Essentials of Photon Decay Theory
For the Hubble
Cosmological Redshift

By

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A PHOTON DECAY EQUATION

$$\nabla^2 \phi = \frac{1}{c^2}\left(\frac{1}{\hbar}\frac{\partial \phi}{\partial t} + \frac{\partial^2 \phi}{\partial t^2}\right)$$

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ABSTRACT

A decay process is proposed for light-like radiation from cosmologically distant galaxies. This is intended as an alternative explanation for the observed redshift. The equation incorporates the Planck action quantum as a diffusivity constant in the denominator of the first partial derivative term of the ordinary expanded wave equation. Action slowly diffuses entropically from the momentum domain into the wavelength domain as the photon travels through vast reaches of space-time. In the process photon momentum diminishes and wavelength increases proportionally at an exponentially diminishing rate. The results are within a factor of two of half-life estimates of 6 billion years derived from current observations of the Hubble constant..

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Note: In this document Doppler Velocity Shift is referred to ‘velocity shift’ and the Hubble Redshift, which is presumed here to result from photon decay, is referred to simply as ‘redshift’.

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INTRODUCTION

> *We are to admit no more causes of natural things than are such as are both true and sufficient to explain their appearance.*
> *Isaac Newton, the Principia, Rules of Reasoning*[1]

The equation presented here would almost certainly have been proposed by 1930 for the redshift, as all the necessary mathematics was well known by that time. It is an exercise in mathematical physics, and appears to predict values consistent with modern observations.

The decay of waves of all kinds is well known in engineering and physics. Damped waves are often used to describe water, sound, and sometimes electric field (light and other electromagnetic or photoelectric) waves in nonlinear media. Photons are the quanta of action in light. They are action waves, in which energy and momentum waves decay slowly into their quantum conjugates. The photon is not an atom.

A fast decay process usually looks like a damped cosine wave. In Figure 1, the decay rate is very fast so that only a few waves occur before the wave momentum shown here becomes smaller, with the wavelength increasing proportionally:

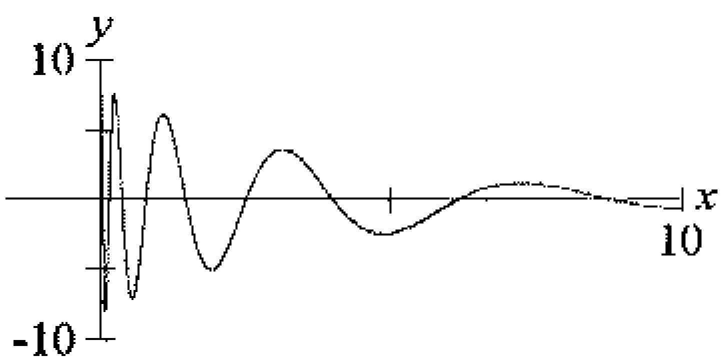

Figure 1

Photons appear to decay the same way, only it requires billions of years for a light wave to decay in momentum or energy by half its amplitude. The losses are into something more fundamental than heat—they are into distance and time, the very conjugates in action of momentum and energy.

Space-time is topologically[2] indeterminate between dimensions conjugate under the action in mathematically defined manifolds at quantum magnitudes. The momentum and wavelength domains in the wave are adjacent domains. In radiation in which redshift is observed action is *concentrated* into the momentum domain and *sparse* in the distance domain. Momentum is high, and wavelength is short compared with the vast distances of space. Equivalently, action is concentrated in the energy domain and sparse in the time domain; the energy is great, and the wavetime is brief in comparison with the time domain in the universe.

Action slowly diffuses from the momentum domain into the distance domain where it appears as longer wavelength. Equivalently, the action diffuses from the energy domain into the time domain where it appears as longer wavetime. The indeterminacy between dimensions is intrinsic to the quantum; that was Planck's discovery. The decay rate slows as the action becomes distributed between the two conjugate domains. The action diffuses from the domain it which it is most dense, to the conjugate domain, because no quantizing conditions exist either in space itself, or remaining with the photon. The only quantization is the total action of the photon.

Photons are quanta; they may be linked as in a continuous wave, or in phase as in coherence. It is conjectured there will be found a range of wavelength, somewhere between the longest presently observed, and many light-years, where the action devolves into a kind of background activity of space such as the known 3 K Cosmic Background Radiation.

The energy at short wavelengths is the normally observed spectral energy which can be measured with the photoelectric effect. The diffusion of action from the energy domain into the time domain is a normal diffusion. Waves decaying somewhat rapidly look like Figure 2:

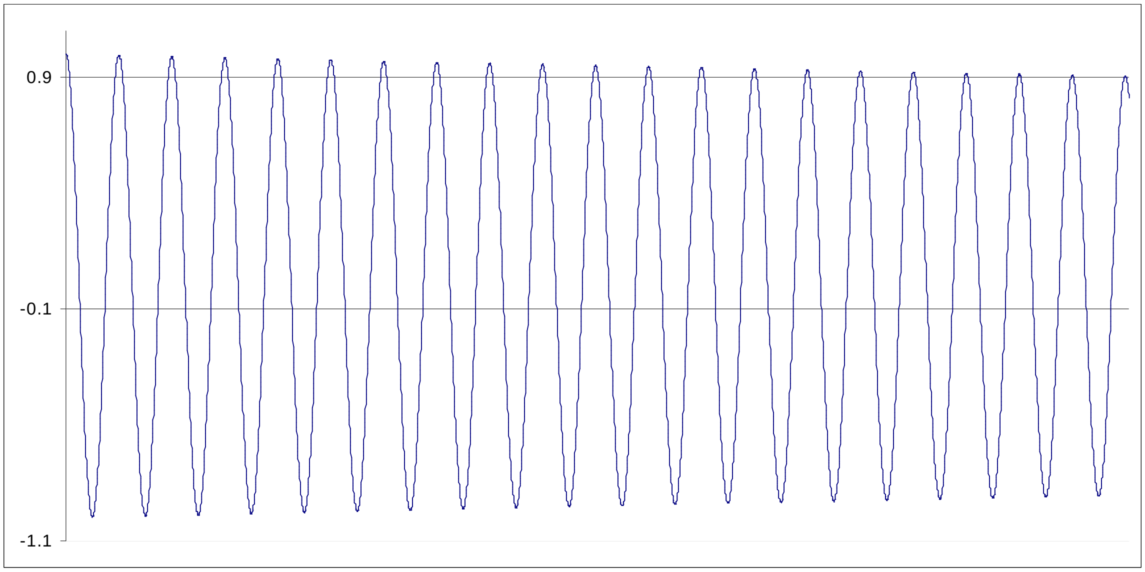

Figure 2

The number of waves is larger and the decay rate is smaller. The actual scale of a redshift wave cannot be depicted clearly in a spreadsheet chart, because the number of waves is astronomical – around 1,000,000 in a meter, and a parsec is 10^16 meters means that in one parsec a light wave undulates or whatever it does some 10^22 times, and in a billion light years, around 10^29 times.

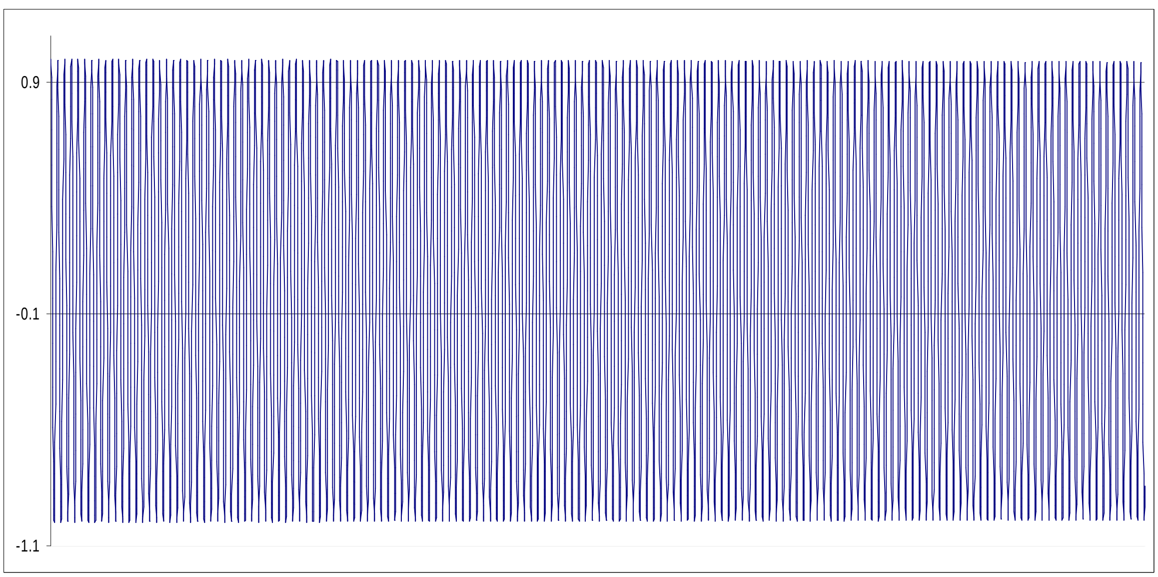

Figure 3

The mathematics is so simple many professional mathematicians could do it in their spare time. The general wave equation is fitted using the Planck action constant as a damping, diffusion or decay constant. The partial time derivative term *d/dt* appears in decay and diffusion processes in widespread economically important global use in machines that emerged largely after the 1900. The entire equation results from setting one variable, in one normal formulation of the wave equation, to the Planck action quantum $\hbar$.

The redshift is a fact extensively studied now and it is quite distinct from velocity shift. While the Doppler explanation for redshift theory begs the question, the cosmological redshift is always to longer wavelengths, while velocity shift may occur either to longer and shorter wavelengths depending on the sign of the velocity. That fact cannot infallibly be assigned to the idea that distant galaxies are receding so rapidly that their local motion is exceeded; the fact may also be the result of the light waves decaying slowly.

This photon or wave decay equation of the redshift, if it is true, preserves the use of redshift as an extragalactic distance estimator in the universe. General relativity offers abundant resources for seeing relative momentum as indistinct from relative position. As velocity increases beyond about 200 kilometers per second energy losses increase rapidly, resulting in what is literally a tax on the energy of galactic motion. The Milky Way Galaxy's velocity is normally around 60 km sec^-1.

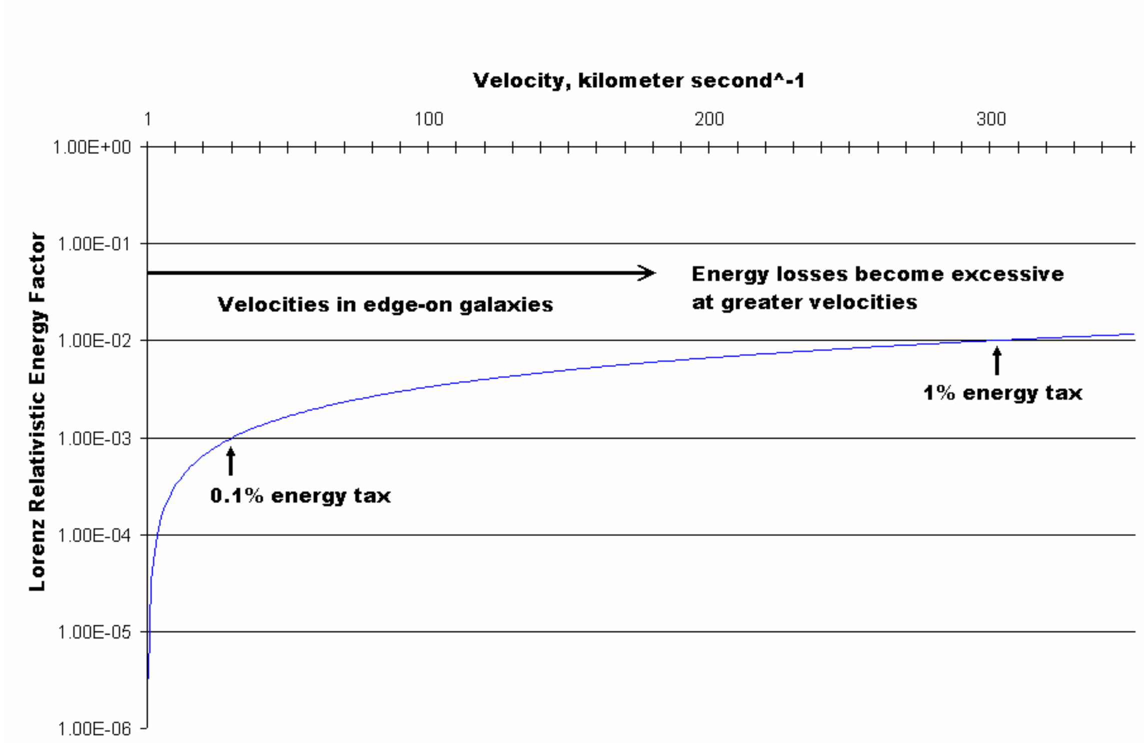

Figure 4

In particular, the relativistic limit on velocity is an improvement, and luminosity estimates are another. These place limits on the error in distance estimated by spectral redshift.

COORDINATING VELOCITY AND DECAY SHIFT

A definite distinction exists between velocity shift toward either longer *or* shorter wavelength, and the redshift which originates in photon decay and appears *only* toward longer wavelengths. Both shifts are important tools in astronomy and cosmology. Whatever theory is proposed, these tools are already well observed in practice and that theory must not require any distortion of the observed data. Much of the observed data is accurate, carefully measured, thoroughly documented and well recorded.

A fundamental uncertainty exists in determining both the distance and the velocity of distant objects with spectra alone. It is possible to determine the distance accurately with spectral shift if the velocity of the distant emitting object is zero. Or, it is possible to determine the velocity of the emitting object accurately if its distance is already known. It is not possible to determine using spectral shift alone both the velocity and distance of an object simultaneously. This is similar to problems of determining momentum and position and momentum of objects here on Earth and in fact is itself a cosmological limit on certainty.

Relativistic energy losses prevent objects from moving very rapidly. For the most part stable velocities everywhere are limited to a few hundred kilometers per second. Velocities exceeding this are rarer in proportion to their magnitude. It is possible to be somewhat certain of distance, within the range of velocities permitted by relativistic energy loss. This is good, and correlates well with the rotation curves[3] of edge-on spiral galaxies, which show the flat velocity limited by relativistic energy loss. For gravitationally bound or interacting systems such as Stephen's Quintet of Galaxies[4] it is possible to determine the relative velocities[5] of the components although, as stated above, spectral shift alone does not permit exact determination of both the velocity of the group and its distance at the same time.

Energy losses are demonstrated on Earth in particle accelerators where greater energy is necessary to accelerate particles to speeds close to that of light than would be the case if relativistic energy losses did not exist. Once acceleration and maintenance energy input ceases, fast particles rapidly lose energy by relativistic energy loss. The assumption that the universe is expanding results in the observed data being misinterpreted to suggest that many galaxies move at velocities in excess of 10,000 kilometers per second, a velocity at which sustained relativistic energy loss is unbelievable.

Velocity shift is excellent for determining relative velocities in objects that are found to be approximately the same distance away from Earth. This includes galactic rotation curves, stellar rotational velocity, stellar orbital velocities in multiple star systems, the velocity of gases in stellar atmospheres and the relative velocities of galaxies which are obviously interacting, as when they are physically intersecting. But a chance exists that velocity or Doppler shift is of no value in distance estimates, whereas redshift is, and there is a good chance, too, that redshift is caused by fundamentally different process, such as wave or photon decay.

Velocity shift is limited to a small range and adds or subtracts from redshift data. If photon decay exists and is not accounted then the object spectrum is red shifted and appears to be moving away from Earth. Many nearby objects exist at intermediate distances where velocity shift and decay shift are of comparable magnitudes. Failure to separate velocity shift from decay shift results in an assumption that velocity shift is caused by recessional velocity that is greater than actually exist. Attempts to determine both distance and velocity with high accuracy require that either or both be gauged by other means.

If either velocity or distance can be determined more accurately in other ways such as Cepheid luminosity-distance correlation, that adds to the accuracy of determination using both sources of spectral shift. For objects at greater distances this is of course difficult because all systems with large redshift are extremely distant and are usually beyond such estimators as Cepheid variables or parallax.

An intermediate example is the Andromeda Galaxy, Messier 31. Photon decay redshift is very small in light from M31 because of its proximity, and the relative velocity between the Milky Way Galaxy Earth and M31 dominates. The two galaxies are approaching each other and the net spectral shift is blue, or toward shorter wavelengths and greater momenta.

The indeterminacy of both absolute distance and radial velocity is an example of shifting the uncertainty in a problem toward a form that serves the purpose better. The distance and radial velocity cannot both be known perfectly, but if the tradeoff is optimized, we can do better. Relativistic energy loss is in our favor in attempting to determine distances to galaxies, because it limits the velocity for most ordinary objects, and that increases the accuracy with which decay redshift can be used to determine distance. With that constraint working for the researcher, decay redshift becomes an even more important tool for understanding extragalactic cosmology. It is essentially an absolute measure at greater distances, and light which arrives on Earth with a good spectrum increases the estimate of confidence in the validity of that measure.

EQUATION DEVELOPMENT

The inception of this work was the idea that the first derivative diffusion equation should be superimposed on the wave equation. Consider *Laplace's Equation*[6]

$$\nabla^2 \phi = 0$$

Equation 1

It is fundamental in many developments in mathematics and is the starting point here. In particular three equations derived from it are appropriate to photon decay theory, these being

The *wave equation* [7]

$$\nabla^2 \phi = \frac{1}{a^2} \frac{\partial^2 \phi}{\partial t^2}$$

Equation 2

The *diffusion equation*[8]

$$\nabla^2 \phi = \frac{1}{a^2} \frac{\partial \phi}{\partial t}$$

Equation 3

And the *vortex equation*[9]

$$\nabla \times \omega = 0$$

Equation 4

The latter lends confidence these first order partial differential equations are truly universal, as the vortex can be observed in eddies, whirlpools, whirlwinds, tornadoes, hurricanes and galaxies, but is not used in this description of photon decay.

Appropriate forms already exist in many presentations of the wave equation which are widely distributed in the literature. Dettman describes the unbounded wave[10] as:

$$\nabla^2\phi = a_1\phi + a_2\frac{\partial\phi}{\partial t} + a_3\frac{\partial^2\phi}{\partial t^2} - f(x,y,z,t)$$

Equation 5

This more complete form is much more versatile than will be needed in the cosmological redshift equation. In the second term of the above equation, a_2 will have to be simply related to $\hbar$, the Planck action quantum.

It must also be correctly related. Operational amplifiers as the "machine" from which my *deus ex machina* was drawn, in the same manner as quantum mechanics was drawn from various machines and relativity was drawn from railroad cars in motion. Machines are formidable rational tools whose importance cannot be overestimated. When they work properly, they are truth incarnate in such principles as they demonstrate. The operational amplifier can be used to simulate both wave and diffusion equations well with high accuracy. Comparison with a machine makes it possible to check whether logic, signs, symbols and ordered symbol relationships in theory are sensible.

A simpler form of the wave equation is ubiquitous in the literature:

$$\nabla^2\phi = a_2\frac{\partial\phi}{\partial t} + a_3\frac{\partial^2\phi}{\partial t^2}$$

Equation 6

It is necessary to be simple and carefully logical, because the equation being developed is based on the idea that the decay process is intrinsic to the nature of the wave in unbounded interstellar and intergalactic behavior, not to its origin (as from an electron transition) and several factors must all be taken into account at the same time.

First, light from space is usually from an excited atom or molecule, but it can be from positron-electron annihilation, Brehmstrahlung, synchrotron radiation or other sources.

Second, when we first observe light we may not know whether it has been redshifted or not, if we do not know the spectrum of which it is a part and whether it corresponds to any particular red-shifted line. Photons can now be accumulated singly in the detector region of a spectrograph. If the source is faint, with a sketchy spectrum and only a few quanta detectable, it may not be known from what part of the spectrum it was emitted and it cannot be correlated with any particular element or transition. It might easily have come from noise and be a part of no particular spectrum at all. Yet it is still light, traveled as other light waves travel, and behaves as all light does when it reaches our eyes or instruments. It is not until enough quanta have been accumulated to form a resolvable spectrum, that a spectrum can be interpreted for elemental lines, and only after the emitted elemental lines have been identified by their relation to other spectral lines or to the envelope of the spectrum can its wavelength shift be determined.

Third, spectral lines are not infinitely narrow even when emitted from electronic transitions. Spectra are often broadened at their source during emission in hot and moving stellar atmospheres, or by stellar rotation. They are also broadened during their long travel from distant objects, though surprisingly little in the pristine clarity of most of space. Many sources are moving at slow, non-relativistic rates of a few hundred kilometers each second. That is what makes it possible to measure the rotation curves of edge-on galaxies, the rotation rates of stars, and even some of the convection rates in the atmospheres of stars.

Fourth, the uncertain relationship between position and momentum is an attribute of space-time. Position is a state of zero velocity. Both are relative to near and distant reference points in both moving and stationary coordinates. No absolute position or velocity in space-time exists. There is (almost only) a field propagation velocity c which is the relation between distance and time. Momentum itself is relative to the object, such as a planet or star or field with the object bringing its own gravity, or to distant references. All these factors create additional logical terms that must be resolved consistently.

Equation 6 makes it possible to merge the diffusion and wave equations:

$$\partial^2\phi = \frac{1}{c^2}\left[f\left(\frac{\partial\phi}{\partial t}\right) + \frac{\partial^2\phi}{\partial t^2} \right]$$

Equation 7

The required constant term will fit into this general form in *f*. It should permit a description of light waves without forcing any distortion upon our concept of celestial photons and without requiring any attempt to adjust the facts which are basically the observed and photographed spectra.

As the equation neared this form it became clear that the Planck action quantum would be involved in the function *f*. Other than c, the only remaining constant in the photon which can be the decay constant is the action quantum ***ħ***, itself. After all, c and ħ are the only two constants that exist in the photon. Two other quantities, the electric and magnetic field constants, affect the photon but are properties of the electric field of space, not of the photon itself. The decay function must be at least a function of ħ and p, more narrowly defined now, to be further refined.

The result must describe a logarithmic decay function since the photon is required (by this hypothesis) to be similar to the decay of radioactive materials. Diffusion itself behaves logarithmically. An approach directly unifying the wave and diffusion equations results in a simpler though still tentative form:

$$\nabla^2\phi = \frac{1}{c^2}\left[f(\hbar, p)\frac{\partial\phi}{\partial t} + \frac{\partial^2\phi}{\partial t^2}\right]$$

Equation 8

Here, the equation is only an approximation. With a little thought, the wavelength λ then emerges from ħ and p and it begins to make better sense:

$$\nabla^2\phi = \frac{1}{c^2}\left(\frac{1}{p\lambda}\frac{\partial\phi}{\partial t} + \frac{\partial^2\phi}{\partial t^2}\right)$$

Equation 9

Momentum *p* and wavelength λ are explicit in this form of the equation. The rate of decay in time depends on the state of the photon at that time. Equivalently as above, the equation can also be written in terms of energy and wavetime to form:

$$\nabla^2\phi = \frac{1}{c^2}\left(\frac{1}{E\tau}\frac{\partial\phi}{\partial t} + \frac{\partial^2\phi}{\partial t^2}\right)$$

Equation 10

Here, energy E and wavetime τ are explicit.

But these are two different variables, and the diffusion constant is fragmented. How are we to signify that momentum and wavelength, or energy and wavetime, which are necessary at any one point in the spacetime journey of the photon, are related to each other in the correct way?

The quantum of action that Planck discovered is the key. The diffusion constant is made into one integral whole by the use of the action quantum. The symbol *ħ* or *h*/2π is an accounting factor having to do with radians.

The photon, a single wave of any light-like radiation, is a free eigenfunction of the unit quantum of action but it can vary in two variables which are related by a ratio fixed by the magnitude of the action quantum. It lasts so long because it is an almost perfectly conservative system. The imperfection in its conservation is only because the wave cannot commute, or swap places, with an earlier or later cycle and has no way to compress wavelength back into momentum or time back into energy. That is the order of time.

When the two variables are related that way and used to predict the half-life, the result first appeared to be around ten billion years. So the form did provide a solution which is somewhere near the value which was at that time being computed at observatories from Cepheid variable based luminosity-distance estimates and from other extrapolations. The equation now takes on the character of a successful solution in that it at least proposed a stable theory which is an alternative to the Expanding Universe theory.

It is now possible to calculate p from λ, or λ from p, using the equation $p * \lambda >= \hbar$, and one can integrate λ to get the path distance or use p, λ and c to obtain the energy and wavetime. It's not really possible to describe this equation without ***ħ***, because we have no other way of corralling both momentum and wavelength to unify the diffusion constant.

The resulting equation

$$\nabla^2 \phi = \frac{1}{c^2}\left(\frac{1}{h}\frac{\partial \phi}{\partial t} + \frac{\partial^2 \phi}{\partial t^2}\right)$$

Equation 11

is explicit in *ħ*, and is essentially the final version presented here.

This contains no more than the necessary information. It touches on relativity and quantum mechanics in the parameter of the first order derivative term, for the quantity *ħc* appears in physical constants and other relativistic mathematics. The appearance of quantum mechanics in the relativistic wave equation means the origin of this thought is in the successful synthesis called quantum electrodynamics and at the same time, care was taken to consider the order of entropy in both thermodynamics and information theory in the preparation of the theory.

It goes in the right direction, which is to say that for an energetic photon (say in the X-ray or ultraviolet) the diffusion rate of action from momentum into wavelength (or from energy into wavetime, whichever you prefer) is faster, while for a lower energy (such as an infrared or microwave) photon, the diffusion rate is lower, in a manner similar to radioactivity.

CONSTANTS AND VARIABLES

Here are several of the constants and variables used in this work. These are concepts important to the development of the photon decay equation. They are standard and empirically valuable sources of understanding in that they are extensively used throughout the world in economically significant production of numerous goods which are appropriate machines.

Symbols[11]				
Class	**Symbol**	**Meaning**	**Value**	**Dimensions**
Constant	c	speed of light	299792458	meters/second
Constant	ħ	action quantum	1.054E-34	Joule-second
External	E	Energy	variable	Joules
External	p	Momentum	variable	Kg-meter/second
Intrinsic	λ	Wavelength	variable	meter
Intrinsic	υ	wavenumber	variable	meter^-1
Intrinsic	τ	Wavetime	variable	seconds
Intrinsic	Hz	Frequency	variable	Hertz

Table 1

The photon decay equation stands reasonable comparison with the reported spectrographic Redshift data when that data is converted to a half-life. Redshift data is often reported as a frequency or wavelength shift in primary data so it will be possible for others in the future to use unbiased primary data. A few relationships on which the equation is based are:

$E = h * \nu$	energy=quantum * frequency
$E = p * c$	energy=momentum * speed of light
$h = p * \lambda$	quantum=momentum * wavelength
$h = E * \tau$	quantum=energy * wavetime
$c = \lambda * \nu$	speed of light=wavelength * frequency
$c = \lambda / \tau$	speed of light=wavelength / wavetime

Table 2

COMPARING PHOTON WITH RADIOISOTOPE DECAY

If photon decay half life is on the order of 2-10 billion years as is suggested by recent estimates of the correlation between distance and redshift, the duration of time should not be a cause of worry in terrestrial affairs. Sufficient phenomena of a statistical nature are attached to both nuclear isotopes and the behavior of light waves, to believe that probability plays a significant role in both the large and small extremes of photon behavior. Many radioisotopes with commensurate half-lives exist, and several much longer. The following table lists several:[12]

Isotope	Half-life, years
Bismuth 210	3x10^6
Cesium 135	3x10^6
Palladium 107	7x10^6
Curium 247	1.6x10^7
Iodine 129	1.7x10^7
Uranium 236	2.39x10^7
Samarium 146	7x10^7
Plutonium 244	8x10^7
Potassium 40	1.28x10^9
Uranium 238	4.5x10^9
Thorium 232	1.41x10^10
Rhenium 187	7x10^10
Platinum 190	6x10^11
Tantalum 180	>1x10^13
Hafnium 174	2x10^15
Zirconium 96	>3,6x10^17

Table 3

As with all information herein, this is empirical data in the public domain. These half-lives have been measured many times in both government and corporate laboratories in both national and international collaboration around the world. Though very slow decay rates have large margins of error, their general trend and approximate half-lives are well established.

COMPARING OBSERVED AND PREDICTED REDSHIFT

The following calculations were performed with a spreadsheet. The result is

Calculation of the photon half-life from observational data

Constant	c	299,792,458	meters/second
Constant	ħ	1.05454E-34	Joule second
Constant	parsec	3.09E+16	meters
Constant	light-year	9.46E+15	meters
Constant	light-years/parsec	0.307	

Calculation of the photon half-life from observational data		
Observed Hubble constant[13]	75,000	m s^-1 mpc^-1
Express as fractional frequency shift	0.0000250173	Mpc^-1
For half-life, divide 0.5 by the fractional frequency shift to get megaparsecs at half frequency	19,986	Mpc
To convert to parsecs, multiply by one million	19,986,163,867	parsecs
Converted to light-years	6,127,784,561	Light-years

Calculation of the photon half-life from the presented equation			
Calculate the denominator $\hbar c^2$		1.05510E+17	Light-seconds
Convert to light years		3,343,324,076	Light-years
The calculated value is 0.54 of the observed Hubble Constant	0.545%		
Or use the denominator $\hbar c^2$ / 2		4.73901E-18	
Use inverse to get light-seconds		2.11015E+17	Light-seconds
Convert to light-years		6,686,648,152	Light-years
This value is much closer	1.09%		

Table 4

This value is close to half of the observed Hubble Constant and it is worth reporting without further comment.

MOMENTUM AND WAVELENGTH

Wavelength and momentum of a photon as it travels through several thousand megaparsecs of space. Note the constant value of action. The momentum relaxes to one-half its original value in six billion light years, and the wavelength increases to twice its original value during the same time.

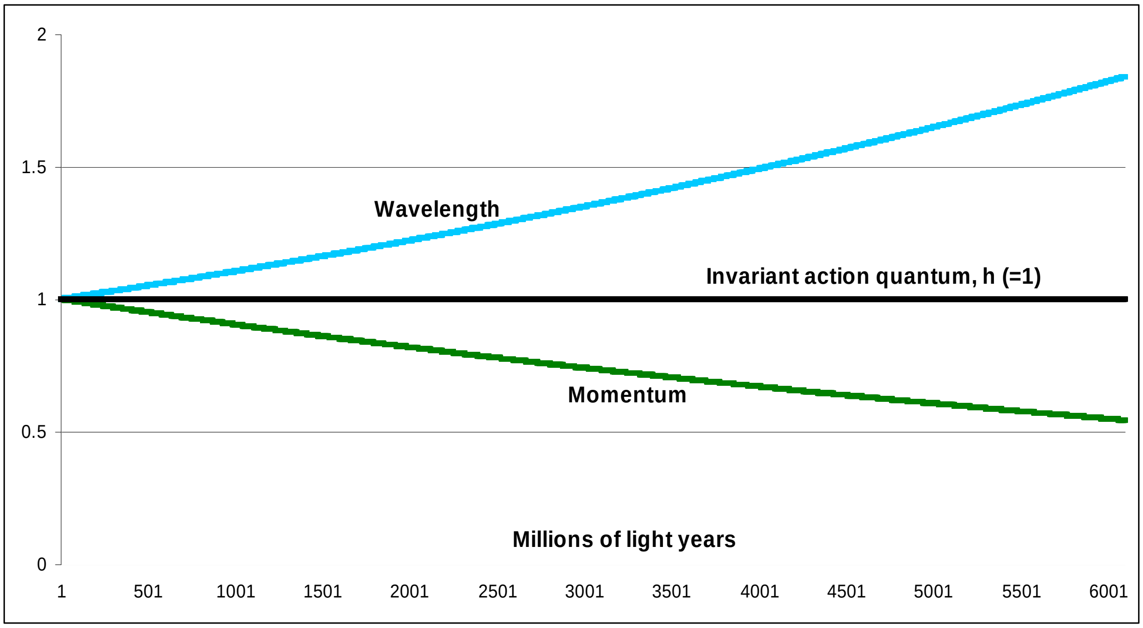

Figure 5

In intergalactic space the photon's action quantum gradually becomes redistributed in a process driven by the implacable entropy of the Third Law. The action moves from high momentum into the empty length dimension of space's distance, where it must remain as wavelength because of the characteristic integrity of the free photon. The momentum p is conjugate inside the photon with wavelength λ under the total action of the photon *h*. By internal is meant that quantities λ and *p* are both internal factors of the photon, and by conjugate is meant that the product of wavelength λ and momentum *p* has the dimensions of and is numerically equal to the action quantum.

CHART II

PHOTON POWER

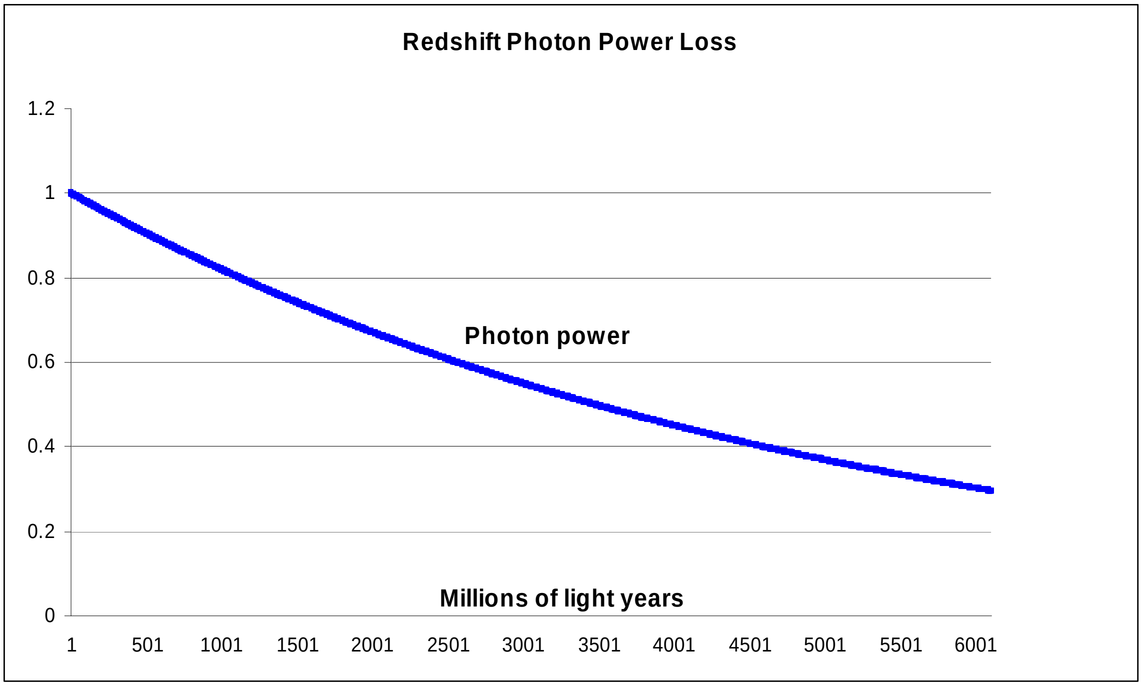

Figure 6

Photon power loss as it travels through space. The time rate of change of the energy is the power of the photon. As energy is lost, wavetime increases and the photon quantum expends from its energy reserve. Because it is a ratio E/τ of energy to wavetime, the power decay rate is faster than for energy alone. The quantity of power is dependent on both photon energy and the photon wavetime.

FUTURE WORK

Separating the constant term c^2 and using Gaussian coordinates where c=1, covariance (x, y, z,-ct) leads to the possibility of adapting the equation to general relativity where the space-time distance d*s* should be set in the metric tensor $g^{\mu\nu}$.

It may be possible to test for photon decay directly. In principle, reflected light could be mixed in frequency with the transmitted light, and if the path distance is sufficient and decay exists, a frequency comparator will result in a 'beat' frequency. Light is around 500 terahertz, and beat frequencies of 0.001 Hertz would be easily detectable, making a decay of one part in 10^15 detectable. However, the constraints on this test are severe and it may not be possible to obtain significant results from any kind of experiment like this on Earth alone, or even within the solar system, due to inadequate length of baseline. This problem is formidable: comparing the returned frequency with the original frequency requires the frequency stability of the terrestrial reference be stable to within the round trip time of the signal.

Tests using transceivers, located at a distant planet, which return an amplified signal to Earth, may be possible. The returned signal will have to be an amplified copy of the original signal because the frequency of the returned signal must absolutely identical. The remote receiver should be isolated from the transmitter with local geological formations (hill or crater) with the received frequency pre-amplified sent to final amplifiers through fiber optics or some other appropriate medium, and then retransmitted back to the original transmitting station on Earth. An estimate of the necessary baseline should be calculated before Congress releases funds. ☺

As a practical matter, since in general relativity the distance in space-time is abbreviated d*s*, and c=1, the quantities called momentum and energy become identical, so that it will be necessary to define a quantity which serves the purpose of both. That is, since energy = momentum * c, when c=1, the quantity must still have a name. In other words it will be necessary to define the action, and the energy-momentum, in terms usable in general relativity.

Michael Lewis
Seattle 2006

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