The photonic soliton

A. Meulenberg*
HiPi Consulting, New Market, MD,

ABSTRACT

The size stability of the photon has been a puzzle for many decades. However, the self-focusing of a laser beam in matter may provide some guidance to this problem. A conceptual basis for this effect will be accompanied by calculations based on the laser models. It does not necessarily fit. Nevertheless, it leads to better models. The notion of a self-generated light pipe for a photon supports the image of the photon as a soliton. Two photon models are developed. In one, there is a circulating high-energy density that creates a finite-radius light pipe, which thus confines the photon to a core, but with an extended evanescent wave about it. It confines by total internal reflection. In the other, the confinement mode is that of a self-generated graded refractive index (GRIN) optical lens, which does not produce an evanescent wave; but, the electromagnetic energy is spread into the region that would be occupied by the evanescent wave of the first model. The models may be equivalent; both indicate the nature of a relativistic boundary condition that should be imposed on Maxwell's equations to allow inclusion of photons into his model.

Keywords: photon structure, soliton, self-focusing, light pipes, total internal reflection, evanescent wave, graded-refractive index, electromagnetic-energy density,

1. INTRODUCTION

Except for the impossible condition of an infinitely-wide plane wave, all mathematical descriptions for light imply a divergence or convergence as a function of time. Nevertheless, we know that light travelling from the furthest stars can still pass through a finite (and very small) sized hole when it reaches us. And with a photomultiplier, we can "count" individual light particles coming from that distant source. The diffraction pattern resulting from such light passing through the small hole is nearly identical to that for similar-wavelength light generated only meters away, but passing through the same hole. The light generated just meters away can be reduced in intensity by various means (e.g., multiple crossed polarizers) so that it will also be changed from a continuous stream of energy to individual pulses going through the pinhole. The creation, cohesion, and individuation processes of light from a distant star or a light bulb in the lab may be slightly different, but the end results are the same.

The nature of light to act as individual events is a basis for the photonic nature of light. These photons, or quanta of light, are generated individually from excited electrons.[1] They can combine into groups to form collective waves or act as waves individually. They can also be separated from waves to act as individuals. As individuals, all light 'particles' of a given wavelength have the same amount of energy (quanta). They apparently have about the same size independent of how far, or how long, they have traveled from their source. A 'beam' of light cannot do that; it must ultimately diverge (even if it is converged first). So individually, at least in this respect, light as a particle acts in a different manner than it does collectively.

This dual nature of light, individual particle and individual or collective wave,[2] still is somewhat confusing to many physicists.[3, 4] The relatively-fixed size of the photon is part of the puzzle; and, it may also be part of the answer. Speaking of the photon as a particle and as a wave (combined as a wavicle) is not difficult to understand, if one thinks in terms of wave 'packets'.[5] These are long, or short, series of self-bound, coherent waves (1 or 2 to $>10^{10}$ cycles long) that travel in space at the speed of light, c. Thus, for visible light, they can be less that a micron in length or many meters in length. Either way, they pass by very quickly (femtoseconds to microseconds) and, thus, these "events," as individuals, appear to be particles. While we have rationalized the wave-particle question, we haven't really defined the photon nature much better. The photonic waves represent an organized oscillation of orthogonal electric and magnetic fields.

* Andrew Meulenberg <mules333@gmail.com>

They are in an extremely high-Q resonance (negligible loss relative to total energy).[6] This means that they maintain their frequency and total energy until they interact with 'something'. That something is either another resonance (sometimes resulting in absorption) or an object of the proper size and charge to cause self-resonance (resulting in scattering) in the light.

One puzzle is how photons of the same wavelength can have the same energy, even though they may differ in length by 10 orders of magnitude. (A model for the photon radius is described in Appendix A.) Mathematically, we can look at the Fourier analysis of the photon and see that, for a single wavelength photon (small distribution in size, Δx), there is an infinity of different wavelengths involved (large distribution in momentum, Δp_x). This is the basis of the Heisenberg Uncertainty Principle. Physically, the wavelengths must all be jumbled together in the same space or they won't all fit in the single-wavelength packet. They must be highly organized though, or the fields will cancel in the wrong places and the total photon energy will be reduced or distributed improperly. Since the field amplitudes are added, the average field intensity of the single wavelength photon will be much greater than that of the very long photons. While the energy per photon is the same, the energy density E_γ/Vol and energy per cycle E_γ /# are quite different. Regardless of number of cycles (# = 2 or 10^8), $E_\gamma = h\nu$ is a valid indicator of photon energy. However, the energy per cycle is approximately equal to E_γ /#. The variations from the equality and in the energy densities are related to the cross-sectional area of the photon (Appendix A) which depends on the frequency distribution of the photon. This concept is important in the developments below, wherein we attempt to describe, with a minimum of mathematics, a consolidated and self-consistent picture of light that integrates the quantum nature of light with Maxwell's equations.

2. SELF FOCUSING OF LIGHT

The stability if light 'particles' over time and space is fundamental to much of physics. Its understanding is vital. A modern understanding may have been aided more with new technology than with new ideas. With the advent of lasers and the capability of very-high energy-density coherent-light beams, it became clear that the linear and small-perturbation models of physics were no longer going to be adequate. Non-linearities in material parameters (such as refractive index n),[7] produced by the interaction of light with these materials, would introduce terms (via the optical Kerr effect, [8] Eq. 1) that could have a major impact on the results.

$$n = n_0 + n_2 I \,. \qquad 1)$$

Here n_0 and n_2 are the linear and non-linear components of the refractive index; and I is the **intensity** of the radiation. This change in refractive index with beam intensity has been called photorefraction.[9] When there is the correct, but delicate, balance between nonlinear and linear effects in the medium, so that a wave structure does not change during propagation, we refer to the result as a soliton.[10] This is the topic of the present paper.

In the mid 60's, Chiao, et al.[11] showed that, beyond a critical power density, P_{cr}, a laser beam should become self focusing.[12]

$$P_{cr} = \alpha\, \lambda^2 / 4\pi\, n_o n_2 \,, \qquad 2)$$

where λ is the radiation wavelength in vacuum and α is a constant which depends on the initial spatial distribution of the beam. The variable in Eq. 2 that is of primary interest in this paper is the non-linear component of the refractive index n_2. An assumption typically has been that n_o and n_2 for vacuum are one and zero respectively. However, there may be reasons to doubt this. As a prelude to the discussion of vacuum, let us look at the critical power density P_{cr} for air ($n_0 \approx 1$, $n_2 \approx 4\times10^{-23}$ m^2/W for λ = 800 nm).[13] From Eq. 2, $P_{cr} \approx 2.4$ GW/m^2. The power density of a photon of the same wavelength is calculated (Appendix B) to be ~1.2 GW/m^2, even if all of the energy were concentrated in a single cycle. Is this sufficient for self focusing? Clearly not for ordinary photons (with energy spread over maybe 10^7 cycles). Could it be so in free space with n_2 smaller than in air? Is there any photorefraction in free space (i.e., is $n_2 > 0$)?

In air, photorefraction has several components contributing to n_2. Principally, there are molecular and electronic polarizability modes that would not exist in free space. Experimental work has been able to separate these components (and others); but, the sensitivity is inadequate to extrapolate down to zero density levels to determine if a residual effect exists. What other evidence is available to provide values of n_2 for free space?[14] The example of the sun bending light may be important for our story. This gravitational attraction is equivalent to a change in refractive index or in the speed of light.[15] However, it may be attributed either to a change in space or to the virtual and real[16,17] things in it.

The optical waveguide that a soliton creates while propagating in matter is not only a mathematical model, it actually exists and can be used to guide other waves at different frequencies. However, if the soliton has varying intensity along its length, then, depending on the 'recovery time' of the medium, other frequencies and phases may see only a portion of this induced non-linearity. If we apply this observed behavior in matter to individual photons, then we can extend the concept into free space where things are different; but perhaps they are similar enough that we can look for the same effects there.

If the gravity field about a star (caused by its mass, which is equivalent to energy) can change the refractive index of space, how much more would an electric field, with its much higher energy density, change it? A nucleus, or an electron, should be surrounded by a high-refractive-index medium. However, it is a short-range effect. If the electric-field strength about a point charge drops off as $1/r^2$, and the field energy is proportional to the square of the field, then (from Eq. 1) the refractive index drops to n_o, from n, as $1/r^4$. Since any change in n about a charged particle is highly localized and the region involved is so small compared to the size of a photon, they would not affect photon velocity unless there were some resonance between the particle and the photon. The concept of resonance is critical because resonance converts the highly localized change in n of a charge into a larger regional effect that can interact with a much larger photon. How does this happen?

Consider an atom with dimensions on the order of an Angstrom (10^{-10} m). If we assume that the dielectric constant varies as n^2 (not necessarily so, since we are not talking about polarization of a charge density of space – unless Dirac's sea of electrons, or the virtual electron-positron pairs being constantly created and annihilated from the quantum foam, are real or represent the polarizability of space), then $\varepsilon = n^2 = ?/r^8$. (The question mark is because we still haven't determined a value or functional dependence for n_2 in space.) Could this field-induced change in dielectric constant about an elementary charge somehow be equivalent to the "dressing" of charges from vacuum-polarization[18] based on the production of virtual electron-positron pairs? Alternatively, does it simply prevent elementary particles from being singularities, or perhaps explain why they are not?

While distortion of space is considered 'natural' in the region of stars, Eq. 1' indicates that it is the field (a gradient) not the total potential that is critical in the non-linearity of refractive index. The electric field strength close to an elementary charge is many orders of magnitude greater than the gravity field at the surface of even a neutron star. Therefore, the refractive index in these local regions of charge should reflect this effect.

3. SELF FOCUSING OF PHOTONS

If an electric field distorts space and increases the refractive index of material, then the 'internal' field(s) of a photon may do so as well. Let us rewrite Eq.1 into a form to reflect this.

$$\boldsymbol{n} = \boldsymbol{n_0} + \boldsymbol{n_2}'\mathbf{E}^2 \quad . \qquad 1')$$

This is equivalent to the Optical Kerr Effect,[19] which led to Eq.1 in the first place. Thus,

$$\boldsymbol{n} = \boldsymbol{n_0} + 3\chi^{(3)}\,|\mathbf{E}_\omega{}^2|/8\boldsymbol{n_0} = \boldsymbol{n_0} + \boldsymbol{n_2}'I \quad , \qquad 1'')$$

where $\chi^{(3)}$ is the 3rd order component of the electric susceptibility[20] of the medium. [The even-order terms drop out due to inversion symmetry of the Kerr medium.][19] There undoubtedly is an equivalent term for the magnetic field energy with the magnetic susceptibility,[21] χ_V, although, by definition, both the susceptibilities of vacuum are zero. Since terms such as "electron sea" and "vacuum polarization" have been acceptable within the physics community, the use of vacuum susceptibilities should be revisited.[18] Alternatively, there could be an additional (very small) term called "energy-induced susceptibility" that could be included in both equations. Or, the addition of another term, e.g., n_3, in Eq. 1 might serve the same purpose, but, without altering the present definitions of magnetic and electric susceptibility. A point about the energy term is that there appears to be no dispersion; any wavelength dependence is only in the energy determination. This is important in that it allows the non-linear photon model to apply to all wavelengths.

For a photon, the electric and magnetic fields (alternating in both directions) can only increase the refractive index (i.e., Δn being proportional to $\mathbf{E}^2$ implies no decrease in n from this source). For a long photon (e.g., 10^8 cycles), the field density is low, so that the effect is small. For a short photon (e.g. 2 cycles), the field density is very high (comparable to that of a charged particle) and the effect is strong. However, in the process of forming a photon from a resonant collection of electric and magnetic fields, the length of a photon is determined by the "stability" of the source fields. The more stable the source, the longer the photon. If the source is unstable, then the uncertainty in both longitudinal and transverse momenta is high and the length of the photon is low (and inherent divergence is high). It appears that, for photons to be stable, the self-focusing effect must be built into both space and the photon. How does this happen?

In quantum mechanics, the potential of a 'barrier' translates into a refractive index. A particle or wave going over a barrier experiences a decrease in its wavelength (i.e., if light, its speed drops below that before the barrier). Since an electric field is the gradient of a potential, there will be a change in velocity of light in the region of a field because of the local potential. Relativistically, in a photon, the oscillating fields provide localized regions of intense energy density and therefore distortion of space. Again, the velocity of light is reduced in these regions that then act as micro-scale lenses and the photon is self-focusing.

4. SELF FOCUSING VS TOTAL INTERNAL REFLECTION

We have been talking about focusing as with a lens that has a thickness proportional to the energy of the local field. There is another focusing mechanism that is similar and equally instructive. We are all familiar with light fibers where light is confined inside a thin optical fiber[22] by total internal reflection (TIR).[23] Generally, TIR is pictured as occurring at interfaces between an optical medium and air resulting in a large difference in refractive index at the surface. This requires that the refractive index of the thicker outer layer of the optical fiber have a lower refractive index than the thin inner core. However, because the necessary critical angle for TIR in light fibers is so low, the required change in refractive index to be an effective self-focusing tool is also very low (<1%). Furthermore, the change in refractive index does not need to be abrupt.

A light pipe operates as an optical waveguide. The central core is a low-loss material that is surrounded by a "cladding" of lower-refractive-index low-loss material ($n_{core} / n_{clad} = n_1/n_2 > 1$). Note: n_2 now means the refractive index for the cladding (the second layer), not the coefficient of nonlinearity n_2 as earlier. Light, if not traveling exactly down the center of a light pipe, is totally internally reflected from the cladding. Thus, it bounces from side-to-side down the fiber without loss. If the fiber core radius, a, is too thin (e.g., $a < 10\lambda$) to have more than one light beam direction to be beyond the critical angle [$\theta_c = \arcsin(n_2/n_1)$], then it is a single-mode fiber. There is no requirement for the fiber to have layers with fixed refractive indices.

For a graded-index fiber,[24] the refractive index, as a function of radius r, can have many shapes (Eqs. 3[25] and Fig. 1):

$$n(r) = n_1(1-2\,\Delta(r/a)^g)^{1/2} \qquad r < \alpha \qquad 3a)$$

$$n(r) = n_1(1-2\,\Delta)^{1/2} \qquad r \geq \alpha \qquad 3b)$$

where

$$\Delta = (n_1^2 - n_2^2) / 2\,n_1^2 \qquad 4)$$

and the exponent g is the parameter that defines the shape of the profile. For a step-index fiber, g = infinity. The parabolic shape (g = 2) of the core's refractive index (out to the constant-*n* cladding) gives the best focusing properties.

A normalized frequency V is defined[26] to characterize an optical fiber.

$$V = k_o a(n_1^2 - n_2^2)^{1/2} = 2\pi a\ (n_1^2 - n_2^2)^{1/2}/\lambda \quad , \qquad 5)$$

where λ is the wavelength in vacuum. V must be greater than 5 for this approximation to be valid. Nevertheless, we will use this as a guide, since we will be making further approximations. For an optical fiber having a power-law refractive index profile, as in Eq. 3, the approximate number of bound modes, is given by

$$\#_{bm} = V^2 (g / (g+2)) / 2 \ , \qquad 6)$$

where g is the profile parameter. For single-mode operation (i.e., # bound modes = 1), Eq. 5 gives $V < 2.405$. However, for g=1 (a linear gradient) and $\#_{bm} = 1$, then V = sqrt(6) = ~2.45, which indicates its being close to a single mode fiber.

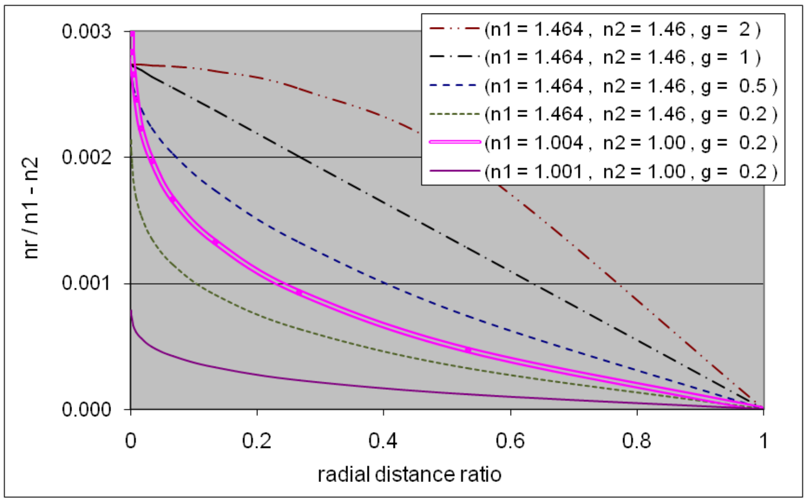

Figure 1. The deviation of n_1 as a function of distance from the center of an optical fiber showing the effects of changing the gradient profile g (from 2 down to 0.2) and of changing n_1 (from 1.464 to 1.001) and n_2 (1.46 to 1).

Waveguide analysis shows that the light energy in the fiber is not completely confined to the core.[27] Especially in single-mode fibers a significant fraction of the energy travels in the cladding as an evanescent[28] wave. We are going to examine the photon as a self-generated light pipe, so we must also include perhaps more realistic shapes ($g << 1$) and refractive indices (n_1 = ~1). The six curves in Fig. 1 display the effects of changing g, n_1, and n_2. The $g < 1$ cases represent a proposed nonlinearity of space and the field-induced increase in n toward the center of the photon. We can use the equations above to look at the similarities and the limits of the analogy.

We consider the refractive index within a photon to be $n_{max} = n_o + \delta = 1 + \delta$, where δ might be 10^{-7}. Thus, if we assume most of the photon energy to be confined to a region within $a = \lambda/2\pi$ (as in Appendix A) and g = infinity, then, from Eq. 5, $V = \sim 10^{-7}$ and we clearly are in the single-mode regime (but the approximation is far from assumptions for validity). At the other extreme (i.e., linearly-polarized photons, with $a >> \lambda/2\pi$ and $g < 1$), V is still <<1. This means that, at least for our application, none of the optical-fiber equations are completely valid. The step-index core fiber can be instructive for the confined photon model. However, another analogue from physical optics may be better for describing the distributed photons and, in this context, is worth a quick study.

The difference between a graded-index, single-mode, light pipe and a **g**raded-**r**efractive-**in**dex (GRIN)[29] concentrating lens is subtle, when $n_{1max} = \sim n_2$. For g <<1, there is no real "surface" from which to reflect light. Therefore, any self-confinement of the photon must be from a focusing effect only. The easiest means of considering this is to look at the phase velocity of light.[30] At the center of a photon, it is slightly lower than at the edges. This would seem to give a poorly-shaped structure for long-distance propagation. Furthermore, the region in the center, containing the greatest portion of the photon energy, must be travelling the slowest. Does this mean that the speed of light is not fixed? It is known that the velocity of light, to within $\Delta c/c < 6.3 \times 10^{-21}$, is independent of frequency.[31] Thus, the group velocity is equal to the phase velocity to that level. Any model of self-focusing in a photon must be consistent with the data. While a variation of c within the photon could cause problems, we know that the photon is perfect in this regard. Thus, for the model to be correct, the internal energy of a photon must distribute itself to be consistent with the field distributions and the self-focusing hypothesis. One such model of the photon is explored in another paper of this conference.[32]

Free space is a *reference state*. Like absolute zero, it is an idealized state that only can be approximated in the real world. The velocity of light is also a reference point. Just as the angular momentum of all photons are equal (Appendix A); it may be that all photons have the same average velocity, but, as the phase velocity is not limited to the speed of light, the edges may travel faster than the centers. On the other hand, the average group velocity of a single photon might depend on the energy densities of its constituent parts. Based on the present model, I would suggest that the best chance of finding a variation of the speed of light in free space would be in the comparison of long photons and very short photons of the same fundamental frequency. The great disparity in energy density between equal energy photons of different length could make light-induced changes in the refractive index of space measureable with present instrumentation.

5. TOTAL INTERNAL REFLECTION AND EVANESCENT WAVES

Heretofore, we have been talking about the central "core" of the photon. It was mentioned earlier that in a single mode fiber, a large portion of the beam energy resides in the cladding. Let us carry this picture of total internal reflection and light fibers over to our model of the confined photon. The penetration depth of evanescent waves incident on a lower refractive index surface at beyond the critical angle α_c is typically a fraction of a wavelength (Fig. 2). We define the penetration depth *d* reflecting the relative decrease of the evanescent wave amplitude in the "z" direction (i.e., I_z / I_o normal to the surface) to be:

$$d = |k_{tz}|^{-1} = \frac{1}{\frac{\omega}{c}\sqrt{n_1^2 \sin^2\alpha - n_2^2}} = \frac{\lambda_i}{2\pi\sqrt{n_1^2 \sin^2\alpha - n_2^2}} \quad . \tag{7}$$

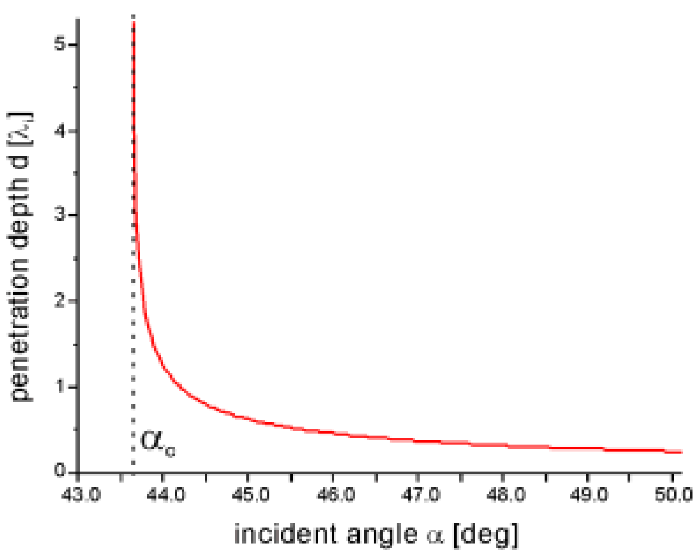

Fig. 2. Penetration depth as a function of the incident angle for $\lambda = 794.5$ nm, $n_1 = 1.45$, $n_2 = 1$, $\alpha_c = 43.6^o$

Assuming $I_z / I_o = \sim\exp(-z/d)$, then, if d gets very large, the evanescent wave decays very slowly with distance. What are the energetics of an evanescent wave? Energy is stored in the radial standing wave, not transmitted radially. However, it moves at the velocity of light along the outside of the photon core. A standing wave absorbs energy until it reaches equilibrium with its source. At that point, it reflects the incident wave (at the core surface) without absorbing more energy. This is the same thing that happens with the EM radiation field about bound atomic electrons. They radiate net energy, which remains bound to the electron, until equilibrium is established. Net radiation from the electron goes to zero when the electron reabsorbs as much EM energy as it emits. Similarly, the evanescent wave is in equilibrium with the body of a photon, or of any elementary particle. As an example of the effect of critical angle, Fig. 2 indicates the great increase in depth of photon energy into the evanescent wave at the critical α_c from the surface for an abrupt change in refractive index.

At the critical angle, $\theta_c = \alpha_c$ and $\sin\alpha_c = n_2/n_1 = n$, and Eq. 7 implies that d blows up. It can't really blow up, since that would imply an infinite, or zero, energy. Therefore, the model must be only an approximation that fails at α_c. Nevertheless, this has interesting implications. If we look at the intensity of the evanescent wave at α_c (Eqs. 8, 9, and 10 below – where the I's are the evanescent wave intensities relative to the incident wave I_o), then we see that, at the critical angle, I_y is always 4. ($\cos^2\theta = 1 - \sin^2\theta = 1 - n^2$ at α_c.).

$$I_x = 4 \cos^2\theta (\sin^2\theta - n^2)/ (1 - n^2) [(1 + n^2) \sin^2\theta - n^2] \quad 8)$$

$$I_y = 4 \cos^2\theta / (1 - n^2) \quad 9)$$

$$I_z = 4 \cos^2\theta \sin^2\theta / (1 - n^2)[(1 + n^2) \sin^2\theta - n^2] \quad 10)$$

For our photonic-soliton model, $\alpha_c = \sim\pi/2$ and $n_2 =\sim n_1 = n = 1$. Therefore, $I_x = 0$ (for the direction of photon propogation), and $I_z = 4$. What does this mean? Since the values of I_y and I_z are the same, we could assume cylindrical symmetry that fits with our model. This might not be thought necessary in a model that creates its own light pipe with an electric field that is always pointing outward. However, in the finite-radius photon model, there is a tangential (longitudinal) component to the field. This would create the equivalent of the I_y component of a planar evanescent wave.

Because the evanescent wave of our model is equivalent to being composed on a cylindrical - rather than a planar - surface, its intensity decay from the surface (at the critical angle) is 1/r, rather than constant (at the critical angle). Its electric-field vector has a tangential and radial component, and it moves (at velocity c) in a spiral direction about the photon axis. Radially, it is still a standing wave (no energy transfer outward from the photon core). Longitudinally, it is also a standing wave. However, in this latter case it is a standing wave (or group of them) moving collectively at the speed of light. In both directions (radially and along the axis of propagation), the spread in wave energy with time is prevented by the distortion of space by the standing-wave fields of the photon.

6. IMPLICATIONS

The presented photon models[32, 33] give a slight nonlinearity to their environment from the distortion of space by the photon fields. Since this nonlinearity is small outside of the photon 'core', the evanescent wave resulting from the interaction of its wave energy with its environment is extensive and the energy of a photon is distributed over a volume large relative to its core. Furthermore, the presence of another photon will "eliminate" the lightpipe effect between them (equivalent to an optical coupler).[34] This refractive index confinement of a photon is like a surface tension and, as for water droplets when close enough, it will draw them together. The photons may not lose their identity, they merely lose the shallow barrier (the refractive-index variation) between them. Unless, the photons are highly collinear, they cross over one another and separate again with almost no change in energy or direction. It is this refractive index gradient that separates the particle nature from the wave nature of light.

The combination of many photons into a wavefront (and back) is equivalent to the collection of raindrops by the surface of the ocean. This explains the property of light from a distant star. Nearly-collinear photons form a wave assembly from the individual photons emitted from the star's atoms and, at great distance across the universe, they decompose into photons again (statistically) as the local energy density drops below a critical level). Are the photons that separate out the same ones that combined earlier? That question, while theoretically interesting, has the same answer as the question of being able to identify individual photons if they didn't combine into a wave assembly. Photons are bosons. Bosons are identical particles; they don't maintain their identity as individuals or as part of a collective. However, the identity problem goes beyond the boson explanation.

The parts of many bosons are mix and match (as for deuterons). A photon, like a wave on the ocean, does not carry any (material) constituent parts along with it. It is a pattern. The fundamental parts are identifiable as wave frequencies, not water molecules. These wave parts are also interchangeable (within limits). However, the totality is greater than the sum of its parts. A photon of a given energy may have a significantly different distribution of constituent frequencies. While a given photon, "precipitating" from a wave assembly, might have a major difference in frequency distribution from the photons that went into the assembly, the totality of photons coming out will reflect the distribution going in - such as the reproduction of characteristic spectral lines.

7. SUMMARY

The introduction of a non-linearity into Maxwell's equations explains the formation and nature of photons as solitons. Physical mechanisms for such non-linearity, such as the total internal reflection of light pipes and the graded-refractive-index optical lenses – based on EM-field-energy-induced distortion of space, have been identified and applied to this concept. This approach is compatible with both relativistic and quantum physics. The result, as a surface-tension-like term, explains the shape integrity of photons over long travel times and distances. It also provides a basis for the reversible transition between photons and plane waves. Thus, while for most applications the non-interference of waves and superposition principles apply, the interaction of photons with themselves and with other photons, under special circumstances, must be considered.

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APPENDIX A: ANGULAR MOMENTUM OF A PHOTON[35]

This appendix addresses the unusual characteristic of photons that requires an angular momentum of one (one times $\hbar$) regardless of the photon energy. Is there a mechanism that can provide the common factor for all photons? This appendix seeks to present that mechanism.

Assume that:

- the angular momentum of a photon, $\mathbf{L}_{\square}$, is real, and not just an accounting term (quantum number) for photons.
- the photon EM fields have an effective mass, "M_{EM}," associated with their field energy.
- the fields (or at least some portion of them) and thus the effective mass are rotating about the velocity vector.
- at some radius[a], r_γ, the rotating M_{EM} has an angular velocity limited by the speed of light, c, (and no rotational portion of the photon exists beyond this radius).
- the resulting photon frequency is $\nu_\gamma = c / 2\pi\, r_\gamma$. (and, since $\nu = c/\lambda$, $\mathbf{r_\gamma = \lambda_\gamma / 2\pi}$).
- $\mathbf{L}_\gamma = M_{EM}\, c\, r_\gamma$. This further assumes that essentially all of the "effective" mass (relativistic at r_γ) is cylindrically located at the extreme radius, r_γ.
- $E_\gamma = M_{EM}\, c^2 = h\nu_\gamma$.[b, 36]

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[a] The existence of a rotating effective mass requires the presence of a confining or restoring force. If the photon cannot generate this within itself (and in a mass-balanced manner), or if the structure of space cannot provide it, then we must examine the nature of electric and magnetic fields more closely. The proper approach is to recognize that field is the gradient of a potential. Thus, there are two off-axis, equal-and-opposite potentials creating each field within the photon. These opposing potentials create effective masses that are periodically spaced and relativistically 'adjusted' to create the resonant vortex-like structure in time called a photon.

Then, the last three bullets combine to yield: $E_\gamma = M_{EM}\, c^2 = (M_{EM}\, c\, r_\gamma)\, c / r_\gamma = L_\gamma c / r_\gamma$; and $E_\gamma = h\nu_\gamma = hc / \lambda_\gamma = hc / 2\pi r_\gamma = \hbar\, c / r_\gamma$; thus, $L_\gamma c / r_\gamma = \hbar\, c / r_\gamma$ and

$L_\gamma = \hbar$ <u>regardless of the photon energy</u>.

The key here is that, if the assumptions and derivation are correct[c], the dimensions of any emitted photon (length and width) are orders of magnitude greater than that of its (atomic) source. There may be several ways of resolving the problem that this difference in sizes produces. The simplest could be to recognize that the anomalous dispersion observed in macroscopic media would be accentuated at the atomic scale and thus the resultant extremely high refractive index would act as a powerful concentrating lens to focus the photon onto the resonant atom.

APPENDIX B: CRITICAL POWER DENSITY FOR SELF-FOCUSING OF LIGHT

For laser light in air (from below Eq. 2): the nonlinear coefficient $n_2 \approx 4\times10^{-23}$ m^2/W => $P_{cr} = 2.4x10^9 W/m^2$.

Can this be related to effects within a photon? [Assume a uniform energy density for a photon consisting of a single cycle.]

A 1 ev photon => λ = ~800 nm and radius $r = \lambda / 2\pi$ (from Appendix A) =>
Photon area = $\pi r^2 = \pi(800nm/2\pi)^2$ = ~5 e-14 m^2
Time per cycle = length/c = 800nm/3e8m/s = ~2.6e-15 s/cycle
1eV = 1.6e-19 J => Photon power (if 1 cycle) = 1.6E-19 J/2.6e-15s = ~6 e-5W/cycle
Power density = 6e-5W/ 5 e-14 m2 = **~1.2GW**/m^2 vs. P_{cr} (for air) ≈ **2.4 GW/m^2**

Thus, even if all of the photon energy were concentrated into a single cycle, the power density would not quite be adequate for self focusing in air. While photons may be millions of cycles long and therefore be much less likely to have the necessary energy densities, they do not have uniform energy densities and the high-field regions could perhaps achieve the levels necessary for self focusing of the photons.

A problem with this above analysis is that it may pertain to the non-linearities introduced in the ionization of the atoms in air and not in the distortion of space that would be needed for photonic 'integrity' in space. It affects a light beam and therefore demonstrates a macroscopic effect on a macroscopic-scale structure. On the other hand, it also demonstrates the focusing effect that would be created by the intense local fields within a photon and would operate on those same fields or on those of other photons. The known local fields are electric and magnetic; however, the potential energy in the photon and in the standing waves involved in interference effects[37] can also be a possible source of distortion of space.[38]

This non-linear 'local-field on local-field' interaction perhaps resolves the issue of non-interaction of waves, with its associated superposition property, versus the observed interaction of coherent light beams and of collinear, proximate, properly-phased, photons.

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[b] The combining of relativistic angular and linear momenta and energies in this development is deliberately ambiguous. Perhaps not all of the effective mass of a photon is contained in the relativistic rotational fields. However, the photon energy cannot exceed $M_{EM}c^2$, which is assumed here to be the rotational component. If so, the conclusions that follow should be valid.

Since the effective 'mass' of a photon is EM, not 'ponderous', it is able to propagate at the speed of light and not be relativistically enhanced (or infinite). The energy of a photon, as $E_\gamma = h\nu_\gamma$, includes both of its energies: kinetic (linear and rotational) and potential (EM field and effective mass). At the speed of light $v_\parallel = v_\perp = c$.

[c] Transfer of linear momentum from the photon is to the atom as a whole, since the electron is being exposed to this momentum through many revolutions. As a consequence, the photon's linear momentum that <u>could</u> be transferred to the electron, as angular momentum, averages to zero. The net transfer of the photon's linear momentum is thus to the electron <u>plus</u> the nucleus (via the coulomb field).

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