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Correlation in Gamma Ray Burst Time Delays between Pairs of Radio Photons

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Abstract

We present a pilot study of time delays Δt in four GRB Radio Afterglow emissions, *i.e.*, delays in the arrival times of radio waves of different frequencies emanating from eight GRB Radio Afterglows. Unlike in most studies on this phenomenon, we do not assume that this time delay is due to the Photon being endowed with a non-zero mass, but that this may very well be due to the interstellar space being a cold rarefied cosmic plasma, which medium's Electrons interact with the electric component of the Photon, thus generating tiny currents that lead to dispersion, hence, a frequency (ν) dependent speed of Light where this speed scales off as ν^{-1}. The said interaction is such that, lower frequency Photons will propagate at lower speeds than higher frequency Photons thus leading to the observed time delays in the arrivals times of Photons of different frequencies. In reasonable accord with the proposed model, we find that for four of these GRB afterglows, there is a strong unsolicited correlation between the observed time delays and the frequency. If this model can be corroborated by a large enough data set, there is hope that this same model might lead to a better understanding of the observed time delays in GRBs.

Keywords

Gamma-Ray Bursts, Photon Mass, Plasma

1. Introduction

Conventional Modern Physics Theories, especially Maxwell's [1] Electrodynamics (MED), Einstein's [2] Special Theory of Relativity (STR), Quantum Electrodynamics (QED) and the Standard Model (SM) of Particle Physics are all based on the seemingly sacrosanct idea that the speed [$c_0 = 2.99792458 \times 10^8\ \mathrm{m \cdot s^{-1}}$ (CODATA 2018)[1]] of Light in *vacuo* is an inviolable *Fundamental Constant of Nature*. This constancy of the speed of Light is assumed to hold for all electromagnetic waves, down from the weakest radio wave to the most energetic γ-rays. In these models (MED, QED, SM *etc*.), Photons are assumed to be massless—*i.e.*, their rest mass, m_0, is taken to be identically equal to zero. Whether or not the speed of Light is a constant across the entire electromagnetic spectrum plays a fundamental role in *All of Physics*. If Photons have a non-zero rest mass—*no matter how small this mass may be*—for so long as it is not identically equal to zero, various *Key Theories of Modern Physics* will be affected drastically. Despite the fact that enormous successes has been achieved based upon the theories aforementioned, it is still necessary to put this assumption of a massless Photon to the test using as many independent methods as is possible—*of which*—the time delay in γ-Ray bursts is one of the scenarios were this idea of massive Photon can be put to the test.

For example—in recent times, astrophysical phenomenon such as the time delays observed in *Gamma Ray Bursts* (GRBs) (see *e.g.*, Refs. [4]-[14]) and *Fast Radio Bursts* (FRBs) (see *e.g.*, Refs. [7] [15] [16] [17] [18]) have brought to the fore of physics this very idea that the Photon may not be massless as we have long assumed. In these time delays, it is observed that Photons of different frequencies supposedly emanating from the same GRB and FRB event arrive at the telescope at different times. Surely, if these Photons are coming from the same GRB/FRB-event where they were supposedly released simultaneously, it is naturally expected that these Photons should arrive at the telescope at the same time if they are travelling along the same path at the same speed as we assume them to be doing. The reality is that, rather surprisingly, Photons of different frequencies arrive at the telescope at different times, with the higher frequency Photons systematically and consistently arriving first. The one common and popular possibility that has been and continues to be explored for this unusual occurrence is that—Photons may very well be endowed with a non-vanishing mass. In Section 3, we discuss this model used to explain how massive Photons should lead to time delays and this being a result of Photons having a non-zero mass.

While we are of the strongly view (see *e.g.*, Refs. [19] [20] [21] [22]) that the Photon may very well be massive, at present, we do not think that this is the reason for the time delays observed in GRBs. For example, we know that the Universe is richly endowed with stars that prodigiously pour out their stellar winds into the interstellar space. Like the Solar wind, this stellar wind of stars should comprise equal portions of fast moving Electrons and Protons. Apart from the Electrons and Protons, there should also be in this stellar wind, a number of unstable charged subatomic particles *e.g.* Pions $\left(\pi^+, \pi^-\right)$, Mouns $\left(\mu^+, \mu^-\right)$, Tauons $\left(\tau^+, \tau^-\right)$, *etc*. These stable fast moving Electrons and Protons must—*somehow*—be smoothly smeared out uniformly, homogeneously and isotropically across all of space. As such, it is logical and reasonable to assume that at the

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[1] [3].

very least, interstellar space must be a rarefied plasma medium.

If we are to accept the above stated assumption—and—knowing very well that the speed of Light in a non-*vacuo* medium such as a plasma is going to be different from its *vacuo* value of unit—and—further knowing that, this speed will not only be different from the *vacuo* value, but will depend on the particular frequency of the Photon, it follows from this—that, it is possible that the time delays observed in GRBs may very well be due to these rays propagating in a rarefied cosmic plasma. Hence, in this article, we explore this possibility that time delays observed in GRBs may be a result of these electromagnetic waves travelling in a rarefied *plasma medium*.

First: as already said, in GRBs events—it has been observed that γ-rays of different energies emanating from the same event arrive at the telescope at different times where these γ-rays are supposed to propagate at the same speed of Light: $v_{\text{g}} = c_0/n$, for the given medium whose refractive index is n. These GRBs were serendipitously discovered (during the so-called *Cold War* in the 1960s by US VELA spy satellites) and first reported by Klebesade and Olsen [23]. Furthermore, these GRBs seem to hold potent seeds to probe Lorentz invariance *via* the observed time delays in the arrival times of γ-rays of different energies from these GRBs events. Lorentz invariance is a very important fundamental symmetry in physics and its violation—*if confirmed by experiments*—can have serious reverberations across all *Disciplines of Physics*.

Second: as already aforementioned, we also have the phenomenon of FRBs, and these FRBs are one of the newest and latest discoveries in the *World of Astronomy*. In a nutshell, a FRB is a high-energy astrophysical phenomenon of unknown origin manifested as a transient radio pulse lasting a few milliseconds on average and the first of such was discovered by pulsar astronomers—Duncan Lorimer and his student David Narkevic in 2007; while they were looking through archival pulsar survey data [18], and, for this reason, a FRB is sometimes referred to as a *Lorimer Burst* [24]. While FRBs are predominately assumed to be of extragalactic origin, their exact origins and cause is uncertain.

Before we close this introductory section, we must hasten to say that the present article is the first in a four paper series.

1) In the present [Paper (I)], we consider four GRB time delays between radio Photons pairs that gave a reasonable good correlation.

2) In the second part [hereafter, Paper (II)], we reconsider the fitting procedure here applied, whereby we improve on the apparent groupings of the GRB time delays.

3) In the third part [hereafter, Paper (III)], we consider yet another set of four different GRB time delays that do not give a good correlation.

4) In the last part [hereafter, Paper (IV)], we are going to consider GRB time delays between γ-ray and radio Photons.

In-closing, we now give the synopsis of the present article. In Section 2, we make a brief review of the currently assumed sources that may be the cause of the observed time delays. In Section 3, we present the massive Photon model as it is widely understood. In Section 4, we present the rarefied cosmic plasma model that we believe explains the reason for the observed time delays in GRBs. Having presented our heads of argument as to what it is we hypothesize may be the reason for the time delays, in Section 5, we apply the proposed model to real data which has been procured from the literature, where this data is analysed and results are presented. Lastly, in Section 6 *&* Section 7, a general discussion is presented and conclusions are drawn, respectively.

2. Plausible Sources of Time Delays

There are about three major sources that may lead to the observed time delays, Δt, and these are, the effects of a *Massive Photon*, *Plasma Effects* and *Intrinsic Processes* associated with the Photon propagating in interstellar space. We will briefly discuss these effects below.

2.1. Mass of Photon

Let: Δt_γ, represent the time delays due to the supposed effects of a massive Photon. The detailed theory of the time delay emanating from the *Photon Mass Effect* is presented in Section 3. In this theory, the time delay is seen to scale-off as the inverse of the square of the frequency of the Photon in question—*i.e.*: $\Delta t_\gamma \propto \left(\nu_l^{-2} - \nu_h^{-2}\right)$ [6] [9], where: ν_l, ν_h, are the corresponding frequencies of the low and high frequency Photons arriving at the telescope respectively.

2.2. Plasma Effect (Oscillations)

It is a well known fact that as Photons travel in the Interstellar Medium (ISM), especially for the low energy radiation such as radio waves, the *Plasma Effect* [also known as *Plasma Oscillations* (PO)] is present [25] [26] [27]. Let: Δt_p, represent the time delays due to the effects of Light propagating in a plasma. The theory of the Plasma Effect views the ISM as a conducting plasma in which moving Electrons/ions interact with Electromagnetic Fields (EMFs) resulting from different physical phenomena (wave polarisation, coupling and damping *etc*) between these POs and EMFs (see *e.g.*, [28] [29]). Just as with the case for Δt_γ, Δt_p scales-off as the inverse of the square of the frequency of the Photon in question *i.e.*: $\Delta t_p \propto \left(\nu_l^{-2} - \nu_h^{-2}\right)$ [6] [9], thus making it difficult to discern between the *Photon Mass Effect* and the *Plasma Effect*.

2.3. Intrinsic Processes

Let: Δt_{int}, represent the time delays due to the intrinsic effects associate with a Photon propagating in intestacies of interstellar space right from its natal environment to the telescope on Earth. Since prompt emissions originate from internal interactions of the burst ejecta, and radio afterglows are from later interactions between ejecta and circumburst medium, from this burst ejecta, radio afterglows and circumburst environment—associated with this, is some intrinsic time delay Δt_{int} which should depend on the exact nature of the interactions at hand and these interactions may differ from one GRB to the next. Such Δt_{int}'s are always positive for radio Photons [6] [7] and their exact value is hard to know, since early radio afterglows are subject to synchrotron self absorptions, and their starting phases are hard to detect [6] [7]. We are of the strong view that these Δt_{int}'s are what should lead to the random scatter in our graphs where we naturally expect a smooth straight line.

2.4. Summary

Thus, for the total time delay Δt, we have:

$$\Delta t = \Delta t_{\gamma} + \Delta t_{p} + \Delta t_{\text{int}} + \Delta t_{\text{other}}, \tag{1}$$

where: Δt_{other}, represents any other unknown effect that may affect the propagation of Light in the ISM. Our contribution lies in this realm of an unknown effect that has not previously been considered. This is the effect of the long wavelength radio Photons absorbing the *in-situ* interstellar Electrons, thus leading to a modification in their speed of propagation in the ISM.

Apart from the fact that the present model is not in any way a modification of Maxwell's [1] theory of Electrodynamics, but a direct application of it, what is interesting about this new idea (model) is that: unlike the time delays due to the *Plasma Effect* and the *Photon Mass Effect* which vary as ν^{-2}, the new mechanism leads to a dispersion relation that requires a ν^{-1} variation in the expected time delays, thus, making a marked variation which distinguishes the present suggestion (model) from the previously assumed effects leading to the observed time delays. In our model, we are of the view that any scatter in the expected linear variation [Δt *vs* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$] should come from Δt_{int}.

3. Theory—Massive Photon Effect

The common point of departure for most massive Photon theories is *Maxwell-Proca Theory of Electrodynamics* (MPED) [30]-[34]. In the MPED theory together with most of its variants, the energy-momentum dispersion of the Photon is given by Einstein's [35] energy-momentum dispersion relation, namely:

$$E^2 = p^2 c_0^2 + m_{\gamma}^2 c_0^4, \tag{2}$$

where: $E = h\nu$, p, and: $m_{\gamma} \neq 0$, are the energy, momentum, and rest mass of the Photon respectively, while: $h = 6.62606896(33)\times 10^{-34}\ \text{J}\cdot\text{s}$ (CODATA 2018), is Planck's constant and ν is the frequency of the Photon in question. Given that the group velocity, v_{g}, of a wave is: $v_{\text{g}} = \partial E/\partial p$. In the case where $m_{\gamma} \equiv 0$, we have that: $v_{\text{g}} = c_0$, while in the case: $m_{\gamma} \neq 0$, we have that:

$$\frac{v_{\text{g}}}{c_0} = \sqrt{1 - \frac{m_{\gamma}^2 c^4}{E^2}} = \sqrt{1 - 2\left(\frac{\nu_*}{\nu}\right)^2} \simeq 1 - \frac{\nu_*^2}{\nu^2}, \tag{3}$$

where: $\nu_* = m_{\gamma} c^2 / \sqrt{2}\hbar$, and, $\hbar = h/2\pi = 1.054571628(53)\times 10^{-34}\ \text{J}\cdot\text{s}$, is Planck's normalized constant.

It is easily seen from Equation (3) that the lower the frequency, the slower the

Photon propagates in *vacuo*. For energetic events with short time scales such as GRBs, assuming Photons with different frequencies arriving at our telescopes are emitted simultaneously, the time delay of the low energy Photons relative to high energy ones thus can be used to calculate the rest mass of a Photon. In reality radiations of different bands arise at different times. For example, during a GRB explosion high energy Photons should be radiated earlier than X-ray to radio afterglows, and radio afterglows with higher frequencies emerge earlier than lower frequency ones. Therefore, by ignoring such intrinsic time delays, this method can be used to put an upper limit on the Photon rest mass.

If: $\mathcal{D}$, is the distance between the Earth and the GRB, and v_l and v_h are the group velocities for the lower and higher frequency Photons, it follows that the time delay Δt, is such that:

$$\Delta t=\frac{\mathcal{D}}{v_l}-\frac{\mathcal{D}}{v_h}=\frac{\mathcal{D}v_*^2}{c}\left(\frac{1}{v_l^2}-\frac{1}{v_h^2}\right), \tag{4}$$

thus, if: Δt, $\mathcal{D}$, v_l, and v_h, are known, the mass m_γ of the Photon can be computed (see *e.g.*, Refs. [36] [37] [38] [39]).

Now, the distance $\mathcal{D}$ is the Light-travel distance or the look-back time ($t=\mathcal{D}/c_0$). This distance is typically calculated (see *e.g.*, [36] [37] [38] [39]) by assuming a Friedman Universe—*i.e.*, the expanding Universe within the framework of the standard Cosmological-Constant Cold-Dark-Matter model (ΛCDM-model); and that the redshift z is solely due to the expansion of the Universe, then, this distance $\mathcal{D}_L$ is given by:

$$\mathcal{D}_L=\frac{c_0}{\mathcal{H}_0}\int_0^z\frac{(1+z)\mathrm{d}z}{\sqrt{\Omega_\Lambda+\Omega_m(1+z)^3}}, \tag{5}$$

where: $\Omega_m=0.315\pm0.007$, and: $\Omega_\Lambda=0.685\pm0.007$, are the matter-density and the darkenergy-density parameters as currently measured, respectively; $\mathcal{H}_0=67.40\pm0.50\ \mathrm{km}\cdot\mathrm{s}^{-1}\cdot\mathrm{Mpc}^{-1}$ [40] is the present day Hubble parameter. Thus, in the present article we adopt the said values for: Ω_m, Ω_Λ, and: $\mathcal{H}_0$, for the computation of the luminosity distances to the GRBs and their host galaxies. We assume a flat *Standard* ΛCDM-*Cosmology Model* and for all our calculations of the luminosity distances to the different GRB's and their host galaxies, we shall use Wright's [41] cosmology distance calculator[2].

The one major problem and setback with this massive Photon theory [summed up in Equation (4)] is that—*technically speaking*—it cannot be falsified because any quadruple of values $(\Delta t,\mathcal{D},v_l,v_h)$ will yield a mass for the Photon since in this theory the mass of the Photon is assumed to be variable. While the Photon mass is assumed to be variable, there is no explicit method of knowing how this mass varies with frequency—this obviously is yet another weakness of the theory. If the explicit variation of the Photon mass with frequency $[m_\gamma=m_\gamma(\nu)]$ was known, this could be used as a critical yardstick to falsify the theory. As currently obtaining, the theory is correct all the way every time—all we must do is to

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[2] http://www.astro.ucla.edu/%7Ewright/CosmoCalc.html: visited on this day: Sunday 5 Apr. 2019.

accept with little or no qualms at all, the mass deduced from the theory—*this surely is a scientifically difficult thing to do*. In addition to all these obvious weaknesses, the theory further assumes that the interstellar space through which these Photons propagate is a proper vacuum with a refractive index identically equal to unity. Beginning in the next section, we present our alternative view to this story. We strongly believe this view is new and is being presented for the first time.

4. Electron Absorption Model

Photons will propagate at the fundamental and sacrosanct Light speed: $c_0 = 2.99792458 \times 10^8\ \mathrm{m \cdot s^{-1}}$, only in a perfect vacuum were the refractive index (n) is identically equal to unity ($n \equiv 1$). On that pedestal of understanding, it is worthy asking if the Intergalactic Medium (IGM) is a perfect vacuum. Is the space between galaxies truly empty enough to constitute a perfect vacuum? A brutally frank and honest answer to this important question would be—"No, the IGM is certainly not a perfect vacuum—there are a number of reasons for this. Stars, pulsars, the Active Galactic Nuclei (AGN) *etc* are constantly pouring out and into the IGM charged particles." However minute the quantities of matter being poured into the IGM; it makes a significant difference in making the IGM a non-*vacuo* medium.

Actually, the IGM is known to be a rarefied plasma (see *e.g.*, [42] [43]) consisting mostly of ionized hydrogen; *i.e.* a plasma consisting of statistically equal numbers of Electrons and Protons. Therefore, the refractive index of the IGM and cosmological space in general cannot be identically equal to unity because of this cosmological, galactic and astronomical rarefied plasma and the magnetic fields. In a such a medium, the speed of propagation of a Photon will certainly dependent on its wave-length as it does here in earth laboratories in the different mediums such as glass, water, salt solutions *etc*. Apart from the rarefied plasma, there exists in the IGM the Intergalactic Magnetic Fields (IGMFs) [44] [45] and as-well cosmological Primordial Magnetic Fields (PMFs) [46] [47].

Logically, it therefore makes sense to imagine or assume that the vastness of all the cosmological space of the observable Universe must be filled with a rarefied plasma. Actually, physicists working with GRBs and using the time delays to estimate stringent mass limits of the Photon do acknowledge (see *e.g.*, [6] [7] [36] [37] [39]) the existence of plasma in the interstellar space. The only problem is that they (see *e.g.*, [6] [7] [36] [37] [39]) argue that the Plasma Effect is negligible. The *Plasma Effect* they talk about is the effect on the propagation of Light due to the oscillations of the Electrons in the plasma.

Our theory is wholly drawn from Maxwell's [1] equations of Electrodynamics and these equations are given by:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_{\mathrm{e}}}{\varepsilon}, \tag{6a}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{6b}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{6c}$$

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{J} + \frac{1}{c_0^2}\frac{\partial \boldsymbol{E}}{\partial t}, \tag{6d}$$

where: $\boldsymbol{E}$, $\boldsymbol{B}$, $\boldsymbol{J}$ and ρ_e, are the electric and magnetic fields of the travelling Photon, the current density of the absorbed Electron and the charge density of the ISM respectively.

Now, taking the **curl** of Equation (6b) and (6d) and also making use of Equation (6a) and (6c) in our computation, we obtain:

$$\square \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{J}}{\partial t}, \tag{7a}$$

$$\square \boldsymbol{B} = -\mu \nabla \times \boldsymbol{J}, \tag{7b}$$

where:

$$\square = \nabla^2 - \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}, \tag{8}$$

is the *D'Alembert operator*. These Equations (7a) *&* (7b) are the well known electromagnetic wave equations of motion for a Photon in a non-*vacuo* medium.

If—*as is the case in Earth based laboratories*—these electrical currents obey Ohm's Law ($\boldsymbol{J} = i\sigma \boldsymbol{E}$) where σ is the conductance of this cosmic plasma, then, the wave equations for $\boldsymbol{E}$ and $\boldsymbol{B}$ will be given by (see *e.g.*, Lorrain *&* Corson [48], p. 468):

$$\square \boldsymbol{E} = -i\mu \frac{\partial \boldsymbol{E}}{\partial t}, \tag{9a}$$

$$\square \boldsymbol{B} = -i\mu \frac{\partial \boldsymbol{B}}{\partial t}. \tag{9b}$$

where, in a perfect vacuum were $\sigma \equiv 0$, we have that: $\square \boldsymbol{E} = 0$, and: $\square \boldsymbol{B} = 0$.

Now, assuming for, $\boldsymbol{E}$, and, $\boldsymbol{B}$, the electric and magnetic field wavefunctions: $\boldsymbol{E} = \boldsymbol{E}_0 \mathrm{e}^{-ik_\alpha x^\alpha}$, and, $\boldsymbol{B} = \boldsymbol{B}_0 \mathrm{e}^{-ik_\alpha x^\alpha}$, where $\boldsymbol{E}_0$ and $\boldsymbol{B}_0$ are constant vectors and k_μ is the four wavenumber, then, these two wave Equations (9a) and (9b), yield the following dispersion relation:

$$\omega^2 - c_0^2 k^2 = -4\omega_* \omega, \tag{10}$$

where: $\omega_* = 2\pi \nu_* = \mu c^2/4$, $\omega = 2\pi\nu$, with ν being the frequency of the Photon and k its wavenumber. Given that the group velocity v_g of a wave is given by: $v_\mathrm{g} = \partial\omega/\partial k$, thus differentiating Equation (10) throughout with respect to k and rearranging, it follows that:

$$v_\mathrm{g} = \frac{c_0^2}{\omega/k}\frac{1}{1+2\omega_*/\omega} = \frac{c_0^2}{v_p}\frac{1}{1+2\omega_*/\omega} = \frac{c_0^2}{v_p}\frac{1}{1+2\nu_*/\nu}, \tag{11}$$

where: $v_p = \omega/k$, is the phase velocity. In a vacuum we have that: $v_\mathrm{g} = v_p = c_0$. This assumption (of: $v_\mathrm{g} = v_p$) can be extended to the scenario of a non-vacuum medium and so doing (*i.e.*, maintaining this condition: $v_g \neq v_p$, in the non-vacuum medium), one obtains:

$$\frac{v_{\mathrm{g}}}{c_0}=\frac{1}{\sqrt{1+\frac{2\nu_*}{\nu}}}. \tag{12}$$

From Equation (12), as before, if: $\mathcal{D}$, is the distance between the Earth and the GRB, and v_l and v_h are the group velocities for the lower and higher frequency Photons, then—to first order approximation where from Equation (12) we have that: $c_0/v_{\mathrm{g}} \simeq 1+\nu_*/\nu$, it follows that the time delay Δt, is such that:

$$\Delta t=\frac{\mathcal{D}}{v_l}-\frac{\mathcal{D}}{v_h}=\frac{\mathcal{D}\nu_*}{c_0}\left(\frac{1}{\nu_l}-\frac{1}{\nu_h}\right). \tag{13}$$

Thus, if: Δt, $\mathcal{D}$, ν_l, and ν_h, are known, the conductance of the interstellar space can be inferred from the value of ν_*, since:

$$\sigma=\frac{8\pi\nu_*}{\mu_0 c_0^2}=8\pi\varepsilon_0\nu_*. \tag{14}$$

For a large enough data set, it is clear that if the laid down theory has any correspondence with physical and natural reality, then, a plot of: Δt *vs* $\left(\nu_l^{-1}-\nu_h^{-1}\right)$, for the same source (*i.e.*, same $\mathcal{D}$) should—accordingly—yield a straight line graph with a slope equal to $D\nu_*/c_0$. In next section, we shall present four such graphs for four GRB afterglows. We must say that—the result from these four graphs is promising, all that is needed is further corroboration from a convincingly large enough data set. If anything, what is required for a plot of: Δt *vs* $\left(\nu_l^{-1}-\nu_h^{-1}\right)$, are only three parameters, namely the time delay Δt, the frequencies $\left(\nu_l,\nu_h\right)$ of the Photon pair.

5. Application of Model to Data

In Section 5.1, we give our choice of the data that we use for the present work and in Section 5.2, we present the analysis and the results obtained thereof.

5.1. Data Sampling

Our data sample is wholly drawn from Zhang *et al.* [6], wherein, Zhang *et al.* [6] draw their data sample from Chandra & Frail [9]. Chandra & Frail [9] compiled radio observations of GRB afterglows procured between January 1997 and January 2011, as well as one Fermi burst, GRB 110428A, with a total of 304 GRBs. Zhang *et al.* [6] used their GRB data to constraint the cosmological upper mass limit of the Photon where these researchers find: $m_\gamma < 1.062\times10^{-47}$ kg, and this result is a factor four improvement on Schaefer's [49] result: $m_\gamma < 4.20\times10^{-47}$ kg.

5.2. Analysis and Results

We here present an analysis of four of the eight GRB afterglow emissions. As predicted by the RLCC-model, these four GRB afterglow emissions that we present show a strong correlation between: Δt *vs* $\left(\nu_l^{-1}-\nu_h^{-1}\right)$, while the other four (namely: GRB 060218, GRB 000926, GRB 031203 and GRB 991208) show a weak correlation. These weakly correlating GRBs (GRB 060218, GRB 000926, GRB 031203 and GRB 991208), are presented in Paper (II).

5.3. Correlating GRBs

Four GRB Radio-Afterglow emissions demonstrated a reasonably good linear correlation between: Δt *&* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$. In descending order of the best correlation as determined by from their R^2-value from the linear regression fitting procedure, these are: GRB 030329, GRB 980425, GRB 000418 and GRB 021004. The said graphs of these GRB Radio-Afterglow emissions are presented in **Figures 1-4**.

5.3.1. GRB 030329

Located at a sky position of R.A. = $10^{h}44^{m}49.95957^{s}$, DEC. = +21°31'17.4357", GRB 030329 was a γ-ray burst that was detected on 29 March 2003 at 11:37 UTC and was the first burst whose remnant afterglow exhibited definite characteristics of a supernova, thus confirming the existence of a relationship between GRB and supernova stanek03. GRB 030329 is associated with SN 2003*dh* and is sometimes identified by the designation of this supernova [50]. GRB 030329 was one of GRBs that manifested on 29 March 2003, with the other two getting the designations GRB 030329*a* and GRB 030329*b* [50].

The burst's optical afterglow was first observed from *Siding Spring Observatory* less than two hours after the burst had been detected. The X-ray afterglow was first detected approximately five hours after the burst by the *Rossi X-ray Timing Explorer* (RXTE) satellite. The radio afterglow was first detected by the *Very Large Array* and, at the time of its discovery, was the brightest radio afterglow ever observed. With a redshift: $z = 0.1685$, the corresponding distance to GRB 030329 is ~587 Mpc.

The data Table for GRB 030329 is presented **Table A1** and the corresponding graph for: Δt *vs* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$, is presented in **Figure 1**. From this figure, it is seen that this GRB Radio-Afterglow exhibits three distinct groups of correlated events and these are (*a*, *b*, *c*, *d*), (*g*, *h*, *i*, *j*) and (*i*, *m*, *n*, *o*). The event *k* appears to be isolated. In Paper (III), we will consider these events independently, where upon,

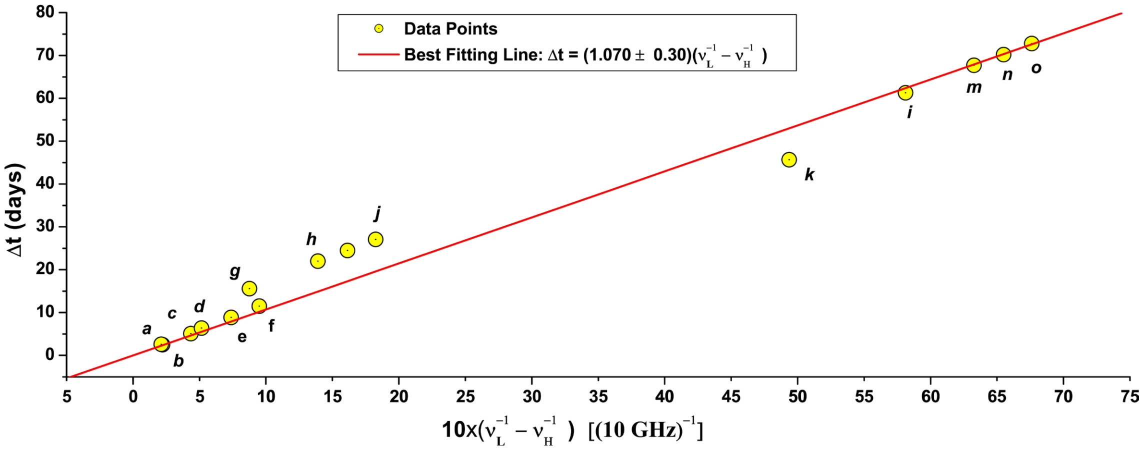

Figure 1. GRB 030329. *The* R^2*-value for this fit is*: 0.98193.

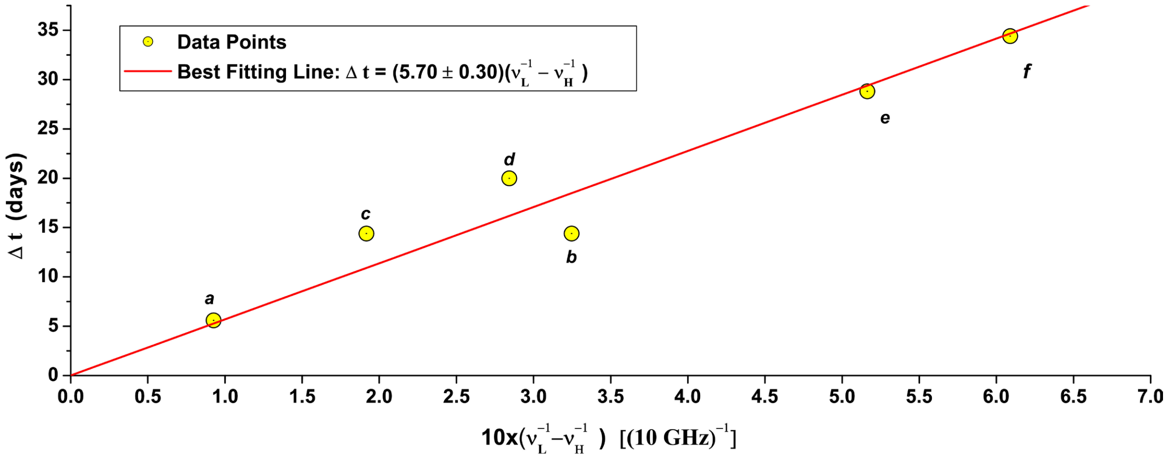

Figure 2. GRB 980425. *The* R^2*-value for this fit is*: 0.93084

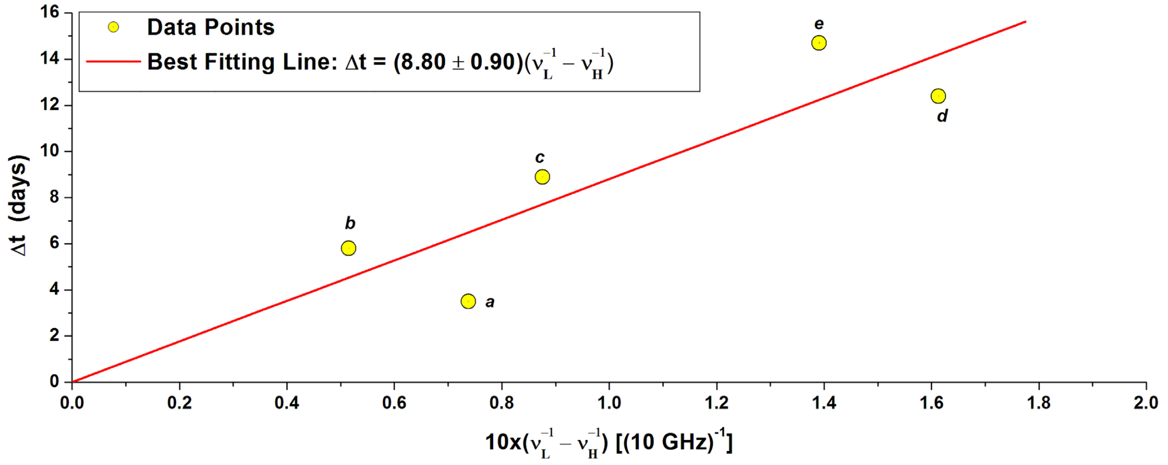

Figure 3. GRB 000418. *The* R^2*-value for this fit is*: 0.70301.

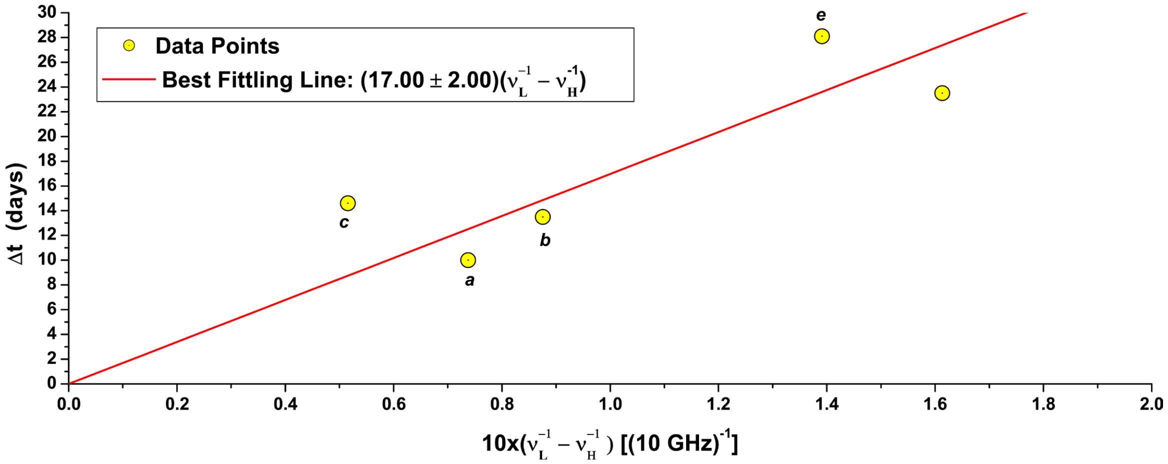

Figure 4. GRB 021004. *The* R^2*-value for this fit is*: 0.70301.

we shall see that these events (*via* their nonzero *y*-intercepts) suggest a non-simultaneous—*albeit*—well correlated emission between the (ν_l, ν_h)-signals. The value for σ obtained is: (7.90 ± 0.30) × 10^{-14} Ω·m.

5.3.2. GRB 980425

Occurring at approximately the same time as SN 1998*bw*, GRB 980425 was a γ-ray burst that was detected by the *Gamma-Ray Burst Monitor* on-board the Italian-Dutch X-ray *BeppoSAX* satellite on 25 April 1998 at 21:49 UTC. The burst lasted approximately 30 seconds and had a single peak in its Light curve. A search for the burst's radio afterglow resulted in one object that was coincident with the previously discovered supernova candidate, giving early credence to the idea that SN 1998bw and GRB 980425 were related. This correlation supports the idea of GRBs as originating from supernova events.

There are six data points for this burst and these are presented in **Table A2**. The resulting Δt *vs* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$ graph for this burst is presented in **Figure 2**. From this figure, it is seen that a reasonable straight line with a correlation coefficient of ~93% is obtained. The data points appear to exhibit two distinct groups of points and these are (*a*, *c*, *d*) and (*b*, *e*, *f*). In a more detailed fitting exercise which is to be conducted in Paper (III), these two groups of data points will be treated separately. The value for σ obtained is: $(1.08 \pm 0.04) \times 10^{-11}$ Ω·m.

5.3.3. GRB 000418

The GRB of April 18, 2000 was first located by Ulysses, NEAR, and KONUS-WIND *via* the IPN (Hurley *et al.*, GCN #642). The optical transient was first discovered in near-infrared images by S. Klose and collaborators (GCN #643). With a SFR of: $\sim 55\mathcal{M}_{\odot} \cdot \text{yr}^{-1}$, the redshift of the starburst host galaxy has been determined to be: $z = 1.118 \pm 0.001$ [51], thus, placing it at a distance of ~7839.20 Mpc.

There are five data points for this burst and these are presented in **Table A3**. The resulting Δt *vs* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$ for this burst is presented in **Figure 3**. From this graph, it is seen that a reasonable fit with correlation coefficient of ~70% is obtained. Just as is the case with GRB 980425, it appears that, for a more rigorous fitting exercise [which is to be conducted in Paper (III)], these data points can be put into two groups—*i.e.*: (*a*, *d*), and, (*b*, *c*, *e*). The value for σ obtained is: $(2.00 \pm 0.30) \times 10^{-13}$ Ω·m.

5.3.4. GRB 021004

On the 4th of October 2002, at the sky position: RA = $00^{\text{h}}26^{\text{m}}47^{\text{s}}$, Dec = +18˚59'13", at exactly 12:06:13.57 UT [52], a long-duration γ-ray triggered the instruments aboard the HETE-2 satellite[3] and the presence of this event in the Universe was immediately transmitted to ground-based observatories around the globe, which observatories began observing it just a few minutes after (*cf.* Refs [14] [53] [54] [55]). According to Fox [56], a fast identification of the optical afterglow allowed observations of the event from its nascent stages, thus, producing one of the best multi-wavelength coverage of a GRB.

Like most (and not all) GRB host galaxies, the host galaxy of GRB 021004 is a

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[3] The HETE-2 satellite [*High Energy Transient Explorer* (HETE)] is a small scientific satellite designed to detect and localize gamma-ray bursts. The HETE program is an international collaboration led by the *Center for Space Research* at the *Massachussetts Institute of Technology*. The coordinates of GRBs detected by HETE are distributed to interested ground-based observers within seconds of burst detection, thereby allowing detailed observations of the initial phases of GRBs.

(very) blue starburst galaxy with no evidence of dust and with very strong Lyα emission lines [57], and, in addition to this, it is observed that this galaxy is a prolific star-forming galaxy found at a systemic redshift: $z = 2.3304 \pm 0.0005$ [58] with a SFR of: $\sim 40\,\mathcal{M}_{\odot} \cdot \text{yr}^{-1}$ [53] [57] [58], thus strongly reinforcing the potential association of some GRB with starburst galaxies (see *e.g.*, [59] [60]).

The data table for GRB 021004 is presented **Table A4** and the corresponding graph for: Δt *vs* $\left(\nu_l^{-1} - \nu_h^{-1}\right)$, is presented in **Figure 4**. While giving a reasonable straight with a correlation coefficient of ~70%, compared to GRB 030329 and GRB 980425, the data points of GRB 021004 have a pronounced scatter. The value for σ obtained from this burst is: (2.00 ± 0.30) × 10^{-13} Ω·m. Interestingly, this σ-value is equal to that for GRB 000418.

5.3.5. Interim Discussion

A summary table for what has been obtained from the four GRBs that exhibit a reasonably good correlation between Δt and $\left(\nu_l^{-1} - \nu_h^{-1}\right)$ is given in **Table 1**. From this table we see from columns (2) and (7), that the redshift of the GRBs does correspond to the redshift of the host galaxy, thus, suggesting—amongst others—that both redshifts (of the GRB and the host galaxy) have a common origin. Thus, if the redshift of the GRB host galaxy is a Hubble-type redshift, then, the redshift of the GRB itself is also a Hubble-type redshift.

The reason for mentioning this seemingly obvious is that, we see in Equation (13) the potential for this equation becoming a new independent yardstick for the measurement of distances to GBRs and their host galaxies and this is on the *proviso* that ν_* is a constant across all cosmic space. Currently, all redshifts in cosmology are assumed to be of a Hubble-type.

Of the four redshifts, GRB 980425 has the lowest redshift ($z = 0.0090$). This redshift is small enough so much that, one can easily apply the usual *Hubble Law*[4] to determine the distance to this event without the need (*e.g.*) for Wright's [41] online cosmology calculator. If we can trust this distance, it means we can safely estimate ν_*, hence the conductance (σ) of intergalactic space. Taking:

Table 1. Summary table for the correlating GRBs.

GRB-Name	z	$\mathcal{D}_L(z)$ (Mpc)	$\frac{\mathcal{D}\nu_*}{c_0}$ (10^{14})	$\nu_*(z)$ (Hz)	$\sigma(z)$ (10^{-11} Ω·m)	**Host Galaxy Redshift**	R^2
GRB 030329	0.1658	821.90	9.20 ± 0.30	0.0109 ± 0.0004	0.0079 ± 0.0003	0.1683 ± 0.0001	0.98193
GRB 980425	0.0090	40.10	49.00 ± 2.00	1.1900 ± 0.0500	1.0800 ± 0.0400	0.0087 ± 0.0000	0.93084
GRB 000418	1.1190	7839.20	72.00 ± 8.00	0.0090 ± 0.0010	0.0200 ± 0.0030	1.1181 ± 0.0001	0.70301
GRB 021004	2.3300	19327.60	150.00 ± 20.00	0.0080 ± 0.0010	0.0200 ± 0.0030	2.3304 ± 0.0005	0.70301

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[4] On 26 October 2018, through an electronic vote conducted among all members of the International Astronomical Union (IAU), the resolution to recommend renaming the *Hubble Law* as the *Hubble-Lemaître Law* was accepted. This resolution was proposed in order to pay tribute to both—Georges Henri Joseph Édouard Lemaître (1894-1966), and, Edwin Powell Hubble (1889-1953), for their fundamental contributions to the development of the modern expanding cosmology model.

$\mathcal{H}_0 = 67.4\,\text{km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$ [40], we obtain that the GRB 980425 is at a distance, $\mathcal{D}$, of: 39.80 Mpc. Given that for this GRB, we have: $\mathcal{D}\nu_*/c_0 = (4.90 \pm 0.20)\times 10^{15}$, it follows from all this—that, we will obtain: $\nu_* = 1.20 \pm 0.05\,\text{Hz}$, hence: $\sigma = (2.70 \pm 0.10)\times 10^{-10}\,\Omega^{-1}\cdot\text{m}^{-1}$.

The IGMCs as obtained from GRB 030329, 000418 and 021004, are in agreement on the order of magnitude of the IGMC, giving: $\sigma \sim 10^{-13}\,\Omega^{-1}\cdot\text{m}^{-1}$. Our expectations prior to the derivation of Equation (13), have been that the IGMC (σ) will emerge as a constant having the same value for all GRBs and this assumption we based on the fact that the Universe is largely assumed to be homogeneous and isotropic. If σ were a constant, this would immediately make Equation (13) a new independent yardstick for the measurement of distances to GBRs and their host galaxies. The factor three difference in the order of magnitude in the IGMC from the said three GRBs and that of GRB 980425, suggests that σ may vary from one GRB to the next.

Of cause, in-order to ascertain whether or not σ is a variable across the sky or not as suggested by the present results, there is need to obtain a much larger data sample where this can be checked. If as many values of σ as possible are to be obtained, it should be possible to make an all-sky map of σ. If obtained, such a potent map will certainly be interesting. The most immediate and important question is—will such an all-sky map reveal a smooth homogeneous and isotopic IGMC or something else? This is something only measurements can reveal unto us. At the moment, we can only imagine and speculate.

6. General Discussion

We have demonstrated that there exists a reasonable and strong inverse frequency $\left[\Delta t \propto \left(\nu_l^{-1} - \nu_h^{-1}\right)\right]$ correlation between the observed time delays and the frequency of the Photons observed at the telescope. Of the four GRBs in our case study, not only does GRB 030329 give the best correlation, this interesting source has the most data points which make this result statistically significant. An closer inspection of **Figure 1**, will reveal that 14 GRB-events associated with GRB 030329 can be grouped into four distinct groups—*i.e.*: with the first group being GRB 030329*a-f*, the second being GRB 030329*g-j*, and the third being the lone event GRB 030329*k* and lastly the forth being GRB 030329*i-o*. The events: GRB 030329a-f, GRB 030329*g-j* and GRB 030329*i-o*, can be fitted neat straight lines that have nonzero *y*-intercepts. In Paper (II), we will consider these events independently, where upon, we shall see that these events (*via* their nonzero *y*-intercepts) suggest a non-simultaneous—*albeit*—well correlated emission between the (ν_l, ν_h)-signals.

In comparison to the Plasma and Photon Mass Effects, what is interesting is that, for the same GRB source, not only is the expected linear correlation between Δt and $\left(\nu_l^{-1} - \nu_h^{-1}\right)$ independent of the distance to the source, but this relationship, unlike the the Plasma and Photon Mass Effect that have a ν^{-2} variation, we here have a ν^{-1} variation on the (ν_l, ν_h)-Photon frequencies.

This is very important in that if this behaviour were to be confirmed for a statistically significant number of GRBs events, it would rule out the Plasma and Photon Mass Effect as possible candidates to the cause of these time delays. At any rate, this would be a significant step forward in our understanding of GRBs and the propagation of EM-waves in the cosmic ISM.

If the cosmic ISM were to be thought of as a conductive medium, then, from the values of the conductance here obtained [~(10^{-14} - 10^{-11}) Ω·m], one can safely say that the cosmic ISM is a poor conductor of electricity; this of cause is expected. Metals have conductances whose magnitude is of the order ~10^{7} Ω·m (see *e.g.*, Refs. [61] [62] [63]). Clearly, from the above stated conductances [~(10^{-14} - 10^{-11})Ω·m] obtained herein, we see that the rarefied cosmic plasma must be a poor conductor of electricity—*for*, its conductance is at least twenty one orders of magnitude smaller compared to ordinary metals.

Now, with regard to the interaction mechanism between the Photon and the plasma in the present model, one will rightly ask: *Since the Photon and the plasma are here interacting, what is different between this proposed interaction mechanism and the Plasma Effect*? To that, we have the following to say. The Compton wavelength of Photon—*or more so*, *its radius*—is much smaller than the wavelength of radio waves. From an intuitive physical standpoint, it is possible to imagine an Electron being engulfed by the Photon in such a manner that the Electron can be pictured to be moving inside the ***E*** and ***B***-fields of the Photon. Succinctly stated, the Electron is absorbed by the Photon in much the same manner as the Photon is absorbed by the Electron in such phenomenon as the *Photo-electric effect* [64], *i.e.*:

$$\mathrm{e}^{-}+\gamma \rightleftarrows \gamma^{-}, \qquad (15)$$

where γ^{-}, is an electrically charged Photon that off-cause does not propagate at the speed of Light c in *vacuo*, but propagates at a lesser speed just as happens with ordinary material bodies. It must be said that, the Photon state "γ^{-}" is not here envisaged as a permanent state of the Photon as it propagates in the ISM, but a relatively short-lived (transitory) state, just as the absorption of the Photon by the Electron can be a short-lived (transitory) state.

In the forward reaction (interaction): $\mathrm{e}^{-}+\gamma \rightarrow \gamma^{-}$, we have the Electron being absorbed by the moving Photon, in which process, the Photon acquires some inertia from the Electron, leading to the alteration of its speed in-accordance with the Equation (12), and, in the reverse reaction: $\gamma^{-} \rightarrow \mathrm{e}^{-}+\gamma$, the Electron is ejected from the Photon system and returns to the cosmic plasma medium from which it originated, in which event thereafter, it [Photon] travels as it would normally do—with the Plasma Effect perhaps coming into the picture. The "fact" that: $\Delta t \propto \left(\nu_l^{-1}-\nu_h^{-1}\right)$, strongly points in the direction of the here proposed "Electron absorption phenomenon" as being the dominate mechanism leading to the observed time delays, with the Plasma Effect having a negligible contribution to Δt. In-closing, allow us to say that: in the next article [*i.e.*, Paper (III)] of our four part series, we shall consider the four GRBs that did not give a good correlation (namely, GRB 060218, GRB 000926, GRB 031203 and GRB 991208).

7. Conclusions

If what has been presented herein be considered reasonable or acceptable—*one can on this basis*—make the following tentative conclusion regarding these observed time delays:

1) The observed time delays may not (as is widely believed or assumed) originate from some supposed *Lorentz violating mechanism*, but, from a (seemingly not considered before) *Plasma-like Effect* to do with *in-situ cosmic Electrons* (and perhaps Protons as-well) in the supposed *rarefied cosmic plasma* interacting with the electric and magnetic components of the propagating Photon.

2) The suggested hypothetical interaction of the *in-situ cosmic Electrons* with the electric and magnetic components of the propagating Photon leads to a modification of the speed (group velocity) of the Photon through the ISM, wherein—it is seen that, the larger the frequency, the faster the Photon and *vice-vesa*, hence, the observed time delay.

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Conflicts of Interest

We the authors hereby declare no conflict of interest regarding the publication of this paper.

Data Availability

No new data were generated in support of this research. As stated in the main text [*i.e.*, Section 5.1], the data underlying this article were wholly derived from Zhang *et al*. [6].

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Appendix

In-order not to distrust the reader, we have placed here in the appendix all the data **Tables A1-A4** for the four sources [GRB 030329, GRB 980425, GRB 000418 and GRB 021004] used to obtain the graphs [**Figures 1-4**, respectively] in the main text.

Table A1. Data for GRB 030329@($z = 0.169$).

From this data—according to **Figure 1**, we obtain: $\frac{\mathcal{D}\nu_*}{c_0} = (9.20 \pm 0.30) \times 10^{15}$.

Event Label	ν_h (GHz)	ν_l (GHz)	t_1 (day)	t_2 (day)	Δt (day)	$\nu_l^{-1} - \nu_h^{-1}$ (10 GHz^{-1})
a	22.50	15.00	8.40	10.90	2.50	2.22
b	43.00	22.50	5.80	8.40	2.60	2.12
c	43.00	15.00	5.80	10.90	5.10	4.34
d	15.00	8.46	10.90	17.30	6.40	5.15
e	22.50	8.46	8.40	17.30	8.90	7.38
f	43.00	8.46	5.80	17.30	11.50	9.49
g	8.46	4.86	17.30	32.90	15.60	8.76
h	15.00	4.86	10.90	32.90	22.00	13.91
i	22.50	4.86	8.40	32.90	24.50	16.13
j	43.00	4.86	5.80	32.90	27.10	18.25
k	4.86	1.43	32.90	78.60	45.70	49.35
l	8.46	1.43	17.30	78.60	61.30	58.11
m	15.00	1.43	10.90	78.60	67.70	63.26
n	22.50	1.43	8.40	78.60	70.20	65.49
o	43.00	1.43	5.80	78.60	72.80	67.60

Table A2. Data for Data for GRB 980425@($z = 0.009$).

From this data—according to **Figure 2**, we obtain: $\frac{\mathcal{D}\nu_*}{c_0} = (4.90 \pm 0.30) \times 10^{15}$.

Event Label	ν_h (GHz)	ν_l (GHz)	t_1 (day)	t_2 (day)	Δt (day)	$\nu_l^{-1} - \nu_h^{-1}$ (10 GHz^{-1})
a	8.64	4.80	12.70	18.30	5.60	0.93
b	2.50	1.38	32.70	47.10	14.40	3.25
c	4.80	2.50	18.30	32.70	14.40	1.92
d	8.64	2.50	12.70	32.70	20.00	2.84
e	4.80	1.38	18.30	47.10	28.80	5.16
f	8.64	1.38	12.70	47.10	34.40	6.09

Table A3. Data for Data for GRB 000418@($z = 1.119$).

From this data—according to **Figure 3**, we obtain: $\frac{D\nu_*}{c_0} = (7.60 \pm 0.80) \times 10^{15}$.

Event Label	ν_h (GHz)	ν_l (GHz)	t_1 (day)	t_2 (day)	Δt (day)	$\nu_l^{-1} - \nu_h^{-1}$ (10 GHz^{-1})
a	22.50	8.46	14.60	18.10	3.50	0.74
b	15.00	8.46	12.30	18.10	5.80	0.52
c	8.46	4.86	18.10	27.00	8.90	0.88
d	22.50	4.86	14.60	27.00	12.40	1.61
e	15.00	4.86	12.30	27.00	14.70	1.39

Table A4. Data for GRB 021004@($z = 2.330$).

From this data—according to **Figure 4**, we obtain: $\frac{\mathcal{D}\nu_*}{c_0} = (1.50 \pm 0.20) \times 10^{16}$.

Event Label	ν_h (GHz)	ν_l (GHz)	t_1 (day)	t_2 (day)	Δt (day)	$\nu_l^{-1} - \nu_h^{-1}$ (10 GHz^{-1})
a	22.50	8.46	8.70	18.70	10.00	0.74
b	8.46	4.86	18.70	32.20	13.50	0.88
c	15.00	8.46	4.10	18.70	14.60	0.52
d	22.50	4.86	8.70	32.20	23.50	1.61
e	15.00	4.86	4.10	32.20	28.10	1.39