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Do We Manipulate Photons or Diffractive EM Waves to Generate Structured Light?

ChandraSekhar Roychoudhuri

Abstract

In the domain of light emissions, quantum mechanics has been an immensely successful guiding tool for us. In the propagation of light and optical instrument design, Huygens-Fresnel diffraction integral (HFDI) (or its advanced versions) and Maxwell's wave equation are continuing to be the essential guiding tools for optical scientists and engineers. In fact, most branches of optical science and engineering, like optical instrument design, image processing, Fourier optics, Holography, etc., cannot exist without using the foundational postulates behind the Huygens-Fresnel diffraction integral. Further, the field of structured light is also growing where phases and the state of polarizations are manipulated usually with suitable classical macro-devices to create wave fronts that restructured through light-matter interactions through these devices. Mathematical modeling of generating such complex wave fronts generally follows classical concepts and classical macro tools of physical optics. Some of these complex light beams can impart mechanical angular momentum and spin-like properties to material particles inserted inside these structured beams because of their electromagnetic dipolar properties and/or structural anisotropy. Does that mean these newly structured beams have acquired new quantum properties without being generated through quantum devices and quantum transitions? In this chapter, we bridge the classical and quantum formalism by defining a hybrid photon (HP). HP is a quantum of energy, $h\nu$, at the initial moment of emission. It then immediately evolves into a classical time-finite wave packet, still transporting the original energy, $h\nu$, with a classical carrier frequency ν (oscillation of the E-vector). This chapter will raise enquiring questions whether all these observed "quantum-like" behaviors are manifestations of the joint properties of interacting material particles with classical EM waves or are causal implications of the existence of propagation of "indivisible light quanta" with exotic properties like spin, angular momentum, etc.

Keywords: structured light, hybrid photon, non-interaction of light (NIW), Huygens principle, photoelectric effect, semiclassical model

1. Introduction

Structured light is a matured applied field of study. It has been steadily inventing many new tools and techniques to manipulate and study, from nanoparticles to molecules to atoms. Other chapters of this book have described these developments.

The purpose of this chapter is to promote the development of out-of-box enquiring questions in physics leveraging the topic of structured light. It is a complex thinking and analytical process to describe a physical phenomenon simply based upon reproducible experimental data. This is because experimental data generation requires detector and deductee to undergo some physical transformation in their relevant parameters after exchanging some energy guided by some allowed force of interaction between them. Since we cannot directly observe the details of the physical interaction process, we cannot be certain from the properties of the measured data as to which property belongs to the detector and which belongs to the deductee. We have not been addressing this important enquiring question explicitly in physics. The field of structured light is a good test optical phenomenon to explore this enquiring question.

Beams of structured light are generated by using classical optical components and the analytical tools of classical optics, which are Maxwell's wave equation and Huygens-Fresnel diffraction integral (or its advanced versions). Then, the concept of "indivisible light quanta" must have come from Einstein's paper on photoelectric effect [1]. However, Lamb et al. [2–4] have clearly shown that the use of semiclassical model, classical light, and quantized atoms yields a much more causal and self-consistent model for light-matter interactions. This chapter, therefore, strengthens this concept behind the semiclassical model by underscoring some neglected but fundamental nature of light from two fundamental angles—"We never see light" (Section 2) and "Light does not see light" (Section 3). Then we discuss the consequences of assigning detector's intrinsic quantum properties to the energy donating classical and Maxwellian light waves as we do for the photoelectric effect (Section 4). Next, in Section 5, we discuss the consequences of ignoring interaction process visualization, which guides us to accept the necessity of introducing the concept of hybrid photon model. Hybrid photon model eliminates the need for accepting the postulate of "wave-particle duality." This duality postulate actually originated in late 1600s during debate between Newton ("corpuscular") and Huygens ("secondary wavelets"), and they agreed that their debate arose out of their ignorance about the deeper structure of light. Unfortunately, founders of mathematical formalism of quantum have promoted the "wave-particle duality" as the new confirmed knowledge. In reality, this postulate should energize us to keep exploring the deeper issues behind quantized emission and absorption of light and classical propagation properties of light. The last section on discussion underscores that we should always try to reevaluate working theories beyond its prevailing successes so we can advance our current understanding. Then discover new phenomena and then invent new tools and technologies.

2. We never "see" light

We only perceive or measure the physical transformation induced by light energy in material bodies, which have their own unique response characteristics due to their unique response properties to light. Therefore, assigning any new physical property, to a physical entity under study, should be done carefully to ascertain that the observed (measured) property is not that of the detecting entity. This is especially important for light. We always infer the incidence (presence) of light after observing (or perceiving) some physical transformation in the detecting element. It could take place through a wide variety of already known phenomena like photoelectric effect, photochemical effect, photothermal effect, photo-acoustic effect, etc. In all such cases, a finite amount of energy from the EM wave is absorbed by the detecting element to undergo some quantitative physical

transformation, which becomes our data. If the detecting element is inherently quantum mechanical in nature, then the amount of energy $\Delta E_{mn} = h\nu_{mn}$ is absorbed by the detector out of the EM waves and will correspond to the specific quantum transition. However, all light-matter interactions are frequency dependent since all materials are individual dipolar atoms and molecules or their assemblies in solid or liquid states. X-rays and γ -rays do not interact with quantum mechanical Si-photoelectric detectors or classical photothermal detectors. We need appropriate materials where X-rays can stimulate the electrons in the inner shells of atoms and γ -rays can stimulate the nuclear energy levels at the core of atoms.

The strength of the *evidence-based science* lies with the corroboration of evidences with a suitable mathematical model. The model must help us to *visualize the interaction processes* that give rise to measurable data (evidence). This is the foundation of our causal approach to explore the laws of nature. This causal approach allows us to keep refining both the measurements and the modeling as we keep integrating diverse observations into a broader and well-validated theory. This is how our scientific advances have been continuing for centuries. Therefore, let us explore the physical process steps behind the generic detection/interaction processes (Ch. 12, in [5]):

1. All measured *data* are some quantitative *physical transformations* in some detector element induced by a deductee-element.
2. All physical transformations must be triggered by some physical interaction (stimulation) process, followed by energy exchange between the detector and the deductee. Discouraging the visualization of such invisible interaction processes has been the key mystifying reason behind our “working” theories, whose purpose has been limited to validate only the measurable data.
3. All energy exchange must be guided (allowed) by some specific and allowed force of interaction existing between the detector and the deductee. Our continuing failure to understand the origin of all forces and unify them is the key bottlenecks behind the causal advancement in modern physics.
4. All forces, short or long range, have finite physical ranges. Therefore, all interactions are fundamentally “local” or physical range dependent.

Thus, we cannot generate observable (measurable) data without some physical transformation in an interactant (detector) whose intrinsic physical properties dictate its specific response characteristics to one or the other force to participate in any interaction, leading to a specified amount of energy exchange leading to the observable transformation. Obviously, recordable data generation is not possible if the interactants are physically beyond the range of their mutual force of interaction. Causal physics require that the interactants recognize each other through their mutually allowed force of interaction. Without a direct hit of a well-collimated laser beam within the active area of a detector of a power meter, we cannot ascertain the energy of the laser beam. Interaction-free data generation cannot take place in the causal world. “Spooky action at a distance” is an unfortunate cultural phenomenon that wants to mystify physics. Nature is systematically causal. That is why our “cause-effect” inter-relating causal mathematical equations, through centuries, have remained the key guiding tool to explore nature. Nature is not mystical.

Measured and analyzed “elliptical polarization” does not imply that the resultant electrical vector of the light beam is rotating circularly as the composite light beam (two collinear, phase-steady, and orthogonally polarized beams with 90° relative

phase delay) is propagating with the resultant E-vector helically rotating around the Poynting vector. In this assumed and imaginary model, the energy of the composite light beam would have been also oscillating due to time-varying resultant amplitude of the E-vector. This would have implied that nature is violating the law of conservation of energy. Fortunately, in this case, our mathematics has been guiding us along the correct and causal path. Jones' matrix has been constructed to find the final energy of a composite light beam as the sum of the two separate energies contained in each of the two orthogonal polarization. The energy in each of the two orthogonal components is the square modulus of the sum of the X-component amplitudes and the Y-component amplitudes, carried out separately. Interested readers should consult Ch. 9 on polarization phenomenon in Ref. [5]. The chapter underscores, using elementary mathematics and the bulk dipolar polarizability χ , that without explicitly inserting this light-matter interaction parameter, the understanding of the ongoing physical process becomes difficult and confusing.

3. Light does not “see” light

The light wave amplitudes cross propagate and co-propagate through each other in the absence of interacting materials. This is why experimental astrophysics can image and analyze individual distant galaxies or stars even though the light selected by a telescope has crossed through the light beams of innumerable galaxies and/or stars. This is the same physical reason why we can see (recognize) each other from a distance, even though the scattered light beams from innumerable other faces and objects are crossing through each other. Alhazen experimentally validated this non-interaction of waves, or NIW, about a thousand years ago [6]. This brilliantly simple experiment is sketched in **Figure 1**.

Alhazen generated the inverted images of a set of candles through a pinhole camera. He found that blocking anyone or more candles does not create any changes in the images of the other candles. Inverted images clearly underscored that the light from all the candles were crossing through each other at the tiny pinhole. Alhazen underscored that he did not understand the deeper nature of light. He was humble.

Much later, Huygens formally postulated NIW in his 1690 book [7] when he presented his principle of wave propagation visualizing the process as the perpetual generation of innumerable secondary wavelets out of every point on the wave front. This also implied that the space is an energetic tension field to be able to support the perpetual wavelet generation and propagation (Ch. 11 in [5, 8–10]). Huygens explicitly articulated non-interaction of waves (**Figure 2**):

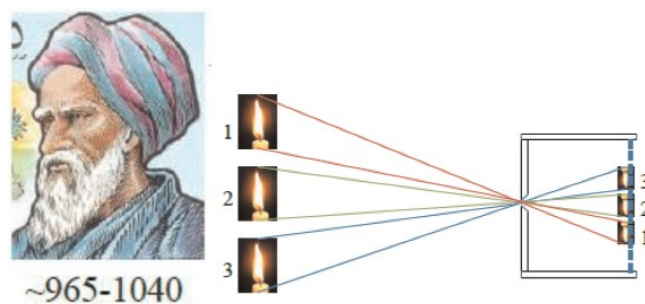


Figure 1.

Alhazen's ancient experiment forced him to conclude that light does not interact with light. We still are struggling with the wave-particle duality [5].

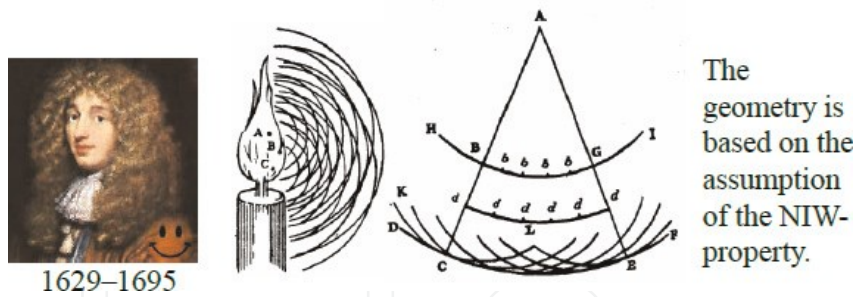


Figure 2. Huygens' visualization of the wave propagation process through indefinite number of secondary wavelets, diffractively evolving through each other, "unperturbed by each other, cross one another without hindering one another in any way" [7]. This is non-interaction of waves (NIW) [5].

For I do not find that any one has yet given a probable explanation of the first and most notable phenomena of light, namelyhow visible rays, coming from an infinitude of diverse places, cross one another without hindering one another in any way. From p. 2 in [7].

In p. 4 of his 1690 book, Huygens clearly anticipated the existence of a universal tension field, like pressure tension of air, but without any material particles, which facilitates the perpetual propagation of waves, as sound does in the air.

In 1817, Fresnel gave the mathematical structure to the Huygens principle in which NIW was automatically built in Huygens-Fresnel diffraction integral (HFDI). The integral literally propagates innumerable spherical wavelets that keep evolving through each other while diffractively evolving as co-propagating and cross propagating through each other [11]. $E(P_{\text{det.}})$ is the resultant amplitude:

$$E(P_{\text{det.}}) = \frac{-i}{\lambda} \iint_{\Sigma} U(P_{\text{source.}}) \frac{\exp(ikr_{s \rightarrow d})}{r_{s \rightarrow d}} \cos \theta \, ds \quad (1)$$

Notice that the above HFDI propagates all spherical wave fronts out of every source point to the detector plane, irrespective of its distance $r_{s \rightarrow d}$ from the source plane. These amplitude wave fronts evolve through each other completely independent of each other irrespective of how far they are propagating. In other words, the HFDI has automatically incorporated the NIW property of the waves.

After Maxwell's wave equation was developed (1867), it was found that HFDI is a solution to Helmholtz equation, a time-independent form of Maxwell's generalized wave equation. Maxwell's wave equation accepts any linear superposition of wave amplitudes as its solution. The physical meaning, in the context of NIW, is that wave properties of the individual propagating wave remain unaltered as they cross propagate and/or co-propagate through each other. In other words, light does not interfere with light in the absence of interacting material, which we have logically derived in section on "We do not see light," except through the "eyes" of interacting materials.

It is then obvious that the generation and spatial superposition of multiple complex light wave fronts will continue to diffractively evolve and co-propagate as independent beams. However, when they finally interact with some materials, the energy transfer to any interacting material will be the square modulus of the sum of the finally evolved "local" wave front incident on the material. If the material is an anisotropic polarized detector, it will respond to the square modulus of the sum of all the amplitude components projected on to its polarization axis. If it is a very small-suspended anisotropic particle and the state of polarization is rotating slowly

in time and if the inertia permits, the anisotropic particle will rotate with the rotating polarizing field since most materials strongly respond to the resultant E-vector. However, the original set of multiple co-propagating wave amplitudes does not reorganize themselves into a single composite wave front because of the overriding NIW property of waves.

4. Consequences of assigning detector's properties to the energy donating entity

Can we logically confirm that the emission of a single photoelectron proves the existence of light as “indivisible light quanta”? We should recognize that the individual “clicks,” which we register in photon counting electronics, are actually a brief current pulse, probably, consisting of billions of amplified electrons. It may not be difficult to validate that this highly amplified current pulse has been originally triggered by a single photoelectron. However, releasing a quantum-mechanically bound electron does not necessarily require the presence of a quantum photon of energy $h\nu_{mn} = \Delta E_{mn}$. The quantum cupful of energy ΔE_{mn} can be acquired by a quantum entity from almost any source of energy under appropriate condition of interactions. Ancient humans used to create fire by using sparks generated by fast mechanical collisions between a pair of stones. They had no idea that they were inducing quantum transitions in the molecules of the stones while transferring the classical kinetic energy out of their moving hands! This is why the quantum formalism does not require any quantum postulate that energy providers to induce quantum transitions have to have energy-matching quantum states. In fact, Boltzmann's classical statistical thermal population density formula has been co-opted by the quantum mechanics. Un-quantized thermal energy can be absorbed during thermal collisions by quantum entities to fill up their quantum cups while accepting only that much of energy that fills up their quantum cups [12].

Toward the end of his life, Einstein, the originator of the concept of “indivisible light quanta,” clearly stated that even after “50 years of brooding,” he still did not understand “what are light quanta” [13]. Author was inspired by Einstein's doubt and delved into exploring the nature of light for many decades [14–16].

In the section on “We do not see light,” we have underscored that detectors see light based on their internal physical properties. This is why visual observation of classical interferometry never pointed us to the quantumness of light. In fact, Newton was the first inventor of two-beam interferometry. He measured the radius of curvature of his plano-convex lens by putting it on a flat mirror and shining light from the top. Note that the debate over wave-particle duality started long time ago during late 1600 by Newton (“corpuscular”) and Huygens (“wavelet”). Nevertheless, they recognized that their debate represented their deeper ignorance about the fundamental nature of light. We still have not fully understood the deeper nature of light. Therefore, we should not make the “wave-particle duality” as our confirmed new knowledge. We should humbly continue to explore the deeper nature of light. That is the purpose of this chapter.

The first solid reasoning behind theorizing emission and absorption of light from materials in discrete energy packets was presented by Planck in 1900 to match analytically the already measured blackbody radiation curve. However, Planck maintained his understanding that the quantum processes are real only during the instants of emission and absorption. After emission, the EM energy packet immediately evolves into Huygens' diffractive wavelets. This is how the diffractive radiation achieves the state of equilibrium energy density within the enclosed blackbody cavity [14].

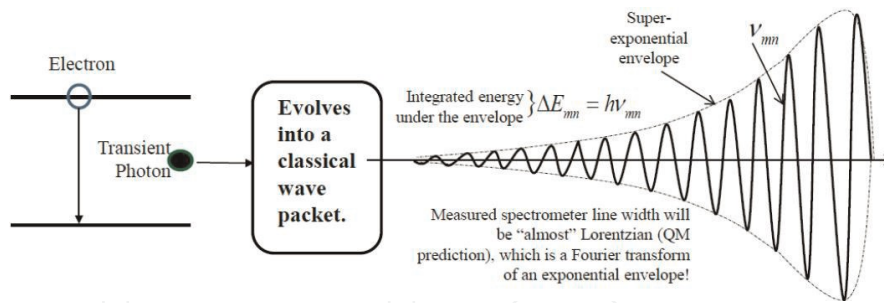


Figure 3. Transient quantum photon, immediately after emission from an atom, evolves into a diffractively spreading classical wave packet with quasi-exponential temporal envelope. All the quantum predictions are preserved. The total energy carried by the wave packet is $\Delta E_{mn} = h\nu_{mn}$ with the unique carrier frequency ν_{mn} . The Fourier transform of the quasi-exponential envelope gives a spectral line width close to Lorentzian, which is the normal spectral line width of spontaneous emissions.

However, during very late 1800, emission of photoelectrons from photocathode showed some uniqueness. Below some optical frequency, there was no photoelectron emission in spite of increasing the radiation density. Young Einstein correctly surmised that there is some “quantumness” hidden behind this frequency dependence and no electron emission after a cutoff frequency. Unfortunately, Einstein assigned this quantumness to light, instead of to the electrons. However, we now know that electrons are always bound quantum mechanically in all materials, even when they are bound collectively in quantum energy bands in solid state [15]. Here, we must recognize that Bohr atom was formulated in 1913 and Quantum Mechanics was formulated in 1925, many years after the 1905 paper by Einstein on the photoelectric effect. However, had Einstein correctly assigned the quantumness, observed in photoelectric effect, to electrons instead of to light, he would have been able to formulate quantum mechanics the Einsteinian way some 20 years earlier.

We believe that Planck’s view of light is correct. EM waves are classical waves, solutions of Maxwell’s equation, and propagates following Huygens secondary wavelets. In fact, Refs. [2–4] have derived the equation for photoelectric emission using the semiclassical method. Here, we present a heuristic approach to present the hybrid photon model that is a quantum at the moment of emission but a classical wave packet with a quasi-exponential temporal envelope. The total energy under the envelope corresponds to the QM predictions: (i) total energy of the wave packet is $\Delta E_{mn} = h\nu_{mn}$, and (ii) the quasi-exponential envelope assures the observed spontaneous emission line width as very close to Lorentzian, the Fourier transform of the amplitude envelope of the light pulse (see Figure 3).

5. Consequences of ignoring interaction process visualization: the necessity of the hybrid photon model

Let us first recognize that Einstein’s photoelectric equation is an energy-balancing equation to match the observed data. This is measurable data modeling epistemology (MDM-E). We need to incorporate interaction process mapping epistemology (IPM-E) over and above MDM-E. Einstein’s formulation did not embody light-matter interaction process, as we have underscored in the section on “Light does not see light.” For accurate semiclassical derivation of the photoelectric effect, the readers should consult the following references [2–4]. We will present here only a heuristic derivation of Einstein’s energy-balancing photoelectric equation, but starting from light-matter amplitude-amplitude stimulation, the E-vector of light

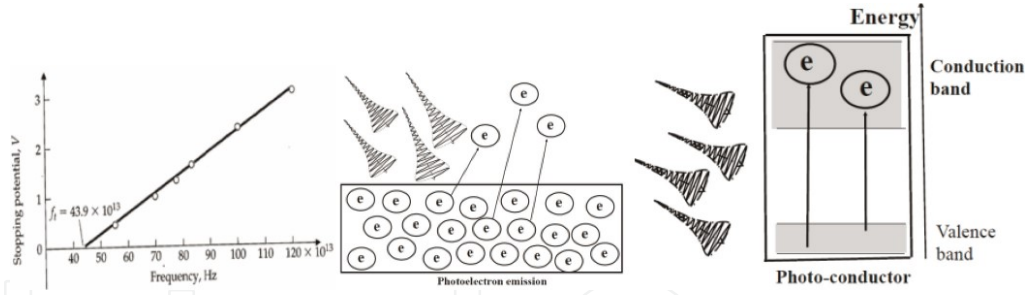


Figure 4. Left diagram: Emission of photoelectrons from a given material stops at a fixed specific frequency [16]. Middle diagram: Photoelectron emission from photocathode. Right diagram: Photoelectron transfer from valence to conduction band.

stimulating the dipoles as $\chi(\nu_q)E(\nu_q)$, containing the bound electrons, where $\chi(\nu_q)$ is the polarizability, or the light-matter *interaction parameter*. Since semiclassical thermal radiation consists of random wave groups emitted spontaneously with random phases, the total dipolar amplitude-amplitude stimulation of a bound electron can be expressed as

$$\Psi = \sum_q \psi_q = \sum_q \chi(\nu_q)E(\nu_q) \quad (2)$$

The bound electron system must absorb the necessary amount of quantum-cup-filling energy, before the electron can be released to the conduction band or become a free-space electron. This energy exchange is a quadratic process:

$$|\Psi|^2 = \left| \sum_q \chi(\nu_q)E(\nu_q) \right|^2 \propto h\nu_q \quad (3)$$

For any quantum system, we must take the ensemble average. A single event (data point), as in Eq. (3), is never sufficient to verify a theory:

$$\langle |\Psi|^2 \rangle = \left\langle \left| \sum_q \chi(\nu_q)E(\nu_q) \right|^2 \right\rangle \Leftrightarrow \langle h\nu_q \rangle = \langle \phi_{work\ fn.} + (1/2)m\mathbf{v}_{el.}^2 \rangle \quad (4)$$

In the right segment of Eq. (4), we have “recovered” Einstein’s photoelectric energy-balancing equation out of dipole amplitude stimulations due to multitudes of waves. The left curve in **Figure 4** represents the photoelectric current [15]. Waves only fill up the quantum cups with the necessary energy if the dipoles are resonant to the frequency ν of the incident waves.

6. Discussions

Visible light is always generated through orbital quantum electron transition processes in atoms. We have presented our *hybrid photon* model where light is released as a quantum energy packet, $h\nu$, as required by quantum formalism. Then we posit that immediately after the release of the $h\nu$ packet, it evolves into a classical wave packet and follows Maxwell’s wave equation and Huygens-Fresnel diffraction integral. We generate structured light using classical optical components and classical optical analytical tools. The possibility of introducing any quantumness in classical light during this process is difficult to imagine. The author is suggesting that we should explore the physical response properties of the material particles that

are inserted into the structured beams and try to visualize the light-matter dipolar interaction processes. This would be a better system-engineering approach to understand different optical phenomena [17, 18].

The key point of the author is that our unquestioned acceptance of the wave-particle duality has been hindering our deeper enquiry into the ultimate nature of light. The author has been attempting to inspire this process over decades by organizing special publications [13] and special conference series at SPIE from 2005 to 2015 [19], publishing experimental papers [20], and writing books [5, 21]. During this long arduous process, the author has recognized that Huygens principle (HP) of “secondary wavelets” has deeper enduring value for physics. HP requires space to be a physical tension field, a complex tension field or CTF, to facilitate the perpetual and well-defined velocity of light. CTF possesses the necessary characteristic properties, which facilitates the perpetual velocity of light, $c = (\epsilon_0^{-1}/\mu_0)^{1/2}$, through the entire cosmic space. CTF must also possess other physical attributes that we have not been exploring actively. Thus, CTF could have serious implications in guiding us to reorganize our investigations to fulfill Einstein’s dream of defining a unified field. CTF could be behind the emergence of both the EM waves and the particles as different kinds of oscillations of the same CTF, which holds 100% of the energy of our cosmic system (Ch. 11 in [5, 8, 17]).

Optical physicists should note that the two major “successful theories” for gravity, those of Newton and of Einstein, have been unable to explain the velocity distribution curves measured for a couple hundred galaxies. Therefore, theoretical physicists have proposed unnecessary postulates of the existence of Dark Matter and Dark Energy, neither of whose existence has been confirmed over the last

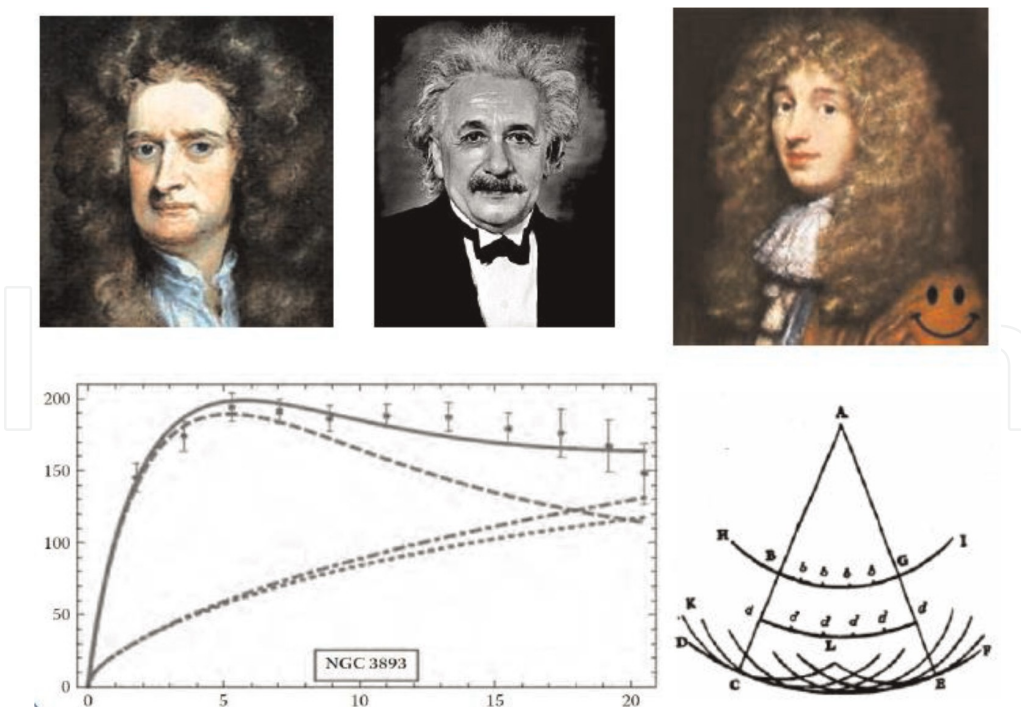


Figure 5.
 Left-bottom curves [22]: Gravity theories of Newton and Einstein cannot match the measured velocity distribution of stars in one particular galaxy. This phenomenon turns out to be true for a couple of hundreds of galaxies. These two theories are very accurate for our solar system, but not good at the galactic scale. Bottom right: Huygens 1690 postulate of secondary wavelets [7], framed into Huygens-Fresnel diffraction integral, is still the core guiding analytical equation for the broad field of physical optics, including generating structured light.

several decades. These theories are definitely not wrong. Those who have been successfully launching and manipulating artificial satellites in our solar system rarely need to go beyond the mechanics of Newtonian gravity. Einstein's gravity correctly predicts the precession of the perihelion of Mercury. However, these two theories must be limited in capability to model gravity in the galactic scale (**Figure 5**).

In contrast, in spite of subtle mathematical issues behind the Huygens postulate [23] of secondary wavelets, it remains the key foundational guide to propagate light through free space and non-interacting materials. To model light-matter interaction, Maxwell's equations have remained quite successful. In the history of physics, all theories eventually yield to new and better theories. Our attempts should be directed along these lines. We should not try to keep promoting the general validity of all working theories.

Optical physicists should explore the *deeper enduring values* behind the Huygens principle and find the limits of its application in different optical phenomena to advance further optical physics. Studies in optical phenomena have been guiding major advances in physics since ancient times. Starting from the 1600s to 1800s, advancements in physics were predominantly pioneered by scientists studying the broad field of optical sciences. However, starting from the early 1900s, this pioneering role has been shifted from guiding fundamental physics to finding only novel technical applications of optics. It is time for optical physicists to pick up more proactive roles in guiding the development of fundamental physics [24].


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