DRAFT: Quantitative Comparison of Redshift Mechanisms

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3rd March, 2010

Abstract

This paper gives a compilation of physical mechanisms that explain the dependence of redshifts and luminosities on the distance to astronomical objects. Forty mechanisms are listed here for the purpose of quantitative comparisons. These mechanisms may not account for all observations but are restricted to particular situations such as the solar limb redshift, the redshift of quasars or the cosmological redshift. However, the paper focuses mainly on the 31 mechanisms giving a quantitative description of how large redshifts are related to distance. For each mechanism a description is given with its properties, limits of applicability and a mention of the adjustable parameters.

1 Introduction

After the first observations of the redshift of nebulae in the early 20$^{\text{th}}$ century, it took Hubble a little over ten years to formulate the empirical *Redshift Distance Law* of galaxies. The observed linear relation between distance and redshift is now called the Hubble law. The similarity between the observed redshift and the Doppler effect seemed to imply large receding velocities of distant galaxies and an enormous amount of kinetic energy. These velocities might also indicate that all matter originated from a single point where an explosion, the "Big Bang", occurred some 13.7 billion years ago. This was recognized in 1929 by Fritz Zwicky who, in order to avoid what was considered "extraordinary implications", suggested another explanation to explain the observed redshift [1]. In Zwicky's mechanism, photons lose energy through interactions with other particles. Such a "tired light" mechanism avoids the Big Bang scenario.

Since then many mechanisms and models were proposed [2] to explain not only the redshift of distant galaxies, but many anomalous phenomena observed in astrophysics. Some of these mechanisms propose an idea similar to Zwicky's, but others maintain the Doppler redshift, space expansion, or a Big Bang scenario. The goal of the present paper is to list these hypotheses and provide quantitative comparisons between the many possibilities. The following descriptions reflect my understanding of the mechanisms. The reader is encouraged to read the original work given in the references.

Four categories are used to classify the redshift mechanisms. These categories are based on how space, time, matter and light combine to produce the redshift:

1. A changing metric of space or time,
2. a changing property of matter,
3. a changing property of light or an interaction of light with itself,
4. an interaction between light and matter.

Because of the wide range of conditions under which redshifts are observed in astronomy, it is likely that more than one mechanism is at play. All redshift mechanisms listed here may have some contribution. This attempt to give objective reviews of the mechanisms is not without some risks. I cannot understand each of these models in all their details. Some descriptions will likely be limited to the limited space available and my understanding of the physics involved in the mechanism. In many cases, the proponents of the ideas supported us and helped to improve the description. References are given to allow the reader to consult the original work.

An important question is how can one determine if a theory is "better" than another. The answer to this is not easy to obtain! However, one necessary first step is to have quantitative predictions from all the theories to be compared. A closer agreement with experimental data is certainly a step in the right direction, but not a sufficient condition to accept a theory. This paper is an attempt to providing quantitative predictions from many theories.

2 Definitions

In order to simplify the list of the many different mechanisms presented here, this section gives definitions used in the majority of cases. In the case of a disagreement with the definitions given in this section, the specific details are given in the description of the mechanism.

2.1 Definitions

The SI System of Units [3] is used in this paper. Although this is the system of units currently used in physics, some redshift mechanisms seem to be based on different definitions of the meter or the second. As a result, the descriptions given below might represent these mechanisms as I see them through the tinted glasses of the SI System. These units are defined locally to an observer in the following way: "The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second". The speed of light is thus $c = 299\,792\,458$ m/s. "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom" [4].

Other constants used in this paper have the following values. Planck's constant is $h = 6.626 \times 10^{-34}$ Js. H_0 is Hubble's parameter at the present epoch. It's exact value is not critical in this paper, but current estimates give $H_0 = 70.1$ (km/s)/Mpc or 2.27×10^{-18}/s. Throughout the paper, I use the dimensionless Hubble parameter h_{100} defined so that $H_0 = 100 h_{100}$ (km/s)/Mpc. The Hubble distance is $D_H = c/H_0$. The subscript 0 is used for values, observed or defined, at the present epoch on Earth.

The comoving distance d_C is a useful quantity in the description of the mechanisms. Although not measured directly experimentally, it describes our intuitive notion of distance: how many times a ruler fits between two points in space. Its precise definition depends on the cosmology. When necessary, the comoving distance will be defined in the description of the mechanisms.

2.2 Experimental considerations: Observables and inferred quantities

In this paper, the mechanisms are described in terms of an experimental procedure which can be followed to obtain the predicted results. The sky is observed with a detector behind a collecting and imaging device such as a telescope. Experimental observations in astronomy are limited to measurements of three observables:

- **The frequency**: The frequency ν_0 of light is measured with a detector that responds to light having a frequency within a range ν_0 to $\nu_0 + \mathrm{d}\nu_0$. The frequency $\nu_0 = c/\lambda_0$ is usually measured with a dispersive device, such as a grating, which selects light at a desired wavelength.
- **The angular size**: The angular size θ_0 is the angle of an object detected by the imaging device. It is relevant to objects that are large enough or separated enough to be resolved. At large distances, this applies to clusters, galaxies and separated objects such as quasars.
- **The spectral radiance**: When light is detected, the spectral radiance $I_0(\nu_0)$ [W m^{-2} sr^{-1} Hz^{-1}] [5] is the energy received by the detector per unit area per unit solid angle in the frequency range ν_0 to $\nu_0 + \mathrm{d}\nu_0$ [6]. The total intensity (or bolometric intensity) is the spectral radiance integrated over all frequencies $I_0 = \int_0^\infty I_0(\nu_0)\mathrm{d}\nu_0$ [7].

The intensity is not to be confused with the luminosity L, the total power radiated by the source, which requires a knowledge of the distance and spatial geometry between the source and the observer.

The following quantities are defined independently of a cosmological model. However, their interpretation requires that the object at a cosmological distance has the same properties as those of a known object. In evaluating these properties, it may be necessary to use a specific cosmology.

- **The redshift** z: The redshift is $z \equiv \Delta\lambda/\lambda = (\lambda_0/\lambda) - 1 = (\nu/\nu_0) - 1$, where λ and λ_0 are the emitted and observed wavelengths respectively, and ν and ν_0 are the emitted and observed frequencies respectively, of an identified spectral line. Here, the redshift is determined with respect to an observer on Earth.

- **Angular diameter distance** d_A: The angular diameter distance d_A is defined as the ratio of an objects physical transverse size to its observed angular size θ_0. The object's physical transverse size is inferred by comparisons with similar objects.

- **Luminosity distance** d_L: The luminosity distance is the distance at which an object would lie based on its observed luminosity in the absence of any absorption. The luminosity distance d_L is defined by the relation $d_L = \sqrt{L/(4\pi S_0)}$ where L is the luminosity of the object and $S_0 = \int_{source} I_0 \mathrm{d}\Omega_0$ is the measured flux from the object, that is, the intensity integrated over the solid angle subtended by the source. The luminosity of the object is inferred by comparisons with similar objects.

- **Magnitude** $m - M$: The distance modulus is related to the luminosity distance through $m - M = 5\log_{10}[d_L/D_H] + C$. The constant C depends of the type of object which is observed. Although it is derived from the luminosity distance, this expression might be more familiar to some readers.

- **Surface Brightness** $\langle SB \rangle$: The surface brightness is related to the angular distance and the luminosity distance through $\langle SB \rangle \propto (d_A/d_L)^2$. Although it is derived from the angular and the luminosity distances, this expression shown explicitly what to expect for the Tolman surface brightness test. When some authors do not agree with this definition, their equation is listed. Note that this definition is different from the usage where the magnitude is used in the definition of the surface brightness.

- **Time dilation factor** F_τ: The time dilation factor F_τ is obtained by observing the temporal variation of the electromagnetic field (e.g. intensity decrease after the explosion of a supernova). The dilated time F_τ is defined as the ratio of the observed duration of an event to the duration of that same event as would be measured at the object. The time duration at the object is inferred by comparisons with similar objects.

- **Wavelength dispersion factor** Δ_λ: Some mechanisms involve a statistical interaction of light with the intergalactic medium. This may produce an increase in the linewidth of spectral lines. Usually interpreted as a result of the higher temperature of the emitting or absorbing gas, an increase in the observed linewidth could also result from the redshift mechanism. The linewidth increase factor Δ_λ is defined as the ratio of the measured wavelength $\delta\lambda_0$ to the observed wavelength of the spectral line. This assumes that: (a) the change in linewidth caused by the time dilation factor is much smaller than the observed linewidth, and (b) at the source, an infinitely narrow linewidth is produced by an emitting or an absorbing gas which is very cold. The temperature of the gas may not always be available experimentally.

- **Angular dispersion** Δ_θ: Some mechanisms involve a statistical interaction of light with the intergalactic medium. This may produce an angular dispersion of the light with each collision. The angular dispersion Δ_θ is the observed angular size of a point source. This assumes that the light originates from a point source. The angular size may not always be available experimentally.

2.3 Format Used to Describe Redshift Mechanisms

The format used for each redshift mechanism is as follows: A description of the redshift mechanism at the undergraduate physics level is given in the first paragraph, completed by a description at the graduate physics level. In order to keep this paper within a reasonable length, only short explanations are given to explain each mechanism. References to published work in journals or web pages are provided.

Conditions of applicability and restrictions: The domain of applicability of the redshift mechanism. This could be for example: the solar limb redshift, the redshift of quasars, and the cosmological redshift. The assumptions required to make the mechanism work, adjustable parameters, and conflicts with currently accepted theories.

Functional relationships: Functional relations between various quantities for large redshifts, measured or inferred: z, d_A, d_L, $m - M$, $\langle SB \rangle$, F_τ, Δ_λ, and Δ_θ. Preferably, the quantities will be given as functions of the redshift. When possible, the equation were taken directly from a published reference or confirmed by the author. However, some had to be derived by us and have not yet been verified by the original author or against any reference.

Discussion: Any experiment that can distinguish the model from other models. If the model has the same properties as another model, an explanation will be given as to why it is not just another description of the same mechanism.

3 Redshifts linked to the metric of space and time

The redshift mechanisms listed in this section depend on the changing metric of space between the emitter and the detector. They can involve a simple change in distance or a more complex space curvature. The properties of space are selected to match the observed Hubble law.

3.1 Doppler

This is given as a simple example. It assumes that galaxies move away from us with velocities that produce a redshift z proportional to their distance in a Euclidian universe. The redshift is a result of the Doppler effect. With the theory of special relativity included in this mechanism, the redshift as a function of velocity is $1 + z = \sqrt{(c+v)/(c-v)}$.

Conditions of applicability and restrictions: One adjustable parameter is needed, the proportionality constant between the redshift and the distance. The mechanism neglects the masses in the universe which would curve space.

Functional relationships:

$$d_A = D_H z,$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 10 \log_{10}[1+z] + 5 \log_{10}[z] + C,$$

$$\langle SB \rangle \propto (1+z)^{-4},$$

$$F_\tau = 1 + z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

3.2 Standard Big Bang

The metric expansion of space increases the wavelength of the light over time. This effect is present everywhere in the universe.

Functional relationships: For the general case (Ω_M, Ω_k) [8]:

$$d_A = \frac{D_H}{(1+z)^2} \frac{2[2 - \Omega_M(1-z) - (2-\Omega_M)(1+\Omega_M z)^{1/2}]}{\Omega_M^2},$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 10\log_{10}[1+z] + 5\log_{10}[d_A/D_H] + C,$$

$$\langle SB \rangle \propto (1+z)^{-4},$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

3.3 Lambda-Cold-Dark-Matter Cosmology

Λ is the cosmological constant introduced by Einstein. Dark matter is described as being cold, non-baryonic, dissipationless and collisionless. The model assumes a nearly scale-invariant spectrum of primordial perturbations and a universe without spatial curvature. The model uses the FLRW (FriedmannLemaîtreRobertsonWalker) metric, the Friedmann equations and the cosmological equations of state to describe the universe from right after the inflationary epoch to the present.
Formulas kindly provided by Philip Mannheim. See also D.W. Hogg, "Distance measures in cosmology" [8].

Conditions of applicability and restrictions: A possible fit to experimental data gives: $\Omega_\Lambda = 0.73$, $\Omega_M = 0.23$, and $\Omega_k = 0.04$.

Functional relationships: In the case where $\Lambda \neq 0$, distances are calculated from the comoving distance

$$d_C = D_H \int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_k(1+z')^2 + \Omega_\Lambda}}.$$

For the general case, d_L must be integrated numerically.

$$d_A = \left| \begin{array}{ll} \dfrac{D_H \sinh\left[\sqrt{\Omega_k} d_C/D_H\right]}{(1+z)\sqrt{\Omega_k}}, & \text{for } \Omega_k > 0 \\[2ex] d_C/(1+z), & \text{for } \Omega_k = 0 \\[2ex] \dfrac{D_H \sin\left[\sqrt{-\Omega_k} d_C/D_H\right]}{(1+z)\sqrt{-\Omega_k}}, & \text{for } \Omega_k < 0 \end{array} \right.$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 10\log_{10}[1+z] + 5\log_{10}[d_A/D_H] + C,$$

$$\langle SB \rangle \propto (1+z)^{-4},$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

3.4 The Chronometric redshift theory

The redshift varies with distance $z = \tan^2(d_C/2R)$ where R is the radius of the universe.
See I.E. Segal.

Functional relationships:

$$
\begin{aligned}
d_A &= \text{ not yet available,} \\
d_L &= \text{ not yet available,} \\
m - M &= 5\log_{10}[d_L/D_H] + C, \\
\langle SB \rangle &\propto (d_A/d_L)^2\,, \\
F_\tau &= \text{ not yet available,} \\
\Delta_\lambda &= \text{ not yet available,} \\
Delta_\alpha &= \text{ not yet available.}
\end{aligned}
$$

3.5 Scale Expanding Cosmos

The length of a meter expands and the pace of time slows down, making time intervals like the second longer in proportion [9]. The wavelength of light is also made longer. The Friedmann-Robertson-Walker line-element assumes that the pace of proper time always has been the same and is therefore different from the SEC line-element with its changing pace of time. The SEC model cannot be modeled by General Relativity (GR) as experienced by an inhabitant because the pace of proper time is changing (the element ds in GR is changing). This changing pace of proper time models the progression of time, which cannot be modeled by GR. The scale expanding cosmos behaves like an ordinary black body cavity without changing the cosmological temperature and the CMB results from thermal relaxation of electromagnetic radiation.

$$d = D_H \ln(1+z)$$

Conditions of applicability and restrictions: General Relativity has to be generalized to include discrete scale adjustments that change the pace of proper time. This means that different epochs belong to separate space-time manifolds in GR - they are not covariant. The proponent of the theory believes that a theory which cannot model the progression of time cannot model the universe, since the progression of time is the most important aspect of all existence. Any model based on GR and the FRW line-element will fail.

Functional relationships:

$$
\begin{aligned}
d_A &= D_H \ln(1+z), \\
d_L &= (1+z)d_A, \\
m - M &= 5\log_{10}[1+z] + 5\log_{10}[\ln(1+z)] + C, \\
\langle SB \rangle &\propto (1+z)^{-2}, \\
F_\tau &= 1+z, \\
\Delta_\lambda &= \text{ not yet available,} \\
\Delta_\theta &= \text{ not yet available.}
\end{aligned}
$$

3.6 New Redshift Interpretation

The model is based on a universe governed by static-space-time general relativity interprets cosmological red shifts as a combination of gravitational red shifts and ordinary Doppler shifts coming from motion in a static geometry. While the spatial geometry is not explicitly given, a number of expressions indicate that Gentry is considering a nearly Euclidean metric.

To be consistent with observed isotropy of matter and cosmic microwave background radiation, Gentry's model is geocentric, placing our galaxy near the center of a static spherical ball of matter with a radius $R \sim 1.4 \times 10^{10}$ light years. This matter consists of two components: ordinary pressureless matter ("galaxies") and a vacuum energy (that is, a cosmological constant). The gravitational potential varies with distance from the center, and the resulting gravitational red shift thus depends on distance from the Earth.

To explain cosmic microwave background radiation, Gentry supposes that his ball of matter is surrounded by a thin shell of hydrogen at a temperature of 5400K. The resulting black body radiation must be gravitationally red shifted to the observed 2.7K at the center of the ball. (Gentry: arXiv:physics/9810051v1 and arXiv:astro-ph/9808021v2)

Functional relationships:

$$d_A = \text{ not yet available},$$

$$d_L = \text{ not yet available},$$

$$m - M = \text{ not yet available},$$

$$\langle SB \rangle \propto \text{ not yet available},$$

$$F_\tau = \text{ not yet available},$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = \text{ not yet available}.$$

3.7 Machian General Relativity

A scale-invariant form of the field equations of General Relativity is postulated, based on the replacement of the Newtonian gravitational constant by an formulation based explicitly on Mach's principle[10].

Functional relationships:

$$d_A = \text{ not yet available},$$

$$d_L = \text{ not yet available},$$

$$m - M = 5 \log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2 \,,$$

$$F_\tau = \text{ not yet available},$$

$$\Delta_\lambda \approx 0,$$

$$Delta_\alpha \approx 0.$$

3.8 Conformal Gravity

A four-dimensional theory of quantum gravity is proposed to fit the accelerating universe data [11, 12]. The cosmological constant is taken as being very large, but not as part of the standard of the Newton-Einstein theory.

Conditions of applicability and restrictions: A possible fit to experimental data gives $q_0 = -0.37$ ia the deceleration parameter.

Functional relationships:

$$d_A = -\frac{D_H}{q_0}\left(1 - \left[1 + q_0 - \frac{q_0}{(1+z)^2}\right]^{1/2}\right),$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 10\log_{10}[1+z] + 5\log_{10}[d_A/D_H] + C,$$

$$\langle SB\rangle \propto (1+z)^{-4},$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

3.9 Quantum Celestial Mechanics Gravitational Potential

The Hamilton-Jacobi equation of the General Theory of Relativity is changed into a Schrödinger-like equation which predicts quantization states for any gravitationally bound system. These Quantum Celestial Mechanics (QCM) states depend only upon the total mass and the total angular momentum of the system. Distant redshifted SNe1a light sources from the Universe that are usually interpreted as cosmological redshifts are shown to be universal gravitational redshifts seen by all observers. An increasingly negative QCM gravitational potential with distance from the observer dictates a non-linear redshift with distance and an 'apparent' gravitational repulsion, i.e. the source clock rate is slower than at the observer. No space expansion is necessary, nor is dark matter and dark energy needed.

The 'apparent' radial velocity $v = \mathrm{d}d/\mathrm{d}t$ versus coordinate distance d leads to a new Hubble relation:

$$v = d\frac{c\sqrt{k}}{1 - kd^2}$$

where $k = 8\pi G\rho_c/3c^2$. Best fit when Hubble parameter is about 62 (km/s)/Mpc. Thus, the 'apparent' radial velocity continues to increase with increasing distance.
See Howard G. Preston and Franklin Potter, "Cosmological Redshift Interpreted as Gravitational Redshift", www.ptep-online.com/index_files/2007/PP-09-06.PDF

Functional relationships:

$$d_A = D_H\frac{a}{2b}\left[\sqrt{1 + (4b^2/a^2)} - 1\right],$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 5\log_{10}[1+z] + 5\log_{10}[d_A/D_H] + C,$$

$$\langle SB\rangle \propto (1+z)^{-2},$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda \approx 0,$$

$$\Delta_\theta \approx 0,$$

where $a = (1+z)^2 + 1$, and $b = (1+z)^2 - 1$.

Discussion: One possible test of the different redshift theories is the interpretation of the SN1a rise-fall time. If it is truly longer for distant observers compared to the shorter rise-fall time at the source SN1a, then 'tired-light' type of cosmological redshifts can be eliminated. The QCM approach has a gravitational potential decreasing with distance from the observer so the clock rates are different at the source and observer, which would explain the rise-fall time difference.

3.10 Gravitational Interaction

The time dimension where the light is emitted is not always parallel to the time dimension where the light will be detected. This produces a projection reducing the observed rate, thus causing a redshift.
See Alexander F. Mayer, www.jaypritzker.org/book
See also Alexander F. Mayer, www.archive.org/details/OnTheGeometryOfTimeInPhysicsAndCosmologyver.2.1.2

Functional relationships:

$$
\begin{aligned}
d_A &= \text{ not yet available}, \\
d_L &= \text{ not yet available}, \\
m - M &= 5\log_{10}[d_L/D_H] + C, \\
\langle SB \rangle &\propto (d_A/d_L)^2, \\
F_\tau &= 1 + z, \\
\Delta_\lambda &\approx 0, \\
Delta_\alpha &\approx 0.
\end{aligned}
$$

3.11 Lobachevsky Space

J. Georg von Brzeski and Vadim von Brzeski use a Lobachevskian geometry of constant negative curvature to describe the universe [13]. The following description is limited to the redshift in empty space as a consequence of the non-Euclidean geometry of space. This model is based on the concepts that light follows the shortest path along geodesics, and that horospheres in Lobachevskian space are orthogonal to the geodesics and can thus be interpreted as wavefronts. A key theorem on the rate of divergence of geodesics in Lobachevskian geometry states that the length of a segment increases exponentially with the hyperbolic distance $\lambda = \lambda_0 \exp(\delta)$. As galaxies are observed at greater distances, space is proportionally larger and the wavelength of light is longer. The hyperbolic distance δ in Lobachevskian geometry can be mapped onto Euclidian space using $d = \rho R$ where $\rho = \tanh(\delta)$.

Conditions of applicability and restrictions: Distances are measured without involving the notion of time. The theory uses an older definition of the primary length standard as defined in the General Conference on Weights and Measures in 1983: "The wavelength of the iodine stabilized HeNe laser is $\lambda_{HeNe} = 632.99139822$ nm".

The Doppler effect (which, in Lobachevskian geometry, follows from the negative curvature of velocity space) is not described here.

The following equations were derived from published references [14, 15]. The luminosity distance is derived from the ratio of intensities of electromagnetic radiation in Lobachevskian space versus Euclidean space $\sqrt{1-\rho^2}(1-\rho)$, combined with the Euclidean $(4\pi r^2)^{-1}$ law [16]. The reader is invited to refer directly to these papers. The time dilation factor corresponds to the low frequency components of the electromagnetic spectrum which are also stretched by a factor $1 + z$.

Functional relationships:

$$
\begin{aligned}
d_A &= \text{ not yet available}, \\
d_L &= \frac{D_H \tanh[\ln(1+z)]}{\left[\sqrt{1-\rho^2}(1-\rho)\right]^{-1/2}}, \\
m - M &= 5\log_{10}[d_L/D_H] + C,
\end{aligned}
$$

$$\langle SB\rangle \propto (d_A/d_L)^2\,,$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

3.12 Spatial Change of Time Flow

The redshift arises when an observer measures the frequency emitted by an object located in another part of space where time flows differently. Since the flow of time varies continuously and monotonically, light that has traveled through space and time is seen with a redshift.

The mechanism is based on the premise that time is not uniform, but migrates between spacetime systems to different 'time flow' system [17, 18, 19]. Based on Noether's theorem, it is demonstrated that energy is not conserved in a non-uniform time frame. As the flow of time does not remain constant, the pace of a process cannot remain constant either. In the corpuscular case the velocity of a particle must grow in a zone of 'slower time flow'. However, as the speed of light obeys the Einsteinian axiom $c = \text{const.}$, the only possibility for a light quantum is that instead of velocity its frequency decreases in a zone of 'faster time flow', i.e., the frequency observed in a zone of faster time flow is lower than the frequency of light emitted in the zone of slower time flow. In other words, a redshift is observed.

This redshift mechanism is far from artificial as it also explains the nature of Cold Dark Matter, the Cosmological Microwave Background Radiation and most importantly, the nature of gravity. Since the inverse-square law of universal gravitation naturally appears as a consequence of the linear dependence of the flow of time on space, the redshift as a function of space must be linear as well.

The above does not imply that the more distant from the Earth an object is the faster it moves away. The redshift is observed even in the solar spectrum. Yet, the Sun does not move away from the Earth.

Conditions of applicability and restrictions: The rate of change of time flow is chosen to produce the observed $d = D_H z$ for small z.

Functional relationships:

$$d_A = D_H z,$$

$$d_L = \text{ not yet available,}$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB\rangle \propto (d_A/d_L)^2\,,$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\theta = 0.$$

Discussion: This theory predicts a monotonous increase of the acceleration g with increasing depth toward the centre of the Earth, due to the decrease of the time flow (which is what really causes gravity).

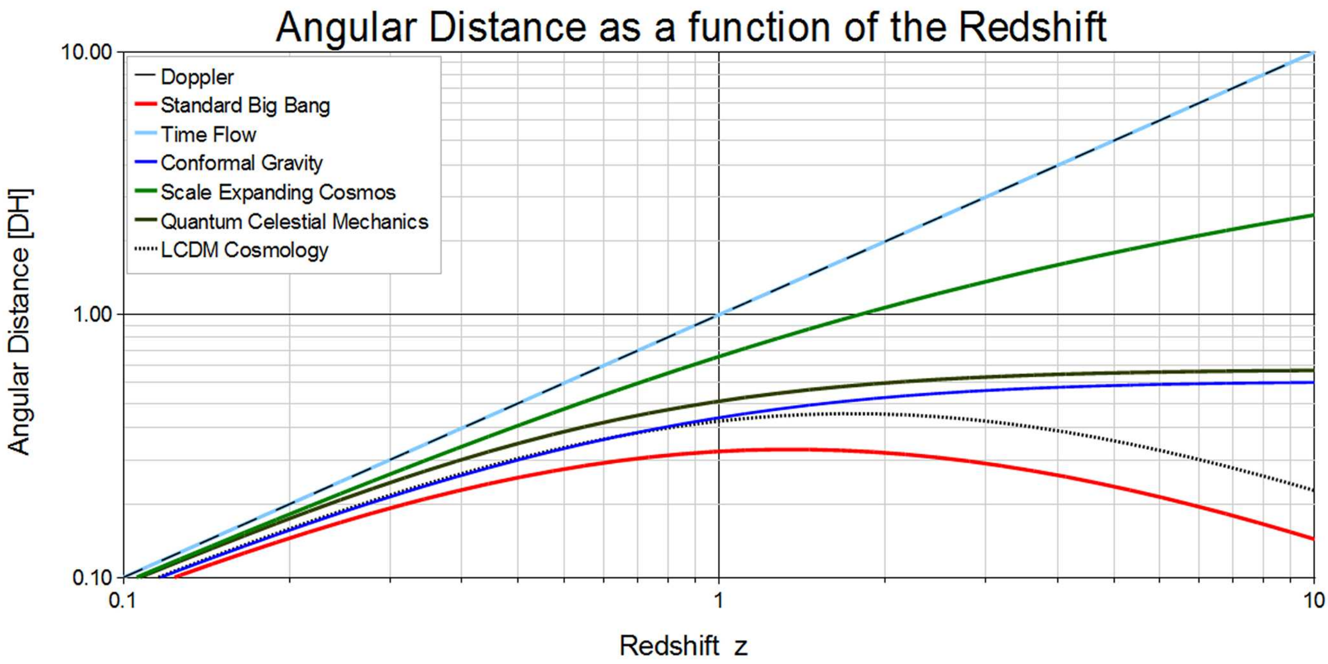

Figure 1: Angular distance in units of D_H for the redshift mechanisms linked to the metric of space.

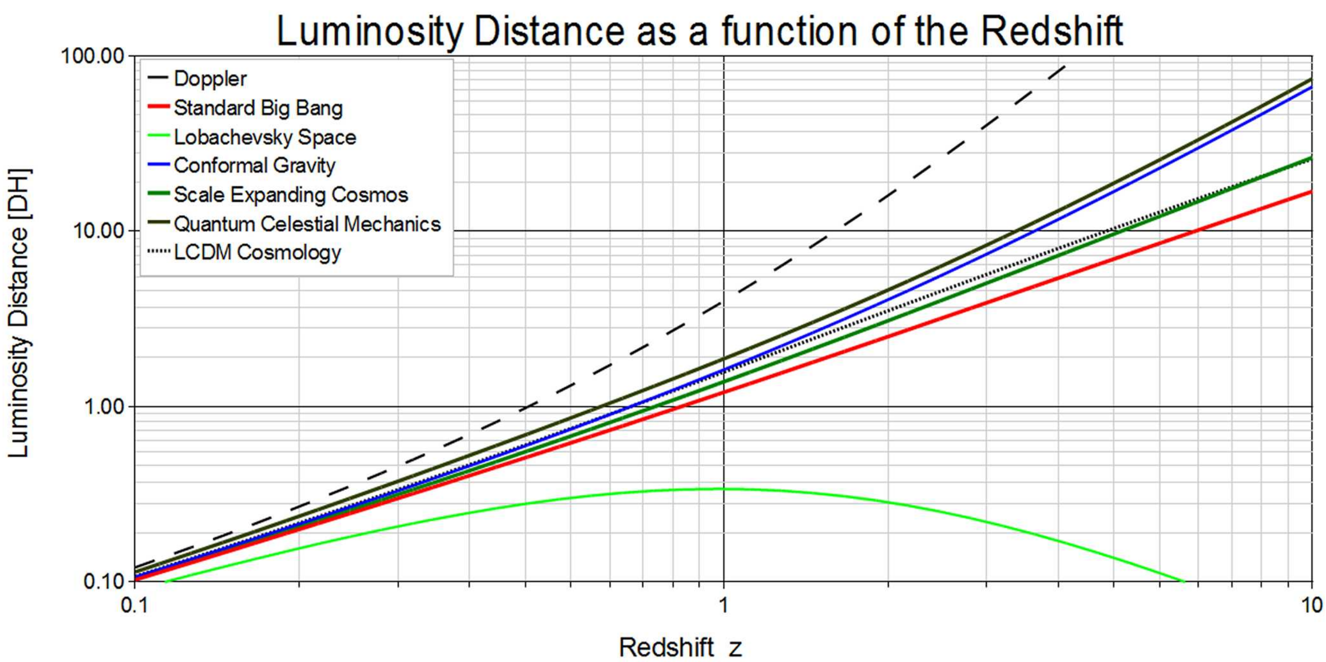

Figure 2: Luminosity distance in units of D_H for the redshift mechanisms linked to the metric of space.

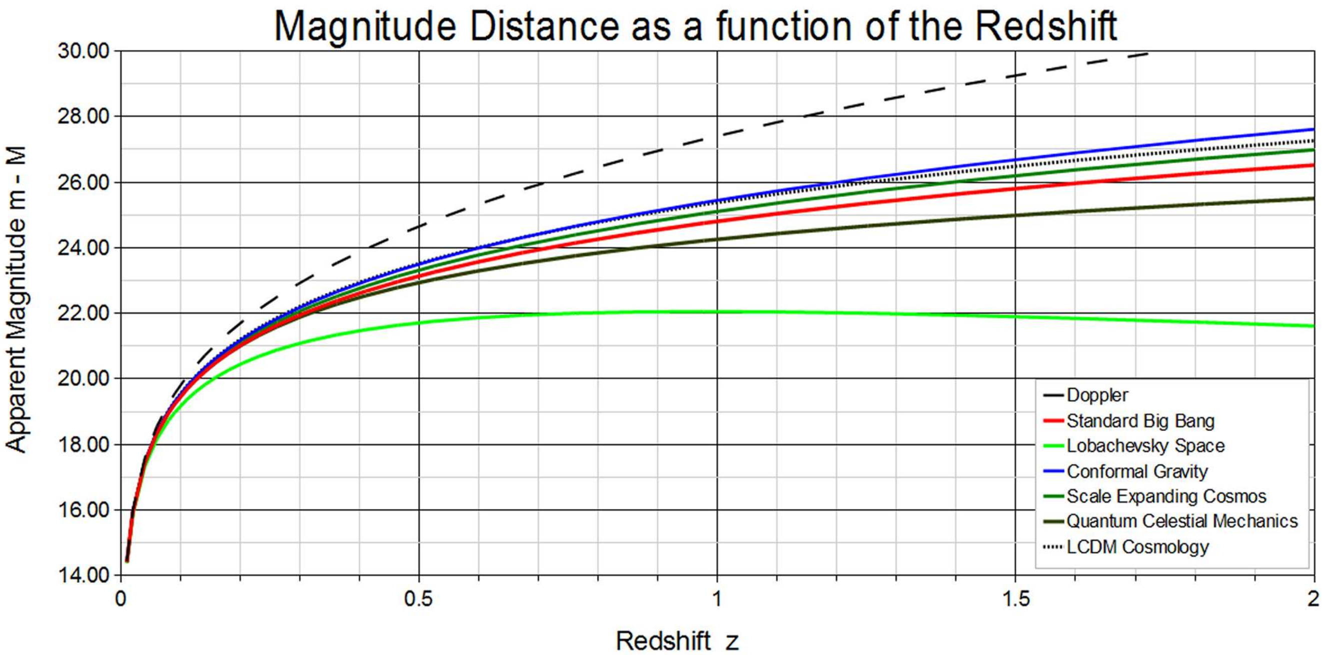

Figure 3: Magnitude distance for the redshift mechanisms linked to the metric of space.

4 Redshifts linked to properties of matter

4.1 Quasi Steady State Cosmology

See R.G. Vishwakarma,...

Conditions of applicability and restrictions: The following definition is used:

$$H(z) = H_0[\Omega_{\Lambda 0} - \Omega_{k0}(1+z)^2 + \Omega_{m0}(1+z)^3 + \Omega_{c0}(1+z)^4]^{1/2},$$

where $\Omega_{\Lambda 0} - \Omega_{k0} + \Omega_{m0} + \Omega_{c0} = 1$. Extinction due to the whisker dust is not included in the equations below.

Functional relationships:

$$d_A = (1+z)^{-1} \int_0^z \frac{\mathrm{d}z'}{H(z')},$$

$$d_L = (1+z)^2 d_A,$$

$$m - M = 10\log_{10}[1+z] + 5\log_{10}[d_A/D_H] + C,$$

$$\langle SB \rangle \propto (1+z)^{-4},$$

$$F_\tau = 1+z,$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = \text{ not yet available}.$$

4.2 Hadron mass variation

The Doppler red shift is explained by Hadrons increasing in mass as they get older.
See Paul Laviolette, 1986, Ap. J., 310, 544-553

Functional relationships:

$$d_A = \text{ not yet available},$$

$$d_L = \text{ not yet available},$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2,$$

$$F_\tau = \text{ not yet available},$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = \text{ not yet available}.$$

4.3 Velocity Dependent Inertial Induction

The model of inertial induction is based on a proposed extension of Machs Principle. According to this model the gravitational interaction between two main particles generates a force which depends not only on their separation but also on their relative velocity and acceleration.
See Amitabha Ghosh, J. Astrophys. Astr. 18, 449454 (1987).

Functional relationships:

$$d_A = \text{ not yet available},$$

$$d_L = \text{ not yet available},$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2,$$

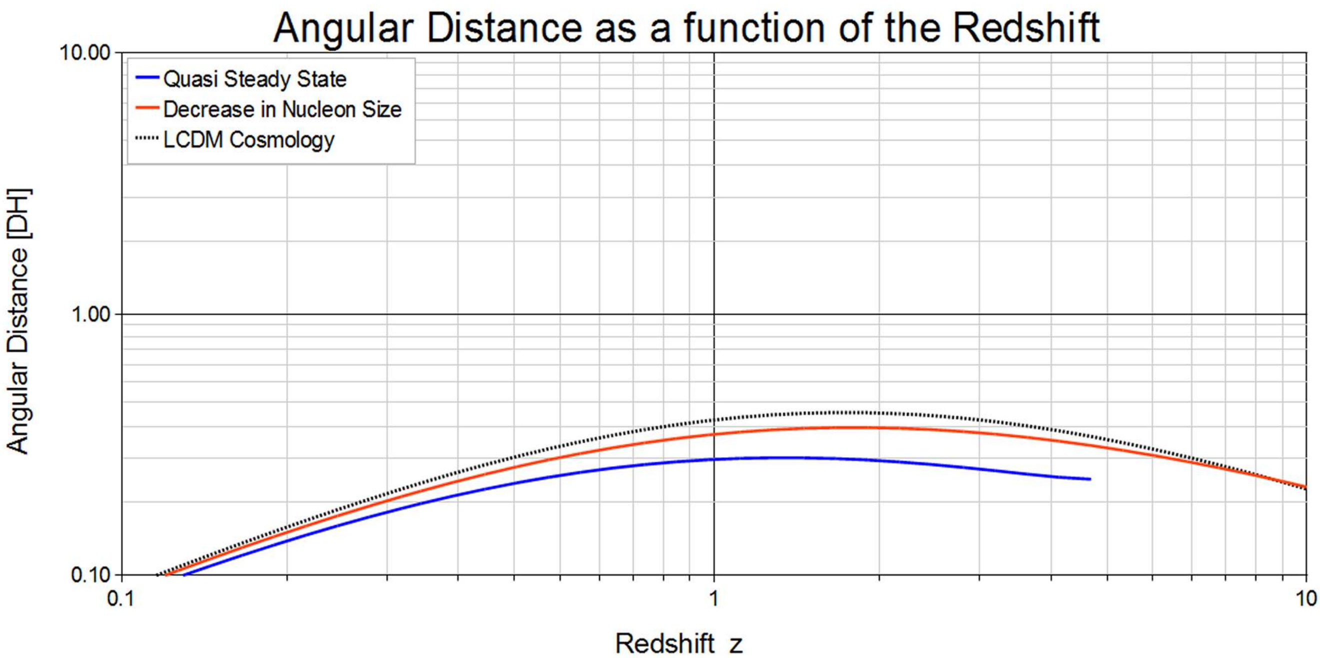

Figure 4: Angular distance in units of D_H for the redshift mechanisms linked to properties of matter. "LCDM Cosmology" is included for comparison.

$$F_\tau = \text{ not yet available,}$$

$$\Delta_\lambda = \text{ not yet available,}$$

$$\Delta_\theta = \text{ not yet available.}$$

Discussion: Unlike all other theories (except the Doppler effect) to explain the observed red shift, this model can be verified from other local effects predicted by this mechanism.

4.4 Exponential decrease in the radius of nucleons

The comoving distance is $D_C = R_0 \ln(1 + z)$, where R_0 is a constant.
See Harry A. Schmitz, www.fractalcosmos.com.

Functional relationships:

$$d_A = D_H \ln(1 + z)/(1 + z),$$

$$d_L = \text{ not yet available,}$$

$$m - M = 5 \log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2\,,$$

$$F_\tau = 1 + z,$$

$$\Delta_\lambda = \text{ not yet available,}$$

$$\Delta_\theta = \text{ not yet available.}$$

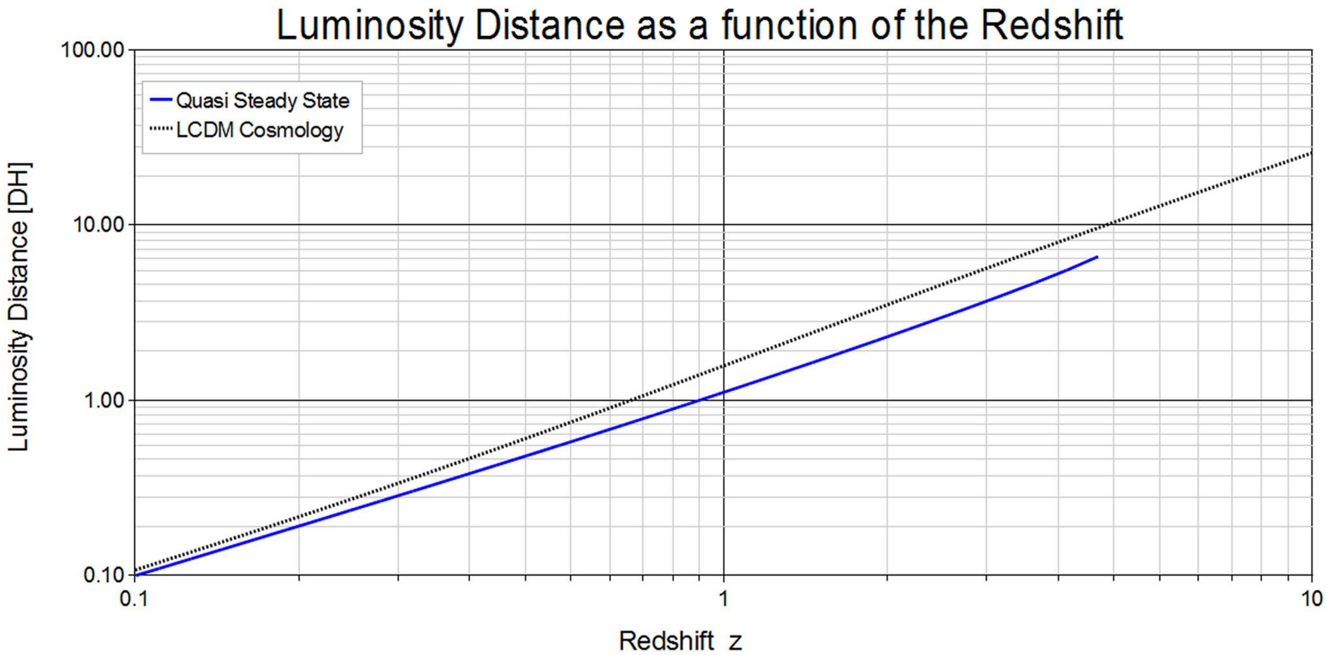

Figure 5: Luminosity distance in units of D_H for the redshift mechanisms linked to properties of matter. “LCDM Cosmology” is included for comparison.

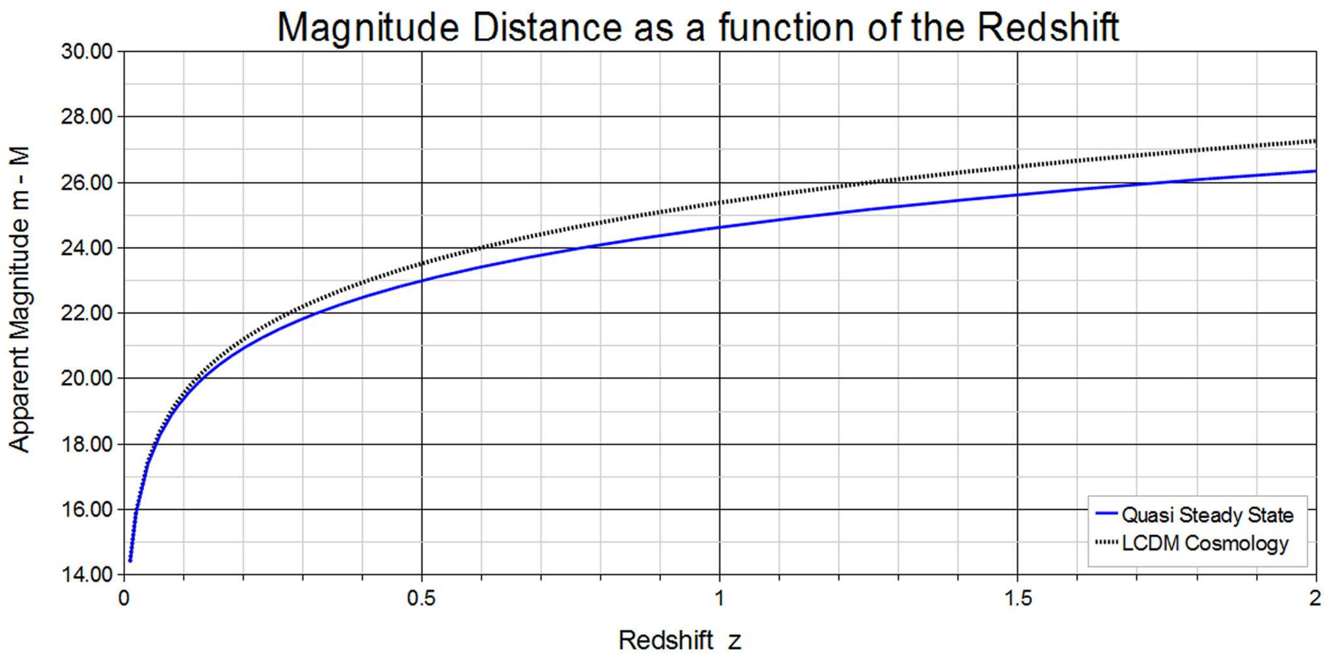

Figure 6: Magnitude distance for the redshift mechanisms linked to properties of matter. “LCDM Cosmology” is included for comparison.

5 Redshifts linked to a changing property of light or an interaction of light with itself

The redshift mechanisms listed in this section depend on a changing property of light, or an interaction between photons and other virtual particles or ether between the emitter and the detector, but do not depend on the presence of matter. They are also referred to as "tired light" mechanisms.

5.1 Photon Decay

Light follows the photon decay equation:

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

See Michael Lewis, members.chello.nl/n.benschop/PhotonDecayRedshift.pdf

Functional relationships:

$$\begin{aligned}
d_A &= \text{ not yet available},\\
d_L &= \text{ not yet available},\\
m - M &= 5\log_{10}[d_L/D_H] + C,\\
\langle SB\rangle &\propto (d_A/d_L)^2\,,\\
F_\tau &= 1,\\
\Delta_\lambda &\approx 0,\\
\Delta_\theta &\approx 0.
\end{aligned}$$

5.2 Effect of Half-Life

The photon simply has a decay lifetime similar to radioactive or unstable particles. In this case, it is the photon's energy that decreases with distance.

$$R = H_d ln(1+z)/ln(2)$$

where $H_d = D_H ln(2)$ is the Hubble wavelength-doubling distance.
See Aladar Stolmar, www2.3dresearch.com/~alistolmar/CMBR.htm

Conditions of applicability and restrictions: No specific mechanism seems to be given to explain why or how the photon decays.

Functional relationships:

$$\begin{aligned}
d_A &= D_H\ln(1+z),\\
d_L &= (1+z)d_A,\\
m - M &= 5\log_{10}[1+z] + 5\log_{10}[\ln(1+z)] + C,\\
\langle SB\rangle &\propto (1+z)^{-2},\\
F_\tau &= 1,\\
\Delta_\lambda &= \text{ not yet available},\\
\Delta_\theta &= 0.
\end{aligned}$$

5.3 Heisenberg Effect

The redshift is due to the Heisenberg Uncertainty Principle when applied to photons and extrapolated across the universe. The photons lose energy to maintain the vacuum of space at 2.7 K due to a quantum mechanical phenomenon in the vacuum of space. The standard equation $E = hc/\lambda$ is used and E when differentiated with respect to λ shows the relationship between dE and dλ. This can be rearranged to give $\mathrm{d}\lambda/\lambda^2 = -\mathrm{d}E/hc$. When the uncertainty principle is adapted for em radiation and modified to take account of the dual polarization of photons (c.f. Planck Radiation) the redshift factor $7.9 \times 10^{-27}\mathrm{m}^{-1}$ is deduced. This provides the fractional apparent increase in wavelength per metre of travel.
See Roy Caswell, ourworld.compuserve.com/homepages/roycaswell/big_bang_or_big_illusion.html

Conditions of applicability and restrictions: No adjustable parameters: calculated from $h^2c^2/(8\pi)$, the redshift is equivalent to an apparent expansion rate of 73 (km/s)/Mpc.

Functional relationships:

$$d_A = c\ln(1+z)/(73\ (\mathrm{km/s})/\mathrm{Mpc}),$$

$$d_L = (1+z)d_A,$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB\rangle \propto (d_A/d_L)^2\,,$$

$$F_\tau = \text{ not yet available,}$$

$$\Delta_\lambda = \text{ not yet available,}$$

$$\Delta_\theta = \text{ not yet available.}$$

5.4 Interaction of a massive Photon with Vacuum Particles

Recent developments in physics and astrophysics lead them to introduce a new tired-light mechanism involving an interaction between a massive photon and Diracs vacuum particles.
See Jean-Claude Pecker, Jean-Pierre Vigier, "A Possible Tired-Light Mechanism", Apeiron, No. 2, p. 19, February 1988

Functional relationships:

$$d_A = \text{ not yet available,}$$

$$d_L = \text{ not yet available,}$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB\rangle \propto (d_A/d_L)^2\,,$$

$$F_\tau = \text{ not yet available,}$$

$$\Delta_\lambda = \text{ not yet available,}$$

$$\Delta_\theta = \text{ not yet available,}$$

5.5 Gravity Nullification Model

The Gravity Nullification model integrates the missing physics of spontaneous decay of particles into the existing physics theories, specifically the general theory of relativity, without altering its original formulation. The redshift arises from the Heisenberg uncertainty relation applied to the energy of the photon.

The redshift as a function of velocity is $1 + z = \sqrt{(c+v)/(c-v)}$ and the distance is

$$d = D_H\left[\frac{z}{\sqrt{1+z}}\right].$$

See Avtar Singh, www.metanexus.net/conference2005/pdf/avtar_singh.pdf

Functional relationships:

$$d_A = \frac{D_H z}{\sqrt{1+z}},$$
$$d_L = d_A,$$
$$m - M = 5\log_{10}[d_L/D_H] + C,$$
$$\langle SB \rangle \propto (d_A/d_L)^2\,,$$
$$F_\tau = \left[\frac{2(1+z)}{(1+z)^2+1}\right],$$
$$\Delta_\lambda = \text{ not yet available},$$
$$\Delta_\theta = 0.$$

5.6 Scalar Potential

The regular electromagnetic four-vector is replaced by a 3-D invariant in 16 dimensions. This implies the existence of a tired-light mechanism by which energy is lost without scattering.
See David Roscoe, CCC2

Functional relationships:

$$d_A = \text{ not yet available},$$
$$d_L = \text{ not yet available},$$
$$m - M = 5\log_{10}[d_L/D_H] + C,$$
$$\langle SB \rangle \propto (d_A/d_L)^2\,,$$
$$F_\tau = \text{ not yet available},$$
$$\Delta_\lambda = \text{ not yet available},$$
$$\Delta_\theta = 0.$$

5.7 Eternal Contracting Universe

The observed cosmological redshift results from a photon losing energy through gravitational radiation. The energy depletion is calculated using general relativity's gravitational radiation effect.
See Donald C. Wilson, CCC2

Conditions of applicability and restrictions: The predicted decay rate is obtained from the binary neutron star system PSR 1913 + 16 observation. There doesn't seem to be other contraints. The predicted energy decay rate is equivalent to a Hubble parameter of 77.5 ± 0.2 (km/s)/Mpc.

Functional relationships:

$$d_A = \text{ not yet available},$$
$$d_L = \text{ not yet available},$$
$$m - M = 5\log_{10}[d_L/D_H] + C,$$
$$\langle SB \rangle \propto (d_A/d_L)^2\,,$$
$$F_\tau = \text{ not yet available},$$
$$\Delta_\lambda = \text{ not yet available},$$
$$\Delta_\theta = \text{ not yet available},$$

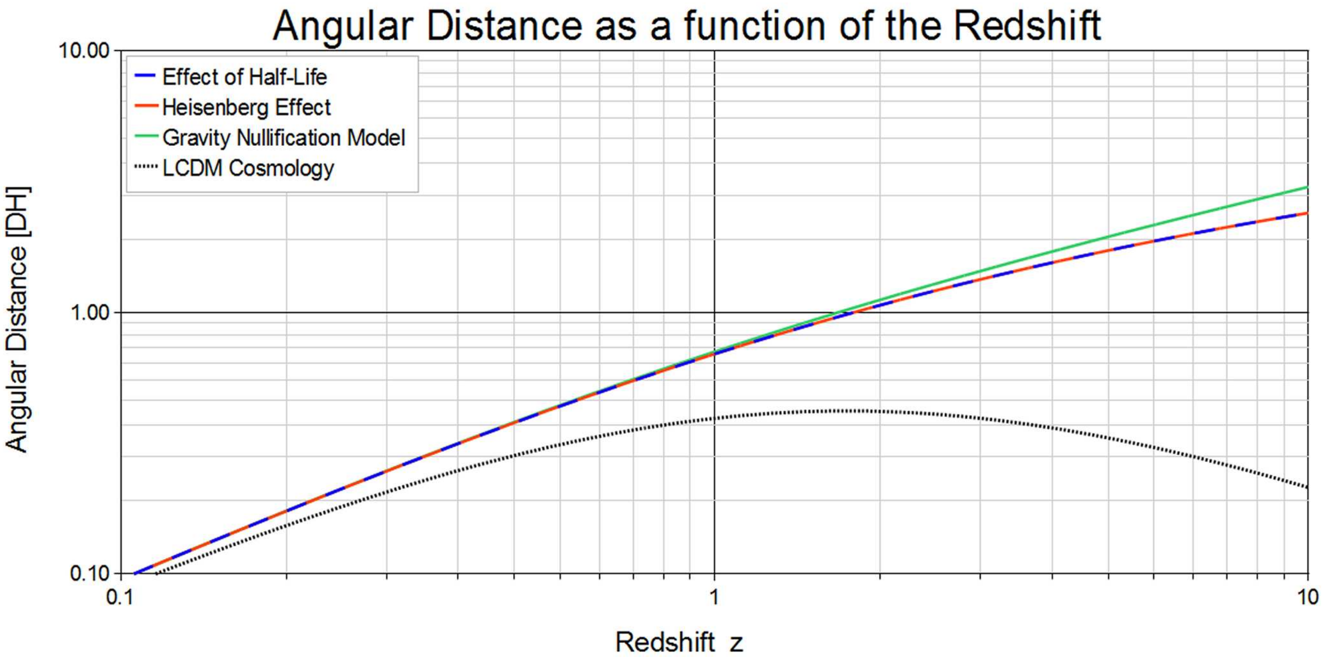

Figure 7: Angular distance in units of D_H for the redshift mechanisms linked to a changing property of light or an interaction of light with itself. "LCDM Cosmology" is included for comparison.

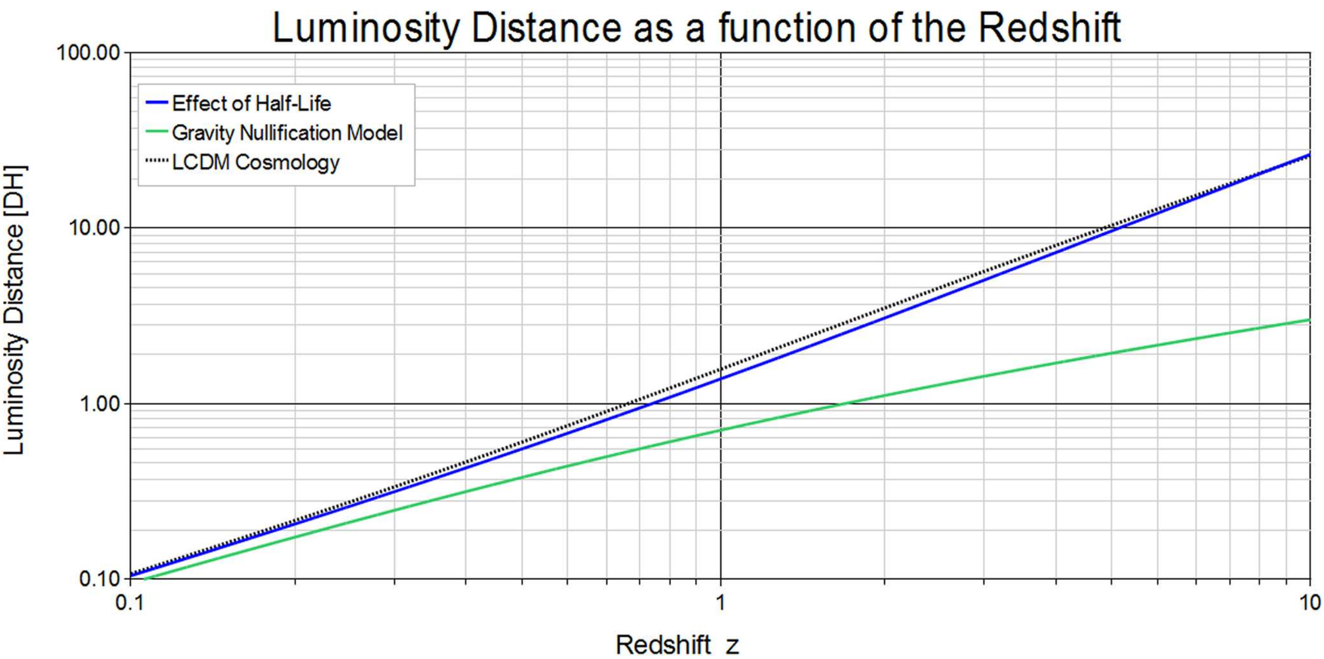

Figure 8: Luminosity distance in units of D_H for the redshift mechanisms linked to a changing property of light or an interaction of light with itself. "LCDM Cosmology" is included for comparison.

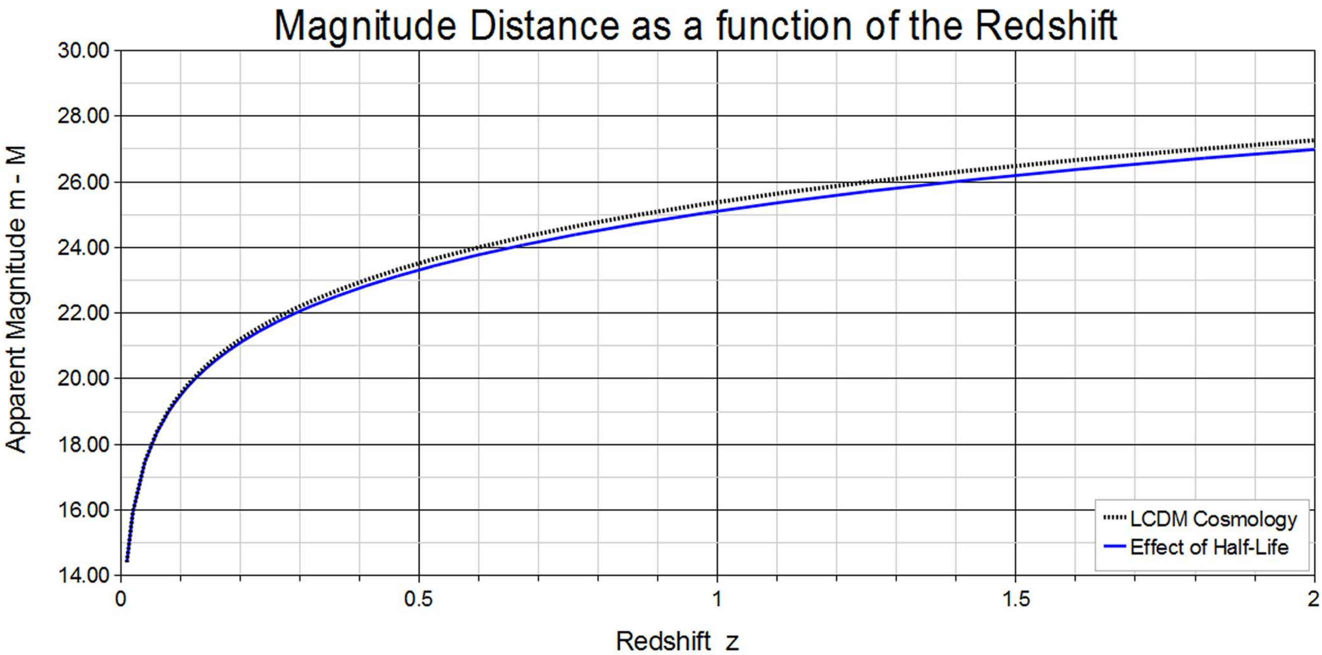

Figure 9: Magnitude distance for the redshift mechanisms linked to a changing property of light or an interaction of light with itself. "LCDM Cosmology" is included for comparison.

6 Redshifts linked to an interaction between light and matter

The redshift mechanisms listed in this section depend on the presence of matter between the emitter and the detector. A redshift $1 + z(N) = \lambda_1/\lambda_0$ caused by the interaction with a column density of matter N is valid everywhere so that $1 + z(N) = \lambda_{i+1}/\lambda_i$ for any i. Repeated redshifts follow the relation

$$1 + z(kN) = \lambda_k/\lambda_0 = \prod_{i=1}^{k} \lambda_i/\lambda_{i-1} = (1 + z(N))^k$$

which is satisfied by

$$N = \rho_0 D_H \ln(1 + z),$$

where ρ_0 is the density of the interacting matter and the column density is given by

$$N(d) = \int_0^d \rho(x)\mathrm{d}x.$$

6.1 Plasma Redshift

Collective interaction between many electrons in a plasma and a photon, resulting in a Doppler-like energy loss redshift and heating of the plasma.

One factor $\sqrt{1+z}$ is due to reduction in photon energy by plasma redshift, while the other factor $1 + z$ is due to removal of photons through Compton scattering on the free electrons in the intergalactic plasma.

$d_C = D_H \ln(1 + z)$,
See Ari Brynjolfsson, arXiv:astro-ph/0401420v3

Conditions of applicability and restrictions: The theory requires a hot, low density, plasma. Explains the redshift on the sun's limb. For the intergalactic redshift, a density of $\rho_0 = 205\mathrm{electrons/m}^3$ is determined from dispersion measurements.

Functional relationships:

$$d_A = D_H \ln(1 + z),$$

$$d_L = \sqrt{(1 + z)^{1+a}} d_A,$$

$$m - M = 2.5(1 + a)\log_{10}[1 + z] + 5\log_{10}[\ln(1 + z)] + C,$$

$$\langle SB\rangle \propto (1 + z)^{-(1+a)},$$

$$F_\tau = 1,$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = \text{ not yet available},$$

where $a = 2$.

6.2 Atomic Secondary Emission

In this mechanism, a photon loses a small amount of energy each time it interacts with an atom [20, 21]. The momentum of the photon polarizes the atom and causes it to emit a small amount of energy. (This was described in terms of a Bremstrahlung mechanism by the author.) The incident photon is re-emitted with a small energy loss. The coherence time of the radiation needs to be short for the effect to work. The spectral width is described by the spectrum of a blackbody radiator at temperature T.

Each interaction with an atom produces a redshift $\delta z = 2.73 \times 10^{-13} T_{10k}^2$, where T_{10k} is the normalized temperature $T_{10k} = T/10000$ K.

Conditions of applicability and restrictions: Dependent on the polarizability of the atoms (or ions) in the intergalactic medium. Not very sensitive on the specific atomic species. Does not work at high density due to the increased collective mass of the medium. Explains the redshift on the sun's limb. Frequency shift $\Delta\lambda/\lambda$ independent of λ in the wavelength region where the index of refraction of hydrogen is constant.

An atomic hydrogen density $\rho_0 = 1.25 \times 10^6\ \mathrm{m}^{-3} h_{100}/T_{10k}^2$ produces $d_C = D_H \ln(1+z)$ which approximates $d_C = D_H z$ for small z. In this model, the comoving and the angular distances are equal.

Functional relationships:

$$d_A = D_H \ln(1+z),$$

$$d_L = \sqrt{(1+z)} d_A,$$

$$m - M = 2.5 \log_{10}[1+z] + 5 \log_{10}[\ln(1+z)] + C,$$

$$\langle SB \rangle \propto (1+z)^{-1},$$

$$F_\tau = 1,$$

$$\Delta_\lambda = 5.22 \times 10^{-7} T_{10k} \sqrt{z},$$

$$\Delta_\theta = 5.22 \times 10^{-7} T_{10k} \sqrt{z}.$$

Discussion: This mechanism is very similar to "Electronic Secondary Emission" described in Sec. 6.4 but in atoms instead of electrons. Because atoms have electronic resonances, this mechanism is not completely independent of the wavelength. The required atomic density is much higher than the required density of electron in Sec. 6.4. This mechanism also predicts a small angular broadening.

6.3 Gravitomagnetic Effect

Due to Lorentz invariance of General Relativity gravitational interaction is limited to the speed of light. Thus for particles, moving within a matter field, retardation leads to loss of energy by emission of gravitational radiation. This 'gravitomagnetic' effect, applied to motion in homogeneous mass filled space, acts like a viscous force, slowing down every motion in the universe on the Hubble time scale. The energy loss rate exactly equals the red shift of photons in an expanding universe, thus showing the equivalence of wavelength stretching in the wave picture and energy loss in the photon picture. The loss mechanism is not restricted to an expanding universe, however, but would also be present in a static Einstein universe.
See Ernst Fischer, "Energy Loss by Gravitational Viscosity", Astro-ph/0805.1638.

Functional relationships:

$$d_A = \text{ not yet available},$$

$$d_L = \text{ not yet available},$$

$$m - M = 5 \log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2,$$

$$F_\tau = \text{ not yet available},$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = \text{ not yet available},$$

6.4 Electronic Secondary Emission

Photons from distant galaxies are absorbed and reemitted by electrons in the intergalactic (IG) space. On absorption and reemission, the electron recoils and the photon loses energy. The emitted photon is therefore redshifted from it's initial wavelength. The Hubble relation arises from the proportionality of the number of interactions to the distance traveled. The recoiling electron emits two low-energy photons each time an interaction occurs, producing radiation contributing to the Cosmological Microwave Background (CMB).

The collision cross section for an electron interacting with a photon is $\sigma = 2r\lambda$, where r is the classical electron radius. Using ρ_0 as the electron density in IG space, an expression for the number of collisions experienced by the photon in traveling a distance d is derived, and hence the redshift z. Comparing this with $z = H_0 d/c$ gives an expression for H_0 by this theory of $H_0 = 2\rho_0 hr/m$.

Each scattering event on an electron produces a redshift $\delta z = 2.43 \times 10^{-12}/\lambda$. Because the cross section increases with λ, the total redshift resulting from this mechanism is independent of λ.
See Lyndon Ashmore, lyndonashmore.com/tired_light_front_page.htm
See also L. Ashmore "Recoil Interaction Between Photons and The Electrons In The Plasma Of Intergalactic Space Leading To The Hubble Constant And CMB," Galilean Electrodynamics Vol. 17, Special Issue 3 (Summer 2006).

Conditions of applicability and restrictions: The relevant column density is calculated from the density of electrons.

An electron density $\rho_0 = 0.80 h_{100}\mathrm{m}^{-3}$ produces the observed $d = D_H z$ for small z. No angular dispersion of the light occurs as this is similar to transmission in a transparent medium.

Functional relationships:

$$d_A = D_H \ln(1+z),$$

$$d_L = (1+z) d_A,$$

$$m - M = 5\log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2,$$

$$F_\tau = 1,$$

$$\Delta_\lambda = \sqrt{2.43 \times 10^{-12}/\lambda_0}\,\sqrt{\frac{z}{1+z}},$$

$$\Delta_\theta = 0.$$

Discussion: A test of this mechanism is to evaluate Hubble's constant from measurements of the density of electrons. For ρ_0, a value is taken from www2.jpl.nasa.gov/basics/bsf1-1.html: "Outside the galaxy, in intergalactic space, the number density of particles is thought to fall off to about one atom or molecule per cubic meter ($10^{-6}/\mathrm{cm}^3$)." Since the hydrogen is fully ionized the same density is used for ρ_0. This gives $H_0 = 4.1 \times 10^{-18}$/s or 124 (km/s)/Mpc.

In the same way one can use this theory to predict the CMB by using conservation of momentum to calculate the energy transferred to the electron on each recoil and the energy and wavelength of the CMB photons emitted. It is found that light/UV photons produce CMB photons in the microwave.

This mechanism is very similar to "Atomic Secondary Emission" described in Sec. 6.2 but in electrons instead of atoms. Because electrons do not have any internal degrees of freedom, this mechanism is truly independent of the wavelength. The required electron density is much lower than the required density of hydrogen in Sec. 6.2. The mechanism produces functional relationships that are almost equal to the relationships for the "Spectral Transfer Redshift" described in Sec. 6.7. Accurate measurements of the line broadening are necessary to distinguish between the two mechanisms.

6.5 Redshift Theorem

Using quantum field theory, a general redshift theorem is derived.

The relevant column density is the path integral of the product of the plasma density and the temperature

$$N_T(d) = B_\omega \int_0^d \rho(x)T(x)\mathrm{d}x,$$

with $B_\omega = 2 \times 10^{-7}$.
See G. Rizzi, A. Laio, "A third hypothesis on the origin of the redshift: Application to the Pioneer 6 data", Physics Letters A, 209, pp. 277-284 (1995).

Conditions of applicability and restrictions: The relation is valid for electromagnetic radiation at the frequency 10^9 Hz $< \omega < 10^{16}$ Hz. The value of the constant B_ω depends on a divergent integral; the value given above produces the observed $d = D_H z$ for small z.

Functional relationships:

$$\begin{aligned} d_A &= \text{ not yet available}, \\ d_L &= \text{ not yet available}, \\ m - M &= 5\log_{10}[d_L/D_H] + C, \\ \langle SB \rangle &\propto (d_A/d_L)^2\,, \\ F_\tau &= \text{ not yet available}, \\ \Delta_\lambda &= \text{ not yet available}, \\ \Delta_\theta &= \text{ not yet available}. \end{aligned}$$

6.6 Photon Structure

It is assumed that the photon has electric dipole moment P normal to its spin, rotating at the photon frequency f and radiating classically.
See Driscoll, Physics Essays 2004.

Functional relationships:

$$\begin{aligned} d_A &= \text{ not yet available}, \\ d_L &= \text{ not yet available}, \\ m - M &= 5\log_{10}[d_L/D_H] + C, \\ \langle SB \rangle &\propto (d_A/d_L)^2\,, \\ F_\tau &= \text{ not yet available}, \\ \Delta_\lambda &= \text{ not yet available}, \\ \Delta_\theta &= \text{ not yet available}. \end{aligned}$$

6.7 Spectral Transfer Redshift

Optical forces transfer energy to the intergalactic medium while removing energy from the photons. Atoms produce a larger redshift near resonances via the dipole force. Electrons cause the largest redshift through the ponderomotive force, that redshift z is independent of the wavelength. Stimulated emission ensures that all interacting photons are emitted in the same direction of an existing light ray. This mechanism does not blur the images of objects. Spectral transfer occurs if the source is extended. At cosmological distances, the redshift occurs because some of the scattered light interacts with the light from the observed object.

Each scattering event on an electron produces a redshift $\delta z = 1.54 \times 10^{-12}/\lambda$ on average. Because the cross section increases with λ, the total redshift resulting from this mechanism is independent of λ.
See Louis Marmet, CCC2

Conditions of applicability and restrictions: An electron density $\rho_0 = 35.6 h_{100}/\mathrm{m}^3$ produces the observed $d = D_H z$ for small z and an extended source.

Functional relationships:

$$
\begin{aligned}
d_A &= D_H \ln(1+z), \\
d_L &= \sqrt{(1+z)^{1+a}}\, d_A, \\
m - M &= 2.5(1+a)\log_{10}[1+z] + 5\log_{10}[\ln(1+z)] + C, \\
\langle SB \rangle &\propto (1+z)^{-(1+a)}, \\
F_\tau &= \text{ not yet available}, \\
\Delta_\lambda &= \sqrt{1.54 \times 10^{-12}/\lambda_0}\,\sqrt{\frac{z}{1+z}}, \\
\Delta_\theta &= 0,
\end{aligned}
$$

where a is a constant to be determined.

Discussion: The mechanism produces functional relationships that are almost equal to the relationships for the "Electronic Secondary Emission" mechanism described in Sec. 6.4. Accurate measurements of the line broadening are necessary to distinguish between the two mechanisms.

6.8 Santilli Isoredshift

This redshift mechanism is explained by an interaction between light and the energy density of the medium through which it propagates. The energy density of the medium is determined by the density of cosmic rays, hydrogen and other matter as well as the density of radiation. Thus, this model involves an interaction of light with matter but also with light itself.
See Ruggero Maria Santilli, "Absence of Universe Expansion, Dark Matter and Dark Energy in the New Isocosmology with Universal Isosymmetry" [22].

Functional relationships:

$$
\begin{aligned}
d_A &= \text{ not yet available}, \\
d_L &= \text{ not yet available}, \\
m - M &= 5\log_{10}[d_L/D_H] + C, \\
\langle SB \rangle &\propto (d_A/d_L)^2, \\
F_\tau &= \text{ not yet available}, \\
\Delta_\lambda &= \text{ not yet available}, \\
\Delta_\theta &= \text{ not yet available},
\end{aligned}
$$

6.9 Forward Scattering by Relativistic Electrons

This mechanism describes light propagation through a high temperature plasma. The redshift results from the relativistic transverse Doppler effect which reduces the frequency of light on forward scattering off high speed plasma electrons. A larger electron temperature produces a larger transverse Doppler effect. The energy and momentum is transferred from the radiation to the medium itself. The strength of the mechanism is related to the 'extinction distance', which is wavelength dependent. When all these factors are taken into account, a redshift is obtained which is independent of the wavelength. Huygen's principle is invoked to keep the light from dispersing.

The relevant column density is given by the dynamic pressure of the plasma

$$N_T(d) = \int_0^d \rho(x)T(x)\mathrm{d}x,$$

where $T(x)$ is the electron temperature.
See R. Fred Vaughan, CCC2
See also R.F. Bonn, "The Effects of Scattering in the Intergalactic Medium", Vaughan Publishing 2008.

Conditions of applicability and restrictions: A density $\rho_0 = 5 \times 10^9$ Km$^{-3}/T_0$ of free electrons produces the observed $d = D_H z$ for small z.

Functional relationships:

$$d_A = D_H \ln(1+z),$$

$$d_L = \sqrt{(1+z)^{1+a}} d_A,$$

$$m - M = 2.5(1+a)\log_{10}[1+z] + 5\log_{10}[\ln(1+z)] + C,$$

$$\langle SB \rangle \propto (1+z)^{-(1+a)},$$

$$F_\tau = 1,$$

$$\Delta_\lambda = \text{ not yet available},$$

$$\Delta_\theta = 0,$$

where $a = 1$.

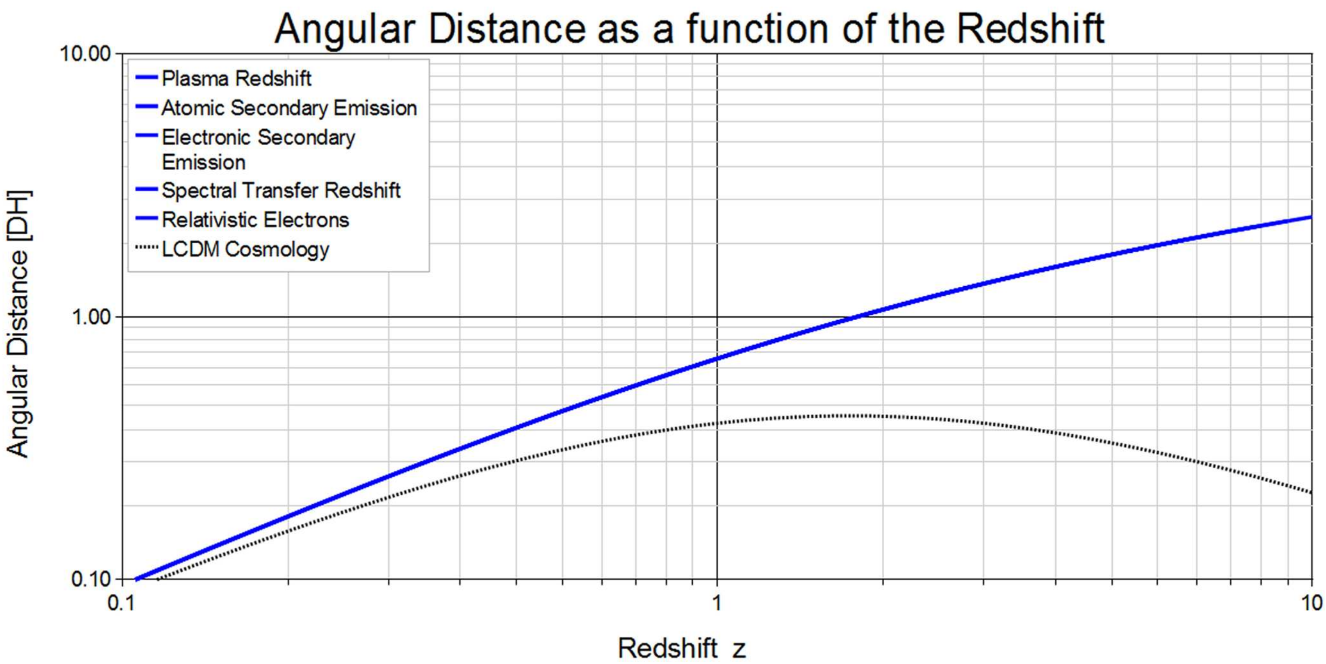

Figure 10: Angular distance in units of D_H for the redshift mechanisms linked to an interaction between light and matter. “LCDM Cosmology” is included for comparison.

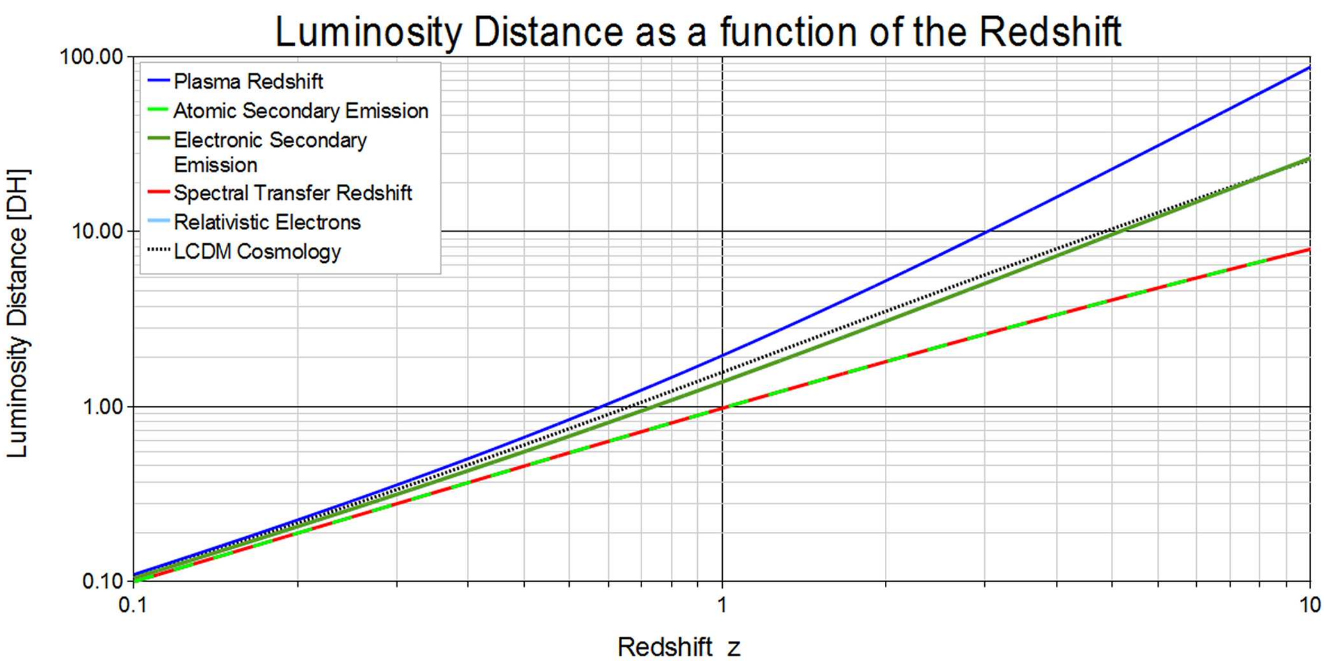

Figure 11: Luminosity distance in units of D_H for the redshift mechanisms linked to an interaction between light and matter. “LCDM Cosmology” is included for comparison.

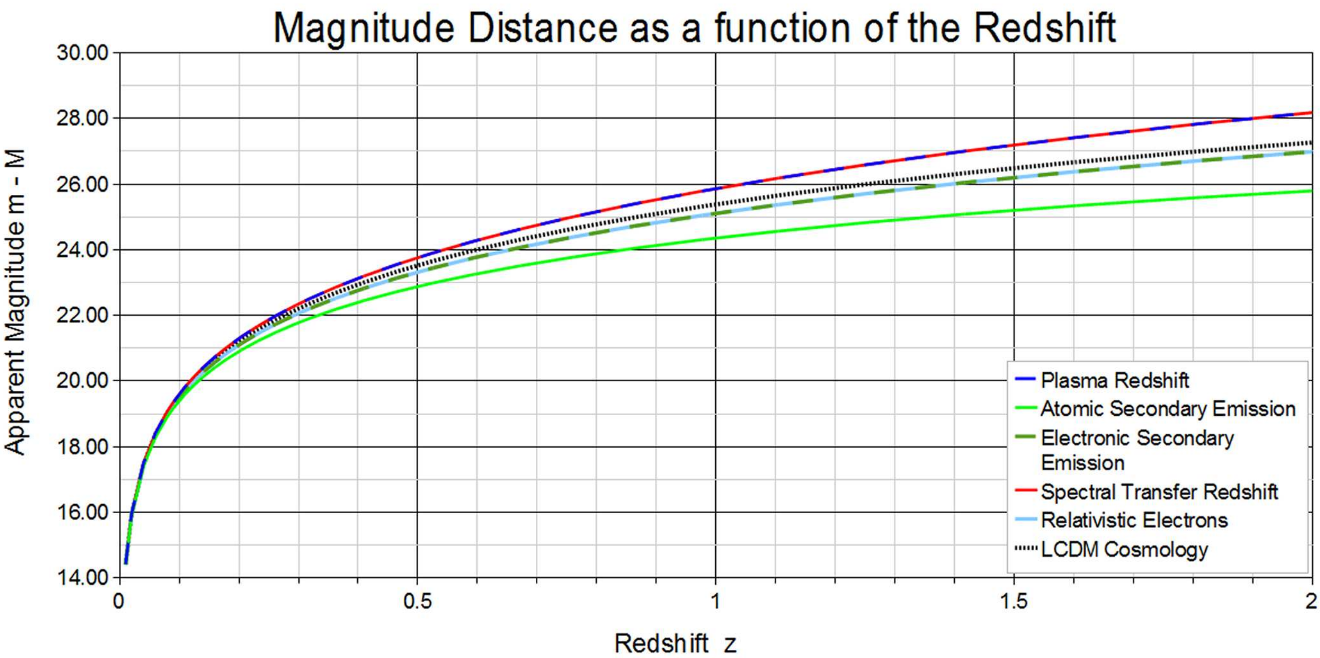

Figure 12: Magnitude distance for the redshift mechanisms linked to an interaction between light and matter. "LCDM Cosmology" is included for comparison.

7 Redshift mechanisms not related to cosmological distances

Other mechanisms have been proposed to explain the redshift but they do not predict a relationship between distance and redshift, or they remain so far without a precise physical model. Therefore they do not offer any quantitative predictions for the dependence of the redshift as a function of distance. However, these mechanisms might affect the light we are receiving. These are listed here for completeness and comparisons.

7.1 Rayleigh Scattering

Light scattering on bound electrons loses energy.

Conditions of applicability and restrictions: Scattering process changes the direction of the light, therefore remote galaxies could not be imaged. Not applicable to cosmological redshift.

7.2 Thomson/Compton Scattering

Light scattered on free electrons loses energy. The Thomson scattering cross section is evaluated for comparison with the mechanisms described above. The frequency shift caused by Thomson scattering off an electron is

$$\delta z = \frac{h\nu}{mc^2} \sin(\theta/2).$$

For light in the visible, this is $\delta z \approx 4.4 \times 10^{-6}$. At high energies, the cross section is given by the Klein-Nischina formula (Compton scattering). For photons in the visible the effect reduces to the classical Thomson scattering with a cross section $\sigma \approx 6.65 \times 10^{-29}\mathrm{m}^2$.

Conditions of applicability and restrictions: Scattering process changes the direction of the light, therefore remote galaxies could not be imaged. Not applicable to cosmological redshift.

7.3 Raman effect

Light interacting with atoms or molecules lose energy by a coherent process which transfers it to the atom/molecule.

7.4 Gravitational Drag

Photons passing near a mass are deflected. They transfer momentum and energy to the mass. The photon changes it's energy and therefore it's frequency. The masses are assumed to be independent of each other, but in reality they are coupled by gravitational forces.
See Fritz Zwicky, prola.aps.org/abstract/PR/v48/i10/p802_1
See also en.wikipedia.org/wiki/Dynamical_friction#Photons

Conditions of applicability and restrictions: Zwicky's original calculation was incorrect. The effect of dynamical friction on photons or other particles moving at relativistic speeds is too small by at least 80 orders of magnitude.

7.5 Finlay-Freundlich Hypothesis

Loss of energy by observed photons traversing a radiation field via a photon-photon interaction.
See Finlay-Freundlich
See also R.A. Alpher, "Laboratory Test of the Finlay-Freundlich Red Shift Hypothesis," Nature **196**, 367 (27 October 1962) and references within

Conditions of applicability and restrictions: No mechanism given except for a proposal that the energy lost reappears as lower frequency radiation, or as neutrino pairs from the exchange of a graviton between two photons.

Discussion: A proposal made by A. Ward (Nature **192**, 858 (1961)) is to attempt to detect the photon interaction with an experiment combining the high sensitivity for resonant absorption associated with the Mössbauer effect with the high-radiation fields from a thermonuclear fusion device.

7.6 Wolf Effect

Coherent effect resulting from the coupling of two partially coherent sources. May explain some features encountered in quasars and the solar limb redshift, but cannot account for the majority of observed shifts of extra-galactic objects. Although the strength of the mechanism is proportional to the density of gas, a relationship between distance and redshift cannot be obtained. The redshift is produced at the source and appears as an intrinsic redshift in the case of quasars.
- Emil Wolf
- en.wikipedia.org/wiki/Wolf_effect

Conditions of applicability and restrictions: Dependent on the density for a shift larger than the linewidth of the radiation.

7.7 Coherent Raman Effect on Incoherent Light

When the propagation of light through a medium is described by Rayleigh scattering and a Huygens construction, the description provides an explanation for the index of refraction and predicts that the frequency of light is not affected. The Coherent Raman Effect on Incoherent Light (CREIL) considers the additional coherent process of the Raman effect to the index of refraction. The Raman effect produces frequency shifts ω on light ($\omega < 0$ for a Stokes scattering). The propagated light is then described with an incident and a transmitted beam which interfere to produce a beat on the outgoing wave described approximately by $\sin(\Omega t) + k_\omega \sin[(\Omega + \omega)t]$. For short pulses $\omega t << 1$ and weak scattering $k_\omega << 1$, the wave simplifies to nearly a simple sine wave at a shifted frequency $\sin[(\Omega + k_\omega \omega)t]$.

The CREIL frequency shifting occurs as the result of several coherent Raman scatterings to produce light at a single shifted frequency. The CREIL is space-coherent (the geometry of the light beams is not changed in homogeneous matter) and a parametric interaction (matter acts as a catalyst) between several light beams. As a result, the images are not blurred.

In astrophysics, it seems that CREIL frequency shifts are only produced in hydrogen excited to $n = 2$ which has convenient spin coupling resonances. These excited atoms are generated thermally (e.g. in a hot plasma such as the solar wind), or by a Ly-α excitation in a "cold" plasma (10000K - 30000K). Under laboratory conditions (10fs pulses), the CREIL is inversely proportional to the cube of the pulse duration. With 1ns pulses the path is increased by a factor 10^{15}, so that the CREIL is only observed at astronomical distances.
See J. Moret-Bailly, "Correspondence of classical and quantum irreversibilities", Quantum Semiclass. Opt. 10, L35 (1998).
See also J. Moret-Bailly, "Propagation of light in low-pressure ionized and atomic hydrogen: application to astrophysics", IEEE Transactions on Plasma Science 31, 1215 (2003).
- Jacques Moret-Bailly, arXiv:astro-ph/0305180v3

Conditions of applicability and restrictions: The relative shift z is nearly independent of λ since $k_\omega \propto \omega$ (the calculation makes an approximation which neglects dispersion). To fulfill Lamb's conditions[1], the CREIL requires short pulses (such as the pulses of time-incoherent light which are ~ 1 ns long), a low pressure gas, and a Raman active resonance in the radio frequency range (< 1 GHz). The effect is dependent on the specific atomic species and the state of the gas.

[1] G. L. Lamb jr., Rev. Mod. Phys., 43, 99 (1971)

The relevant column density is given by the density of atomic hydrogen H^* excited in the $n = 2$ state by heat or radiation.

A density $\rho_0 = 14300 h_{100}/\ \mathrm{m}^3$ of H^* and a temperature of 3 K produce the observed $d = D_H z$ for small z. However, since excited atomic hydrogen is not generally found in intergalactic space, the effect will be seen locally around some objects such as quasars.

Functional relationships:

$$d_A = D_H \ln(1 + z),$$

$$d_L = \text{ not yet available},$$

$$m - M = 5 \log_{10}[d_L/D_H] + C,$$

$$\langle SB \rangle \propto (d_A/d_L)^2 ,$$

$$F_\tau = 1,$$

$$\Delta_\lambda = 0,$$

$$\Delta_\alpha = 0.$$

Discussion: The following effects result from the CREIL:
- a correlation between high redshift and high temperature of a bright star,
- a "proximity effect" caused by the excitation of "cold" atomic hydrogen by the far UV radiated from a hot star,
- a Karlsson periodicity in the Ly-α forest of the quasars (also, possibly a Tifft-Napier periodicity of the redshifts of the galaxies and "voids" in the Universe),
- an "anomalous acceleration" such as the one seen for the Pioneer probes, where the solar wind is cold enough to generate excited atoms,
- in supernovae, a redshift along the path of emission inside a Strömgren sphere (such as the Ly-α emission seen inside the equatorial ring of SNR1987A), but a blueshift where superradiant light is emitted tangentially to the sphere where the intensity of Ly-α is large. There is no redshift where atoms are de-excited by superradiant emission,
- a CMB bound to the ecliptic because of the presence of thermal radiation at that location,
- dispersion observed in the multiplets of the quasars.

7.8 Thermalization

"Hot" radiation thermalizes with the "cold" intergalactic medium. The effect would depend on the density of the intergalactic medium and its temperature.
See Charles Gallo, meetings.aps.org/link/BAPS.2006.APR.J7.7

Conditions of applicability and restrictions: No precise model is given for the interaction.

Discussion: Measurements of neutrino redshift proposed by C.F. Gallo (IEEE Transactions on Plasma Science, **31**, 1230 (2003)) as an experimental test of Doppler versus non-Doppler redshifts.

7.9 Dispersive Extinction

The dispersive scattering and absorption of starlight by the space medium causes a shift of Gaussian lines.

The relevant column density is given by

$$N(d) = \int_0^d \lambda \beta^2 \rho(x) \mathrm{d}x.$$

See Ling Jun Wang, www.utc.edu/Faculty/LingJun-Wang/RedshiftEssay.pdf

Conditions of applicability and restrictions: The frequency shift $\Delta\lambda/\lambda$ of a spectral line is proportional to λ and the square of its linewidth β. Derivation assumes $z << 1$.

Discussion: Because the redshift results from absorption of the blue components of a spectral line, the luminosity distance increases at an exponential rate. Extinction is very significant for large distances. The dependence of the effect on the wavelength is problematic. The solar limb redshift may show a dependence on wavelength, but we know that the extinction is not as large as required by this theory.

8 Conclusions

This paper was written to collect as many redshift mechanisms as possible in a single, coherent presentation. Many questions arise: "Which one of these best describes the observations?" "Which one, if any, is right?" There are so many proposed mechanisms with even more adjustable parameters, it is possible that a few might fit experimental results within measurement errors. However, this doesn't mean that the model is right. Another method might be required in the future to decide which, if any, of these provides a good explanation for the redshift.

During the great depression of the 1930's, it was observed that men wearing gold watches were in better health than other people. The correlation between gold and the weight of these men was explained with some assumed property of gold. Although the theory explained the observations very well, it was certainly incorrect - richer men who could afford to buy gold had enough money to feed themselves. This anecdote is to be remembered when considering the above models and how well they fit experimental data.

9 Acknowledgements

The author is grateful to Paul Marmet, Halton Arp, Chuck Gallo, Philip Mannheim, Lyndon Ashmore and Ari Brynjolfsson for working outside the boundaries of accepted ideas. Their ideas and many discussions improved my understanding of cosmology and helped me discover and develop the "Spectral Transfer Redshift." Many thanks also to the authors of the theories presented in this paper, J. Georg von Brzeski, R. Caswell, J. Masreliez, A. Mayer, J. Moret-Bailly, E. Poliakov, F. Potter, H.A. Schmitz, A. Singh, R.F. Vaughan, and R.G. Vishwakarma for their patience in answering my questions, as well as D. Shaw for his classical approach to the subject which resulted in fruitful discussions.

A Appendix

While light is used in most observations, particles such as protons, alpha particles, electrons, etc. are also detected.

- **The frequency**: In the case of particles, the detector measures the energy of the particles E_0 which is often proportional to the size of the output pulses.
- **The spectral radiance**: When particles are detected, the spectral radiance is defined in this paper as the energy received by the detector per unit area per unit solid angle in the energy range E_0 to $E_0 + \mathrm{d}E_0$ as $I_0(E_0)$ [W m^{-2} sr^{-1} J^{-1}]. The total intensity is the spectral radiance integrated over all energies $I_0 = \int_0^\infty I_0(E_0)\mathrm{d}E_0$.

The redshift can also be defined from the energy of a particle. However, the interpretation requires that the object at a cosmological distance has the same properties as those of a known object:

- **The redshift** z: It is difficult to determine the redshift from the energy of particles because several uncontrolled interactions can affect their energy. In terms of the energy, the redshift is $z = (E - E_0)/E_0$, with E the energy of the emitted particle and E_0 the observed energy of the detected particle.

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