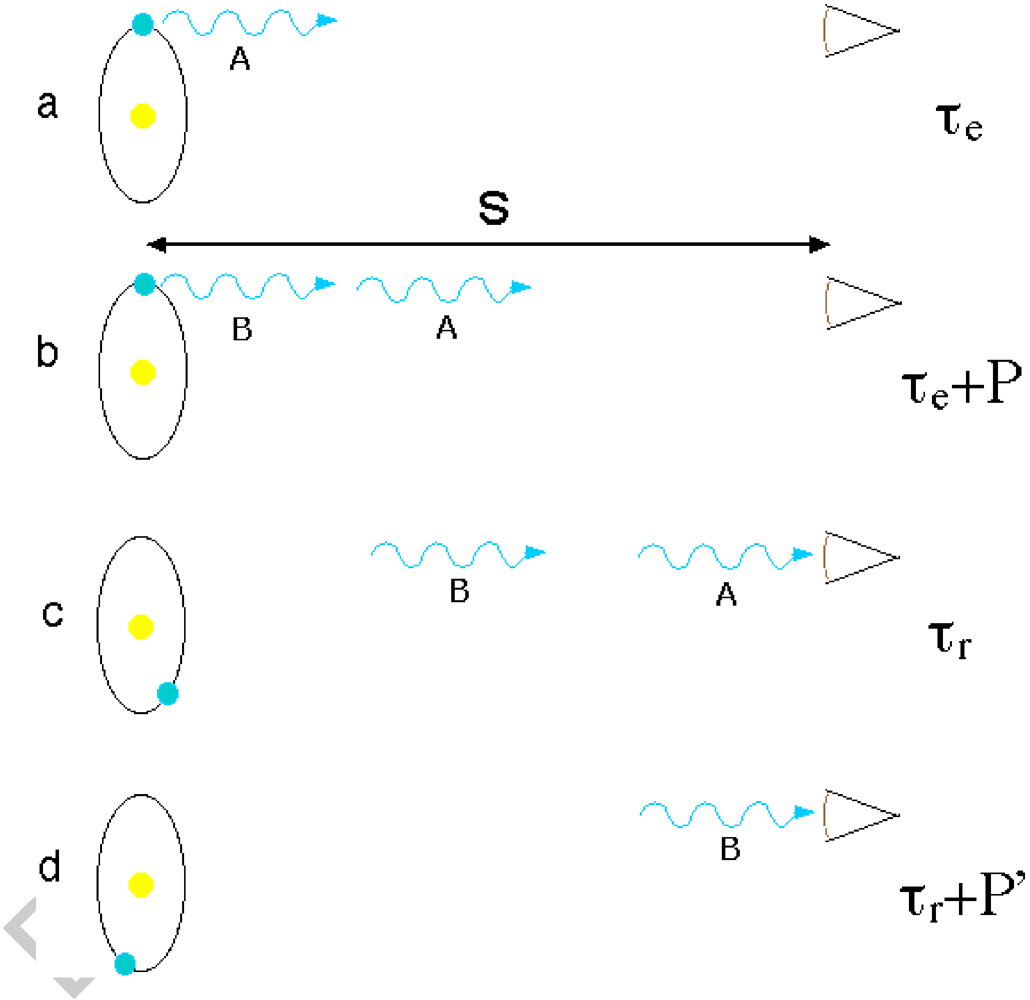

Fig. 1.— Analysis of light travel from a binary star. (a) At time τ_e a photon, A, is emitted from one companion of a binary star. (b) After the companion has completed one orbit, in a time P, a second photon, B, is emitted at time $\tau_e + P$. (c) Photon A arrives at the observer at time τ_r and (d) photon B arrives at the observer at a later time, $\tau_r + P'$.

star emits a photon which we will label as ‘A’, at a time, τ_e, and travels the distance, s, then it will be received at a time τ_r (Figure 1c). After the companion has completed one orbit with a period P, a photon which we will label ‘B’ is emitted at time, $\tau_e + P$ (Figure 1b), travels over that same distance, s, at a different speed, and arrives at the observer at the time $\tau_r + P'$ (Figure 1d), where P is not necessarily equal to P'. From the basic kinematics of Equation 2-1, we can write (assuming that the distance of the object is fixed between time τ_e and $\tau_e + P$) a relationship equating the distance travelled by the two photons as

$$s = \int_{\tau_e}^{\tau_r} c(\tau)\ d\tau \ = \ \int_{\tau_e+P}^{\tau_r+P'} c(\tau)\ d\tau \tag{2-4}$$

or, inserting our Equation 2-3 for $c(\tau)$, we get

$$s = \bar{c} \int_{\tau_e}^{\tau_r} \zeta(\tau)\ d\tau \ = \ \bar{c} \int_{\tau_e+P}^{\tau_r+P'} \zeta(\tau)\ d\tau \tag{2-5}$$

To keep our initial results as general as possible, we’ll avoid setting a specific functional form for $\zeta(\tau)$. At present, lets just say that the indefinite integral of $\zeta(\tau)$ is some function $Z(\tau)$ or:

$$Z(\tau) \ = \int \zeta(\tau)\ d\tau + C \tag{2-6}$$

With this redefinition, Equation 2-5 becomes

$$s \ = \ \bar{c}\ \left(Z\left(\tau_r\right) \ - \ Z\left(\tau_e\right)\right) \ = \ \bar{c}\ \left(Z\left(\tau_r + P'\right) \ - \ Z\left(\tau_r + P\right)\right) \tag{2-7}$$

In most of our cases of interest, P and P' will correspond to time intervals on the order of radio and gamma-ray oscillations, binary star orbits and pulsar periods. These intervals are much smaller than the time intervals on the dynamical scale, τ, which will generally be the total travel time of the light across the cosmos. Therefore, we can expand $Z\left(\tau_r + P'\right)$ and $Z\left(\tau_r + P\right)$ using a Taylor expansion:

$$\begin{aligned} Z\left(\tau_e + P\right) \ &\approx \ Z\left(\tau_e\right) \ + \ P\ \frac{dZ\left(\tau_e\right)}{d\ \tau_e} && \text{(2-8)} \\ &\approx \ Z\left(\tau_e\right) \ + \ P\ \zeta\left(\tau_e\right) && \text{(2-9)} \\ Z\left(\tau_r + P'\right) \ &\approx \ Z\left(\tau_r\right) \ + \ P'\ \frac{dZ\left(\tau_r\right)}{d\ \tau_r} && \text{(2-10)} \\ &\approx \ Z\left(\tau_r\right) \ + \ P'\ \zeta\left(\tau_r\right) && \text{(2-11)} \end{aligned}$$

We then incorporate these expansions into Equation 2-7. Cancelling the common $Z(\tau)$ components, we get the relationship:

$$P\ \zeta\left(\tau_e\right) \ = \ P'\ \zeta\left(\tau_r\right) \tag{2-12}$$

which can be manipulated to

$$P' \ = \ P\ \frac{\zeta\left(\tau_e\right)}{\zeta\left(\tau_r\right)} \tag{2-13}$$

Since $\zeta(\tau_e)$ is greater than $\zeta(\tau_r)$ in Setterfield's model, then a phenomenon that has a constant period, P at some location where the speed of light is $\bar{c}\ \zeta(\tau_e)$ will appear to have a period of P' at the time of reception of the signal when the speed of light is $\bar{c}\ \zeta(\tau_r)$ which will be greater than the period at the time of emission. Bear in mind that this effect is only noticeable if you know the period at the point of emission, $P = P(\tau_e)$. In the case of the orbital periods of binary stars and the spin rates of pulsars, this is determined from observations, which would tell us $P' = P(\tau_r)$, but not P. However, there is a second-order effect, which will be covered in Section 2.3. Also note that *this effect depends only on the speed of light at the point of emission and the point of reception.* So long as the speed of light is piecewise-continuous along it's path (this even includes sudden 'jumps' in the speed, such as Setterfield's quantization claims which will be discussed in Section 5.5), the speed at the endpoints will be the only factor determining the change in the observed periods. While this may not seem that important at first glance, consider that Setterfield's model claims that the speed of light has varied significantly in the past 250 years.

One might argue that the period, P, could change relative to the dynamical time scale in such a way that this effect vanishes. Yet Setterfield has already claimed that orbital motion is a periodic phenomena which is constant on a dynamical time scale. Setterfield wants to keep orbital periods constant. The Julian calender, adopted in 45 BC by Julius Caesar(Tøndering 2005), is based on 365.25 days per year, only slightly different than our current year, therefore one should assume orbital periods and the spin rate of the Earth's rotation have not changed significantly over this time period.

Now let's examine some special cases of this equation to understand some details of its behavior before proceeding to the next step of the analysis.

Consider the case where we have a phenomenon that is constant in the dynamical time scale so $P(\tau_e) = P_0$ is constant for all τ_e. The location of this object is still in a region of space where the speed of light is decreasing so we write this mathematically as $\zeta(\tau_e + \delta\tau) < \zeta(\tau_e)$ for some positive time-step $\delta\tau$. Now consider an observer receiving photons from this object at some later time, τ_r when the speed of light has decreased to its modern day value and undergoes no further decline ($\zeta(\tau_r) = 1$). What can we say about the period observed at a later time? At τ_r, Equation 2-13 is

$$P(\tau_{r1}) = P_0 \frac{\zeta(\tau_e)}{1} \tag{2-14}$$

while at a later time

$$P(\tau_{r2}) = P_0 \frac{\zeta(\tau_e + \delta\tau)}{1}. \tag{2-15}$$

Since $\zeta(\tau_e + \delta\tau) < \zeta(\tau_e)$, we see that

$$P(\tau_{r2}) < P(\tau_{r1}) \tag{2-16}$$

so at later times, so long as the speed of light is decreasing at the point of emission, the observed period at the point of reception will *decrease* (i.e. the frequency will *increase*). This might seem counterintuitive, considering our reasoning based on Figure 1. You'd think we would expect the period to increase, since each photon takes longer to make the trip. This example illustrates how easily our 'physical intuition' can mislead us.

In Section 2.3, we will place this behavior on a firmer mathematical footing.

2.2.1. A Non-Calculus Method for Deriving Equation 2-13

There is a way to derive the above result without the use of the calculus. Our assumption above, that the time interval between peaks in the oscillations or pulses are very small compared to the light travel time between emitter and receiver is another way of saying that light speed does not change significantly between the first and second emitted peak. This means that, in this approximation, the relative velocity of the two adjacent peaks remains essentially zero between the points of emission and reception and the pulses arrive at the receiver separated by the same physical distance, say d, as they were at the time of emission. However, because the two pulses are travelling at different speeds at emission and reception, the pulses are received with a different time interval between them compared to the point of emission.

$$d \;=\; P(\tau_e)\;\bar{c}\,\zeta(\tau_e) \;=\; P(\tau_r)\;\bar{c}\,\zeta(\tau_r) \tag{2-17}$$

which after some basic algebra, becomes

$$P(\tau_r) \;=\; P(\tau_e)\,\frac{\zeta\left(\tau_e\right)}{\zeta\left(\tau_r\right)} \tag{2-18}$$

The same as equation 2-13.

2.2.2. A Graphical Method for Deriving Equation 2-13

It turns out that there is also a very simple graphical method to derive Equation 2-13. This explanation would be accessible to students without a strong mathematics background.

Consider a simple space-time diagram like Figure 2. We can choose our coordinate system so we only need to examine motion in one spatial dimension, x, and dynamical time, τ. If we consider two different observers at rest in this system, the Emitter and Receiver, their space-time trajectory will be straight lines at some fixed position on the x-axis and running parallel to the τ-axis.

In this diagram, we represent the trajectories of photons as the curved red lines. If the photons traveled at a constant speed, these lines would be straight. However, we want to consider the case where the speed of light decreases with time over all space so these lines are curved. In the case of the speed of light decreasing with time, the photon trajectories will start with a higher speed (a large amount of distance in x is covered for a fixed amount of time on the left side of the figure so

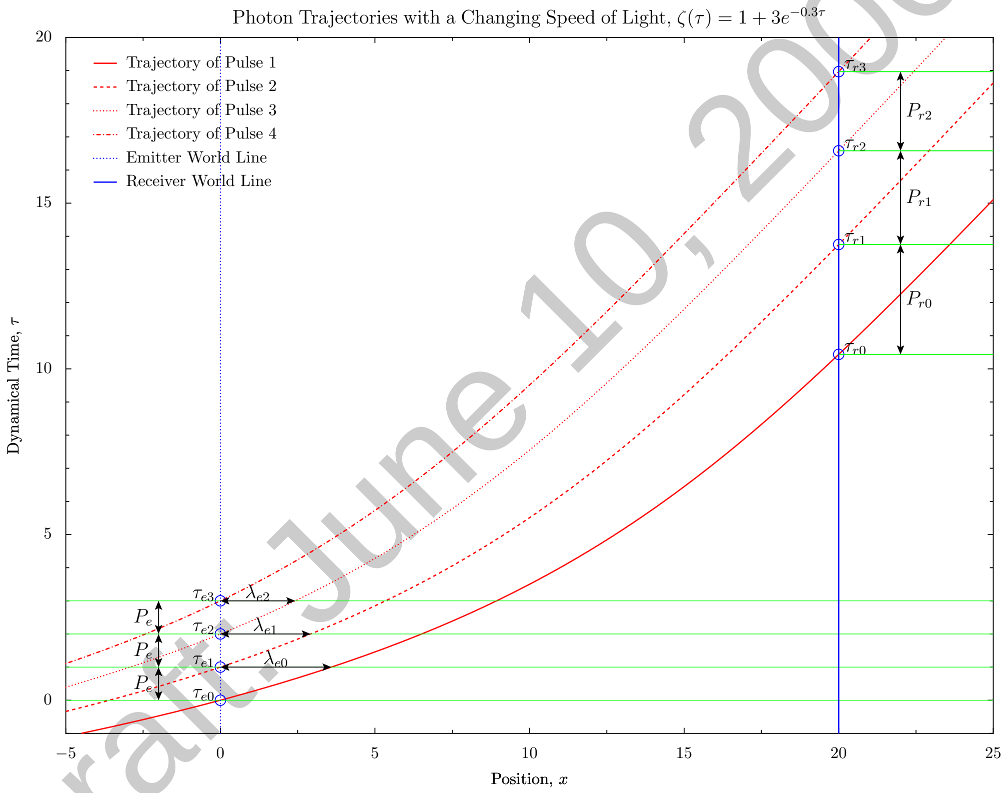

Fig. 2.— Graphical analysis of time dilation when the speed of light changes. The red lines represent the paths of photon wavecrests. The blue lines represent the space-time path of emitters and receivers. Photons emitted from the blue circles at $(x, \tau) = (0, \tau_{e0,e1,e2,e3})$ propagate with time along the red curves to arrive at the receiver at space-time coordinates $(x, \tau) = (20, \tau_{r0,r1,r2,r3})$. See the text for details in interpretation.

the slope of the blue curve is small) and decrease to a slower speed (a smaller amount of distance in x is covered for the same amount of time on the right side of the figure so the slope is steep). The speed of the photons is represented by the slope of their trajectory in this diagram, with a *steeper* slope representing a *slower* speed.

Consider a photon traveling from the Emitter to the Receiver. The first wave crest of the photon is emitted at point τ_{e0} on the emitter's world-line with some velocity, $\bar{c}\zeta(\tau_{e0})$. The wave travels out from the emitter at a decreasing speed, represented by the red curve. The next wave crest leaves the emitter at time, $\tau_{e1} = \tau_{e0} + P_e$. At this point, we know the distance between the wavecrests, by definition, is the wavelength, λ_{e0}. Now a key point: because in this model, we have the speed of light changing to the same value over the *entire* universe, the velocity of the *entire* segment of the wave is $c\zeta(\tau_{e0} + P_e)$ at that instant. *And because the speed varies over the entire universe by the same amount, the separation of these adjacent wavecrests will not change relative to each other after emission. Their separation will remain a constant, so the wavelength, λ_{e0}, will not change as the wave travels across the universe.*

The first wavecrest arrives at the Receiver (located at a distance of 20 units in this diagram) at the time, τ_{r0} and the second at time $\tau_{r1} = \tau_{r0} + P_{r01}$. Now note the projections of the events τ_{e0}, τ_{e1}, τ_{r0}, and τ_{r0} on the τ-axis. These tell use the time between the events. We immediately notice that the arrival time between events τ_{r0}, and τ_{r1}, P_{r01}, is larger than the time between emission events τ_{e0}, and τ_{e1}, P_e (which we choose to be constant). We've exaggerated the change in the signal speed in Figure 2 to better illustrate the concepts, but in the practical application, the wavelength, λ, will be much smaller than the light travel distance and the travel intervals between the wavecrests, P_e and P_r, are much smaller than the light travel time. Under these conditions, the light-travel speed will not change significantly during these intervals. Therefore, we can write

$$\lambda \;=\; P(\tau_e)\;\bar{c}\;\zeta(\tau_e) \;=\; P(\tau_r)\;\bar{c}\;\zeta(\tau_r) \tag{2-19}$$

which can also be manipulated to

$$P(\tau_r) \;=\; P(\tau_e)\,\frac{\zeta\,(\tau_e)}{\zeta\,(\tau_r)} \tag{2-20}$$

as expected.

Note that as time progresses, the distance between wavecrests/pulses decreases, so $\lambda_{e0} > \lambda_{e1} > \lambda_{e2}$. This decrease causes the time between successive pulse arrivals to decrease so $P_{r0} > P_{r1} > P_{r2}$ so phenomena which have a fixed period in the dynamical system will appear to have a decreasing period (speed up) to a distant observer. This is consistent with Equation 2-16.

2.3. Second-Order Implications on Dynamical Periodic Phenomenon

if c is Changing

In Section 2.2 we saw how a changing speed of light will impact the observations of periodic phenomena. This is fine when we can make a statement about the period of the phenomena at the point of emission, but what about when we don't know this period? Would there be any other observations which might be useful for determining if the speed of light is undergoing a rapid change?

Yes, there is.

Consider that as the speed of light changes, the travel time of photons from the source to the observer changes. In the case of a monotonically decreasing speed of light and fixed emitters and receivers, each photon will take a longer time to reach the observer so $\tau_r - \tau_e$ will steadily increase. Therefore the ratio $\zeta(\tau_e)/\zeta(\tau_r)$ will change.

Let's take a closer look. First, let's recast Equation 2-13 to keep the time-dependencies apparent:

$$P(\tau_r) \ = \ P(\tau_e)\,\frac{\zeta(\tau_e)}{\zeta(\tau_r)} \tag{2-21}$$

Now let's examine how the period at the location of the observer appears to change at that observer's location. With a couple of applications of the Chain Rule from calculus, we find

$$\begin{aligned}
\frac{d\ P(\tau_r)}{d\ \tau_r} \ &= \ P(\tau_e)\,\frac{d}{d\ \tau_r}\left[\frac{\zeta(\tau_e)}{\zeta(\tau_r)}\right] \ + \ \frac{\zeta(\tau_e)}{\zeta(\tau_r)}\,\frac{d\ P(\tau_e)}{d\ \tau_e}\,\frac{d\ \tau_e}{d\ \tau_r} && \text{(2-22)}\\
&= \ \frac{P(\tau_e)}{\zeta^2(\tau_r)}\left[\zeta(\tau_r)\,\frac{d\zeta(\tau_e)}{d\ \tau_e}\frac{d\tau_e}{d\ \tau_r} - \zeta(\tau_e)\,\frac{d\zeta(\tau_r)}{d\ \tau_r}\right] && \text{(2-23)}\\
&\quad + \frac{\zeta(\tau_e)}{\zeta(\tau_r)}\frac{dP(\tau_e)}{d\ \tau_e}\frac{d\tau_e}{d\tau_r} && \text{(2-24)}
\end{aligned}$$

Based on our model, all the quantities are known but for $d\ \tau_e/d\ \tau_r$. However we can determine this term by applying the constraint that the distance between source and observer, s, is a constant (to examine the case of relative motion between source and observer, see the problem sets in Section 8). Starting with Equation 2-7

$$s \ = \ \bar{c}\ \left(Z(\tau_r) \ - \ Z(\tau_e)\right) \tag{2-25}$$

we take derivatives with respect to the time the light is received

$$\frac{d}{d\ \tau_r}\left(\frac{s}{\bar{c}}\right) \ = \ \frac{d\ Z(\tau_r)}{d\ \tau_r} \ - \ \frac{d\ Z(\tau_e)}{d\ \tau_e}\,\frac{d\ \tau_e}{d\ \tau_r} \tag{2-26}$$

which, since s is assumed constant, and $dZ/d\tau = \ \zeta$, yields

$$0 \ = \ \zeta(\tau_r) \ - \ \zeta(\tau_e)\ \frac{d\ \tau_e}{d\ \tau_r} \tag{2-27}$$

and reduces to

$$\frac{d\ \tau_e}{d\ \tau_r} \ = \ \frac{\zeta(\tau_r)}{\zeta(\tau_e)} \tag{2-28}$$

This expression is basically the equation for the "slowing-down" effect referred in some c-decay rebuttals. Processes in distant space would appear to run slower than the same process near Earth. Installing this result into Equation 2-24 and performing some cancellation, we obtain:

$$\frac{d\,P(\tau_r)}{d\,\tau_r} = P(\tau_e)\left[\frac{1}{\zeta\,(\tau_e)}\,\frac{d\zeta\,(\tau_e)}{d\,\tau_e} - \frac{\zeta\,(\tau_e)}{\zeta^2\,(\tau_r)}\,\frac{d\zeta\,(\tau_r)}{d\,\tau_r}\right] + \frac{dP(\tau_e)}{d\,\tau_e} \tag{2-29}$$

We now have an expression for $dP(\tau_r)/d\tau_r$, the change in period as measured by the receiver of the signal. We see that it has two components. One, $dP(\tau_e)/d\tau_e$, is the intrinsic change in the period of the source, measured at the time of emission, τ_e. The other term is the apparent change in the period of the source due to the change in speed of the signal travelling to the observer.

2.4. Why Supernovae Reflections are Bad Diagnostics for the Value of c at Distant Locations

Recently, the light from SN 1987A was observed after it excited gases near the remnant. Knowing the angular distance on the sky and the time since the explosion was first observed, along with some simple assumptions about the shape of the remnant, it is possible to obtain a distance estimate to the supernova which turned out to be close to the result obtained by other methods(Panagia et al. 1991; Gould 1994). In this calculation, the speed of light is used and one might be tempted to regard this as additional evidence that the speed of light was the current value 100,000 years ago when the star originally exploded. Unfortunately, this is not the case. Consider

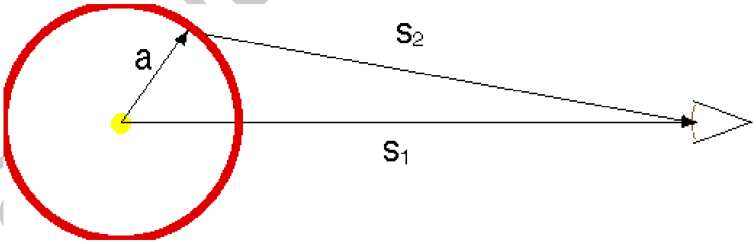

Fig. 3.— Geometry for the supernova reflection analysis. Some photons emitted from the supernova (yellow) travel a distance, s_1 directly to the observer, while others are absorbed and re-emitted at the ring of material from the stellar wind (red) before traveling to the observer, travelling a total distance $a + s_2$.

Figure 3. Photons travel from from the original point of the supernova (the yellow dot on the left) a distance s_1 to the observer (the eye on the right). Other photons travel from the initial point of the explosion to a ring of material around the supernova (the red ring) at a distance, a, around the remnant. From there, they excite atoms to radiate (for this analysis we'll assume this process to be instantaneous) which sends their photons to the observer a distance s_2 from the ring. By comparing the time it takes for different points on the ring to fluoresce, one can obtain both the size and orientation of the ring. Knowing the angular size of the ring on the sky, one can then deduce the distance to the supernova.

One would think that the assumption that the speed of light is the present day value at the location of the supernova would be key in this calculation. However, consider photons emitted from the explosion at (dynamical) time τ_e and arrive at the observer at time τ_{r1} after travelling the distance, s_1. Mathematically:

$$s_1 \;=\; \bar{c} \int_{\tau_e}^{\tau_{r1}} \zeta(\tau)\; d\tau \tag{2-30}$$

Other photons strike the ring at some intermediate time, τ_r, (having travelled the distance a) and are "reflected" towards the observer to arrive at time τ_{r2}. We write this as:

$$\begin{aligned} a + s_2 \quad &= \quad \bar{c} \int_{\tau_e}^{\tau_r} \zeta(\tau)\; d\tau \;+\; \bar{c} \int_{\tau_r}^{\tau_{r2}} \zeta(\tau)\; d\tau && \text{(2-31)} \\ &= \quad \bar{c} \int_{\tau_e}^{\tau_{r2}} \zeta(\tau)\; d\tau && \text{(2-32)} \end{aligned}$$

What is the time difference between the arrival of the direct and reflected photons? Let's compute the differences in the distances that the two sets of photons must travel, $a + s_2 \;-\; s_1$:

$$a + s_2 \;\; - s_1 = \;\bar{c} \int_{\tau_e}^{\tau_{r2}} \zeta(\tau)\; d\tau \;-\; \bar{c} \int_{\tau_e}^{\tau_{r1}} \zeta(\tau)\; d\tau \tag{2-33}$$

Again, using some basic rules for manipulating the limits in integral equations, we see:

$$\begin{aligned} a + s_2 \;\; - s_1 \quad &= \quad \bar{c} \int_{\tau_e}^{\tau_{r2}} \zeta(\tau)\; d\tau \;+\; \bar{c} \int_{\tau_{r1}}^{\tau_e} \zeta(\tau)\; d\tau && \text{(2-34)} \\ &= \quad \bar{c} \int_{\tau_{r1}}^{\tau_{r2}} \zeta(\tau)\; d\tau && \text{(2-35)} \end{aligned}$$

Here we see the (somewhat) counterintuitive result that the differences in arrival times of the photons will depend only on the value of the speed of light at the *observer* between the two times in question. Therefore, if, as Setterfield claims, the speed of light has been constant since about 1967, any direct and reflected photons received after that time will only indicate that the speed of light is at its present day value.

We can see this result in an intuitive way, but we must consider the entire travel path of the photons. The photons which travel directly to the observer travel a distance s_1 in some time τ_d. The photons along the other path will travel the same distance in the same time so at time τ_d, they will be a distance $a + s_2 - s_1$ from the observer. How long will these photons take to cross this last distance to the observer? It will be based on the speed of the photons after the time τ_d which, in the case where the speed of light has dropped to a constant value in recent decades, will take a time $(a + s_2 - s_1)/\bar{c}$ - the same amount of time if the speed of light had been constant the entire time.

While timing studies of reflections will not reveal information about changes in the speed of light at distant locations, studies of the spacing of spectral lines from these sources can reveal changes in atomic properties which are dependent on the speed of light at the time of emission.

2.5. c-Decay and Redshift Measurements I: The Dynamical Time Scale

The important issue to understand in computing frequency or wavelength changes in a signal propagation problem is that it depends on the times of emission of wavecrests from the source and the times of reception of those wavecrests by the receiver. For an introduction on how this is computed for the classical and relativistic Doppler shifts, as well as the cosmological redshift, see Appendix A.

Now let's examine computing a frequency change in the Setterfield hypothesis. We'll start with the case of light frequencies defined as constant in dynamical time. Setterfield claims emission mechanisms are defined in atomic time and we'll treat that case in section 2.6.

We start with Equation 2-21. Let the periods, P, be the time between successive wavecrests in an electromagnetic wave (so $P = 1/\nu$, where ν is the frequency). The fundamental relation for waves between frequency, wavelength, and wavespeed is

$$c = \lambda\nu \tag{2-36}$$

Using the speed of light at the points of emission and reception, respectively, we compute the wavelengths at these two locations:

$$\lambda_e \;=\; P(\tau_e)\;\bar{c}\;\zeta(\tau_e) \tag{2-37}$$

$$\lambda_r \;=\; P(\tau_r)\;\bar{c}\;\zeta(\tau_r) \tag{2-38}$$

Now let's compute the received wavelength, λ_r, in terms of the emitted wavelength, λ_e:

$$\begin{aligned}
\lambda_r &= P(\tau_r)\;\bar{c}\;\zeta(\tau_r) && \text{(2-39)}\\
&= \left[P(\tau_e)\,\frac{\zeta(\tau_e)}{\zeta(\tau_r)}\right]\;\bar{c}\;\zeta(\tau_r) && \text{(2-40)}\\
&= \left[\frac{\lambda_e}{\bar{c}\;\zeta(\tau_e)}\;\frac{\zeta(\tau_e)}{\zeta(\tau_r)}\right]\;\bar{c}\;\zeta(\tau_r) && \text{(2-41)}
\end{aligned}$$

which, after some cancellation, generates the interesting result:

$$\lambda_r \;=\; \lambda_e \tag{2-42}$$

Opps!! The received wavelength is the same as the emitted wavelength so there is *no* redshift! This is not unexpected. After all, we previously determined that the distance between pulses (and wavecrests), will not change during propagation in the case were the speed changes instantaneously everywhere.

However, our convention of using wavelength for computing the redshift is based on the assumption that the speed of light is a constant. If it is not, we need to also examine possible changes in frequency between emission and reception.

Since we know that there is a change in period between the emission and reception, let's remap the definition in terms of frequency. First, we must return to the fundamental definition of the redshift, z

$$z = \frac{\lambda_r - \lambda_e}{\lambda_e} \tag{2-43}$$

If we substitute in the definition of wavelength in terms of frequency (Equation 2-36) using the speed of light today, $\bar{c}$, this becomes

$$z = \frac{\bar{c}/\nu_r - \bar{c}/\nu_e}{\bar{c}/\nu_e} \tag{2-44}$$

$$= \frac{\nu_e}{\nu_r} - 1 \tag{2-45}$$

$$= \frac{P(\tau_r)}{P(\tau_e)} - 1 \tag{2-46}$$

$$= \frac{\zeta(\tau_e)}{\zeta(\tau_r)} - 1 \tag{2-47}$$

$$\tag{2-48}$$

where we use the definition that frequency is the inverse of the period, $\nu = 1/P$. With this equation, we can see that if the photons are emitted from a location where the speed of light is, say, 10^4 of it's present day value, then $z = 9,999$. If we compare this result to Setterfield's graph at Dolphin (1987), we immediately see a discrepancy. The right side of the graph displays z values less than unity and the corresponding values of light-speed on the left side are measured in the millions of times the current value.

How did Setterfield get this result? Again, there is no consistent answer to this crucial part of his model. We should note that at the time of this writing (May 2006), the highest confirmed quasar redshift is $z = 6.4$(Fan et al. 2003) and the highest galactic redshift is $z \approx 7$(Egami et al. 2005). The cosmic microwave background radiation corresponds to a redshift of $z \approx 1100$ (Kolb and Turner 1990, p.14). In addition, we should examine whether the redshift would be observed to undergo changes over time. By analogy with our analysis in Section 2.3, we compute $dz(\tau_r)/d\tau_r$

$$\frac{d\, z(\tau_r)}{d\, \tau_r} = \frac{d}{d\tau_r}\left[\frac{\zeta(\tau_e)}{\zeta(\tau_r)} - 1\right] \tag{2-49}$$

$$= \frac{1}{\zeta^2(\tau_r)}\left[\zeta(\tau_r)\frac{d\zeta(\tau_e)}{d\,\tau_e}\frac{d\tau_e}{d\,\tau_r} - \zeta(\tau_e)\frac{d\zeta(\tau_r)}{d\,\tau_r}\right] \tag{2-50}$$

$$= \frac{1}{\zeta(\tau_e)}\frac{d\zeta(\tau_e)}{d\tau_e} - \frac{\zeta(\tau_e)}{\zeta^2(\tau_r)}\frac{d\zeta(\tau_r)}{d\tau_r} \tag{2-51}$$

where we've made use of Equation 2-28.

2.6. c-Decay and Redshift Measurements II: The Atomic Time Scale

In Section 2.5 the calculations assume that spectral processes at the source point, frequencies and wavelengths, are constant on the dynamical time scale. However, in Setterfield's model, he assumes that atomic and nuclear processes operate on a faster timescale. Mathematically, we would write this as

$$\zeta\left(\tau\right)=\frac{dt}{d\tau}>1. \tag{2-52}$$

At the point of emission, τ_e, frequencies are higher than their value measured at τ_0, our current time, ν_0 by a ratio written mathematically as

$$\nu\left(\tau_e\right)=\frac{\zeta\left(\tau_e\right)}{\zeta\left(\tau_o\right)}\nu_o \tag{2-53}$$

This tells us the frequency (measured in dynamical time) at the point of emission, $\nu\left(\tau_e\right)$. We now recast Equation 2-13 into frequency measurements using $P=1/\nu$:

$$\frac{1}{\nu\left(\tau_r\right)}=\frac{\zeta\left(\tau_e\right)}{\zeta\left(\tau_r\right)}\frac{1}{\nu\left(\tau_e\right)} \tag{2-54}$$

Inserting our previous results for the frequency at the point of emission:

$$\begin{aligned}
\nu\left(\tau_r\right) &= \frac{\zeta\left(\tau_r\right)}{\zeta\left(\tau_e\right)}\nu\left(\tau_e\right) && \text{(2-55)}\\
&= \frac{\zeta\left(\tau_r\right)}{\zeta\left(\tau_e\right)}\frac{\zeta\left(\tau_e\right)}{\zeta\left(\tau_o\right)}\nu_0 && \text{(2-56)}\\
&= \frac{\zeta\left(\tau_r\right)}{\zeta\left(\tau_o\right)}\nu_0 && \text{(2-57)}
\end{aligned}$$

But since the time of reception, τ_r is the time of the rest measurement, τ_0, this expression reduces to the not-so-surprising result

$$\nu\left(\tau_r\right)=\nu_o \tag{2-58}$$

so we measure *no* change in frequency from the distant source compared to measurements in Earth-based laboratories.

In essence, Setterfield's separate atomic/dynamical time scales linked via the speed of light cannot produce a frequency change for atomic processes at all!

Up to this point, the analyses performed in Sections 2.2, 2.3, and 2.4 have yielded results that are independent of our choice of the functional form of $\zeta(\tau)$. If we want to proceed further into making specific predictions, we must add more detail in specifying our model.

3. Analysis of Simple c-Decay Models

Now that we have some generic expressions for phenomena that would be observed in a universe with a variable speed-of-light, we perform some tests in the case of a simple variable-c model. This gives us a chance to get a feel for the magnitude of the quantities we seek to measure and test the computer software which will enable us to test a wider range of models.

3.1. A Class of Power-Law Decay Models

In this section, we'll consider a more 'realistic' model for $\zeta(\tau)$ which possesses some of the general characteristics of the Setterfield model. As in the earlier analysis, we'll let τ designate the dynamical time and we'll look for a function such that $\zeta(\tau)$ can have a very large value at $\tau = 0$ and goes to unity at some future time, $\tau = T$. We'd also like the function to have a few 'free' parameters that we can adjust to examine a wider range of models. After some trial-and-error, we'll settle on

$$\zeta\,(\tau) \;=\; \begin{cases} 1 \;+\; A\,(T \;-\; \tau)^{\alpha}, & \tau \;<\; \mathrm{T} \\ \qquad 1, & \tau \;\geq\; \mathrm{T} \end{cases} \tag{3-1}$$

which has a number of desirable characteristics. When the index α is unity, the speed-of-light will decrease in a linear fashion - one of the simplest models we could choose. When $\alpha > 1$, the change in the speed will be non-linear with the property that it is large, but finite when $\tau = 0$ and gently approaches unity as $\tau \;\rightarrow\; \mathrm{T}$. The quantity A is a normalization factor.

We'd like to examine a series of models corresponding to a universe of a specific size and this choice of model gives us some of this freedom. To determine this constraint, we want

$$D \;=\; c\int_0^T \zeta\;(\tau)\;d\;\tau \tag{3-2}$$

where D is the distance to the most distant observable feature in our model cosmos and T is the amount of dynamical time we want for the light from that object to reach the observer. Applying to our Model (Equation 3-1), we find

$$\begin{aligned} D \;&=\; \int_0^T \left[1 + A(T-\tau)^{\alpha}\right]\,d\;\tau \\ &=\; \left[\tau \;-\; \frac{A}{\alpha+1}(T \;-\; \tau)^{\alpha+1}\right]_0^T \\ &=\; T \;+\; \frac{A}{\alpha+1}\;T^{\alpha+1} \\ &=\; T\,\left(1 \;+\; \frac{A}{\alpha+1}\;T^{\alpha}\right). \end{aligned} \tag{3-3}$$

We would prefer to analyze a class of models with different values of α subject to the constraint that they correspond to a universe of the same size, D, and same dynamical age, T. To do this, we need to determine the normalization parameter, A. With some basic algebra, we solve equation 3-3 for A to find

$$A \; = \; \frac{\alpha+1}{T^{\alpha}} \left(\frac{D}{c\,T} \; - \; 1 \right) \tag{3-4}$$

Now we can generate some 'model universes' where $D \; = \; 14.8 \times 10^9$ years and $T = 7800$ years. Figures 4-5 show samples of these models.

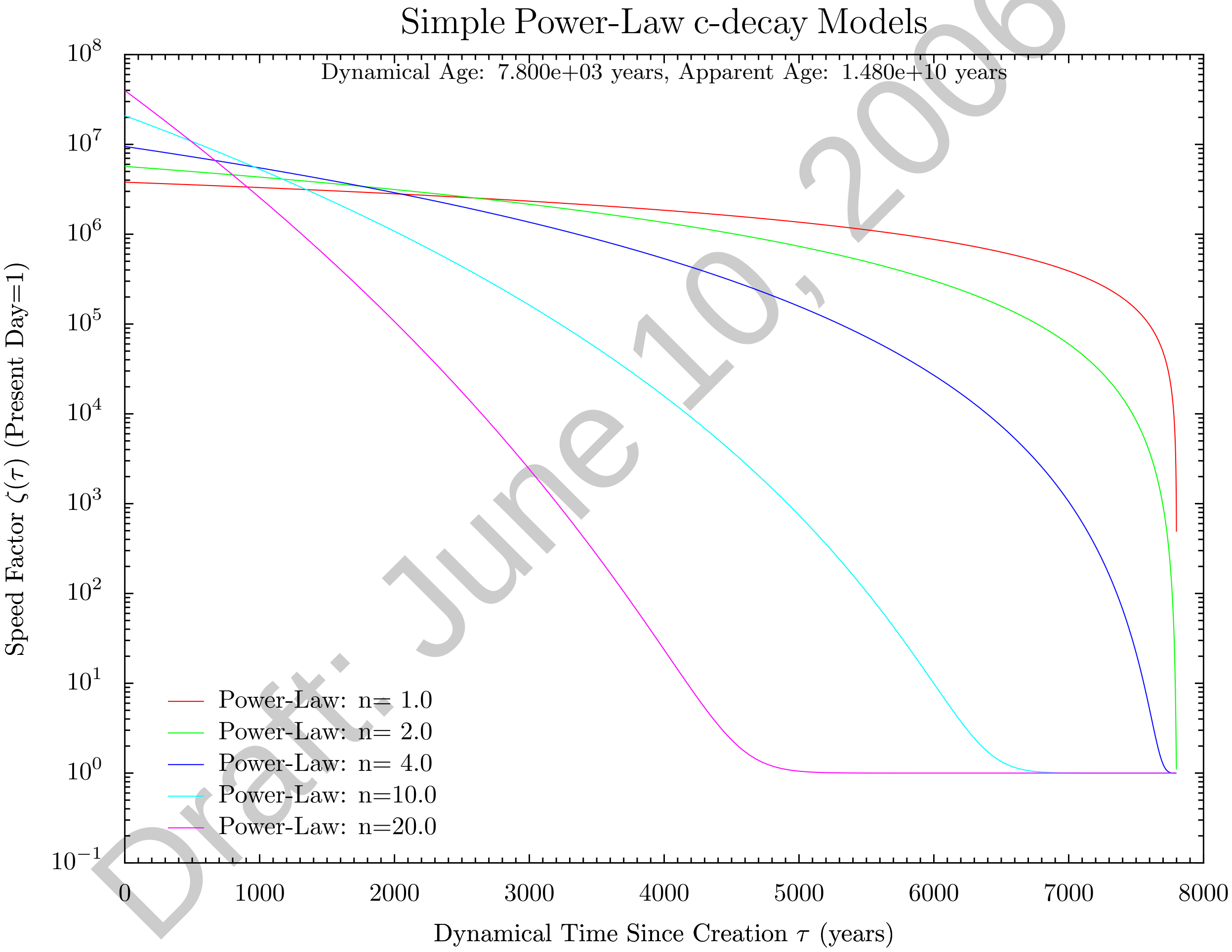

Fig. 4.— Plot of $\zeta(\tau)$ vs. τ for the simple power-law model for a set of values of the power-law index.

4. Dynamical Issues with Changing 'Constants'

The speed of light is not an isolated physical constant, but is interlinked with many other physical phenomena and variation of one 'constant' can have far-reaching implications. Setterfield attempts to deal with these issues by invoking variation in a host of other physical constants,

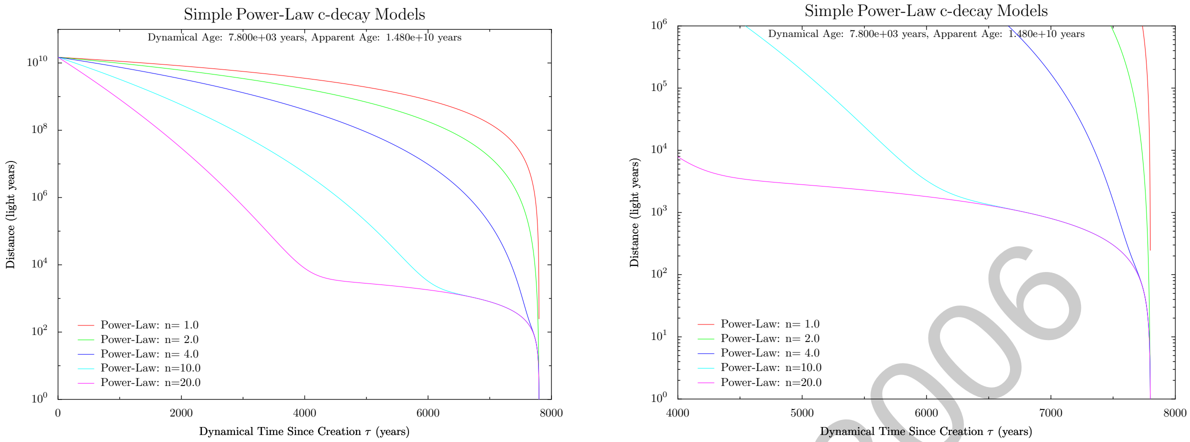

Fig. 5.— Plot of the 'look-back' time at a given distance for photons received at $\tau = 7800$ years for the simple power-law model for a set of values of the power-law index. The left graph covers cosmological distances while the right graph displays distances on a galaxy-size scale.

such as the fine-structure constant and other quantities. These decisions lead him into even larger problems.

One of the initial arguments against such a radical change in the speed of light was that through Einstein's mass-energy equivalence, $E = mc^2$, if c were extremely large in the not-so-distant past, the energy released by the nuclear isotopes in the Earth interior would be sufficient to keep the surface of the Earth unlivable even thousands of years ago(Strahler 1999, p. 118). Setterfield tries to address this by claiming that masses change such that $E = mc^2 = constant$ over cosmic history. In our notation, this means

$$m(\tau) = \bar{m}/\zeta(\tau)^2 \tag{4-1}$$

where the $\bar{m}$ on the right-hand side of the equation is the mass measured today. So in the past, masses were much lower than their present value.

However, this creates another problem. For a circular orbit, the orbital period is easily shown from Newtonian gravity, to be

$$P_{orbital} = 2\,\pi\sqrt{\frac{r^3}{G\;m}} \tag{4-2}$$

which Setterfield claims is basically a constant over cosmic history (assuming no tidal braking, etc.). Assuming that the orbital radius remains constant, if m changes, the orbital period is no longer constant, so Setterfield revises his hypothesis to claim that actually $G\,m$ is constant which fixes the orbital period problem. With this change, it means everywhere we see G, we must replace it with

$$G(\tau) = \bar{G}\;\zeta(\tau)^2 \tag{4-3}$$

where the $\bar{G}$ on the right hand side of the equation is the gravitational G measured today.

The final 'changing constant' we will consider is Planck's Constant, h. If c alone is changing, then the Fine Structure Constant, $\alpha = e^2/hc$ will vary and this would create a shift in the spectral lines of some elements. A *very small* possible variation in α has been reported (Webb et al. 1998) in distant quasars, but this is as yet inconclusive. However, if c changes as dramatically as Setterfield claims, α would be subject to considerably larger variation. To alleviate this, he proposes that the electric charge, e, is constant, and that Planck's constant, h, varies such that $hc = constant$. This means we must perform the replacement

$$h(\tau) = \bar{h}/\zeta(\tau) \tag{4-4}$$

Setterfield goes on to propose other alterations to the underlying physics, but these are sufficient to demonstrate additional fundamental problems with Setterfield's hypothesis.

4.1. Implications with Conservation of Momentum

Consider the energy equation for a particle of mass, m, moving with (vector) velocity $\vec{v}$. It's linear momentum, another conserved quantity, is

$$\vec{P} \;=\; m\,\vec{v} \tag{4-5}$$

Replacing m with it's corresponding Equation 4-1, we obtain

$$\vec{P}\,(\tau) \;=\; \frac{1}{\zeta\,(\tau)^2}\,(\bar{m}\;\vec{v}) \tag{4-6}$$

and we see that now momentum is increasing with time.

You might point out, and correctly so, that these quantities scale together, that the ζ factors will exactly cancel in any interaction and even in the distant past, a collision of billiard balls will behave exactly the same then as now.

4.2. Problems with Conservation of Angular Momentum

Consider the definition of angular momentum for a particle of mass, m, moving with (vector) velocity $\vec{v}$ and position $\vec{r}$ with respect to some reference point. Its angular momentum, another conserved quantity, is

$$\vec{L} \;=\; m\,\vec{v}\;\times\;\vec{\mathrm{r}} \tag{4-7}$$

and if we install the Setterfield hypothesis, this becomes

$$\vec{L} \;=\; \frac{1}{\zeta\,(\tau)^2}\,[\overline{m}\;\vec{v}\;\times\;\vec{\mathrm{r}}] \tag{4-8}$$

Again, we have the angular momentum varying with time the same as the linear momentum, but there's an added complication.

Equation 4-4 gives the variation of Planck's constant with time. But Planck's constant, in the form of $h/2\pi$ is also the quantum unit of angular momentum. Therefore, the total angular momentum of a system with orbital and spin angular momentum would be

$$\vec{L} \; = \; \frac{1}{\zeta\left(\tau\right)^{2}}\left[\overline{m}\;\vec{v}\;\times\;\vec{\mathrm{r}}\right] \; + \; \frac{1}{\zeta\left(\tau\right)}\frac{\overline{h}}{2\;\pi}\;s \tag{4-9}$$

where s is the spin quantum number. The total angular momentum, $\vec{L}$ no longer scales in a simple form with τ, unless $\zeta(\tau) = 1$, i.e. the speed of light is unchanging. This suggests that orbital angular momentum may have some additional interactions with the electron spin and that these would vary with cosmic age. We could expect shifts in atomic energy levels in multi-electron atoms due to the interactions between the spin and orbital magnetic moments. This issue would require further study to determine it's full implications.

4.3. Problems with Conservation of Energy

Consider the energy equation for a particle of mass, m, moving with velocity v, in a gravitational field of a body of mass, M, at a distance, r. It has a total energy of

$$E \; = \; \frac{1}{2}\;m\;v^{2} \; - \; \frac{G\;M\;m}{r} \tag{4-10}$$

If we install the Setterfield hypothesis, we must replace the value of G with Equation 4-3 and M and m with the corresponding Equation 4-1 we find

$$E\left(\tau\right) \; = \frac{1}{\zeta\left(\tau\right)^{2}}\left[\frac{1}{2}\;\bar{m}\;v^{2} \; - \; \frac{\bar{G}\;\bar{M}\;\bar{m}}{r}\right] \tag{4-11}$$

and discover that the total energy of the system is no longer constant, but, since ζ was larger in the past, must now be *increasing*. Because energy can change form, being stored as kinetic, potential, thermal, electromagnetic, etc., this can impact other areas as well. To see an impact on atomic issues, see Section 5.5.3.

Where is this energy coming from?

In addition, consider a system such as a star where the gravitational force is balanced by pressure from nuclear reactions. The gravitational binding energy of such a system was lower in the past based on the relation of Equation 4-11. If the nuclear reaction rates are assumed identical and the nuclear energy release is constant (per Setterfield's claim represented in Equation 4-1), how did these distant stars hold together when the gravitational binding energy is much lower? At the least, we would expect these stars to find a very different equilibrium point. This would require a detailed examination and solution of the equations of stellar structure (such as described in Clayton (1968, chapter 6)). We'll examine another impact, much closer to home, in Section 5.4.

5. The Setterfield Hypothesis Confronts Reality

5.1. Defining $\zeta(\tau)$ in the Setterfield Hypothesis

In this section, we'll apply the framework established in the previous sections to the specifics of the Setterfield model.

We will have to deal with this issue in two parts. As we previously note (Section 2.1), light travelling from the cosmos has two components which must be considered in its propagation to observers on Earth. First is the properties of the photons at the point of emission (in this case a distant star or galaxy), the wavelength, λ_e; frequency, ν_e, and, in the case of Setterfield's theory, speed $c\zeta(\tau_e)$. Second, we must consider how propagation through the cosmos and reception by the observer may change these properties. Standard cosmology and relativity indicate that the emission properties of atoms in a distant galaxy will appear identical to observers in that galaxy. It is the travel across the cosmos that causes the wavelength and frequency to change (see Appendix A.3 for the derivation).

To start, we must determine the form of $\zeta(\tau)$ over the scale of cosmic time. Setterfield has changed his published values over the years but I will try to examine the ones that I have encountered. I have yet to see a complete, consistent, or even *usable* dataset from Setterfield that is good for any calculation other than the ones he presents. Nonetheless, we must construct a complete $\zeta(\tau)$ curve based on the mish-mash of "data" he has presented over the years for any type of viable hypothesis testing. After all, how can *any* theory become accepted if it can't be used by others to apply to other observations?

5.1.1. *Changes In c Over the Past 250 Years*

To start this construction process, we'll use the function for the speed of light over the past 250 years specified at Dolphin (2003)

$$c(\tau) = 299792 + 0.031(1967.5 - \tau_{Gregorian})^2 \tag{5-1}$$

where $\tau_{Gregorian}$ is the Gregorian year. This equation applies for times prior to 1967, after which Setterfield assumes c reaches it's presently measured constant value. While the original document uses the symbol t to specify the time in this equation, it's unclear whether Setterfield means the dynamical time or the atomic time. We'll assume that the time specified is the dynamical $\tau_{Gregorian}$ since that is the timescale where the speed of light is non-constant. We can rework the problem with the alternate interpretation in a future edition. Also, so our equation for $\zeta(\tau)$ stays greater than or equal to unity, for this analysis, we adopt $\bar{c} = 299792 km/sec$ for this subsection of the function. We must also map the Gregorian year into the dynamical time from the start of Creation.

Some of Setterfield's more recent writing suggest he may be abandoning this claim (see Section 5.1.3). I find this somewhat bizarre since he derived this function from historically measured values for the speed of light and his entire theory was built by extrapolating from these measurements. If he's now claiming these measurements are are not actual changes in the speed of light, that essentially kills his theory!

5.1.2. Changes In c Between 2560 B.C. and 1750 A.D.

In this range of years, Setterfield claims that mismatches between ages determined by tree-rings and carbon-dates show his variation in the speed of light(Setterfield 2003a). The function form he claims shows some additional increase in the past, eventually reaching a (local) maximum before decreasing over the range.

His justification for this model is unclear. I can agree that a seasonal variation (on the Earth's orbital timescale, i.e. Setterfield's dynamical timescale) would create well defined rings in tree growth. However, the atomic timescale, which controls the spectral frequencies and nuclear decay rates, is much faster than the dynamical scale. This means that other atomic processes, such as the chemical reactions governing the growth of the trees, are much faster as well. One would expect trees would process nutrients much faster so the actual distance between the rings would represent a faster rate of growth, thereby making the rings thicker. We would expect the rings to get thicker and thinner based on this scale. Is this observed beyond variation that can be attributed to climate changes?

5.1.3. Changes In c Prior to 2743 BC

Setterfield has presented a number of different values for the speed of light in early times(Dolphin 1987, 2003; Setterfield b). In this section, we'll collect them and try to organize them into some coherent form suitable for additional analysis. These are summarized in Table 1.

On examinating these tables, we note some issues of interest. It states that around 2304 BC, the speed of light has become *approximately* it's present day value. Naturally, this depends on one's definition of 'approximate'. By 'approximate', does Setterfield mean that Equation 5-1 is still valid, or is he abandoning his original claims of this large a variation in the speed-of-light over the past 250 years? I've found no details on Setterfield's site describing the reason for this change, but 'approximately' c could mean anywhere between $1.1 \times c$ to $1.00001 \times c$. Setterfield has gone from claiming very specific measured changes to a 'fuzzy' value. This is a common characteristic of failing theories - their advocates get more vague about the details that generate testable predictions. We will deal with this problem by presenting this dataset as *two* models, one with, the other without the recent variability.

Setterfield presents an additional functional form (Setterfield 2001) which we'll discuss later.

Table 1: Some claimed datapoints published by Setterfield

Calendar Year	τ (years)	Model A ζ	Model A 'Lookback'	Model B ζ	Model B 'Lookback'	Model C ζ	Model C 'Lookback'
-5800	-8			8.70×10^{7}	2.00×10^{10}		
-5792	0					1.06×10^{7}	1.48×10^{10}
-5650	142			6.53×10^{7}	1.50×10^{10}		
-5562	230						1.25×10^{10}
-5357	435						1.01×10^{10}
-5167	625						8.96×10^{9}
-4997	795						7.62×10^{9}
-4832	960						6.42×10^{9}
-4670	1122						5.34×10^{9}
-4505	1287	6.33×10^{6}	4.30×10^{9}	1.96×10^{7}	4.50×10^{9}	5.80×10^{6}	4.35×10^{9}
-4138	1654						3.35×10^{9}
-4136	1656	4.92×10^{6}	2.50×10^{9}	1.08×10^{7}	2.50×10^{9}	4.30×10^{6}	2.50×10^{9}
-3656	2136	3.09×10^{6}	8.30×10^{8}				
-3634	2158						8.16×10^{8}
-3536	2256	2.64×10^{6}	6.00×10^{8}	2.60×10^{6}	6.00×10^{8}		6.50×10^{8}
-3534	2258						5.96×10^{8}
-3399	2393						3.58×10^{8}
-3301	2491	1.74×10^{6}	2.30×10^{8}	1.10×10^{6}	2.30×10^{8}		
-3269	2523					1.10×10^{6}	1.96×10^{8}
-3139	2653					6.15×10^{5}	9.70×10^{7}
-3005	2787	6.15×10^{5}	6.30×10^{7}	6.15×10^{5}	6.30×10^{7}		6.30×10^{7}
-2875	2917					7.80×10^{4}	1.00×10^{6}
-2826	2966			7.00×10^{4}	1.00×10^{6}		
-2743	3049						5.00×10^{3}
-2304	3488					≈ 1	

5.1.4. Putting It All Together

All-in-all, it seems that since 1987 Setterfield has published as many as five different forms for the variation of the speed-of-light, but has yet to show the algorithm or data from which he obtained these values. With a bit of computer programming, we'll be able to examine all of these possibilities. For clarity, we will designate the five models 'Setterfield A', 'Setterfield B', 'Setterfield C', 'Setterfield D', and 'Setterfield E' and summarize them as

Setterfield A: 'Original' values published in a graph apparently from the original 1987 paper(Dolphin 1987).

Setterfield B: Values published in a table on Lambert Dolphin's web site(Dolphin 2003).

Setterfield C: Using the values from Setterfield (b), assuming that $\approx c$ means that Setterfield is still claiming variability since 2560 B.C. described above.

Setterfield D: Using the values from Setterfield (b), assuming that $\approx c$ means precisely today's value for the speed-of light with no variability since 2304 B.C.

Setterfield E: Uses the new function published in 2001(Setterfield 2001). This function has so many problems associated with it that it is almost unusable in this part of the analysis. For a detailed description of why, see Section 5.6.

We will construct a functional form for $\zeta(\tau)$ for the four Setterfield models, A through D. These four models choose their 'Creation Time' near 5800 B.C. For simplicity, we'll choose our $\tau = 0$ point at 5792 B.C. for all four models which matches precisely with Setterfield C & D and differs by only eight years for Setterfield A & B. With this origin, we can select a dynamical age of the universe of 7800 years which would correspond to the year 2008 A.D.

One of the greatest difficulties I encountered in the process of assembling these datasets was generating a smooth transition over the gap between 2743 B.C. and 2560 B.C., which exhibits a change in value on the order of 10^5. I cover the mathematical nuances of solving this problem in Appendix B.

Using these datasets, we can construct a set of continuous functions for the values of the speed of light over the range of dynamical time. We plot these results in Figure 6. Using the spline fits for these curves, we can integrate over time and compute the distance (or equivalent 'lookback time' in atomic years). In Figure 7, we compute the distance travelled by photons emitted in a given year (dynamical time) since creation which are arriving today (or more specifically, 2008 A.D.).

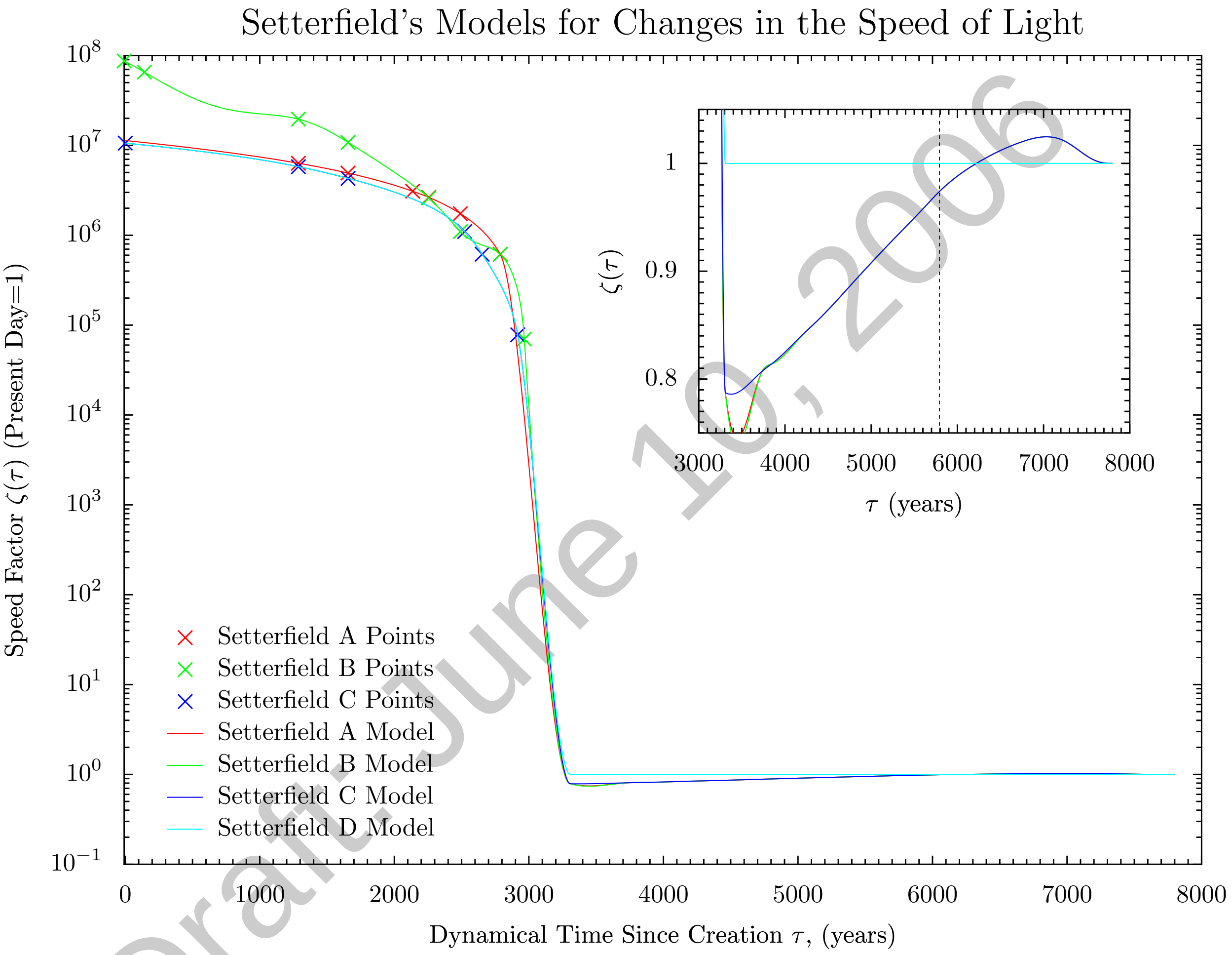

Fig. 6.— Setterfield Models values of ζ vs. time since Creation. The 'data' points correspond to speed of light specified in Table 1. 'Model' correspond to the functional form used to generate a piecewise-continuous function which needs to pass through these data points. Small amounts of curvature in the lines between the points are due to the logarithmic scaling of the graph. The inset shows a vertical rescaled view of the claimed more recent variation. See the text for additional details. The inset exhibits a slight difference between Setterfield A & B vs. C between year 3200 and 3700 which is due to a slight overshoot in the spline-fitting routine. This deviation does not seem to adversely affect other derived results.

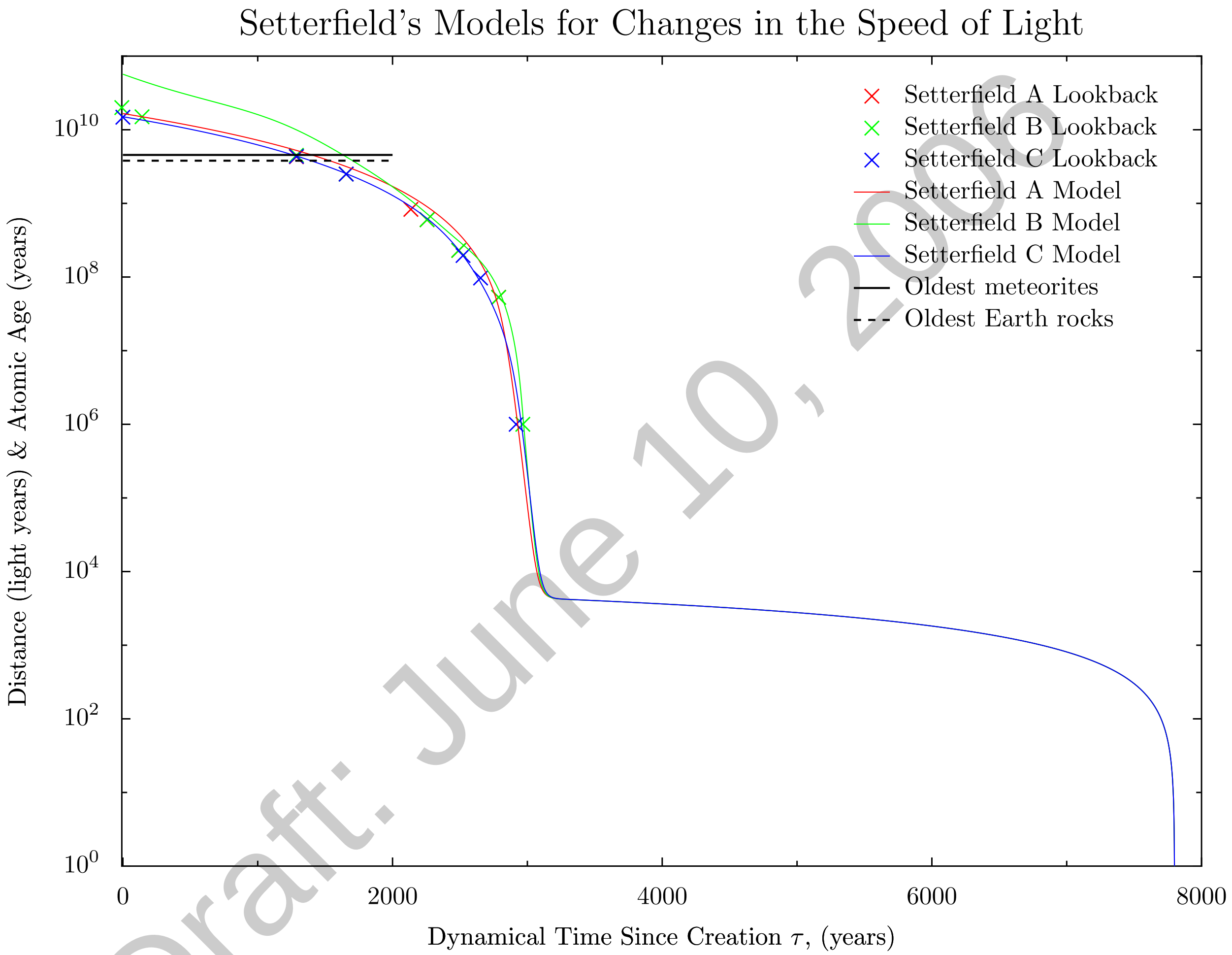

Fig. 7.— Comparison of lookback times computed from proposed ζ values and values published by Setterfield. Here, 'data' points correspond to the distances specified by Setterfield in Table 1. 'Model' corresponds to distance computed by evaluating equation 3-2 for the model form for $\zeta(\tau)$. The distances are computed at the given emission epoch, assuming a observation epoch of $\tau = 7800.0$ which corresponds to about 2008 A.D. A close match between the the points and the curve suggests Setterfield is using equation 3-2. The function 'Setterfield B' has the largest mismatch. 'Setterfield D' is not plotted in this graph since it is very close to 'Setterfield C' on this scale. See the text for additional details.

5.2. The Setterfield Hypothesis and Pulsar Observations

Pulsars provide some of the highest precision timing observations available in astronomy. In the first edition of this paper, I used the listing of the known pulsars and their timing information available in dataset 7156 at the Astronomical Data Center(ADC)(J.H. et al. 1993). The ADC has since closed but the data tables have been moved to the CDS repository(CDS). A newer catalog, larger and more up-to-date, is maintained by the Australia Telescope National Facility (ATNF) and documented in Manchester et al. (2004). We will utilize this dataset in this edition.

There have also been a number of interesting developments in the pulsar field since the first edition of this monograph.

The basic model, that pulsars are rotating compact objects, most likely composed of predominantly degenerate neutrons, with very strong magnetic fields, is still quite intact(Michel 2003), in spite of Setterfield's claims to the contrary. Some details of the emission mechanism, strong magnetic fields, and initial rotation rates are still subject to debate but these have no strong impact on the *observed stability* of the rotation. At the time of the first edition, only a few pulsars had distances determined by radio parallax(Chatterjee et al. 2001; Brisken et al. 2000; Toscano et al. 1999). That number has expanded considerably and I make use of this additional data in this edition.

As an example of how successful the current pulsar model still is, the distance to the Vela pulsar (PSR B0833-45) had a 'canonical' value of 500 parsecs based on measurements around the time of the pulsar's discovery. However, recent x-ray observations gave the model problems at that distance so some researchers adopted a smaller distance. These smaller distance estimates received more support recently when parallax measurements of the pulsar by the Hubble Space Telescope revised the distance to 294^{-50}_{+76} parsecs(Caraveo et al. 2001).

Isolated neutron stars (Walter 1997), and the Crab Pulsar (Hester and Scowen 1996) have also been imaged by the Hubble Space Telescope.

Because pulsars are powered by rotation, they are tied to Setterfield's dynamical time scale and can provide a (nearly constant) P_e as we have defined in the previous analyses. For the most part, isolated pulsars are observered to spin-down (P_e increases, so $\dot{P} = dP(\tau_e)/d\tau_e > 0$) as the interaction of the magnetic field and surrounding plasma converts the rotational energy into electromagnetic radiation. The precise location and micro-physics details of this mechanism are still subject to some debate, but these issues have little impact on the stability of the rotation mechanism.

Pulsars also experience periodic 'glitches' on short timescales where the spin period suddenly decreases. These are believed to be caused by a structural re-arrangement of the neutron star material, a 'starquake', to relieve structural stress. The redistribution decreases the moment of inertia of the star which increases its spin rate to conserve angular momentum. Some pulsars accrete material from companion stars and the angular momentum of the infall can increase the spin rate as well, but these are generally spin-rate increases on a much longer timescale than the glitches.

To map these observations into Setterfield's model, we first recognize that the periods and period changes observed are not necessarily P_e and $dP(\tau_e)/d\tau_e$, quantities intrinsic to the pular, but P_r and $dP(\tau_r)/d\tau_r$, the quantities measured by the Earth-based observer. These measured quantities must then be adjusted for the light-travel time effects to determine the quantities intrinsic to the pulsar. To start this analysis, for simplicity, we'll assume that the intrinsic pulsar spin period, P_e, measured in dynamical time, is a constant, so $dP(\tau_e)/d\tau_e = 0$.

We also want to examine quantities in a form where we can easily distinguish the observational quantities against the theoretical prediction. Such a quantity would be $dP(\tau_r)/d\tau_r/P(\tau_r)$ which can be constructed from the observed values. We compute the corresponding contribution of this value in Setterfield's hypothesis using Equations 2-21 and 2-29 combined with the assumption that $dP(\tau_e)/d\,\tau_e = \; 0$

$$\frac{d\;P(\tau_r)/d\;\tau_r}{P(\tau_r)} \;=\; \frac{P(\tau_e)\;\left[\frac{1}{\zeta(\tau_e)}\;\frac{d\zeta(\tau_e)}{d\;\tau_e} - \frac{\zeta(\tau_e)}{\zeta^2(\tau_r)}\frac{d\zeta(\tau_r)}{d\;\tau_r}\right]}{P(\tau_e)\;\frac{\zeta(\tau_e)}{\zeta(\tau_r)}} \tag{5-2}$$

which after some cancellation, yields

$$\frac{\dot{P}}{P} \;=\; \frac{\zeta\,(\tau_r)}{\zeta^2\,(\tau_e)}\frac{d\zeta\,(\tau_e)}{d\;\tau_e} - \frac{1}{\zeta\,(\tau_r)}\frac{d\zeta\,(\tau_r)}{d\;\tau_r} \tag{5-3}$$

To actually compare these quantities, we need to compute the left-hand side of Equation 5-3 for each pulsar available. This is easily done from the pulsar data tables. We lock the pulsar observations to Epoch 2008.0 This introduces a small error since each pulsar observation will be based on data from an earlier epoch and the spin period will have undergone a small change between that time and 2008 A.D. We leave it as an exercise for the student (Section 8) to estimate this error and determine if it significantly affects the results. We plot a point with the value of $d\;P(\tau_r)/d\;\tau_r/P(\tau_r)$ for each pulsar with respect to the pulsar distance.

Next we plot the value of the right-hand side of Equation 5-3. We've fixed the value of $\tau_r = 7800.0$ (2008.0 A.D.) and from this, we can compute the distance the signal has travelled since the time of emission, τ_e. We plot this result as a continuous function over the range.

We encounter a few issues in plotting. First, the values of interest tend to be small in absolute value. The ideal solution is to use a logarithmic vertical scale but a number of values are also negative which causes the logarithmic function to fail. We get around this problem by plotting the negative values separately from the positive values, and taking the absolute values of the data points. We designate the data sign information through the color and symbol used in plotting – black to indicate the positive values and red to indicate the negative values. The results are plotted in Figure 8.

If the pulsars' intrinsic period is constant, we expect the pulsar datapoints to lie along the path corresponding to a Setterfield model, in this case Setterfield C used in the graph. This is clearly not happening. If the pulsars have a small intrinsic spin-down, we expect the pulsar datapoints to be scattered in a small band around the curve of the Setterfield model. Again, this is not the case.

In the case of a constant speed of light, the left-hand side of Equation 5-3 evaluates to zero and the pulsar data points scatter in a narrow band around this value. This graphical result is more consistent with a constant speed of light and small instrinsic pulsar spin-changes than it is with the Setterfield model.

Is there a way around this problem? Not easily. One could try to tune each pulsar spin-down rate such that the differential signal travel time is exactly cancelled. Such fine tuning generates not just physical problems, but theological problems as well[1]. One could propose a mechanism where the pulsar spin-rate change is linked to the change in the speed of light such that this effect is cancelled, but Setterfield has not presented such a model.

Author's Correction Note: In the first edition of this paper, the graph corresponding to Figure 8 had a major error. That graph was generated using only Equation 5-1 which defined time as increasing into the past and flipped the sign of the relationship between distance to the object and the time of emission. This changes terms in the differential arrival time calculation so that $d\zeta/d\tau > 0$, which yielded $dP/d\tau > 0$. When I recently achieved a successful assembly of Setterfield's different data segments, I recognized that for time, τ, increasing into the future (the usual convention) that this value would be negated. This flips the sign of the values in this graph. While this changes some issues in the interpretation and implication of this effect, *it does not improve the agreement of Setterfield's model with the data.* In fact, because Setterfield claims some epochs where the speed of light decreases with time, the sign error becomes moot as he must now explain differences in both spin-up *a*nd spin-down behavior. Note that Equations 2-29 and 2-13 are still correct, they were only plotted erroneously.

5.3. The Setterfield Hypothesis and Binary Star Observations

High-precision period observations of pulsars have been made almost since the time of their discovery. Changes in the rotational period are an important parameter in understanding the energy budget for these objects. However, in the analysis above, the results are dependent on the model for the pulsar spin.

To remove this part of the model dependency, we'll go back to Setterfield's original claim that $GM = constant$ over cosmic history, as described in Section 4. All other things being equal, this means that the orbital periods of celestial objects will remain constant, providing another constant period 'clock' which can be used to determine if the travel time of light rays from the 'clock' to

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[1] Most notably the 'Deceiver God' problem.

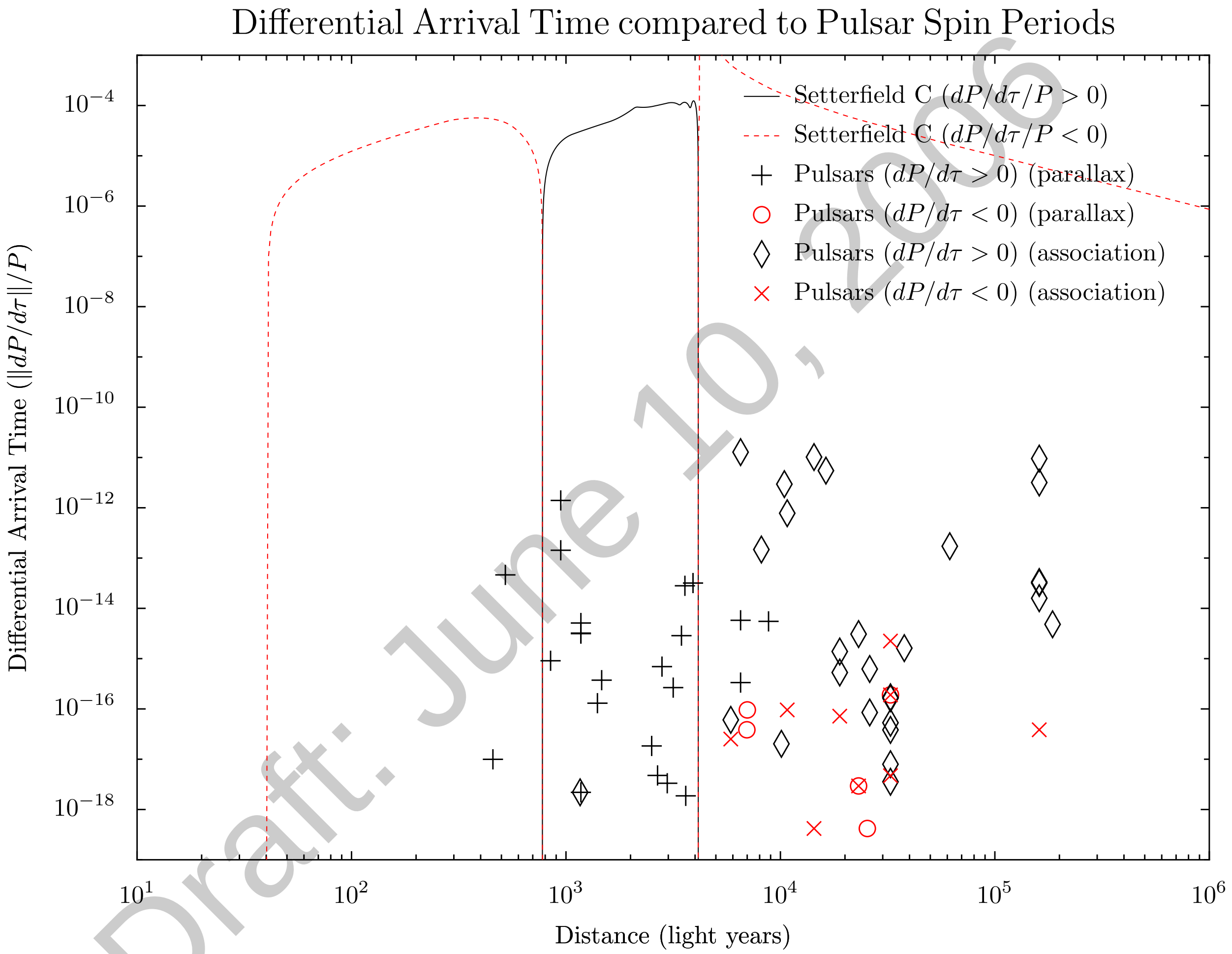

Fig. 8.— Setterfield Model Comparison to Pulsar Timing Data. The distances and curve are computed assuming a observation epoch of $\tau = 7800.0$ corresponding to about 2008 A.D. Pulsar data are plotted for pulsar distances determined by parallax and distances based on associations (Magellanic clouds, globular clusters, supernova remnants, etc.) where a reliable distance is available. Red datapoints and curves are actually *negative* data values. See authors correction note at the end of this section.

an observer on Earth has changed. For such a comparison, the best objects for this test will be distant binary stars. The stars must be distant since the speed of light must still be changing at the point of emission for the effect to be observed. The advantage of this is that gravitationally-bound binary star systems have been known for over two hundred years, so the baseline of observations is far longer than that available for pulsars. The downside is that many of these observations are not as precise as pulsar observations. Another issue is that period changes in binary star orbits has not been that intense a field of study so much more effort is required to find data of sufficient precision.

Tikkanen (1998) has performed an analysis which includes a binary star observation and is available online.

In recent years, however, a number of binary pulsars have been discovered and their orbits and timing have been measured to very high precision. Changes in these orbital periods have been used as tests of the General Theory of Relativity, particularly the issue of orbital energy loss by gravitational radiation. So far, these observations have matched the relativistic predictions to very high precision(Will 2006) and include the assumption that the speed of light has been constant.

Nonetheless, we plot period changes in Figure 9 and compare them to Setterfield's model.

Here again, we see that Setterfield's model still predicts a much larger differential arrival time, by factors of thousands and millions, than the observed relative period change.

5.4. Did Adam and Eve Suffocate?

Another consequence of a theory with distinct dynamical/gravitational and atomic timescales that Setterfield evades is what happens when a system's structure depends on the interaction of these two timescales. Gases in gravitational fields provide an excellent 'laboratory for these tests', such as the self-gravitating gaseous objects (such as stars) and planetary atmospheres. Here we will do an analysis that demonstrates that the implications of Setterfield's hypothesis are not always in difficult-to-measure distant space.

We can continue along these lines and examine the claim of mass changes described in Section 4. I have not found any reference where Setterfield invokes a change in the Boltzmann constant, k, which is important in thermodynamics and the gas laws[2].

Molecules in gases do not move at uniform speeds. Through multiple mutual collisions, their speeds are eventually distributed in the form of the Maxwell-Boltzmann distribution

$$f\left(v\right) = \frac{dN}{dv} = 4\pi\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} v^2 e^{-\frac{mv^2}{2kT}} \tag{5-4}$$

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[2] $1.3806503 \times 10^{-23} m^2\ kg\ s^{-2} K^{-1}$

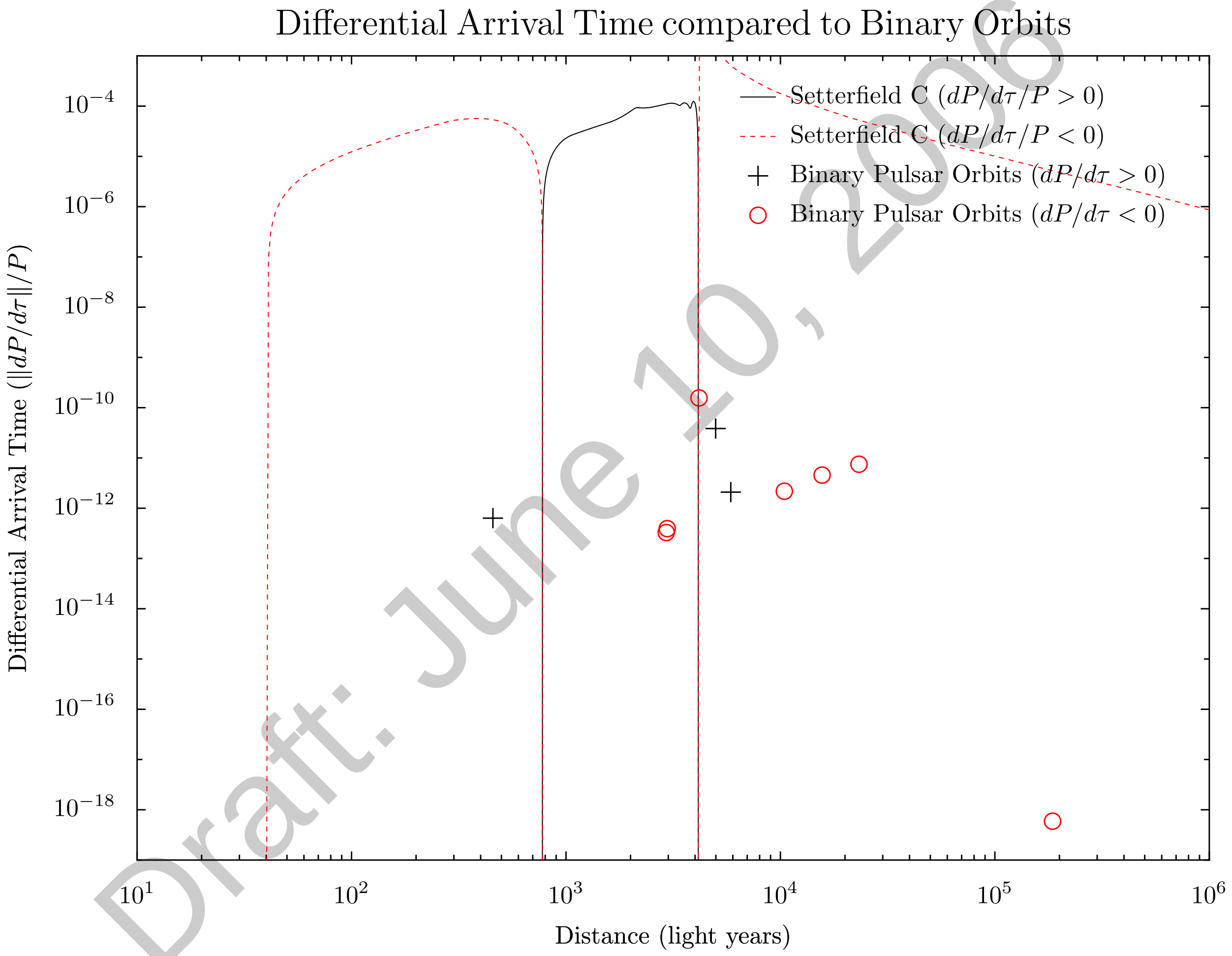

Fig. 9.— Setterfield Model Comparison to binary pulsar orbital period data. The distances are computed assuming a observation epoch of $\tau = 7800.0$ corresponding to about 2008 A.D. Red datapoints and curves are actually *negative* data values.

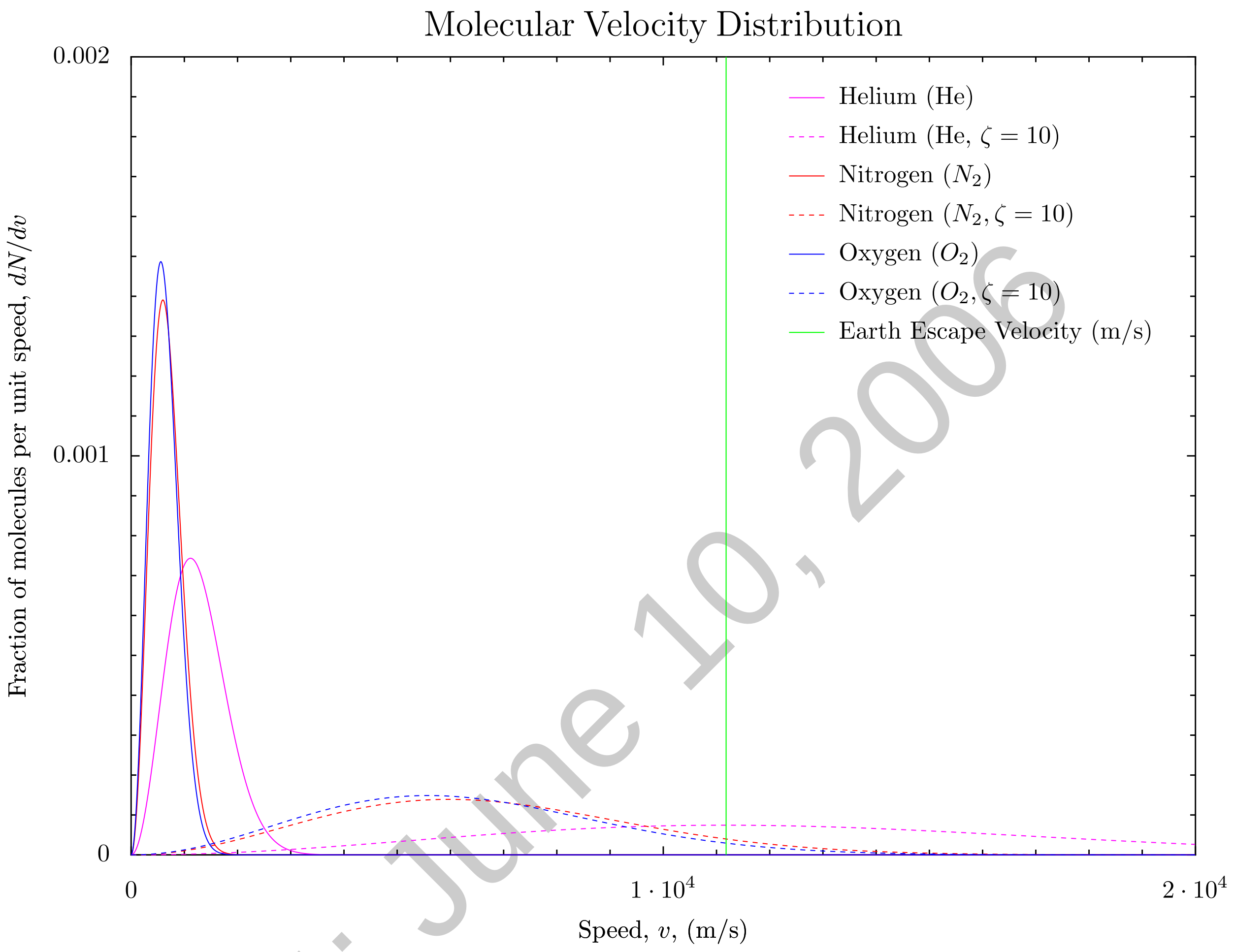

Fig. 10.— The Maxwell-Boltzmann distribution of some selected atmospheric gases at $T = 300K$. The solid lines represent molecular speeds distributions with present day masses. The dashed lines represent molecular speeds correspond to $\zeta = 10$.

which distributes the molecular velocities over a wide range. From Figure 10 we see that the vast majority of molecular oxygen and nitrogen molecules in the Earth's lower atmosphere have speeds below 2000 meters/sec. The vertical green line marks the escape velocity of the Earth

$$V_{escape} = \sqrt{\frac{2GM_E}{R_E}} \tag{5-5}$$

which we see is well above the molecular speeds. Only a very tiny fraction of the molecules can escape from the Earth into space.

However, this distribution is based on the molecules having their present-day mass. According to Setterfield, in the past, these molecules would be lighter, and we mean *much* lighter. If we go back to a time where $\zeta = 10$, corresponding to sometime between 2304 B.C. and 2826 B.C.[3], the molecular masses will be one percent of their present day value. Then we find that a much larger fraction of the molecules have speeds to the right of the green line, in excess of Earth's escape velocity. If Setterfield's claim that $GM = constant$ is correct, then this value of the escape velocity will be the same as it is today.

The problem gets even worse the further back into the past you go. In Figure 11, we plot the RMS molecular speed

$$V_{rms} = \left(\frac{3kT}{m}\right)^{\frac{1}{2}} \tag{5-6}$$

as a function of time with a changing atomic mass. Prior to $\tau = 3000$ (about 2800 B.C.), the Earth could not have retained an atmosphere as most of the atmospheric molecules would have speeds in excess of the Earth's escape velocity.

Setterfield could try to avoid this problem by allowing the Boltzmann constant to vary. However, this has strong implications for the Gas Laws and thermodynamic properties derived from them. Until/unless I find Setterfield claiming this, I'll leave it as a computational exercise for the interested student.

I'd like to thank Kari Tikkanen for pointing out this issue to me.

5.5. Setterfield's 'Quantization'

When Setterfield tries to apply quantum theory to his claims, his analysis and results go so wrong so quickly that a detailed analysis like the kinematical analysis in the previous section becomes nearly impossible. I will try to point out the errors at each step and may deal with a more refined analysis in a future edition.

Most of the comments in this section are directed to the analysis in Setterfield (2001). As we saw in sections 2.5 and 2.6, neither Setterfield's changing speed of light, combined with his dynamical or atomic time scales can create a redshift-distance relationship even close to what we currently observe.

When Setterfield starts invoking his interpretation of quantum theory, he seems to ignore all his prior claims of redshift due to a changing speed-of-light in favor of what is apparently a change in spectral characteristics at the point of emission, basically an 'intrinsic' redshift model. The errors he makes in this analysis are described in the next sections.

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[3] Setterfield's tables of speed-of-light vs. time are very steep in this region so the specific year is very sensitive to the functional form.

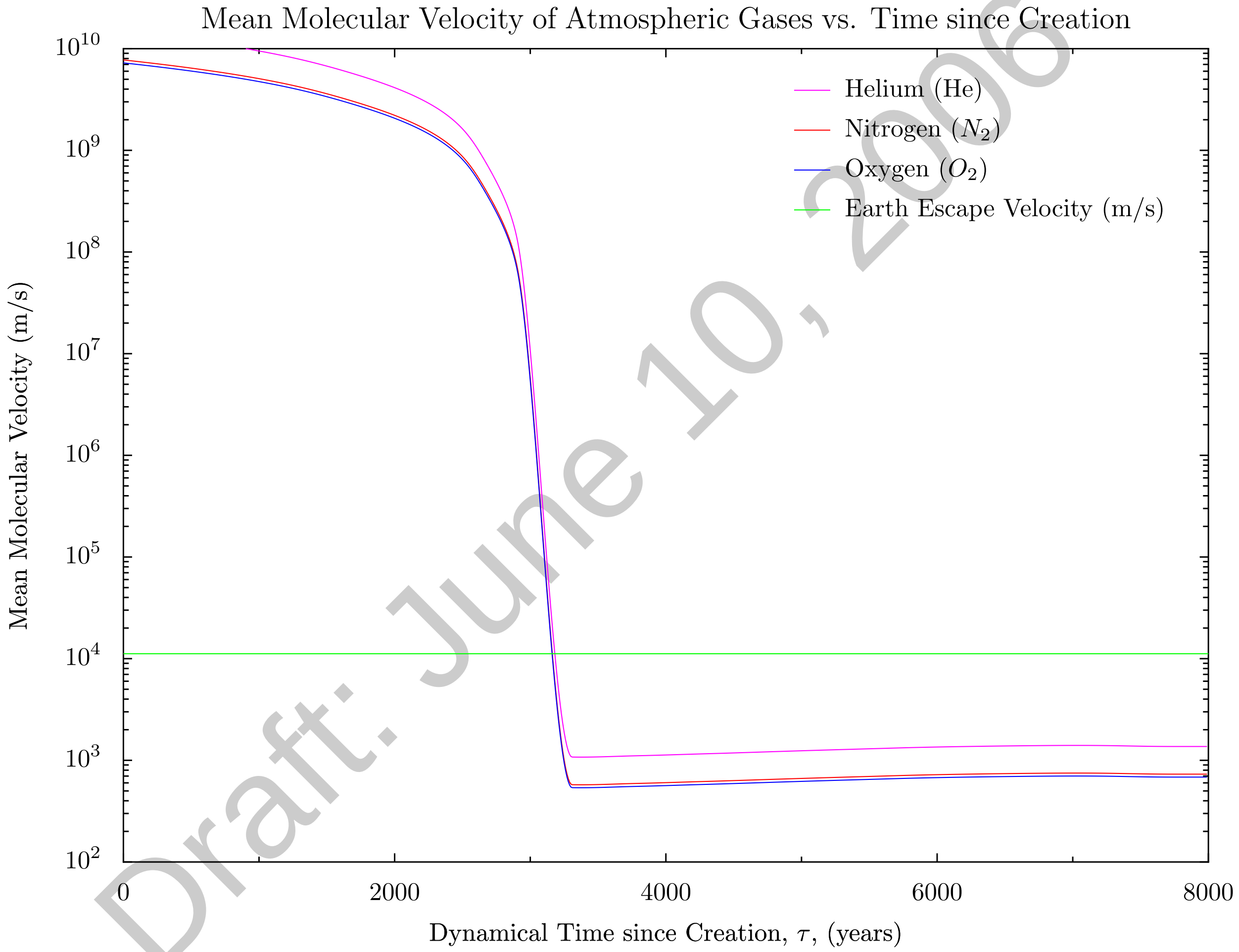

Fig. 11.— A plot of RMS molecular speed over time, using the model 'Setterfield C'. The green line again marks Earth's escape velocity. Prior to about $\tau = 3000 years$, there is no way the Earth could have retained an atmosphere.

5.5.1. *Use of Tifft's Quantization Claim*

W.G. Tifft(Tifft 1976, 1977, 1979, 1991) claims to have measured 'quantization' in extragalactic redshifts. Setterfield invokes these results to build a cosmological redshift model. Unfortunately, Tifft's redshift quantization results are highly dubious as it appears he is over-interpreting noise in his data samples when convolved through his analysis.

Galactic rotation curves reveal rotational velocities on the order of 200-300 km/sec(Mihilas and Binney 1981, pp 491-503.) that either spread the spectral line on both side of the galaxy's accepted redshift values, or shifts the values on either side of the redshift value. The behavior depends on the type of galaxy (spiral vs. elliptical) and the orientation of the spectral measurement slit.

Tifft claims to measure a quantization interval nearly an order of magnitude smaller than the width of the spectral line created by the motion of the stars and gas within the galaxy. If you plotted the position of each galaxy in a spectral coordinate, such as wavelength of a specific spectral line, the width of the galaxy in these coordinates would be larger than the separation in the quantization – the galaxies must overlap!!. It is difficult to determine just what could be getting "quantized" in a large extended object like a galaxy. In addition, redshift values exhibit a near gaussian distribution around a mean trend based on the Hubble Law. Gaussian distributed data are notorious for generating false periodicities in small datasets under many of the common tests for periodicities(Newman et al. 1994; Newman and Terzian 1996). This issue of false periodicities (created by large error bars) in small, gaussian-distributed samples is well-known to digital signal processing engineers as well(Bendat and Piersol 1986, pp. 278-290).

I had originally planned to write up a detailed discussion and samples in this section but the redshift quantization has been picked up by other creationists(Humphreys 2002) who generated a few additional issues to address. I will conduct that analysis in a future work.

5.5.2. *Use/Misuse of the Bohr Model*

In 1913, Niels Bohr discovered that he could compute the spectral lines of hydrogenic[2] atoms using the classical energy equation constrained by a quantum condition, that electrons travelled in orbits such that their wave nature would be reinforced, i.e. that the distance around a circular orbit had to be an integral number of wavelengths for the electron occupying that orbit. While this prescription was successful in this limited case, it gave grossly incorrect predictions for the angular momentum of atomic states and attempts to apply it to multi-particle systems met with failure. It would be over a decade before this problem was solved by totally replacing the Bohr model with the Schrodinger wave equation. The energy levels derived from the Bohr model could also be derived from the Schrodinger equation, but the Schrodinger equation generated correct results for a wider range of problems, including atomic angular momentum (once electron spin was discovered and incorporated) as well as being applicable to multi-electron atoms and molecules..

Today, all computations from first principles of atomic and molecular properties in physical chemistry use the Schrodinger equation or it's equivalent. Nonetheless, the Bohr model survives in introductory chemistry and physics classes as a simple illustration of quantum theory that is accessible to students with a limited mathematics background. Today, no legitimate scientists are doing *real* science using the Bohr model.

In spite of these facts, Setterfield bases his quantum mechanical work on the Bohr model, erroneously claiming that wave mechanics is a 'refinement' of the Bohr model. While this might be acceptable if the Bohr model generated the same results as predictions using the full quantum theory treatment, Setterfield never presents a full quantum theory treatment, probably because he has not performed such an analysis. I would suspect such a treatment would require, at the very least, the three-dimensional, time-dependent Schrodinger equation (for a non-relativistic analysis). However, using a relativistic wave equation, such as the Klein-Gordon or Dirac equations, would probably be more appropriate.

I'm sure Setterfield's 'refinement of the Bohr Model' statement would be a big surprise to all those researchers in quantum mechanics who are developing new semiconductors, molecular structure modeling and computational chemistry[4], exploring theoretical models for high-temperature superconductivity, high-speed computing and quantum computing. They probably haven't computed *anything* using the Bohr model since high-school chemistry.

In actual fact, this starting assumption is so erroneous and contradictory to experiment that *all* subsequent aspects of Setterfield's derivation are nonsense. However, we'll continue examining some of this for the entertainment value.

5.5.3. Misuse of the Energy Equation

Here we'll go into some of the details of just how poorly Setterfield compounds his mistakes. Not only does he incorrectly apply the Bohr model, but he then incorrectly calculates *within* that model.

Starting from almost the very first equation, Setterfield proceeds to make error after error. He starts out with an energy equation(Setterfield 2001, Equation 2)

$$E_t = E_k + E_p = \frac{e^2}{8\pi\varepsilon_o r} - \frac{e^2}{4\pi\varepsilon_o r} = -\frac{e^2}{4\pi\varepsilon_o r} \qquad (5\text{-}7)$$

---

[2] atoms and ions with a single electron

[4] Using quantum mechanics to design compounds with specific properties before the compound has been chemically produced.

claiming it to be the energy equation for an electron, but this is false, or to be generous, incomplete. He revisits this error in Setterfield (2001, Equation 7), noting that

$$E_k = \frac{1}{2}m_e v^2 = \frac{e^2}{8\pi\varepsilon_0 r} \tag{5-8}$$

and briefly mentions that masses, in this case the electron mass, m_e, changes in his model. He subsequently slips this fact under the rug. The solution of this system is not based on simple ratios, but on a balance of quantities, and one of the terms needed in the balance changes in his model.

He quickly recasts quantities in terms of the Rydberg constant[5] (which would not be a constant if the electron mass is changing) and proceeds to define new quantities. This is an apparent effort to remove that annoying variable electron mass out of his equations, where it is less likely to attract the attention of an alert reader.

Let's examine the parts of the derivation that Setterfield does not want you to see. We will basically use the fundamental principles of the Bohr model but applied under the conditions of a varying electron mass. The regular derivation of this model can be found in almost any introductory quantum mechanics textbook(Powell and Crasemann 1961, pp. 16-17).

We start with the energy equation, this time retaining the fact that the electron mass changes as ζ^{-2}. Here, we'll retain the conventional present-day definitions of electron mass, m_e, electron charge, e, and Planck's constant, $\hbar$. To generalize to hydrogenic atoms, we'll replace the nuclear charge $+e$ with $+Ze$ for nuclei with atomic number, Z. As before, ζ contains the cosmological time variation.

$$E = \frac{1}{2}\frac{m_e}{\zeta^2}v^2 - \frac{Ze^2}{r}. \tag{5-9}$$

We'll continue with the semi-classical calculation, performing the force balance of the electrostatic attraction and centripetal force.

$$F = \frac{m_e}{\zeta^2}a = \frac{m_e}{\zeta^2}\frac{v^2}{r} = \frac{Ze^2}{r^2} \tag{5-10}$$

from which it is trivial to demonstrate that the total energy of the atomic *system*, the electron and nucleus, (not just the electron), is

$$E = -\frac{1}{2}\frac{Ze^2}{r}. \tag{5-11}$$

We must also cast the Bohr quantum condition in terms of the varying electron mass

$$n\hbar = \frac{m_e}{\zeta^2}vr \tag{5-12}$$

where n is the quantum number of the state in question. Next we use the force balance equation, Equation 5-10, to solve for the electron velocity, which we need in a more concise form

$$v = \left(\frac{Ze^2}{r}\frac{\zeta^2}{m_e}\right)^{\frac{1}{2}}. \tag{5-13}$$

---

[5] $R_\infty = \frac{m_e e^4}{2\hbar^3 c}$

.

We substitute this into the Bohr condition

$$\begin{aligned} n\hbar &= \frac{m_e}{\zeta^2}\left(\frac{Ze^2}{r}\frac{\zeta^2}{m_e}\right)^{\frac{1}{2}} r \\ n^2\hbar^2 &= \frac{m_e^2}{\zeta^4}\left(\frac{Ze^2}{r}\frac{\zeta^2}{m_e}\right) r^2 \\ &= \frac{m_e}{\zeta^2} r Ze^2 \end{aligned} \tag{5-14}$$

Which means the radius of the Bohr orbitals are given by

$$r = \frac{n^2\hbar^2}{m_e Ze^2}\zeta^2. \tag{5-15}$$

The atomic radii are no longer constant (a result obtained only by simple-minded ratios), but increase as ζ^2. This is because atomic structure is driven by a *balance* of forces, not simple ratios.

Now we can plug this result back into the energy equation

$$E = -\frac{1}{2}\frac{Z^2e^4m_e}{\hbar^2}\frac{1}{\zeta^2}\frac{1}{n^2} \tag{5-16}$$

and see the new Balmer formula based on the Setterfield universe.

$$E_\nu = E_m - E_n = -\frac{1}{2}\frac{Z^2e^4m_e}{\hbar^2}\frac{1}{\zeta^2}\left[\frac{1}{n^2} - \frac{1}{m^2}\right] \tag{5-17}$$

Comparing this to the standard Balmer formula, we now see that the Rydberg constant is no longer a constant (a result again obtained by simple ratios), but varies as ζ^{-2}.

This results creates two big problems for Setterfield's model:

- Atoms were bigger in the past, so probably macroscopic objects had to be larger as well (was the Moon larger in the sky?)
- How does this impact the use of these relationships in his cosmological model?

5.6. The Nonsensical Properties of 'Setterfield E'

Shortly before completion of the first edition of this monograph (so close that I did not discover this until about a year later), Setterfield began to elaborate on his quantum mechanical basis for changes in the speed of light(Setterfield 2001). As part of this, he presented a functional form for the change in c over cosmic history(Setterfield 2001, Equation 110):

$$c = k\left[\frac{(1+T)}{\sqrt{1-T^2}} - 1\right] \tag{5-18}$$

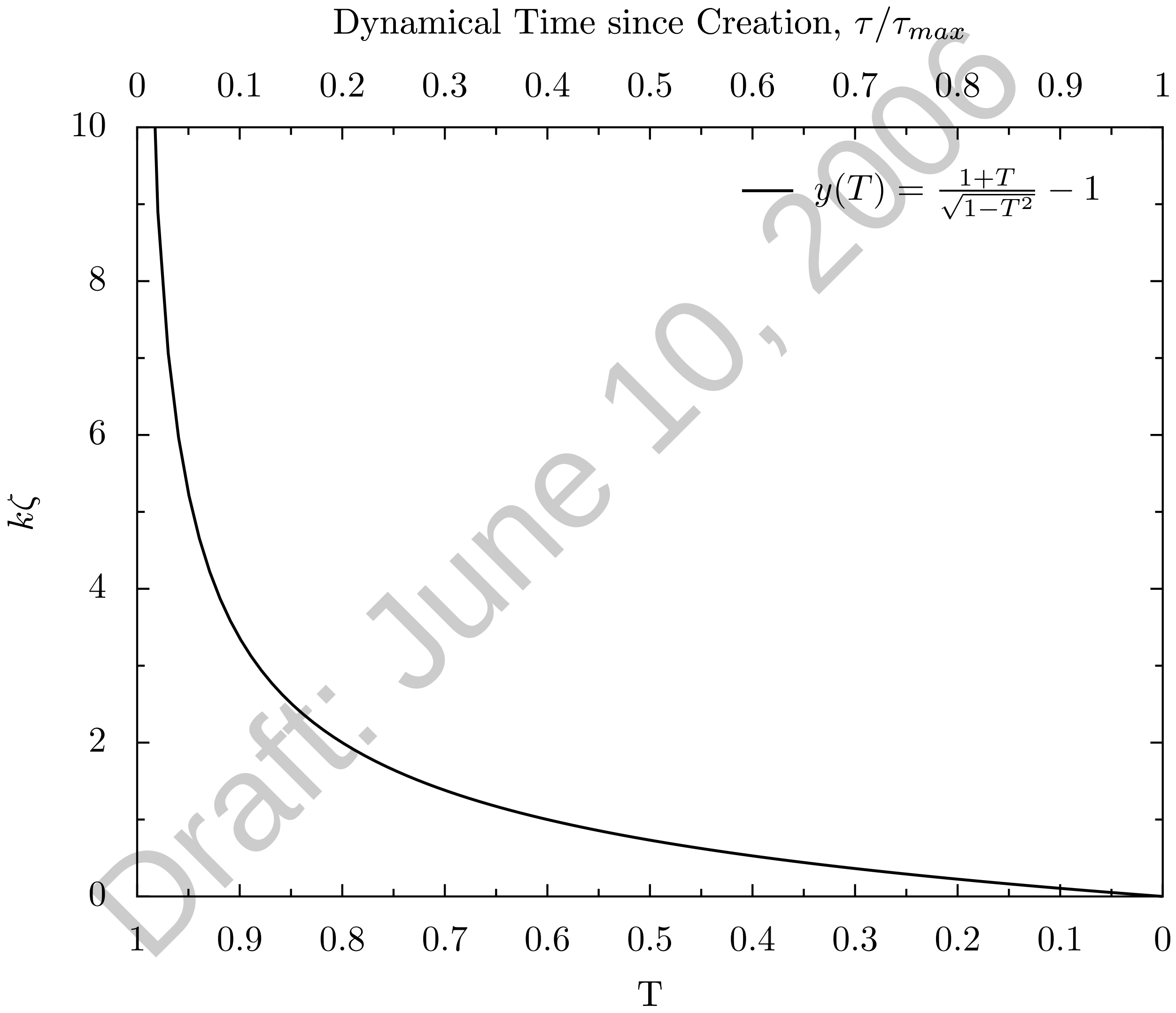

Fig. 12.— Plot of the function 'Setterfield E', with x-axis labeling using conventions in Setterfield and this monograph.

which is plotted in Figure 12. Some preliminary analysis suggested this equation had some serious problems. Examining Setterfield'sanalysis revealed that I had only scratched the surface. For the remainder of this analysis, I will refer to this function as 'Setterfield E'.

It's not clear where this function came from, though it does bear an uncanny resemblance to Equation A33, where Setterfield has substituted x and T for v/c. I suspect he appropriated it for this use from some other source. Perhaps he thought it made his analysis 'look' more relativistic? He claims this is a result of the derivation in Setterfield and Dzimano (2003) but as we'll see, this claim conflicts with even simple observations, making any appeals to bizarre zero-point energy issues irrelevant.

In this form, Setterfield claims that T represents a dimensionless dynamical time where $T = 0$ corresponds to the present and $T = 1$ corresponds to the moment of Creation. One obvious test that every physicst is familiar with when confronted with such an equation is to check the extrema values, to see if they make sense. We can immediately see a problem. While $c(T = 1) = \infty$, which is certainly not ruled out in Setterfield's model, for present day, this function evaluates to $c(T = 0) = 0$!!!

His model claims the speed of light today is zero!

Is this some issue with his claimed quantization? While he writes much on this alleged quantization, generating equations for level numbers, I have never seen it actually appear in any of his expressions for the speed of light. These are always smooth functions like Setterfield E. Such quantization could readily expressed mathematically using summations of Heaviside functions and carried in each calculation.

Let's reform this equation into this monograph's notation to ensure we're treating things consistently. c becomes $\bar{c}\zeta(\tau)$ and the dimensionless T becomes $(\tau_{max} - \tau)/\tau_{max}$ where τ is the dynamical time since the time of Creation and τ_{max} is the age of the Universe in dynamical time.

$$\zeta\left(\tau\right) = \frac{k}{\bar{c}}\left[\frac{1+\frac{\tau_e}{\tau_{max}}}{\sqrt{1-\left(\frac{\tau_e}{\tau_{max}}\right)^2}} - 1\right] \tag{5-19}$$

If we wish to compute the 'lookback time', in this case, the distance corresponding to the dynamical time of emission τ_e, that is just the signal speed, c, integrated over the travel time, τ_e to the present, τ_{max}, the current age of the Universe (Equation 2-1).

$$\begin{aligned} s &= \int_{\tau_e}^{\tau_{max}} c\,d\tau & \text{(5-20)} \\ &= -\int_{1-\frac{\tau_e}{\tau_{max}}}^{0} \frac{k}{\bar{c}}\left[\frac{1+T}{\sqrt{1-T^2}} - 1\right]\tau_{max}dT & \text{(5-21)} \\ &= -k\tau_{max}\left[\sin^{-1}T - \sqrt{1-T^2} - T\right]\Big]_{1-\frac{\tau_e}{\tau_{max}}}^{0} \end{aligned}$$

$$= \quad -k\tau_{max}\left[-\sin^{-1}\left(1-\frac{\tau_e}{\tau_{max}}\right)+\sqrt{1-\left(1-\frac{\tau}{\tau_{max}}\right)^2}-\frac{\tau}{\tau_{max}}\right] \tag{5-22}$$

(5-23)

But wait a minute, in (Setterfield 2001, Section 9.3), he also presents Equation 108

$$z = \frac{1+x}{\sqrt{1-x^2}} - 1 \tag{5-24}$$

where x is the relative distance between the observer ($x = 0$) and the edge of the cosmos ($x = 1$, $\approx 15 \times 10^9 lightyears$). Even worse, he states

> Furthermore, since increasing astronomical distance means that we are looking further back in time, there should also be a direct relationship between astronomical distance x in (108) and dynamical time T(Setterfield 2001, Section 9.4).

Wrong!

The only way Setterfield's equations 108, 109, and 110 can be mathematically consistent is if $x = T$ for all values of x and T. While both x and T will increase as one moves to earlier emission times, *they will only be directly proportional if the photon speed is constant.* To see this, note that in our convention, the condition that $x = T$ can be expanded to

$$x = \frac{s}{s_{max}} = \frac{\tau_{max}-\tau}{\tau_{max}} = T \tag{5-25}$$

where we have defined s as the distance in physical units and s_{max} as the distance to the edge of the Universe in physical units. Solving for the distance

$$s = \frac{\tau_{max}-\tau}{\tau_{max}} s_{max} \tag{5-26}$$

which is the time-distance relationship the signals (photons) must satisfy. So is x really the lookback time, the distance from which we see an object with redshift, z?

There is only one way that photons from position x can make it to the observer such that $x = T$ for all times, and that's if the photons are travelling at:

$$v = \frac{ds}{d\tau} = \frac{s_{max}}{\tau_{max}} \tag{5-27}$$

which is a *constant*!!. For the values we've been able to discern from Setterfield's writing, $\tau_{max} \approx$ 7700 years and $s_{max} \approx 15 \times 10^9$ light-years, this speed is $\approx 1.9 \times 10^6$ light-years/year or $\approx 1.9 \times 10^6$ times the present speed-of-light. This sets up a physical and mathematical contradiction with his Equation 110.

There is one interesting quantity we can obtain from this analysis. Let's take a closer look at the *real* lookback time, Equation 5-23:

$$s = -k\tau_{max}\left[-\sin^{-1}\left(1-\frac{\tau_e}{\tau_{max}}\right)+\sqrt{1-\left(1-\frac{\tau}{\tau_{max}}\right)^2}-\frac{\tau}{\tau_{max}}\right] \tag{5-28}$$

How far does a photon travel if emitted from the time of Creation, $\tau_e = 0$? This would correspond to the distance to the 'edge' of the Universe, s_{max}. Plugging in the values

$$s_{max} = k\tau_{max}\sin^{-1}(1) = k\tau_{max}\frac{\pi}{2} \tag{5-29}$$

.

We can use this expression to obtain a value of k,

$$k = \frac{2}{\pi}\frac{s_{max}}{\tau_{max}} \tag{5-30}$$

or, with $\tau_{max} = 7800 years$, and $s_{max} = 14 \times 10^9 years$, we get $k = 1.14 \times 10^6$ in units where $\overline{c} = 1$. Using this value in Equation 5-19 and plotting the results with Setterfield's earlier models yields Figures 13 and 14. A number of issues immediately stand out.

- In both figures, the curve exhibits very poor agreement with datapoints Setterfield has published in the past, both for the speed of light and the corresponding 'lookback time' or accumulated atomic age.
- On the lookback time graph, we note that the radioisotopics ages of the Earth and the oldest meteorites correspond to $\tau \approx 1200 - 2000 years$, not the time frame of Creation Week. Why is this? The ages corresponding to Creation Week are much larger than the radioisotopic ages (see Table 2)
- This function exhibits an incredibly large values for the speed of light in the past hundred years, in blatant conflict with observation (see Table 3).

5.7. Miscellaneous Bloopers in Setterfield's Claims

In Setterfield's attempt to claim the universe is static, he makes numerous blunders beyond those covered in the previous sections.

- Setterfield tries to make an issue using Gentry's claim that the cosmological curvature, R, is a mathematical construct. The problem with this claim is that *all* physical quantities beyond mass, time, and distance, are mathematical constructions derived from their relationship

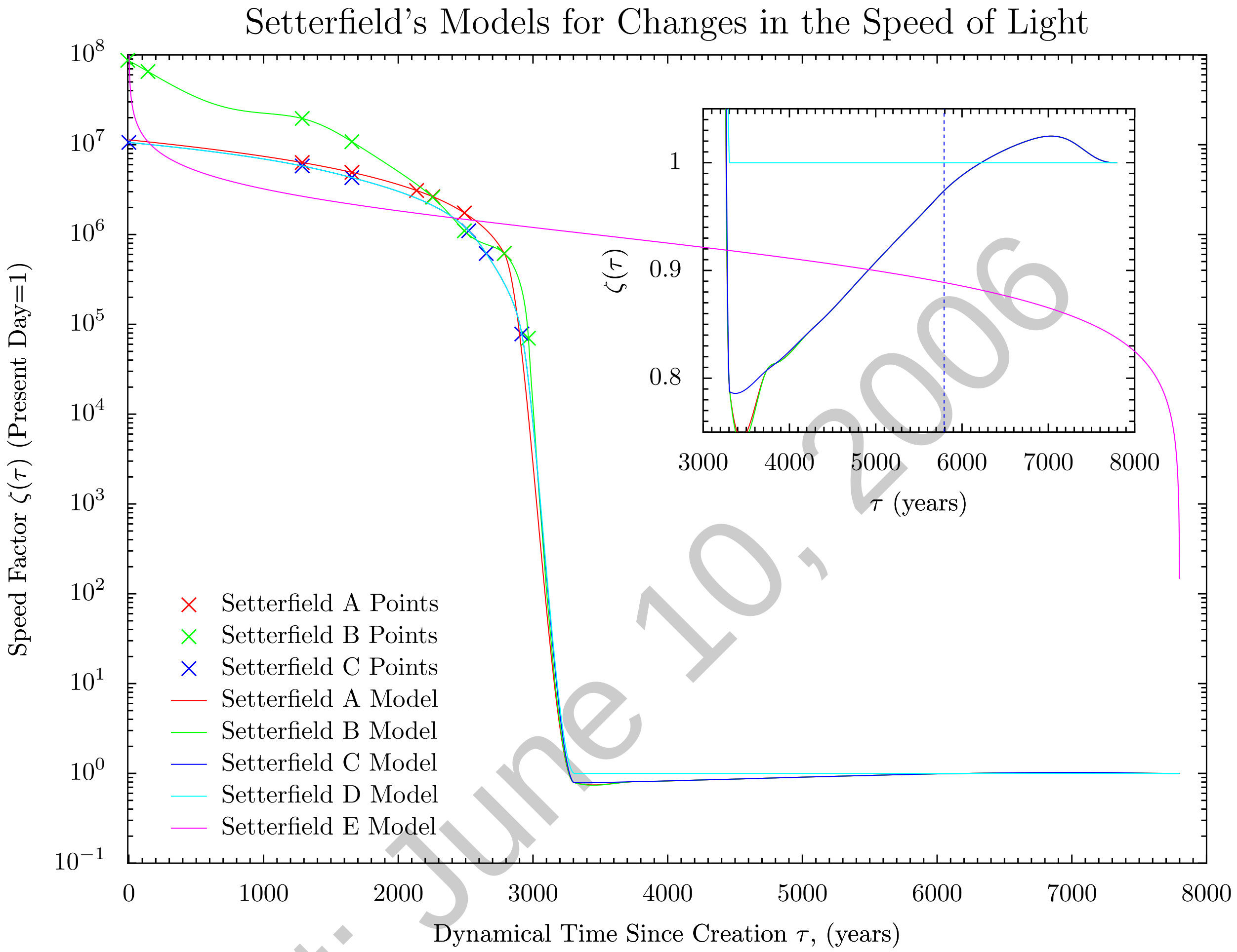

Fig. 13.— Plot of the function 'Setterfield E' scaled to fit the other Setterfield Models. Note how quickly the speed of light increases in the recent past

Table 2: Lightspeed and atomic age values corresponding to Creation Week using Setterfield E. Note that none of the days of Creation Week match the ages of the Earth and solar system.

Creation Day	ζ ($\overline{c} = 1$)	atomic age (years)
0	∞	1.40000×10^{10}
1	2.726×10^9	1.39851×10^{10}
2	1.928×10^9	1.39789×10^{10}
3	1.574×10^9	1.39741×10^{10}
4	1.363×10^9	1.39701×10^{10}
5	1.219×10^9	1.39666×10^{10}
6	1.112×10^9	1.39634×10^{10}
7	1.030×10^9	1.39605×10^{10}

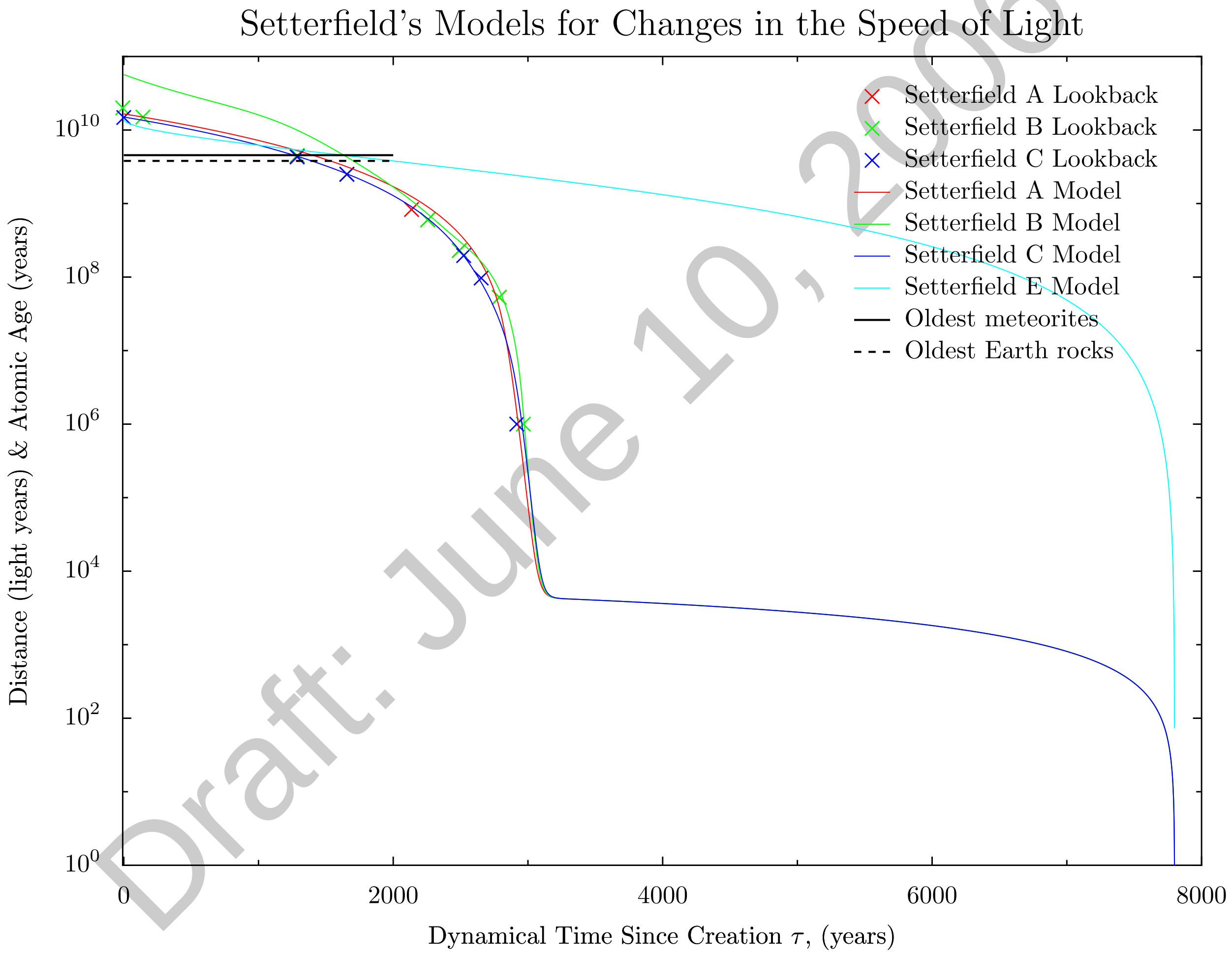

Fig. 14.— Plot of the the 'lookback time' for Setterfield E scaled to fit the other Setterfield Models.

Table 3: Lightspeed and atomic age values corresponding to the past 100 years using Setterfield E.

τ years	year (A.D.)	ζ ($\overline{c} = 1$)	atomic age (years)
7700.0	1908.0	14744.5	735629.0
7710.0	1918.0	13261.4	595601.3
7720.0	1928.0	11780.2	470394.9
7730.0	1938.0	10301.0	359990.5
7740.0	1948.0	8823.7	264368.7
7750.0	1958.0	7348.3	183510.3
7760.0	1968.0	5874.9	117396.1
7770.0	1978.0	4403.3	66006.9
7780.0	1988.0	2933.6	29323.8
7790.0	1998.0	1465.9	7327.8
7791.0	1999.0	1319.2	5935.3
7792.0	2000.0	1172.6	4689.4
7793.0	2001.0	1025.9	3590.2
7794.0	2002.0	879.3	2637.6
7795.0	2003.0	732.7	1831.6
7796.0	2004.0	586.1	1172.2
7797.0	2005.0	439.6	659.3
7798.0	2006.0	293.0	293.0
7799.0	2007.0	146.5	73.2
7799.1	2007.1	131.9	59.3
7799.2	2007.2	117.2	46.9
7799.3	2007.3	102.6	35.9
7799.4	2007.4	87.9	26.4
7799.5	2007.5	73.2	18.3
7799.6	2007.6	58.6	11.7
7799.7	2007.7	43.9	6.6
7799.8	2007.8	29.3	2.9
7799.9	2007.9	14.6	0.7
7800.0	2008.0	0.0	0.0

to these more fundamental values[3]. Quantities such as velocity, energy, momentum, voltage, current, etc. were originally defined based on their usefulness in other equations and measured by their ability to move a meter or scale through some displacement.

- In an earlier version of Setterfield's web site, he also claims that redshift, z, values greater than one are a problem for relativity. In Appendix A we demonstrate why this is wrong.

- According to Setterfield's chronology((Setterfield b)), the Earth, Moon, and the rest of the Solar System were created a few days into the year zero, which would mean that in his model, the age of the Earth, Moon, and meteorites should be just less than the age of the Universe. If this is the case, why do isochron ages from the Moon and chondrite meteorites indicate the Solar System formed 4.5×10^9 years ago, considerably less than 14×10^9 years? Creationists sometimes claim that the Fall or the Biblical Flood 'reset' the radioisotope clocks. An apparent age of 4.5×10^9 years, by Setterfield's chronology, would fall between 1122 and 1287 years after Creation, well after the Fall. Neither does the Flood match Setterfield's time table, located at an atomic time of 650 million years ago according to his table. Yet in Setterfield (2002, A Brief History of the Earth) he is so bold as to state

  > The data do not contradict the Scriptural record that oceans and a supercontinent existed as early as Day 3 of Creation Week.

  One wonders if he actually reads his own material.

5.8. Quick Reference to Failures of the Setterfield Hypothesis

Here we present a summary the many failures of the Setterfield Hypothesis examined in this paper. In Section 5.2 of this paper, I point out correction to an error I discovered in the previous iteration of this paper. Let's see if Setterfield will respond to the problem issues issues with his hypothesis with something more substantial than lip-service.

5.8.1. Model Independent Failures

1. Setterfield's claim of a recently decaying speed of light would predict a large differential arrival time for photons emitted from objects periodic on the dynamical time scale. This large differential is not observed in pulsar spin periods or binary pulsar orbital periods (Sections 2.3, 5.2 and 5.3).

---

[3] One could make the case that mass is also a mathematical construction since initially calibrations were performed using a balance-beam scale to a reference mass.

2. Setterfield's supplemental claim that atomic processes operate on a time scale (atomic time) scaled directly with the speed of light indicates that there would be no observed change in frequency or wavelength of photons as they traverse the cosmos to Earth (Section 2.6).

3. For some of his recently published models (C & D in our notation), figure 7 displays excellent agreement between Setterfield's published values and those computed using equation 2-4. This basically tells us that Setterfield is using this equation for computing the light travel time. *This is the only result Setterfield has published which can be connected to any real science.* This also tells us that *Setterfield IS doing a classical calculation, NOT a quantum mechanical one, contrary to his claims.*

4. Setterfield acknowledges the existence of the 'slowing down effect'(Setterfield 2003b) which is described in Sections 2.2 & 2.3 but then applies it inconsistently. He invokes the effect in distant supernovae and AGN but ignores it for objects closer to Earth such as pulsars.

5. It is unclear how Setterfield derives his values for the speed-of-light for times prior to about 500BC. His model appears as if he manufactured the values to generate the 'real' and 'apparent' ages of the Universe he desired and then force-fit them against a graph of the range of observed redshifts. Even stranger is the fact that he *changes* these values with no explanation. One would assume either some input data or something in his model has changed to justify this. Perhaps he is correcting an error made in the previous papers, but I can find no explanation. For all I can discern, the numbers were made-up to fit a large universe into a short time-span.

6. Setterfield makes no testable predictions of his model where the results would be *different* if the speed of light were different in the past. Only those kinds of tests can lend support for his model against the accepted model. In fact, most of his effort seems concentrated in trying to *hide* any differences.

7. Numerous other researchers have searched for variation in fundamental physical constants and have generally determined that if there is any variation, it has very small over much of the 15 billion year history of the Universe. Yet Setterfield claims variation thousands, millions, even billions of times larger than reported by these other researchers. Why is that?

8. Every other derivation of these frequency shifts (see Appendix A) explicitly or implicitly invoke the travel time of photons/wavecrests/etc. but Setterfield does not. Why not?

9. He claims 'quantum jumps' in the values of the speed of light, yet I've found none of his functions or datasets which actually show this. There are mathematical techniques for handling these types of discontinuities in functions.

10. He claims the speed of light has changed measurably in the past 250 years yet then says all consequences of these changes are invisible out to the Magellanic Clouds. If the timing effects are not visible, then how were differences in the speed of light measured? Again, this does not

appear in any of the mathematical details he has published. Things may get interesting as instrument sensitivity increases, since we will probably be detecting pulsars in nearby galaxies in the next ten years.

11. If Setterfield claims that the Solar System and Earth formed during Creation Week, the atomic ages generated by his models do not agree with this chronology.
12. By allowing atomic masses to change in the past, it is simple to show that the Earth could not have retained an atmosphere prior to about 2800 B.C. ($\tau \approx 3000$ years).

5.8.2. Failures in Setterfield's Quantum Mechanical Analysis

1. Setterfield expends many words describing alleged quantum mechanical aspects of his claims while ignoring major experimental and observational facts - that photons still obey the classical time-distance-velocity relationship (equation 2-4) when propagating over macroscopic distances in relatively empty space. This is a consequence of the Correspondence Principle.
2. Setterfield claims that wave mechanics is a *refinement* of the Bohr model. Blatantly false. All researchers who has developed successful applications using quantum mechanics (superconductivity, microelectronics, materials science, etc.) have not used the Bohr model in their work.
3. Setterfield implements the Bohr model incorrectly, ignoring known physical principles and the impact of a variable electron mass.
4. Setterfield's claim that the speed of light is linearly proportional to the redshift is mathematically impossible with the known *definitions* of distance, velocity, wavelength, and redshift (equations 2-4,2-36,2-43). Since he is apparently using equation 2-4, what is he using instead of equations 2-36 and 2-43?

5.8.3. Failures Specific to the Model Setterfield E

1. Setterfield E predicts radically different values of the variation of the speed of light with dynamical time compared with previous models. What was wrong with the previous 'data'?
2. The model Setterfield E exhibits no oscillatory behavior or jumps in its functional form. Yet Setterfield claimed these effects exists.
3. Setterfield has left the time scaling ambiguous. Defining $T = 0$ as the present, does he mean *today*, or perhaps 1967.5 when he claims the variation stopped.
4. Generates radically larger values for the speed of light in the recent past (the last century), contrary to observations.

5. Lookback time and dynamical time are not proportionally related, as Setterfield claims.
6. This model predicts that the speed of light today is *zero*!

It will be interesting to see if Setterfield will actually address these errors.

5.9. Setterfield's Responses to the First Edition

Setterfield has yet to contact me directly. Most of these responses I discovered through searches and notifications by other parties. Some of these links have since vanished. I have found no links from his site to mine.

Setterfield responded to the first edition result with the claim that recent observations of pulsars cast doubt on the accepted model of these objects and that accurate predictions are not possible.(Setterfield 2003b). However, the reference he gives (New Scientist, 28 April, 2001, page 28),(Appleyard and Appleby 2001) is a popular science magazine, not exactly the best source for detailed science information. After some effort, I was able to track down the *original* reference for the article and the follow-ups(Ardavan 1998, 2000,?; Ardavan et al. 2002, 2003, 2004).

Ardavan's pulsar model is based off a single set of radio band observations by Sallmen et al. (1999) of the Crab Pulsar. The Ardavan model, while interesting, encounters the problem that it must still be consistent with the observations of over a thousand pulsars, across wavelengths from radio to gamma rays, going as far back as 1967. Ardavan has not confirmed this so Setterfield's claim that the pulsar model is in doubt is *highly* premature. In addition, while Ardavan uses the term 'super-luminal' in the title of his pulsar model, it is not super-luminal in the same context of the Setterfield hypothesis, but super-luminal in the phase vs. group velocity context. Ardavan's model still relies on pulsar spin to drive the pulses, but his emission region appears to be outside the light-cylinder (most current models have the emission region inside the light-cylinder). It may even be possible for the Ardavan's model to co-exist with current models in the sense of being one of several emission mechanisms possible for pulsars under some conditions.

Even if Setterfield is claiming that *any* of the uncertainties in pulsar radiation processes can account for the *huge* discrepancy of differential pulse arrival times between his hypothesis and the actual pulsar observations, it is *his* responsibility to present better evidence for the claim. Yet he does not even show calculations of an order-of-magnitude estimate to how uncertainties in the pulsar radiation mechanisms, such as those claimed by Ardavan, would cover factors of millions and billions in differential timing, both for spin-up and spin-down scenarios. This fact makes Setterfield's claim scientifically worthless.

In addition, Setterfield points out that all the pulsars in my sample are relatively nearby in the Milky Way and that his redshift effects will not be apparent until one is beyond the Magellanic Clouds. How convenient. It's not clear how these effects would be so distant when he uses measurements of the speed of light over the past 250 years, implying detectable changes within 300 light-years of Earth. The differential arrival time analysis is a simple mathematical extension of the method used to measure the speed-of-light - signal propagation time over a known distance. Nonetheless, Setterfield will soon have to deal with the issue of extragalactic pulsars. Initial searches have already been conducted (McLaughlin and Cordes 2003) and new instruments which may detect them in large numbers may soon be online(SKA 2006). No doubt when he reads this he will start 'hedging his bets'.

As for the 'metric' (sic) that I'm using...(Setterfield 2003b).

I use the experimentally established interrelationship of distance-velocity-time (equation 2-4), wavelength-frequency-wave speed (equation 2-36), and the definition of redshift (equation 2-43). These relationships are minimum required in any determination of frequency changes in electromagnetic radiation (Appendix A), as demonstrated in their many technology applications, such as electronic communications, radar, LIDAR, and GPS. Setterfield's photon propagation model is inconsistent with all of these working technologies.

In regards to Setterfield's claims about pulsar ages, what researchers call the pulsar age (usually called the 'characteristic age' in professional journals) is a simple parameterization of the rate of the rotation slowdown (Manchester and Taylor 1977, pp. 110-112) from which an 'age' can be computed based on very simple assumptions of the energy-loss mechanism. They are not regarded as an actual age of the pulsar so much as a simple number which researchers can use to compare different models.

Setterfield has claimed that I've made errors in my calculations but is notoriously unspecific(Setterfield 2003b). Considering the simplicity of the errors that have been identified (and corrected), combined with the fact that the corrections did not improve agreement with the observations, I have no reason to regard the identified errors as having any relationship to Setterfield's alleged errors[6].

6. Real Variable-Speed-of-Light Research

6.1. Magueijo's Variable Speed-of-Light Hypothesis

Is Setterfield's c-decay the same as the variable speed-of-light theories being advocated by Barrow and Magueijo (1998)? The short answer is 'No'.

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[6] As a personal historical note as a scientist, it is *very* easy to remember the details in correcting errors. Having been on both sides of this, it is memorable, not just when you discover a mistake in your own work, but when someone thinks they have found an error and you get to correct them. Setterfield's allusions to unspecified errors, like so many other of his claims, are indistinguishable from being made up.

- Barrow and Magueijo (1998) have c changing rapidly as a mechanism of inflation in the very early stages ($< 10^{-30} seconds$) of the Big Bang and then holding a roughly constant value in the billions of years since then. Setterfield is claiming c has undergone *significant* change in the past few thousand years.

- Barrow and Magueijo (1998) recognize the issues described in this paper. They do not have the changing c responsible for the redshift of galaxies. Their large values for c take place before galaxies are formed, even before the Cosmic Microwave Background (CMB), nucleosynthesis, or baryogenesis. For more information on Big Bang cosmology, one of the best online resources is Wright (2006).

Setterfield mentions on his web site that he is changing references to his theory from 'c-decay' (cDK) to 'variable speed-of-light' and has even made references to this work implying that mainstream science is somehow confirming his 'theory'. Any such inference is totally false.

7. Summary & Conclusions

Probably one of the most frustrating issues with Setterfield's work is his failure to map his results into a consistent mathematical form. This is most frustrating when dealing with how he defines his time, t. He fails to clearly synchronize the dynamical and atomic time scale from some common zero point which is crucial for doing more sophisticated analysis of his claims.

These analyses depend only on the definitions of velocity, distance, and time (Equations 2-1 and 2-2) and the relation between wavespeed, wavelength, and frequency (Equation 2-36), equations which are fundamental in the past 300 years of physics. If someone claimed that their theory showed that particles travel distances proportional to the square of their velocity, we would know it was false theory from the start. Such a relationship is impossible based on the definitions of the quantities. Setterfield's model is in this league, making numerous claims in blatant contradiction to the predictions made by use of these relations.

In the physical sciences, especially physics and astronomy, the real language is mathematics. If you can't develop an unambiguous mathematical formulation of your theory, then it is probably not good science. In addition, your verbal descriptions of the theory and its predictions should be consistent. Setterfield E (and its predecessors) was clearly not subjected to even the most basic of consistency checking.

Setterfield makes horrific errors even when working with the fundamental concepts of physics, errors that don't work in classical Newtonian physics. Why would his understanding of quantum mechanics be credible?

Setterfield's theory is indistinguishable from a "hack job". In many cases, he appears to appropriate equations from other sources and simple change the variables. I regard it as no coincidence that his fundamental equation $c = kz$ and the function I have labelled 'Setterfield E' (Equation 5-19 have strong resemblance to the Hubble Law and the relativistic redshift relation. I suspect he took these equations, with *no clue* of what they really meant or the fundamental relations from which they are derived (Appendix A) , changed some variables around, and called it a 'theory'.

The Creationist search for a 'Magic Scale Factor' that enables the universe to appear billions of years old while actually being less than ten thousand years old *and* staying consistent with current observational data, remains unfulfilled.

8. Problem Set

In any advanced undergraduate or graduate-level physics and astronomy course, the true test of the students' mastery of the subject is tested by their ability to qualitatively and quantitatively analyze other aspects of a problem. Here I present several 'problems for the students'. Most of these require at least a firm grasp of the calculus. Others require understanding of differential equations.

1. Re-derive Equations 2-13 and 2-29 for the case where the source and receiver may be moving relative to one another (i.e. s is not constant). This would be the equivalent of the Doppler effect in a universe where c is changing.

2. From Equation 2-29, demonstrate that one way to eliminate the light travel time shift in the period (i.e. get $dP(\tau_r)/d\tau_r = dP(\tau_e)/d\tau_e$) is to have $\zeta(\tau) = 1$ for all τ. That is, the speed of light is constant. Is there another functional form for $\zeta(\tau)$ that can achieve this?

3. There is another way to get $dP(\tau_r)/d\tau_r = 0$ in Equation 2-29 and that is to define $dP(\tau_e)/d\tau_e$ so that it exactly cancels the light speed decay term. What type of constraint(s) would this place on the emitting object and why? Would an observer at a different location see $dP(\tau_r)/d\tau_r = 0$ (note that τ_r would be measured at their location)?

4. In Section 4.2 we point out that having masses change with time creates a problem with angular momentum conservation. Consider the case for a spinning object where angular momentum *is* conserved and the object will spin up with dynamical time. Consider the two cases outlined in Section 4.2 by testing the problem when the moment of inertia varies as ζ^{-1} and as ζ^{-2} so that the spin frequency varies as ζ and ζ^2, respectively. Can this yield cancellation of the c-decay term in Equation 2-29? What would this imply for planetary rotation and orbital periods?

5. In Sections 2.2 & 2.3 we demonstrated that dynamical periodic phenomena will appear to 'speed up' over time when timed by a distant observer. This seems to conflict with our physical intuition that such periodic phenomena should appear to slow down since each group of photons takes longer to make the trip from emitter to receiver. Is this a problem? Explain?

6. The function for the light travel in Figure 2 is $\zeta(\tau) = 1 + 3e^{-0.3\tau}$. Given that $\tau_{e0} = 0.0$, $\tau_{e1} = 1.0$, $\tau_{e2} = 2.0$, and $\tau_{e3} = 3.0$, compute the arrival times $\tau_{r0,r1,r2,r3}$, the corresponding periods, $P_{r01,r12,r23}$, and wavelengths, $\lambda_{e0,e1,e2}$. Do the wavelengths at emission match those at reception? You will need a root-finding routine for this problem.
7. Compute the epoch correction described in Section 5.2. Use $\dot{P}$ (and higher-order derivatives if available) to estimate $\dot{P}/P$ in Epoch 2008.0. In the ATNF catalog, the epoch for the pulsar period measurements are given in Modified Julian Date (MJD).
8. Examine Equation 2-12. Under what conditions of $P(\tau_e) = constant$ will the period appear to *increase*?

9. Revisions & Still Under Development

This is a short description of changes since the August 22, 2001 release (now referred to as the First Edition) of this document.

- Numerous revisions in organization.
- This version and the supporting software and web site have been committed to a CVS (http://www.cvshome.org) repository for better tracking of changes for future releases.
- Switched to the AAS LaTeX macro system for page formatting (http://www.aas.org/aastex/).
- Added appendix with the derivations of three different types of frequency shifts.
- Installed the 'Analysis of Simple c-Decay Models' section.
- Coverage of the multiple models Setterfield has proposed over the years.
- Fixed a sign error in description of pulsar spindown rates. This did not impact computational results. Thanks to the reader who pointed this out.
- Added the graphical derivation of equation 2-13.
- Fixed the sign error in plotting Equation 5-1 in Figure 8 and revised corresponding text.
- Switched from the Princeton pulsar catalog to the ATNF pulsar catalog.

There are a number of additional components I'd like to add to this work to make it as complete as possible. Here's a summary of some the components still under development.

c-Decay and Binary Star Orbital Periods: Because Setterfield also defines his hypothesis with the constraint that $GM = constant$, orbital periods will be constant in the dynamical time scale. Thanks to this, Setterfield has defined a clock to which we can apply the pulsar analysis to test limits on changes in the observed orbital periods of binary stars. I have found a number of datasets of binary star data but the sheer volume of data has proven daunting and numerical precision has been a problem. Pointers to references on binary stars for which there are accurate period measurements going back as much as one hundred years are highly desirable. Optical double stars are particularly desirable.

c-Decay and Supernovae Light Curves: This section still under development. I am in need of supernovae lightcurve data and some simple light-curve models.

c-Decay and Stellar Structure: Enhance the analysis from the interaction of the gravitational and atomic time-scales.

c-Decay and 'Superluminal' Astrophysical Sources: This section still under development.

More discussion with real VSL research: Todd Greene provided many useful links and notes.

Noether's Theorem: Section on this and implications for conservation laws.

Placing Limits on the Rate of Change of c: We can take our pulsar results from section 5.2 and use them to place an upper limit on the variability of the speed of light over the past few thousand years.

The author wishes to thank those researchers who've graciously made their observational data readily available on the World Wide Web. There are several online sources I have used in this work:

- Princeton Pulsar Group (http://pulsar.princeton.edu)
- ATNF Pulsar Catalog (http://www.atnf.csiro.au/research/pulsar/psrcat/)
- Astronomer's Bazaar (http://cdsweb.u-strasbg.fr/cats/Cats.htx)

Thanks to those who pointed out errors in the text and suggested additional material to include: Todd S. Greene, Kari Tikkanen, and Sverker Johansson.

A. How Do We Compute Redshift?

An important point to remember is that frequency shifts due to the Doppler effect or gravitational influences are not arbitrary intrinsic properties of an observation. They are in fact derived from more fundamental concepts, in this case the readily calculable effect of the light travel time between the emission and reception of consecutive wavecrests. We'll demonstrate this fact in this appendix. In addition, due to new high-precision techniques of measuring Doppler shifts, the IAU has established some standards. Details can be found in Lindegren and Dravins (2003).

A.1. Classical Doppler Effect

First we examine the derivation of the Doppler effect in the classical (non-relativistic) case. In Figure 15, we have a simple graphical representation of the space-time trajectory of an emitter (red), observer (green), and the wave crests of photons (yellow) in this case. A wave crest is emitted at time t_{e_1} from an object at position $x = d_1$ and travels to an observer at the origin. In the case of a constant photon speed, the wave crest will be received by the observer at

$$t_{r_1} \;=\; t_{e_1} \;+\; \frac{d_1}{c} \tag{A1}$$

and for the next wave crest emitted at a later time, t_{e_2}, when the emitter has moved to position, d_2, the wave crest will arrive at the observer at the origin at a time t_{r_2}

$$t_{r_2} \;=\; t_{e_2} \;+\; \frac{d_2}{c} \tag{A2}$$

Because the emitter is in motion, it's positions at the times of emission are related by

$$d_2 \;-d_1 \;=\; v\; (t_{e_2} \;-\; t_{e_2}) \tag{A3}$$

Now we compute the difference in the time of arrival of the two wave crests from the point of view of the receiver (observer). Subtracting equation A1 from equation A2, we obtain

$$\begin{align}
\Delta t_r \;&=\; t_{r_2} -\; t_{r_1} \tag{A4}\\
&=\; t_{e_2} \;+\; \frac{d_2}{c} -\; t_{e_1} \;+\; \frac{d_1}{c} \tag{A5}\\
&=\; t_{e_2} -\; t_{e_1} \;+ \frac{d_2 -\; d_1}{c} \tag{A6}\\
& \tag{A7}
\end{align}$$

and substituting Equation A3 for $d_2 - d_1$, we find

$$\begin{align}
\Delta t_r \;&=\; t_{e_2} -\; t_{e_1} \;+ v\;\frac{(t_{e_2} \;-\; t_{e_2})}{c} \tag{A8}\\
&=\; \Delta t_e \Big(1 + \;\frac{v}{c}\Big) \tag{A9}\\
& \tag{A10}
\end{align}$$

where we've made the substitution $\Delta t_e = \; t_{e_2} \; - t_{e_2}$. Since Δt_e and Δt_r represent the differences in arrival times of the successive wavecrests, they are inversely related to the frequencies, ν_e, and ν_r, measured by the emitter and observer, respectively. Substituting

$$\frac{1}{\nu_r} = \;\frac{1}{\nu_e}\Big(1 + \;\frac{v}{c}\Big) \tag{A11}$$

which becomes

$$\frac{\nu_e}{\nu_r} = \;\Big(1 + \;\frac{v}{c}\Big) \tag{A12}$$

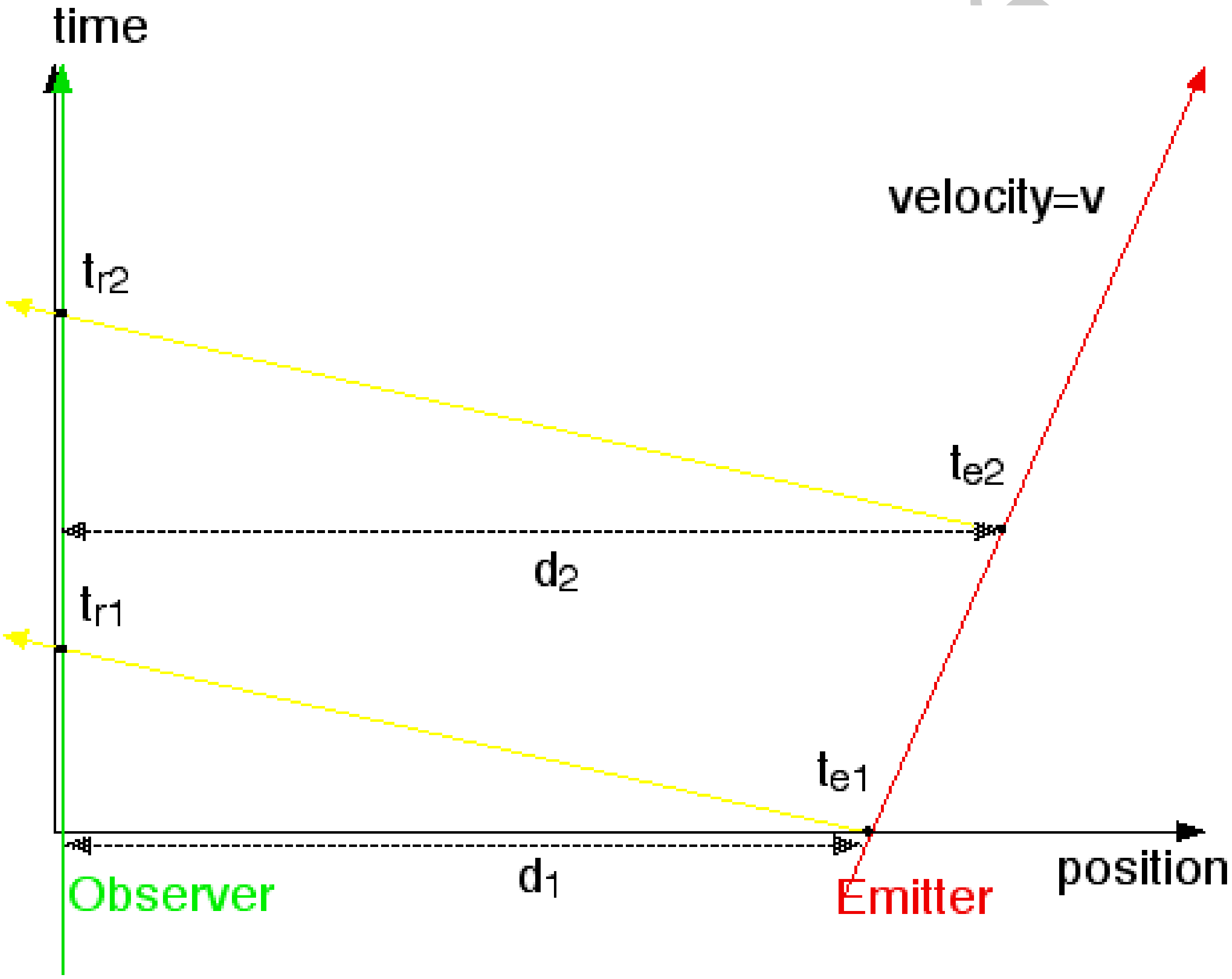

Fig. 15.— Geometry for computing Doppler shift in a classical framework.

Since we want to consider things in terms of wavelength, we make the substitution $\nu = c/\lambda$ to obtain

$$\frac{\lambda_r}{\lambda_e} = \left(1 + \frac{v}{c}\right) \tag{A13}$$

Using the definition of the redshift parameter, z,

$$z = \frac{\lambda_r - \lambda_e}{\lambda_e} \tag{A14}$$

Equation A13 can be manipulated to find

$$z = \frac{\lambda_r}{\lambda_e} - 1 = \frac{v}{c} \tag{A15}$$

which is the equation for the classical Doppler Effect. This is a simple linear function which is plotted for the range $-c \leq v \leq +c$ in Figure 17. Here we see that when $v < 0$, $z < 0$ which corresponds to a blue shift of an approaching emitter.

A.2. The Doppler Effect in Special Relativity

Next we'll produce the equation for the Doppler effect in the framework of Special Theory of Relativity. This analysis is outlined in Wheeler and Taylor (1992, problem L-5) and is also analyzed using momentum space in problem 8-18 of the same work. For clarity in the derivation, we'll start by writing out the one-dimensional Lorentz transformations producing the time and position coordinates in the O' reference frame from the O frame.

$$x' = (x - v\,t)\,\gamma \tag{A16}$$
$$t' = \left(t - \frac{v}{c}\frac{x}{c}\right)\gamma \tag{A17}$$
$$\tag{A18}$$

and their inverse

$$x = (x' + v\,t')\,\gamma \tag{A19}$$
$$t = \left(t' + \frac{v}{c}\frac{x'}{c}\right)\gamma \tag{A20}$$

where $\gamma = 1/\sqrt{1 - (v/c)^2}$. Derivations of these transformations from first principles are available in a number of books on Special Relativity. We start with two observers, which we designate O and O', where O' is moving along the positive x-axis of O with a velocity, v. Both of these observers have clocks which measure time in their reference frame. We will set the synchronization of these clocks by an event, in this case, the emission of a photon by observer O' from their origin and heading in the $-x'$ direction. For simplicity, the both observers will set their clocks to zero the instant they observe the photon, so $t = 0$ and $t' = 0$. Both observers will also define the origin of their spatial coordinate systems by the position of the first photon emitted, so $x = 0$ and $x' = 0$ at these instants.

Next we consider a second event. For simplicity, it will be the emission of a second photon by O' from their origin, but it could just as easily be the passage of the next wavecrest of the first photon. This second photon is emitted by O' at a time, t'_e, as measured on O''s clock and at a time t_e as measured on O's clock. By this time, the origin of O' will now have moved relative to O to a position $d = x = vt_e$. Therefore, to observer O, the second photon is emitted from space-time coordinates of

$$(t, x)_O = (t_e, v\, t_e). \tag{A21}$$

To observer O, this photon will appear to travel at the speed of light, c, and arrive at the origin of O at a time, t_r given by

$$t_r = t_e + \frac{d}{c} \tag{A22}$$

$$= t_e \left(1 + \frac{v}{c}\right). \tag{A23}$$

Therefore, the two events measured by observer O, the reception of the first photon and the second photon, are separated by a time $\Delta t_r = t_r - 0 = t_r$. Now let's determine the time the photon was emitted based on the clock used by O'. We insert the coordinates of the photon emission, equation A21, into the appropriate Lorentz transformation, equation A17, to find t'_e

$$t'_e = \left(t_e - \frac{v}{c}\frac{v\, t_e}{c}\right)\gamma \tag{A24}$$

$$= t_e \left(1 - v^2/c^2\right)\gamma \tag{A25}$$

$$= \frac{t_e}{\gamma} \tag{A26}$$

We can now use Equation A23 to express t_e (the emission time measured by O) in terms of t_r (the reception time measured by O) and combine with Equation A26

$$t'_e = \frac{t_e}{\gamma} \tag{A27}$$

$$= \frac{t_r}{(1 + v/c)}\frac{1}{\gamma} \tag{A28}$$

$$= t_r \frac{\sqrt{1 - (v/c)^2}}{(1 + v/c)} \tag{A29}$$

which can be expressed as

$$\frac{t'_e}{t_r} = \frac{\sqrt{1 - (v/c)^2}}{(1 + v/c)} \tag{A30}$$

Since we've synchronized clocks to the emission of the first photon, we also know that the time differences between $\Delta t_e = t_e - 0 = t_e$. Using $\Delta t'_e = 1/\nu'_e$ and $\Delta t_r = 1/\nu_r$ we recast this equation in terms of frequency

$$\frac{\nu_r}{\nu'_e} \;=\; \frac{\sqrt{1 \;-\; (v/c)^2}}{(1 \;+\; v/c)} \tag{A31}$$

or, using the relation between frequency and wavelength,

$$\frac{\lambda_r}{\lambda'_e} \;=\; \frac{(1 \;+\; v/c)}{\sqrt{1 \;-\; (v/c)^2}} \tag{A32}$$

we now have a relationship between the photon wavelength measured by an observer at the emitter, λ'_e, and by the receiving observer, λ_r. Now we can determine the redshift, z

$$z \;=\; \frac{\lambda_r}{\lambda'_e} \;-\; 1 \;=\; \frac{(1 \;+\; v/c)}{\sqrt{1 \;-\; (v/c)^2}} \;-\; 1 \tag{A33}$$

We also plot this equation in Figure 17. In this case, the domain of the equation is $-c \;\leq\; v \;\leq\; +c$. We note that when $|v| \;<<\; c$, the relativistic and classical z are almost identical. We can also see that redshifts greater than one do not pose a problem in relativity. In fact, it is blueshifts less than negative unity that pose a problem, but redshift values can range between zero and positive infinity and still correspond to an emitting object moving less than the speed of light.

A.3. Redshift in Cosmological Models

In the case of computing the cosmological redshift, we perform a similar analysis, only this time the metric of the intervening space-time comes into play and the mathematics are a bit more sophisticated. This derivation is based on a similar analysis outlined in Adler et al. (1975, Section 12.5). However, we will repeat this derivation using the more modern metric notation in Schutz (1985, Equation 12.14). We'll start with the Robertson-Walker metric[7]

$$d\,s^2 \;=\; -\,d\,t^2 \;+\; R^2\,(t)\left[\frac{d\,r^2}{1 \;-\; k\,r^2} \;+\; r^2\,d\,\Omega^2\right]. \tag{A34}$$

This metric is homoegenous and isotropic for all values of k[8]. The element of solid angle is given by

$$d\,\Omega^2 \;=\; d\,\theta^2 \;+\; \sin^2\!\theta\;d\,\varphi^2 \tag{A35}$$

and using coordinates where $c = 1$. The cosmic expansion is contained in the $R(t)$ factor which we can define as dimensionless. We then define the physical coordinate locations in the time-independent co-moving system (r, θ, φ). We define the coordinates of emitting galaxy, G_e, in the

---

[7] Sometimes called the Friedmann-Robertson-Walker (FRW) metric.

[8] Creationists often take issue with these criteria since they are based on the assumption that Earth occupies no special place in the Universe. That argument is for another paper.

co-moving system as $(r_e, \theta_e, \varphi_e)$ with consecutive wavecrests emitted at times t_e and $t_e + \Delta t_e$. The consecutive wavecrests are received by the observer, G_r, located at $(r_r, \theta_r, \varphi_r)$ at times $t_r + \Delta t_r$. In the co-moving system, the 3-space line element is defined as

$$d\,\ell^2 \;=\; \frac{d\,r^2}{1\;-\;k\,r^2} \;+\; r^2\,d\,\Omega^2 \tag{A36}$$

Since the photons travel on null geodesics, $d\,s^2 \;=\; 0$, we can determine the co-moving coordinate distance between the galaxy and the observer by integrating

$$0 \;=\; -\,d\,t^2 \;+\; R^2\,(t)\;\,d\,\ell^2 \tag{A37}$$

over the light-travel time.

$$\ell \;=\; \int_{t_e}^{t_r} \frac{d\,t}{R(t)} \tag{A38}$$

Since the next wave crest must travel the same path, we also require

$$\ell \;=\; \int_{t_e+\Delta t_e}^{t_r+\Delta t_r} \frac{d\,t}{R(t)} \tag{A39}$$

which we can manipulate through the rules of the calculus to show

$$\int_{t_e}^{t_r} \frac{d\,t}{R(t)} \;=\; \int_{t_e+\Delta t_e}^{t_r+\Delta t_r} \frac{d\,t}{R(t)} \tag{A40}$$

$$= \int_{t_e+\Delta t_e}^{t_r} \frac{d\,t}{R(t)} \;+\; \int_{t_r}^{t_r+\Delta t_r} \frac{d\,t}{R(t)} \tag{A41}$$

$$= \int_{t_e}^{t_r} \frac{d\,t}{R(t)} \;-\; \int_{t_e}^{t_e+\Delta t_e} \frac{d\,t}{R(t)} \;+\; \int_{t_r}^{t_r+\Delta t_r} \frac{d\,t}{R(t)} \tag{A42}$$

which reduces to

$$-\int_{t_e}^{t_e+\Delta t_e} \frac{d\,t}{R(t)} \;+\; \int_{t_r}^{t_r+\Delta t_r} \frac{d\,t}{R(t)} \;=\; 0 \tag{A43}$$

Since the cosmological expansion progresses over a very long timescale, the scale factor, $R(t)$ changes very slowly. Compared to the timescale between the wavecrests of photons used in astronomical observations, Δt_e, $R(t)$ is essentially constant so Equation A43 can be reduced to

$$-\,\frac{\Delta t_e}{R\,(t_e)} \;+\; \frac{\Delta t_r}{R\,(t_r)} \;=\; 0. \tag{A44}$$

Using the inverse relationship between time and frequency, this can be manipulated into

$$\frac{\nu_r}{\nu_e} \;=\; \frac{R\,(t_e)}{R\,(t_r)} \tag{A45}$$

or, in terms of wavelength at the point of emission, λ_e, and reception, λ_r,

$$\frac{\lambda_r}{\lambda_e} \;=\; \frac{R\,(t_r)}{R\,(t_e)}. \tag{A46}$$

and recasting to determine the redshift

$$z \;=\; \frac{\lambda_r}{\lambda_e} \;-\; 1 \;=\; \frac{R\left(t_r\right)}{R\left(t_e\right)} \;-\; 1 \tag{A47}$$

Now let's simplify our notation before proceeding further. Since we want to examine quantities in terms of things we can measure *today*, or t_r, let's write the curvature and time at t_r as R_0 and t_0 respectively. Next, let's expand the curvature for an arbitrary time, $R(t)$, as a Taylor series around t_0, using the dot notation to designate differentiation with respect to time:

$$\frac{1}{R\left(t\right)} \;=\; \frac{1}{R_0} \;-\; \frac{\dot{R}_0}{R_0^2}\;\left(t \;-\; t_0\right) \;+\; \left[\frac{\dot{R}_0^2}{R_0} \;-\; \frac{\ddot{R}_0}{2}\right]\;\frac{\left(t \;-\; t_0\right)^2}{R_0^2} \;+\; O\left(t^3\right). \tag{A48}$$

where $O(t^n)$ represents terms of order t^n and higher which we will ignore in this expansion. We use this expansion in equations A38 and A47.

$$\begin{aligned}
\ell \;&=\; \int_{t_e}^{t_r} \frac{d\,t}{R(t)} && \text{(A49)}\\
&=\; \left.\frac{\left(t \;-\; t_0\right)}{R_0} \;-\; \frac{\dot{R}_0}{R_0^2}\,\frac{\left(t \;-\; t_0\right)^2}{2}\right]_{t_e}^{t_0} \;+\; O\left(t^3\right) && \text{(A50)}\\
&=\; -\,\frac{\left(t_e \;-\; t_0\right)}{R_0} \;+\; \frac{\dot{R}_0}{R_0^2}\,\frac{\left(t_e \;-\; t_0\right)^2}{2} \;+\; O\left(t^3\right) && \text{(A51)}
\end{aligned}$$

Using the substitution $x \;=\; \left(t_0 \;-\; t_e\right)/R_0$, this simplifies to

$$\ell \;=\; x \;+\; \frac{\dot{R}_0}{2}\;x^2 \;+\; O\left(x^3\right). \tag{A52}$$

Similarly, we can recast the equation for the redshift, z, to

$$\begin{aligned}
z \;&=\; \frac{R\left(t_0\right)}{R\left(t_e\right)} \;-\; 1 && \text{(A53)}\\
&=\; \frac{R_0}{R_0} \;-\; \frac{\dot{R}_0}{R_0}\;\left(t_e \;-\; t_0\right) \;+\; \left[\dot{R}_0^2 \;-\; \frac{1}{2}\ddot{R}_0\,R_0\right]\;\frac{\left(t_e \;-\; t_0\right)^2}{R_0^2} \;-\; 1 \;+\; O\left(t^3\right) && \text{(A54)}\\
&=\; \dot{R}_0\;x \;+\; \left[\dot{R}_0^2 \;-\; \frac{1}{2}\ddot{R}_0\,R_0\right]\;x^2 \;+\; O\left(x^3\right) && \text{(A55)}
\end{aligned}$$

Next, we use equation A52 to replace x in equation A55 and regroup the terms in orders of ℓ.

$$z \;=\; \dot{R}_0\;\ell \;+\; \frac{1}{2}\left[\dot{R}_0^2 \;-\; \ddot{R}_0\;R_0\right]\;\ell^2 \;+\; O\left(\ell^3\right) \tag{A56}$$

We can then rewrite this as

$$z \;=\; \dot{R}_0\;\ell \;+\; \frac{\dot{R}_0^2\;\ell^2}{2}\;\left(1 \;+\; q_0\right) \tag{A57}$$

where we define q_0 as the 'deceleration parameter':

$$q_0 \;=\; -\,\frac{\ddot{R}_0\;R_0}{\dot{R}_0^2} \tag{A58}$$

Note that the first term on the right-hand side of Equation A57 is the basic linear Hubble Relation. The second term describes first-order variations from this linear relationship.

B. Analysis Tools

This appendix is devoted to describing some mathematical details and analysis tools used in this paper which don't fit in the main body of the text. This is primarily for use by those who really wish to reproduce or extend the results.

B.1. Splicing Data Sets

Setterfield has presented data of his claims for changes in the speed of light in a disorganized manner. Except for Setterfield E (see Section 5.6), I have found no single dataset from Setterfield covering the time from the moment of creation to the present day. To remedy this, I have to join the separate datasets in some consistent fashion.

To join two functions for this analysis, we need to ensure continuity in the data value and first derivative. This requires a 3rd-order polynomial. The function to splice between (x_1, y_1) and (x_2, y_2)

$$y = ax^3 + bx^2 + cx + d \tag{B1}$$

and its first derivative

$$\frac{dy}{dx} = 3ax^2 + 2bx + c \tag{B2}$$

We can set this up as a linear system to solve as

$$\begin{bmatrix} y\left(x_1\right) \\ y\left(x_2\right) \\ \left.\frac{dy}{dx}\right|_{x_1} \\ \left.\frac{dy}{dx}\right|_{x_2} \end{bmatrix} = \begin{bmatrix} {x_1}^3 & {x_1}^2 & x_1 & 1 \\ {x_2}^3 & {x_2}^2 & x_2 & 1 \\ 3{x_1}^2 & 2x_1 & 1 & 0 \\ 3{x_2}^2 & 2x_2 & 1 & 0 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} \tag{B3}$$

The dynamic range of Setterfield's data is so huge, this solution sometimes overshoots and yields speeds less than zero. To fix this issue, we can remap the data on a logarithmic scale using the substitution:

$$y = \log\left(\zeta\right) \tag{B4}$$

with the derivative

$$\frac{dy}{dx} = \frac{1}{\zeta}\frac{d\zeta}{dx} \tag{B5}$$

which will map our speeds to the positive side of the y-axis.

B.2. Extracting Pulsar Data

The primary pulsar database used is that available from the Australia Telescope National Facility(ATN). Data can be retrieved by web interface or by downloading and compiling the *psrcat* package available on the site.

Because we wanted to plot on a logarithmic scale, we needed to separate the data with positive and negative values for easier plotting. We also separated the data into three categories:

- Pulsars with distances via parallax;
- Pulsars with distances based on an association with another astronomical object of known distance;
- Binary pulsars where the orbital period change has been measured.

In unix, the commands extracting these categories from the psrcat.db file are:

```
% export PSRCAT_FILE=/path/to/file/psrcat.db
% psrcat -c1 "p1/p0" -c2 "3260*dist" -c "psrj dist p0 p1 c1 c2" \
> -l "px>0 && c1>0" -x >pulsarParallaxPlus.txt

% psrcat -c1 "p1/p0" -c2 "3260*dist" -c "psrj dist p0 p1 c1 c2" \
> -l "px>0 && c1<0" -x >pulsarParallaxMinus.txt

% psrcat -c1 "p1/p0" -c2 "3260*dist_a" -c "psrj dist_a p0 p1 c1 c2" \
> -l "dist_a>0 && c1>0" -x >pulsarAssociationPlus.txt

% psrcat -c1 "p1/p0" -c2 "3260*dist_a" -c "psrj dist_a p0 p1 c1 c2" \
> -l "dist_a>0 && c1<0" -x >pulsarAssociationMinus.txt

% psrcat -c1 "pbdot/pb" -c2 "3260*dist" -c "psrj dist pb pbdot c1 c2" \
> -l "exist(pbdot) && c1>0" -x >pulsarBinariesPlus.txt

% psrcat -c1 "pbdot/pb" -c2 "3260*dist" -c "psrj dist pb pbdot c1 c2" \
> -l "exist(pbdot) && c1<0" -x >pulsarBinariesMinus.txt
```

where we have computed $(dP/dt)/P$ and converted the distances from kiloparsecs to lightyears.

C. Technology

In this section, I'll describe the technology used to perform this analysis and generate this document, lest readers think this required access to high-power computing capability and corresponding budget.

Most of the calculations ran in minutes on an Apple PowerBook G3/333 (Lombard) and newer machines under Mac OS X version 10.1.5 and later (http://www.apple.com). These were my personal machines purchased for home use, off-the-shelf.

Computer programs for generating the models and tables were written using Python v2.2 and later (http://www.python.org), an open-source, object-oriented programming language freely available for a variety of computing platforms. A variety of Python extension modules were used. Among them, Numeric and later numarray (http://www.stsci.edu/resources/software_hardware/numarray), as well as GSL (http://www.gnu.org/software/gsl/) and PyGSL (http://sourceforge.net/projects/pygsl), were used for numerical analysis.

The graphs themselves were generated using various versions of GNUplot (http://gnuplot.sourceforge.net/) and more recently, PyX (http://pyx.sourceforge.net/). Other supporting graphics were generated using AppleWorks v6.2 (http://www.apple.com/appleworks/).

Typesetting was performed using OzTeX (http://www.trevorrow.com), a shareware Macintosh port of LaTeXand TeX, a typesetting markup language from the American Mathematical Society (http://www.ams.org/tex/) which is very popular in scientific publishing. Equation typesetting and some mathematical checks were performed using MathEQ and LiveMath Maker (http://www.livemath.com/). Computer Modern fonts were used to generate higher-quality PDF files from the PostScript.

I'd also like to thank the participants in the OzTeX and MacPython mailing lists who answered many questions from me on keeping my configuration working through all the updates.

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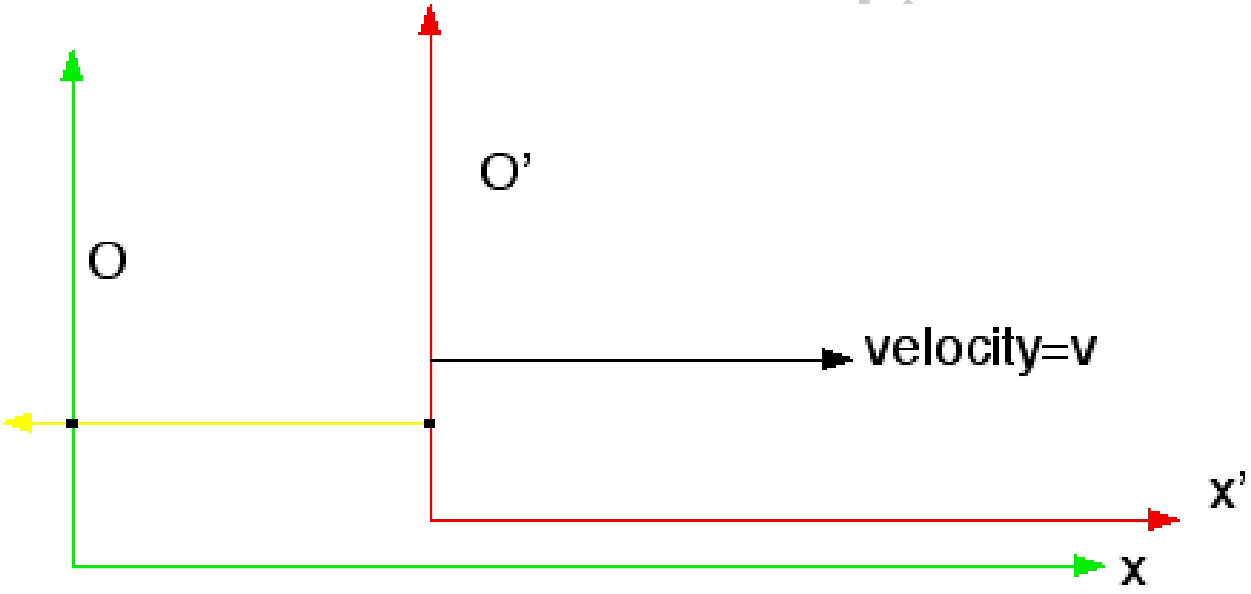

Fig. 16.— Graphical representation for computing the Doppler effect in a relativistic framework.

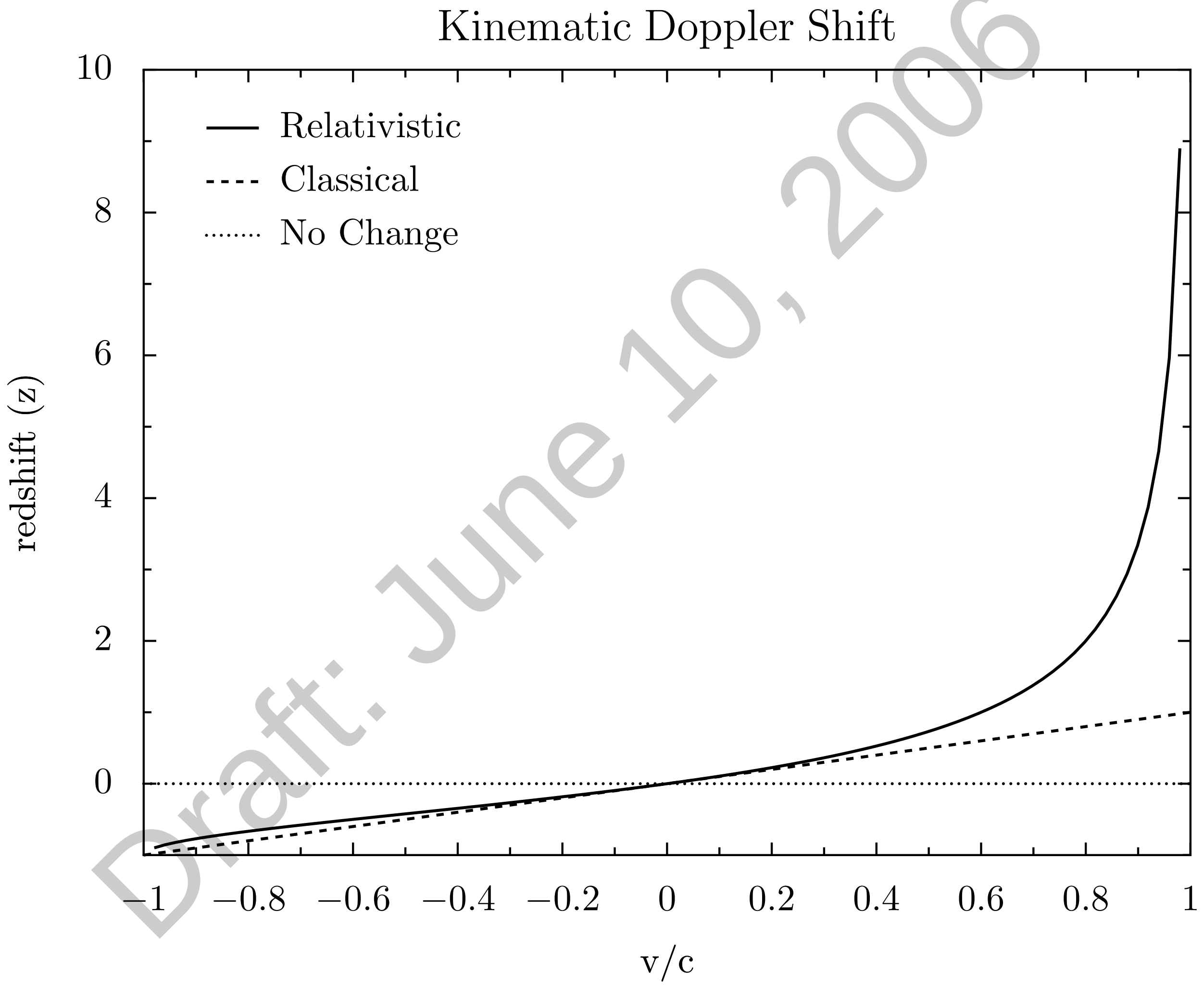

Fig. 17.— Plot of redshift (z) vs. velocity of the source in units of the modern-day speed of light.