A careful examination of key experiments supporting time dilation

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Abstract

Time dilation seems proven by numerous experiments and is widely accepted by the physics community. However, by re-examining key historical experiments, this paper finds that the claimed time dilation is merely a photon emission frequency dilation of either a moving source or a source in a gravity field.

Key words: time dilation; relativity theory; transverse Doppler effect; gravitational redshift; photon emission frequency

1. Introduction

Over a hundred years, Einstein's relativity theory has been extensively tested at great precisions and becomes an import pillar in physics. Time dilation is a key concept in Einstein's special and general relativity theories. It seems that the effect of time dilation has been proven time and again by relativistic phenomena and experiments, such as the Ives and Stilwell (1938 [1], 1941 [2]), Hay et al (1960) [3], Kundig (1963) [4], Kaivola et al (1985) [5], Reinhardt et al (2007)[6], and Chou et al (2010) [7]. The application of GPS seems a living testimony of time dilation in a gravity field. However, a detailed re-examination of key historical experiments shows that the claimed time dilation effect of a moving light source is merely a decrease in photon emission frequency and that the time dilation effect in a gravity field actually is rejected by experiments.

Of the numerous experiments testing time dilation, this paper examines only representative seminal experiments. One is the iconic experiments by Ives and Stilwell ([1, 2]), which investigated time dilation caused by moving atoms/ions. The other is the influential experiments by Chou et al [7], which used laser cooling techniques to measure at high accuracy the time dilation of Al^+ ions either in motion or at different elevations. In Section 2, we re-examine the time dilation effect in a gravity field and assesses the implication of the experiment by Chou et al

[7]. Section 3 focuses the time dilation effect of a moving atom clock measured by Ives and Stilwell ([1], [2]). Without invoking time dilation, Section 4 uses a concept of photon density to derive a formula which can explain the experimental results of Ives and Stilwell (1938, 1941), while Section 5 explains quantitatively the gravity-induced change in optical clock frequency measured by Chou et al [7]. Section 6 concludes the paper.

2. The experiments of Chou et al (2010) actually rejected time dilation in a gravity field

Chou et al [7] examined the time dilation effect caused by both the speed of the light source and the strength of gravity field. They built two nearly identical optical clocks and compared the clock tick frequency under two scenarios: (1) setting the ions of one clock in harmonic motion by a RF electrical field while keeping the other clock stationary at the same elevation, (2) raising one clock to a higher elevation (about 33cm) than the other. Since the time dilation measurement of moving ions in Chou et al [7] is similar to that in Ives and Stilwell [1,2], we delay this effect to the next section so that we can focus on the effect of different elevations.

The experiment shows that the frequency of the clock at higher elevation is greater than that of the other clock. The amount of tick frequency change was consistent with the prediction from the General relativity. Since the clock frequency indicates time, it seems to suggest that the time is dilated for the clock at a position closer to ground. Chou et al have concluded that the experiment results supported time dilation, however, if we scrutinize the details of the experiment, we will find it has actually rejects time dilation.

An optical clock has three major components. (1) a highly stable reference frequency or 'clock transition', which is provided by optical absorption of transition of different states of atoms or ions. (2) a laser or local oscillator that can stabilize its frequency to the clock transition. (3) a femtosecond comb that can count the frequency of local oscillator, or clock ticks. Based on Rosenband et al [8] and Chou et al [7], the transition frequency of their atom clocks was the $^1S_0$ – $^3P_0$ transition frequency of Al^+ ions in a trap. The probing laser (local oscillator) utilized a reference laser transported to the ion traps through optical fiber. The signals from the two atomic clocks at different elevations were then transmitted through phase-stabilized optical fibers to femtosecond comb for frequency comparison.

There is no issue with the experimental setup and results, but the issue lies in the interpretation regarding the function and property of the optical fibers. The implicit assumption in the interpretation of Chou et al is that the optical fibers simply transmit signals and do not change the frequency of the signals, so the frequencies measured at femtosecond comb are viewed to be the same as those of optical clocks at two elevations. This assumption is generally acceptable when the claimed time dilation effect is absent or ignored. However, since the main purpose of the experiment is to examine the time dilation effect, the assumption is not plausible for interpreting the experimental results.

Since the time dilation effect is supposed to affect the pace of everything from the ticks of optical clock to the ageing process of a living being (except the constant speed of light in vacuum, which is the foundation of Einstein's relativity theory), the frequency of the light transmitted through optical fibers should also be affected by time dilation. In the paper of Chou et al, the frequency change at different elevations is explained by time dilation due to different strengths of gravity field, so the logic consistency compels one to consider also the transmissional frequency change caused by the same time dilation effect.

We can have a close look at how the time dilation effect fails to explain Chou's experiment. Based on the general relativity theory, the higher 'clock transition' frequency at the higher elevation is due to the less time dilates in a weaker gravity field. When the optical fibers transmit the signals at the higher elevation to the femtosecond comb at lower elevation for comparison, the same amount of time dilation between two elevations would cause the less dilated (and thus higher frequency) signals at higher elevation to be dilated back to the same frequency at the lower elevation. As a result, there should be no frequency difference measured at the femtosecond comb. In other words, if the claimed time dilation effect is considered fully and consistently, a null result is expected. This expectation conflicts with experimental outcomes, so the experiments in fact unequivocally rejected the time dilation explanation.

There may still be doubt about the above reasoning of signal frequency dilation during transmission: how is it possible that the frequency of signals arriving at the lower elevation is less than the frequency of the atomic clock signal at the higher elevation given that both frequencies are measured based on the same time standard at the lower elevation? Since there is no signal accumulated in the optical fibre, surely both frequencies based on the same time standard should be equal. This reasoning neglects the other consequence of the general relativity: the curved spacetime in a gravity field. As photons travel along geodesics during each total internal reflection within the optical fibre, the distance between consecutive photons increases in a gravity field. Given that the light speed is constant, the increased distance between photons means that the time for consecutive photons arriving the detector will increase, so the light frequency decreases. As a result, the reasoning of frequency dilation during transmission is also consistent with the general relativity theory.

Our reasoning so far is confined to time dilation effect caused by gravity and temporally ignores the time dilation effect of higher speed at the higher elevation. One may argue that the effect of different velocities of the clocks may offset the frequency change for signals in the optical fiber. As the earth rotates, the atomic clock at higher elevation moves slightly faster. It can also be argued that the faster clock ticks at high elevation may imply a higher velocity of the clock based on the time scale at the lower elevation. As the signals travel from the clock of higher velocity to the comparer (i.e. the femtosecond comb) of lower velocity, a time dilation effect due to velocity difference may cause the signal frequency to increase and thus offset the frequency decrease caused by gravity. Qualitatively speaking, this reasoning has a merit, but it does not hold quantitatively. It is well-known that time dilation effect of a GPS caused by the gravity of the earth is about 7 times greater than the time dilation effect caused by the velocity of the GPS, so the time dilation effect due to velocity cannot offset the gravity-induced frequency change.

One may also use Einstein's equivalence principle for gravity to explain the frequency change. Einstein presented a gravity field by a reference frame in a free fall. As photons travel in this reference frame (i.e., into the gravity centre), the potential energy of gravity is added to photons, so the light will experience an increase in frequency, i.e. a blueshift. Applying this reasoning to Chou's experiment, the measured signal frequency at the higher elevation is unchanged but, as the signals (photons) travel to the lower elevation, they are actually blue-shifted and then are perceived as a higher frequency light by an observer at the lower elevation. As such, the measured frequency change is consistent with the prediction by the general relativity.

The above blueshift explanation seems consistent with time dilation hypothesis: the blueshifted atomic clock signals from the higher elevation to the lower elevation seemingly indicate a higher frequency of that atomic clock, which is consistent with the less dilated time at the higher elevation. However, this reasoning mixes up the measured frequency change based on different time standard and the true frequency change based on the same time standard. If one equals the blueshifted signal frequency with the frequency of atomic clock at the higher elevation, measured based on the time standard at the lower elevation, the true frequency (a frequency measured based on the same time standard) of the signal during travel has not changed at all, so there is no blueshift at all. The claimed blueshift is purely a measurement issue due to changing time standard as the signal travel towards the gravity centre. No matter the claimed blueshift is a shift of true frequency or simply a measured shift due to different time standard used, the claim is at odd with time dilation.

A true blueshift (a frequency shift measured based on the same time standard) in fact directly contradicts the time dilation hypothesis. The claimed time dilation effect of a gravity field is that, as time is more dilated at the lower elevation, everything slows down. If so, how can the light frequency act oppositely – getting blueshifted when photons (light) travel to a lower elevation? This explanation of blueshift during light travel also implicitly requires that the frequency at the higher elevation is unchanged according the time standard at the lower elevation[1]. The powerful refutation of this blueshift explanation comes from the application of GPS. Since the claimed blueshift of light signals during the travel changes neither the speed of light nor the initial time stamp, it essentially should have no impact on the GPS system. According to the implicit assumption of no frequency change at the higher elevation (using the same time standard), the frequency of an unadjusted atomic clock on the GPS satellite is the same as that of the identical clock on the ground (both are measured using the time standard on the ground), so the GPS time stamp in the space will be on par with that on the ground and there is no need to adjust the GPS clock before sending it into the space. The application of GPS system shows this is not true, so the blueshift explanation does not hold water.

[1] The blueshift argument is to claim that the frequency change occurs through a blueshift during transmission rather than directly at the clock at the higher elevation. If one makes an argument that a frequency increase occurs both at the clock and through blueshift, one faces the difficulty in making two explanations consistent and in explaining how much frequency increase occurs in each channel and why, because the total frequency increase has to satisfy the quantity predicted in the general relativity.

A measured blueshift argument also contradicts with the time dilation hypothesis. A thought experiment may drive the point home. Suppose a light source emits photons 400 Tera times in 1 second (400 Tera Hertz frequency) at a position A which is far away from a gravity centre. The time standard at a position B close to the gravity centre is that 1 second at position B is equal to 2 seconds at the position A. As such, the measured time for the 400 Tera photon emissions to hit a detector at position B will be 0.5 second. This gives a light frequency of 800 Tera Hertz and thus indicates a blueshift of light frequency, compared with the 400 Tera Hertz frequency at position A. In this thought experiment, however, only the measured light frequency changes due to different time standards used, while the true light frequency is fixed: the number of photon emissions is fixed for an equivalent amount of time (e.g. 1 second at position A and 0.5 seconds at position B). In other words, the pace of the photons hitting the detector at position B has not slowed down, which indicates that the time is not dilated when photons travel from position A to position B; on the other hand, the time standard or clock setting at position B is different and this leads to the measured blueshift. In short, the measured blueshift is purely a measurement issue caused by different time standards while the unchanged true frequency of the light ray from position A to position B implies no time dilation.

It is natural to ask: why are the time standards different at positions A and B? The answer is that atomic clocks at positions A and B emit photons at different frequencies. However, this difference in frequency cannot be attributed to time dilation because it is ruled out by the unchanged true light frequency of travelling photons in our thought experiment (otherwise, one is committing the fallacy of logic inconsistency). Later in this paper, we will explain what causes the frequency difference. To check the performance of different hypotheses (time dilation, blueshift, and frequency change directly caused by gravity), we put in the appendix the predictions of possible hypotheses. From the appendix, we can see that only the straightforward hypothesis of frequency change is consistent internally, with the practice of GPS, and with the prediction from the general relativity.

3. The experiments by Ives and Stilwell (1938, 1941) proved only light frequency change

The experiments by Ives and Stilwell [1,2] examined time dilation in the Thomar-Lorentz theory, which is based on existence of aether. Since this theory is also based on the Lorentz transformation, the predicted time dilation effect is similar to that in the special relativity theory. As the undetectable aether is discarded by physics community, the confirmation of time dilation predicted by the Thoma-Lorentz theory is generally viewed as confirmation of the relativistic Doppler effect in the special relativity theory. The explanation of the Ives and Stilwell experiments based on the time dilation argument can be shown briefly as follows.

The ordinary Doppler effect can be expressed as:

$$\frac{\lambda}{\lambda_0} = \frac{c - v * cos\theta}{c} = 1 - \frac{v}{c} cos\theta \tag{1}$$

where λ and λ_0 are the perceived and original wavelength of light, respectively; c is the speed of light, v the speed of the moving light source, and θ the angle between v and the light ray towards the observer.

Based on the time dilation effect, the special relativity suggested that there would be a relativistic or higher-order Doppler effect on the top of the ordinary Doppler effect. Incorporating this time-dilation effect into the ordinary Doppler effect, we have the formula of the full Doppler effect:

$$\frac{\lambda'}{\lambda_0} = \gamma\left(1 - \frac{v}{c} cos\theta\right) = \frac{1 - \frac{v}{c} cos\theta}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

where $\gamma = 1/\sqrt{1 - \frac{v^2}{c^2}}$ is the Lorentz factor.

If the light source or the observer moves in a direction perpendicular to the light ray (i.e. $\theta=\pi/2$), the ordinary Doppler effect is zero (according to eq. 1), but there will still be a redshift of light frequency to be observed (according to eq.2), namely the transverse Doppler effect. Einstein suggested experimental observations of this effect to confirm his theory. However, it is hard to observe a Doppler effect from the 90º angle. Ives and Stilwell (1938, 1941) came up with an ingenious idea of measuring the higher-order Doppler effect.

Ives and Stilwell used an electrical field to accelerate ions (H_2^+ and H_3^+) to very high speed which should cause a time dilation and thus a redshift for light emitted by the ions. They used a mirror to reflect the light travelling opposite to the ions travelling direction, so they could measure the wavelength of both the directly-emitted light (θ= 0) and the reflected light (θ= π). The full Doppler effect can be obtained quantitatively by applying binominal approximation to equation (2). For the direct light ray (θ= 0), the equation becomes:

$$\frac{\lambda 2}{\lambda_0} = \frac{1-\frac{v}{c}}{\sqrt{1-\frac{v^2}{c^2}}} \approx \left(1-\frac{v}{c}\right)\left(1+\frac{1}{2}\frac{v^2}{c^2}\right) = 1-\frac{v}{c}+\frac{1}{2}\frac{v^2}{c^2}-\frac{1}{2}\frac{v^3}{c^3} \tag{3}$$

For the reflected light (θ= π), we have:

$$\frac{\lambda 1}{\lambda_0} = \frac{1+\frac{v}{c}}{\sqrt{1-\frac{v^2}{c^2}}} \approx \left(1+\frac{v}{c}\right)\left(1+\frac{1}{2}\frac{v^2}{c^2}\right) = 1+\frac{v}{c}+\frac{1}{2}\frac{v^2}{c^2}+\frac{1}{2}\frac{v^3}{c^3} \tag{4}$$

The first and second terms at the right hand side of eqs (3) and (4) indicate the ordinary Doppler effect, with a blueshift for the direct ray and an equal-sized redshift for the reflected ray. The rest of terms at the right hand side are higher-order Doppler effect, or transverse Doppler effect. Given $0<v<c$, this effect is positive for both equations, indicating a red shift for both rays. Combining both the ordinary and higher-order Doppler effects, we should find an asymmetric shift of wavelength: the spectrum line of the reflected ray redshifts more than the blue-shift of the direct ray.

Since measuring the wavelength of a spectrum line is more difficult and less accurate than measuring the amount of shift of the spectrum line, Ives and Stilwell measured the average of the two shifted spectrum lines and compared it with the original spectrum line caused by atoms at rest. The average wavelength of the Doppler shifts of both rays can be calculated as:

$$\bar{\lambda} = \frac{\lambda 1 + \lambda 2}{2} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\lambda_0 \approx \left(1+\frac{1}{2}\frac{v^2}{c^2}\right)\lambda_0 > \lambda_0$$

The shift of average wavelength can be expressed explicitly by the difference between this average and the original wavelength, which consisted of the relativistic Doppler effect in Ives and Stilwell (1938):

$$\Delta\lambda = (\bar{\lambda} - \lambda_0) \approx \frac{1}{2}\frac{v^2}{c^2}\lambda_0$$

The positive relativistic Doppler effect Δλ is regarded as time dilation effect. The Ives and Stilwell experiment confirmed the asymmetrical Doppler shift and also showed that the size of relativistic shift from the original wavelength is consistent with the prediction of the time dilation shown in equation (2). As a result, this experiment is viewed as a confirmation of time dilation.

Actually, the experiments only proved that the light frequency emitted by moving ions changed. Ives and Stilwell (1941, p374) concluded on their experiments: 'The net result of this whole series of experiments is to establish conclusively that the frequency of light emitted by moving canal rays is altered by the factor $\left(1-\frac{v^2}{c^2}\right)^{1/2}$. There is an apparent logic gap if one claims that their experiments prove time dilation because the velocity of atoms/ions may affect their photon emission rate through mechanisms other than time dilation. The next section provides an alternative explanation.

4. Explaining photon emission frequency change caused by moving atoms

Although the experiments of Ives and Stilwell (1938, 1941) did not prove time dilation, the frequency changes measured in the experiments do prove that the formulas provided in either the theory of Larmor and Lorentz or the relativity theory are correct. Science history repeatedly shows that a correct formula does not necessitate a correct theory. A typical example is Fresnel's partial aether dragging theory (1818) [9]. In this theory, Fresnel derived a formula for the velocity variation of light travelling in a moving medium. Fizeau (1851) [10] and Michael (1886) [11] conducted the water tube experiments and proved Fresnel's formula, but the aether dragging theory is discarded later. In this section, we provide a photon density hypothesis to explain quantitatively the frequency change caused by moving light source. The hypothesis is based on two simple assumptions

First, we assume that light (photon) speed is independent of the speed of the source. This assumption is supported by observations and experiments such as stellar aberration, the Doppler effect of light, observation of the movement of binary stars, the speed of γ rays from mesons, and the one-way Michelson and Morley experiments.

Second, we assume that photon emission frequency is proportional to the inverse of emitted photon density because the pressure of emitted photons can adversely affect the further emission of photons from the emitter.

The radiation pressure of photons on the receiver is widely accepted and proven by photoelectric effect. This pressure results from the momentum the photons gained from the light source. On the other hand, when atoms impart momentum to photons, the atoms also experience an opposite force from the photons – the recoil effect which is widely recognised in atomic physics and underpins the recoil limit in laser cooling. In other words, photons also exert recoil pressure on the light source.

Our extension to the radiation pressure and recoil pressure is that the size of pressure depends on the density of a chain of photons already emitted. Quantum mechanics has showed that the size of radiation momentum and recoil momentum (p=hf/c, f is the frequency of light observed or emitted) depends on the frequency of the photon emitted, so we can infer that the size of radiation pressure and recoil pressure is also positively related to light frequency. However, if the photon emission frequency is unchanged but the light source is moving forward, the photon density ahead of the source increases and the light frequency perceived by a stationary observer also increases (i.e. Ordinary Doppler effect), so we can conclude that the radiation momentum increase. Since the radiation momentum is transferred from the light source through recoil momentum, the recoil momentum must also increase even though the emission frequency does not change. This reasoning based on the Doppler effect shows that the recoil momentum/pressure is actually dependent on the density of photon emitted rather than the emission frequency.

Since the recoil pressure reduces the momentum and energy of atoms and thus negatively affect their subsequent ability of emitting photons, it is possible that the recoil pressure can reduce the frequency of further emissions. The more photons in one direction are emitted per seconds, the larger recoil pressure will be. The former leads to a high density of photons and the latter to lower frequency of photon emissions. As a result, our second assumption is plausible.

We can express the second assumption quantitatively. The inversely relationship between emitted photon density d and the emission frequency f can be described by:

$$f \propto \frac{1}{d} \text{ or } fd = constand$$

If the rest mass m_0 has an emission frequency of f_0 and a photon density of d_0, the assumption can be further expressed as:

$$fd = f_0 d_0 \quad or \quad f = f_0 d_0/d \tag{5}$$

The number of photons emitted per second in a given direction can be calculated as:

$$N=f*e*m_0 \tag{6}$$

where m_0 is mass at rest, e is the number of photons per emission per unit of mass, f is emission frequency (the number of emissions per second), and N is the number of photons per second emitted by the total mass m_0.

For a stationary emitter with photon emission frequency f_0 , its emission rate (photon number per second) N_0 will be:

$$N_0=f_0em_0 \tag{6'}$$

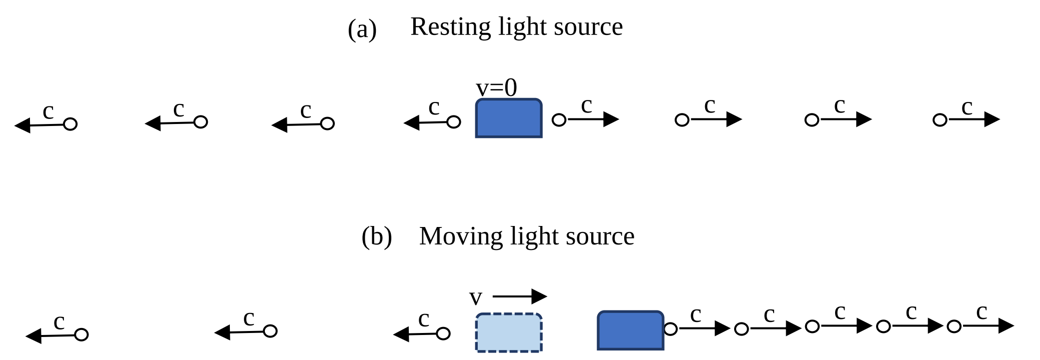
Denoting c as the speed of light in a vacuum, as shown in panel (a) of Fig. 1, we can infer that if N_0 photons are emitted in 1 second and cover the distance of c in any direction, the line density of photons can be calculated for the object at rest:

$$d_0=N_0/c \tag{7}$$

When the emitter is moving, the structure of the photon density will change, shown in panel (b) of Fig. 1. As the movement reduces the distance between two photons in front of the source and increase distance between two photons behind, the density of photons increases in front of the emitter and decrease behind the emitter. The change in photon density structure may also affect the average photon density and thus affect the photon emission frequency. Since the moving source emits photons in any direction, this may make the calculation of photon density very complicated.

However, the key fact is that, only on the two opposite directions of the source movement (i.e. ahead and behind the source), the light rays are not shifting. The chain of photons in this stable light rays can affect the new photon emissions from the source. On any other directions, the light ray of a moving source is constant shifting, so the old photons cross (transit) the paths of the newly emitted photons very briefly and no old photon stays permanently in the path of the newly emitted photons. As such, the densities of these old photons do not generate a stable pressure in these directions and thus have no influence on the frequency of further emission of new photon. Consequently, the emission frequency in all directions depends only on the line density of photons on the axis of source movement.

Fig.1 Speed of light source, photon density, and relative mass



Assuming the emission frequency of the moving source is f, we can calculate the number of photons N emitted in 1 second. Based on equations (6) and (6’), we have:

$$N=fem_0=(f/f_0)*(f_0em_0)=N_0f/f_0 \tag{8}$$

The photon density ahead and behind the source can be calculated respectively as:

$$d_1=N/(c-v) \quad \text{and} \quad d_2=N/(c+v)$$

As such, the average line density of the light source can be expressed as:

$$d=(d_1+d_2)/2=Nc/(c^2-v^2) \tag{9}$$

One may argue that the average density can be calculated by 2*N* photons (*N* photons ahead and *N* photons behind the object) covering a distance of (c+v)+(c-v). This approach is invalid or inaccurate because it gives more weighting (because of the longer distance) to the photons behind the source.

Plugging equations (7) and (8) into equation (9), we have:

$$d=(N_0 f/f_0)c/(c^2-v^2) = d_0(f/f_0)c^2/(c^2-v^2) \quad (10)$$

Plugging equation (5) into equation (10), we have:

$$d^2=d_0^2c^2/(c^2-v^2)$$

Solving the above equation and using equation (5) again, we obtain:

$$d = d_0/\sqrt{1-\frac{v^2}{c^2}} \quad (11)$$

$$f = f_0\sqrt{1-\frac{v^2}{c^2}} \quad (12)$$

In terms of the wavelength of light emitted by moving objects, equation (12) can be rewritten as:

$$\lambda_M = \lambda_0/\sqrt{1-\frac{v^2}{c^2}} \quad (13)$$

where λ_0 is the wavelength from a stationary light source and λ_M is the wavelength from a moving light source.

The change in wavelength described by equation (13) will also be perceived by the observer, so the ordinary Doppler effect in equation (1) should be upgraded to:

$$\lambda' = \frac{\lambda}{\lambda_0} * \lambda_M = \frac{c-v*cos\theta}{c}\frac{\lambda_0}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1-\frac{v}{c}*cos\theta}{\sqrt{1-\frac{v^2}{c^2}}}\lambda_0 \quad (14)$$

This equation is exactly the same as equation (2), which is derived based on time dilation. Using equation (14), we can produce the same relativistic effect as that from the special relativity theory. As such, the results from Ives-Stilwell experiment can be explained either by time dilation hypothesis or simply by photon density hypothesis. In other words, the Ives and Stilwell experiments are not necessarily the evidence of time dilation.

A word of caveat is necessary here. Fig. 1 is very similar to a graph that explains the longitude or ordinary Doppler effect, while the resulting equation (12) is similar to the transverse or relativistic Doppler effect. This may cause confusion for some readers. It is important to highlight that here we are dealing with photon density rather than photon frequency perceived by the observer. Although the ordinary Doppler effect or the PERCEIVED frequency/wavelength change at the observation point can be demonstrated by a similar graph, we concern in Fig. 1 and in the resulting equations (11) and (12) only the change in photon density, which is objective regardless of the state of the observer.

The other caveat is regarding the definition of stationary light source. Given the extensive and heated arguments in the history about a favourable/absolute stationary frame, this caveat is fundamental for a broader understanding of the photon density hypothesis. Traditionally, we select a reference frame to judge if a light source is stationary. To explain the photon density hypothesis, we propose a concept of reference environment. Any experiments must occur in certain environment. Since the experimental environment is of vital importance to experimental results, we shall use the experimental environment as the reference frame and call it reference environment. With respect to the reference environment, the speed of light is constant and any object that is stationary in the environment is viewed as stationary. Since the experiment environment can move at any speeds (e.g. a lab stationary on the earth, on a train, or in a space station), we do not need to assume any favourable/absolute stationary frame for a stationary light source. In this paper, we consider only the experimental results within the experimental environment. The more complicated measurements between different reference environments are also explainable, but they are out of scope of this paper.

5. Explaining photon emission frequency change in a gravity field

We show in Section 2 that time dilation hypothesis cannot explain the experiments of Chou et al [7] in a consistent way, so it is necessary to come up with a hypothesis explaining the experimental results. Here we use graviton density/pressure to explain photon emission frequency change in a gravity field.

Due to the negative gravitational potential, a free photon at infinity distance from the centre of the mass has higher energy than a photon in a gravity field. The energy conservation requires that if the free photon travels into the gravity field, its speed should increase. The increase speed can be calculated through Einstein's equivalence principle (e.g. Cheng, 2005).

Einstein used a free fall reference frame for the gravity field. Since the photon speed is c with respect to this reference frame, the speed of photons viewed from a stationary inertial frame should increase at an acceleration rate determined by gravity strength: $a=GM/r^2$. When free photons at speed c travel from a position A at infinitely away from the centre of the mass to a position B of distance R from the centre of the mass, their speed should increase to c' through the acceleration rate:

$$c' = c + \int_0^{t1} a dt = c + \int_\infty^R a d(\frac{r}{c}) = c + \int_\infty^R \frac{GM}{cr^2} dr = c + \frac{GM}{cR} = c(1 + \frac{GM}{c^2R}) \qquad (15)$$

where G is the gravitational constant, R is the distance from the gravity center of mass M.

In reality, however, the light speed at point B in the gravity field is actually c. This speed difference can be explained by the resistance or pressure from graviton density. It is widely accepted that gravity field is caused by gravitons and the higher gravity force indicates higher density of gravitons. Similar to the impact of pressure of photon density discussed in Section 3, the density of gravitons may also cause pressure (through momentum impact) on photon emissions and thus negatively affect photon emission frequency.

As the photons or the light source moves towards the gravity centre, they encounter gravitons of increasing density, which adversely affect the speed of photons and photon emission rate of the emitter. In other words, the effect of graviton pressure can be described by how much the light speed being depressed by the pressure, or the ratio of the would-be speed c' calculated in equation (15) to the actual speed c in the gravitational field:

$$\frac{c\prime}{c} \approx 1 + \frac{GM}{c^2R}$$

Assuming the graviton pressure indicated by the above equation is inversely related to the photon emission frequency, the emission frequency f' in a gravitational field will be less than the frequency f outside the gravitational field (infinitely away from the mass centre) and can be expressed as the following ratio:

$$\frac{f'}{f} = \frac{c}{c'} = 1/(1 + \frac{GM}{c^2R}) \approx 1 - \frac{GM}{c^2R} \tag{16}$$

The equation shows that the photons emitted in a gravity field appear to be redshifted by $\frac{GM}{c^2R}$. If the light sources are at different distance R_1 and R_2 from the mass centre, their light frequencies f_1 and f_2 satisfy:

$$\frac{f_1}{f_2} = \frac{1+\frac{GM}{c^2R2}}{1+\frac{GM}{c^2R1}} \approx 1 + \frac{GM}{c^2R_2} - \frac{GM}{c^2R_1}$$

In terms of frequency shift, the above equation can be rewritten as:

$$\frac{\Delta f}{f_2} = \frac{GM}{c^2R_2} - \frac{GM}{c^2R_1} = \frac{GM(R_1 - R_2)}{c^2R_1R_2} \tag{17}$$

This result is the same as that derived from the General Relativity. The calculated redshift from this equation is consistent with the application of GPS, so the application of GPS proves only the emission frequency dilation in a gravity field. This frequency dilation could be caused by graviton pressure or by time dilation in a gravity field.

If R_1 and R_2 are close to the radius of the earth R, i.e. , $R_1 \approx R$, $R_2 \approx R$, $R_1 - R_2 = \Delta h$, $f_2 = f_0$, on applying Newton’s law of gravitation the above equation becomes:

$$\frac{\Delta f}{f_0} = \frac{GM\Delta h}{c^2R^2} = \frac{g\Delta h}{c^2} \tag{18}$$

This equation is exactly what used in Chou et al (2010) for time dilation effect in gravity field. as we explained in section 2 that time dilation hypothesis is in conflict with the experimental results, here we can examine the results of Chou et al by our gravity pressure hypothesis. Since no time dilation is involved in our graviton pressure hypothesis, the optical fibres used in Chou et al [7] should not affect the signal frequency when signals are transmitted from the optical clocks at different elevation to the femtosecond comb for comparison. As such, the frequency change of the clock at higher elevation is preserved and can be compared at the femtosecond comb to give a result that quantitatively agrees with equation (18). Consequently, the graviton pressure hypothesis can explain consistently the results of Chou et al [7].

6. Conclusions

After a careful examination of key historical experiments, we find that the experiment of Chou et al actually disproved the time dilation hypothesis while the experiments by Ives and Stilwell proved only an emission frequency dilation, instead of popularly accepted time dilation. As time dilation is a key concept in Einstein's relativity theory, this finding may have significant implications on the theory. The paper also provides alternative explanations for light frequency change caused either by moving emitters or by different strengths of gravity fields. These explanations can also be applied to other relativity experiments and observation such as the life time of muons of high velocities, no frequency change for light reflected from a transversely moving mirror, and planetary precession. Due to space limitation, we have not discussed them here.

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Appendix: Performance of various hypotheses on atomic clock frequencies in a gravity field

Table 1 contains 4 different hypotheses and 2 combined hypotheses. The frequency of the atomic clock at lower elevation is assumed as 100 Hz (a low hypothetic value for easiness of demonstration) for all scenarios. The amount of frequency shift or time dilation is set at 10%, which can be consistent with the predictions (equation 17 in section 5) from the general relativity for certain gravity field and elevations (distances from the gravity centre).

Table 1: Comparing predictions from different hypotheses

	I. Atomic clock L freq.(Hz) based on time standard L	II. Atomic clock H freq.(Hz) based on time standard H	III. Atomic clock H freq.(Hz) based on time standard L	IV. Atomic clock H freq.(Hz), transmitted to L, based on time standard L	Brief comments on: consistency with predicted frequency change from general relativity (GR), with the practice of GPS system, and internal consistency.
A: 10% freq. increase from L to H, without time dilation	100	110	110	110	Consistent internally, and with GR and GPS.
B: 10% time dilation from H to L	100	100	110	100	Consistent internally and with GPS. Inconsistent with GR.
C: 10% true blueshift for signals travelling from H to L	100	100	100	110	Consistent internally and with GR. Inconsistent with GPS.
D: B+C	100	100	110	121	Inconsistent internally and with GR. Consistent with GPS.
E: 10% measured blueshift for signals travelling from H to L	100	100	100	110	Consistent internally and with GR. Inconsistent with GPS
F: B+E	100	100	110	110	Consistent with GR and GPS. Inconsistent internally.

L – at lower elevation; H – at higher elevation

Hypothesis A involves a 10% frequency increase at the higher elevation, so the frequency of atomic clock at higher ground increases to 110 Hz. Since neither time dilation nor blueshift is involved, the 110Hz frequency is unchanged for measurements in II, III, and IV. This hypothesis provides a simple and straightforward explanation and is easy to comprehend. The hypothesis is consistent internally, and the amount of predicted frequency change is consistent with the prediction from GR and with the practice of GPS.

Hypothesis B involves a 10% time dilation from the higher elevation H to lower elevation L, so the frequency of atomic clock at higher ground increases to 110 Hz in terms of the time standard at the lower elevation (column III). Because the time standard for the measurement instrument at the higher elevation is also affected by the same amount time dilation, one will still measure 100 Hz at the higher elevation (column II). When the light/signals of the atomic clock travels from H to L, the time will dilate back to the L standard (the same amount of time dilation effect of moving from L to H but in the opposite direction), so the light frequency will be dilated back to the initial value of 100Hz (column IV). Apparently, the clock frequency of signals travelling from the higher elevation to lower elevation (value in column IV) equals the frequency of the clock at the lower elevation. This result is inconsistent with the GR prediction that the frequency of light from the higher elevation should be blueshifted and thus have higher frequency than the light emitted at the lower elevation.

Hypothesis C involves a 10% true blueshift (a frequency increase based on the same time standard at the lower elevation) for signals travelling from H to L. Since neither time dilation nor frequency change is involved for two atomic clocks, the frequency in columns I, II, III are the same. The 10% blueshift leads to a 110Hz signal frequency is measured, so the hypothesis is consistent with GR prediction. However, since the frequencies of the two atomic clocks are the same, the time stamps from the clocks are on par so there is no need to adjust the clock frequency at the higher ground. This is inconsistent with the practice of GPS.

Hypothesis D is a combination of hypotheses B and C, involving a 10% time dilation from H to L and a 10% true blueshift for signals travelling from H to L. The time dilation effect is the same as in hypothesis B, so the results in columns II and III are the same as in hypothesis B. The 10% true blueshift based on result in column III leads to a 121Hz signal frequency in column IV, which is greater than that predicted from GR. The true blue shift for signals from H to L is also at odd with time dilation effect, so the combined hypothesis is inconsistent internally.

Hypothesis E shows a 10% measured blueshift effect (measured blueshift based on time standards at different elevation). Since neither time dilation nor frequency difference is assumed at two elevations, the time standards at the two elevations are the same, so the measured blue effect is also a true blueshift effect. As a result, the predicted results in this hypothesis is the same as in hypothesis C.

Hypothesis F is a combination of hypotheses B and E. The assumption of time dilation leads to the same results in columns II and III as in hypothesis B. Since the measured blueshift is based on the frequency standard 100Hz at the higher elevation (column II), the 10% measured blueshift results in 110 Hz in column IV. This measured blueshift actually means no true frequency change (the results in columns III and IV are the same). The unchanged frequency is not consistent with prediction from time dilation hypothesis, so the combination is inconsistent internally.

From Table 1 it is clear that only hypothesis A can provide a consistent explanation and thus is plausible. All other hypotheses involve time dilation or blueshift and are associate with various inconsistency. Since both time dilation and blueshift explanations cannot pass logic test or are not consistent with results from experiments or observations, they are implausible.