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125 Years of Radiative Transfer: Enduring Triumphs and Persisting Misconceptions

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Abstract. The evolution of phenomenological and microphysical approaches to radiative transfer (RT) and directional radiometry (DR) is outlined. The importance of the seminal 1887 paper by Eugen von Lommel is discussed. It is shown that owing to recent advances, the disciplines of RT and DR have finally become legitimate branches of statistical electromagnetics.

Keywords: Radiative transfer, Directional radiometry, Electromagnetics, Polarization, Maxwell equations.
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INTRODUCTION

Although the radiative transfer equation (RTE) originated in the paper by Eugen von Lommel published 125 years ago [1], the heuristic conception of the radiative transfer theory (RTT) can be traced back to much earlier publications including those by great scientists such as Galileo, Kepler, and Newton. Many other prominent scientists contributed, either explicitly or implicitly, to the development of photometry and the RTT before and after Lommel (Fig. 1). Despite the extensive use of the RTT and directional radiometry (DR) in numerous areas of applied science and engineering, both disciplines had remained thoroughly phenomenological until quite recently and their physical basis had remained uncertain. This had led to the widespread characterization of the RTT by physicists as a semi-empirical theory lacking solid physical foundation. This situation has finally changed owing to the emergence of a new microphysical paradigm based on the direct and self-consistent use of the Maxwell equations. This paradigm solves the long-standing problem of establishing the fundamental physical link between the RTT and phenomenological DR on one hand and the Maxwell equations on the other. It also establishes the link between the RTT and the spectacular effect of weak localization of electromagnetic waves in particulate media, otherwise known as coherent backscattering (CB). As a consequence, it has become possible to clarify the physical content of measurements with directional radiometers and their relation to the solution of the RTE.

In this paper I briefly outline the history of the phenomenological and microphysical approaches to the RTT and DR from the time of Johannes Kepler until now. Given space limitations, this outline is necessarily constrained and is intended primarily to trace the evolution of the conceptual basis of these important disciplines from being purely phenomenological to becoming firmly rooted in electromagnetic theory.

PHENOMENOLOGY

A thorough account of the early history of photometry was provided by D. L. DiLaura in [2]. He attributes the culmination of medieval optics to Johannes Kepler's *Ad Vitellionem Paralipomena* [3], which contains one of the most fundamental elements of photometry: the attenuation of light with the inverse square of distance. However, establishing photometry as a scientific discipline was the result of pioneering studies by Pierre Bouguer and Johann Lambert. Bouguer's *Essai d'Optique* [4] was published in 1729, while its thorough augmentation, *Traité d'Optique* [5], appeared posthumously in 1760 (Fig. 2). Bouguer's research was mostly experimental and based on several ingeniously designed photometric instruments. In particular, in *Essai d'Optique* he describes the use of the inverse-square law to derive the ratio of luminous intensities of two light sources and discovers the famous exponential attenuation law (sometimes incorrectly attributed to Lambert) by studying the diminution of light as it passes through translucent media (Fig. 3a). In his *Photometria* [6] published in 1760 (Fig. 2), Lambert develops the mathematical foundation of radiometry by introducing specific definitions of photometric quantities and a unified set of photometric principles. He was the first to extensively use mathematics, including calculus, to interpret experimental results

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as a way of developing appropriate mathematical models and physical theories. The impact of Bouger's and Lambert's work was so profound that even now much of illumination engineering is based on their treatises. Perhaps the only notable augmentation was the incorporation of the solution concentration into the Bouguer's exponential attenuation law by August Beer [7].

A major contribution by Eugen von Lommel was to consider the amount of radiant energy crossing an imaginary rather than an actual physical surface element. This allowed him to conceptualize the directional flow of radiant energy through space and derive the integral form of the RTE as a way of solving the problem of the diffusion of light through a turbid medium composed of isotropically scattering centers [1]. Virtually identical results were published independently by Orest Khvolson in 1889 [8] (see also the instructive historical account in [9]).

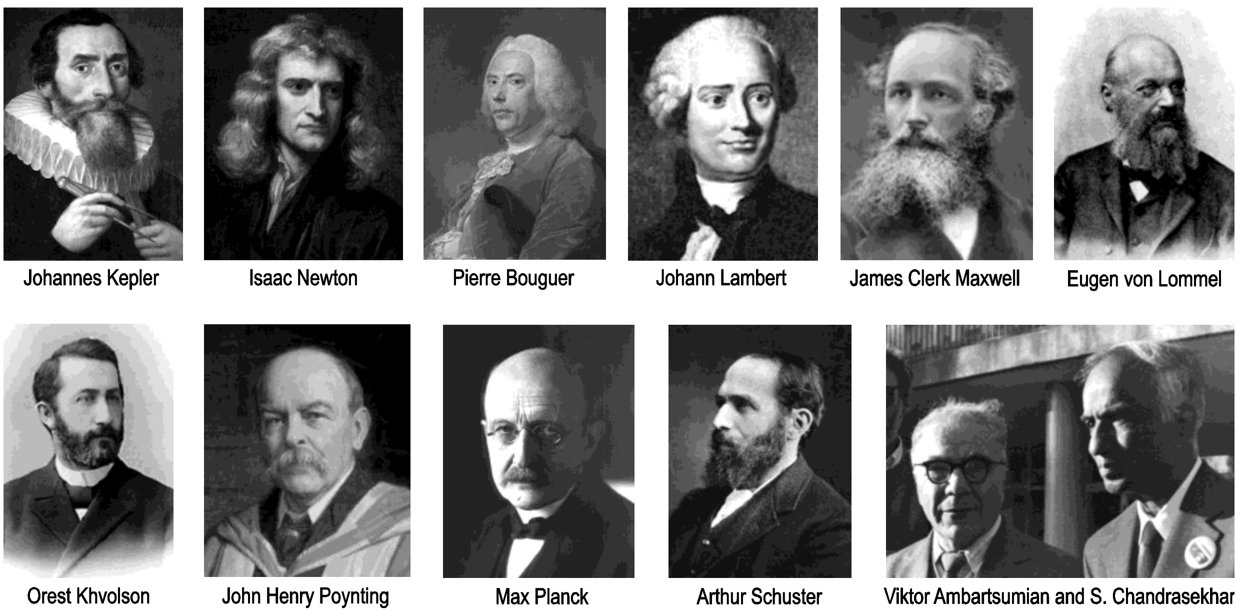
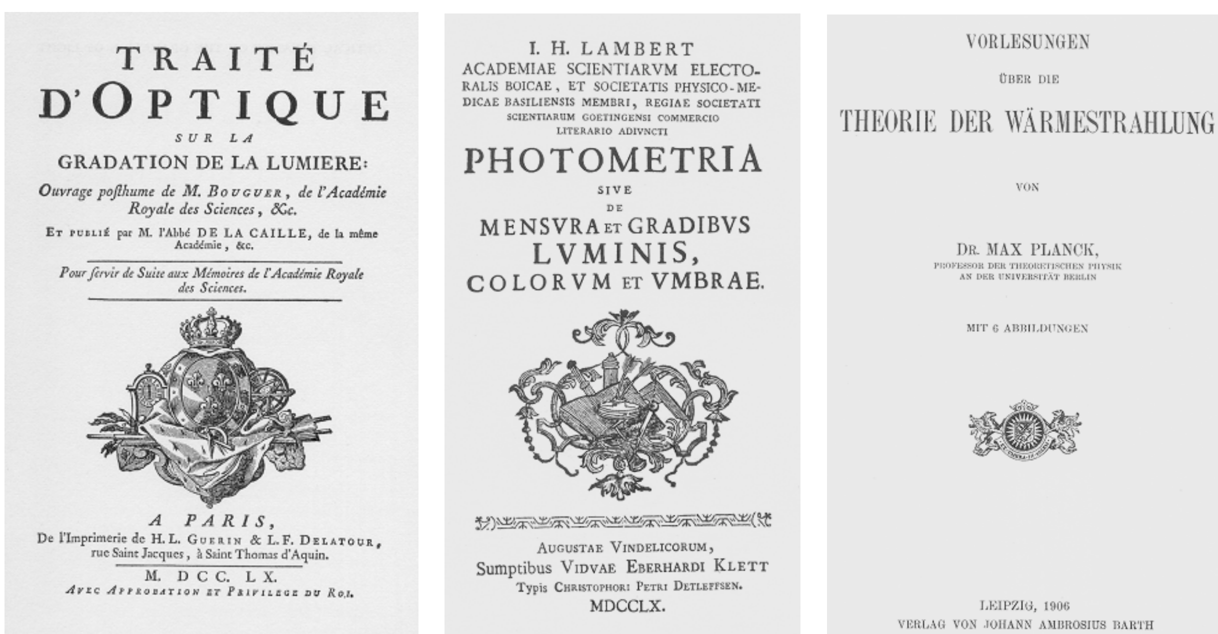


FIGURE 1. Many prominent scientists contributed to the disciplines of directional radiometry and radiative transfer.



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VORLESUNGEN ÜBER DIE THEORIE DER WÄRMESTRAHLUNG
VON
DR. MAX PLANCK,
PROFESSOR DER THEORETISCHEN PHYSIK AN DER UNIVERSITÄT BERLIN
MIT 6 ABBILDUNGEN
LEIPZIG, 1906
VERLAG VON JOHANN AMBROSIUS BARTH

FIGURE 2. Title pages of the treatises by Bouguer [5], Lambert [6], and Planck [11].

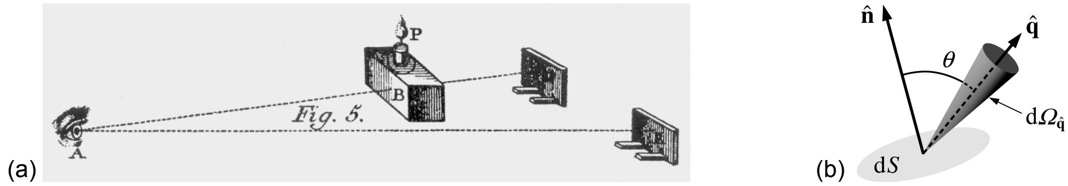

FIGURE 3. (a) Experimental setup used by Bouguer to discover the exponential attenuation law. (b) Definition of the phenomenological specific intensity.

Unfortunately, the pioneering work by Lommel and Khvolson has remained largely unnoticed. The first introduction of the RTE has traditionally been attributed to Arthur Schuster [10] who, in fact, proposed what is now known as the two-stream approximation rather than the integral or integro-differential form of the RTE.

The most important quantity of the phenomenological RTT and DR is the specific intensity (otherwise known as radiance), which is postulated to have primordial physical existence and *a priori* defined properties. The classical definition of specific intensity was given by Max Planck in his famous *Theorie der Wärmestrahlung* [11] (Fig. 2). On page 1 of the English edition of this book [12], one can find the following manifesto: "The state of the radiation at a given instant and at a given point of the medium cannot be represented… by a single vector (that is, a single directed quantity). All heat rays which at a given instant pass through the same point of the medium are perfectly independent of one another, and in order to specify completely the state of the radiation the intensity of radiation must be known in all the directions, infinite in number, which pass through the point in question." Based on this premise, Planck defined the specific intensity $I(\mathbf{r}, \hat{\mathbf{q}})$ by stating that the amount of radiant energy dE transported through an arbitrarily chosen differential element of area dS in the interior of a medium in directions confined to a differential element of solid angle $\mathrm{d}\Omega_{\hat{\mathbf{q}}}$, centered around the propagation direction $\hat{\mathbf{q}}$, during a differential time interval dt is given by $\mathrm{d}E = I(\mathbf{r}, \hat{\mathbf{q}}) \cos\theta \, \mathrm{d}S \, \mathrm{d}t \, \mathrm{d}\Omega_{\hat{\mathbf{q}}}$, where $\mathbf{r}$ is the position vector of the differential surface element and θ is the angle between $\hat{\mathbf{q}}$ and the normal $\hat{\mathbf{n}}$ to dS (Fig. 3b). This definition was eventually adopted in the classical works by E. Arthur Milne [13], Eberhard Hopf [14], and Subramanyan Chandrasekhar [15] as well as in virtually all subsequent monographs and textbooks on RTT and DR (see, e.g., [16–24]). Although in his treatise Planck specifically considered black-body electromagnetic radiation, his concept of the specific intensity was extrapolated to encompass diffuse multiple scattering of light by cloudy and other particulate media.

The theoretical notion of the specific intensity was eventually supplemented by the conventional belief that it can be measured with a suitable directional radiometer as well as calculated by solving the RTE. It is the alleged computability and measurability of the specific intensity coupled with its alleged physical existence that have made $I(\mathbf{r}, \hat{\mathbf{q}})$ the central point of the phenomenological RTT and DR and their countless applications.

François Arago was among the first to criticize phenomenological photometry for its complete neglect of the polarization state of light. This criticism was eventually addressed by nominally replacing the specific intensity with the four-element specific intensity column vector $\mathbf{I}(\mathbf{r}, \hat{\mathbf{q}})$. Richard Gans [25] was the first to consider the transfer of polarized light in a plane-parallel Rayleigh-scattering atmosphere; however, he analyzed only the special case of perpendicularly incident light and considered only the first two components of the specific intensity column vector. The case of arbitrary illumination and arbitrary polarization was first studied by Chandrasekhar [15]. Georgi Rozenberg [26] postulated the most general form of the vector RTE for sparse scattering media composed of arbitrarily shaped and arbitrarily oriented particles.

MICROPHYSICS

After having summarized the milestones of the phenomenological RTT and DR, it is appropriate to quote from a 1978 paper by Emil Wolf [27]: "The strong intuitive appeal of the basic radiometric concepts has been largely responsible for a fact that is seldom noted: namely, that the relationship between radiometry and modern theories of radiation (i.e., Maxwell's electromagnetic theory and the quantum theory of radiation) has up to now not been clarified." In 1995, the authors of Ref. [28] wrote: "In spite of the extensive use of the theory of radiative energy transfer, no satisfactory derivation of its basic equation… from electromagnetic theory… has been obtained up to now." In fact, even much earlier, in 1965, Rudolph Preisendorfer [29] complained about a profound disconnect between the "mainland" of fundamental physics and the island of the phenomenological RTT and DR.

To understand the nature of this disconnect, let us consider an idealized liquid-water cloud illuminated by a plane electromagnetic wave or, more generally, a quasi-monochromatic parallel beam of light with infinite lateral extent

(Fig. 4). Suppose that we need to evaluate the radiation budget of a macroscopic volume element ΔV bounded by the closed spherical surface ΔS. According to the Poynting theorem [30], the net average rate at which electromagnetic energy enters this volume element is given by the integral

$$W_{\Delta S} = -\int_{\Delta S} \mathrm{d}^2\mathbf{r}\,\langle \mathbf{S}(\mathbf{r},t)\rangle \cdot \hat{\mathbf{n}}(\mathbf{r}), \tag{1}$$

where $\mathbf{S}(\mathbf{r},t)$ is the Poynting vector at the point $\mathbf{r}$ at the moment t, $\langle \cdots \rangle$ denotes averaging over a sufficiently long period of time, and the unit vector $\hat{\mathbf{n}}(\mathbf{r})$ is directed along the local outward normal to the boundary. If $W_{\Delta S} = 0$ then the incoming radiation is balanced by the outgoing radiation. Otherwise there is absorption of electromagnetic energy inside the volume element. The radiation budget of the volume V occupied by the entire cloud is evaluated similarly, except now the integral in Eq. (1) is taken over the closed boundary S (Fig. 4).

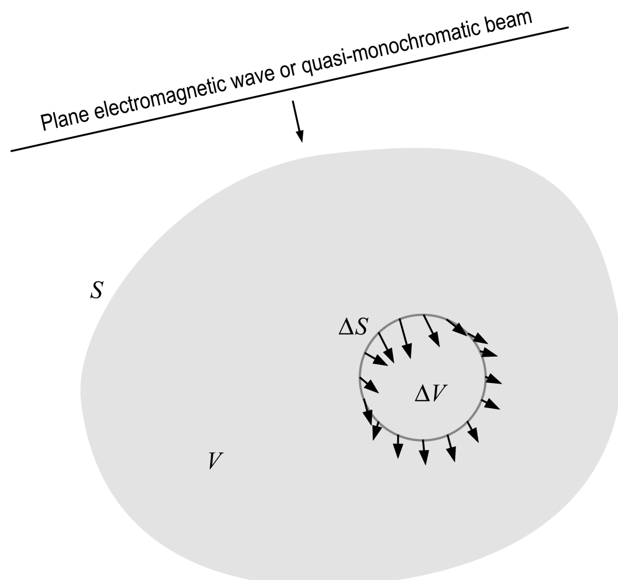

FIGURE 4. Time-averaged radiation budget of a volume element ΔV bounded by a closed surface ΔS. The arrows symbolize the distribution of $\langle \mathbf{S}(\mathbf{r},t)\rangle$ over the boundary ΔS.

Suppose that we have at our disposal a Poynting-meter, i.e., a device that can measure both the direction and the absolute value of the time-averaged local Poynting vector. Then measuring $\langle \mathbf{S}(\mathbf{r},t)\rangle$ at a sufficiently representative number of points densely distributed over the boundary ΔS and evaluating the integral in Eq. (1) numerically would solve the above radiation-budget problem.

Unfortunately, none of the instruments that have ever been used in the disciplines of atmospheric radiation and remote sensing can, strictly speaking, be considered a Poynting meter. Instead, it was demonstrated in [31] that traditional instruments called well-collimated radiometers (WCRs) operate as wavefront angular filters rather than energy-propagation angular filters.

Even more fundamentally, the local instantaneous Poynting vector $\mathbf{S}(\mathbf{r},t)$ is a *monodirectional* vector. This means that even if one assumes that $\mathbf{S}(\mathbf{r},t)$ describes the direction and rate of local electromagnetic energy flow, then at any moment this flow occurs in only one direction. Similarly, $\langle \mathbf{S}(\mathbf{r},t)\rangle$ represents the local monodirectional energy flow averaged over time. Unlike the Poynting vector, the specific intensity, by its very construct, is intended to describe polydirectional energy flow: electromagnetic energy is postulated to propagate simultaneously in all directions at any moment in time at any point $\mathbf{r}$. The situation becomes even more problematic if we recognize that even the Poynting vector cannot describe the direction and rate of instantaneous local energy flow [27]. Indeed, adding the curl of any vector field to $\mathbf{S}(\mathbf{r},t) = \mathbf{E}(\mathbf{r},t) \times \mathbf{H}(\mathbf{r},t)$ yields a vector field $\mathbf{S}'(\mathbf{r},t)$ which also satisfies the Poynting theorem for the same pair of the electric and magnetic fields $\{\mathbf{E}(\mathbf{r},t), \mathbf{H}(\mathbf{r},t)\}$.

A traditional phenomenological way of addressing this profound inconsistency has been to claim that, in fact, the electromagnetic field must be quantized, which, allegedly, results in the emergence of photons as localized and "independent" particles of the electromagnetic field forming a "photon gas" (see, e.g., [32]). The specific intensity is then claimed to quantify the instantaneous directional distribution of all the photons passing through the differential surface element dS in Fig. 3b. However, this approach faces an insurmountable problem: the real photons appearing in quantum electrodynamics (QED) are neither Newtonian corpuscles nor Einstein's energy quanta localized at points in space. Each QED photon is a quantum of a single normal mode of the electromagnetic field and as such occupies the entire quantization volume (e.g., the entire cloud in Fig. 4) and cannot be localized [28]. Therefore, the photons cannot be used to define the specific intensity at an observation point $\mathbf{r}$ [27].

Despite being poorly defined, the heuristic concept of the polydirectional specific intensity has often been viewed as worth keeping. This has led to several attempts to identify a microphysical quantity that would satisfy the RTE and thereby could be considered a legitimate proxy for the phenomenological specific intensity (e.g., [33, 34]). However, all such attempts have failed to clarify the issue of the requisite non-negativity and physical measurability of such proxies, have not resolved the contradiction between the monodirectionality of the (time-averaged) Poynting vector and the polydirectionality of the phenomenological specific intensity, and could not establish the physical link between the RTT and the phenomenon of CB [35, 36].

Fortunately, we do not need to use the specific intensity as the fundamental starting point and consider it a primordial physical quantity *a priori* possessing certain desirable properties. Instead, we need to focus on addressing the following *well-defined problems of actual practical importance*:

1. How to evaluate theoretically the time-averaged radiation-energy budget of a volume of particulate medium?

2. Given the widespread practical use of WCRs, how to model theoretically the particular measurement afforded by a WCR and thereby clarify its ability to serve as (i) an energy-budget instrument and/or (ii) a diagnostic tool suitable for optical characterization of a particulate medium in laboratory, *in situ*, or remote-sensing studies?

Indeed, it is the solution of these two specific problems that one needs in the final analysis, the imaginary "angular distribution of the local electromagnetic energy flow" being irrelevant besides being unphysical.

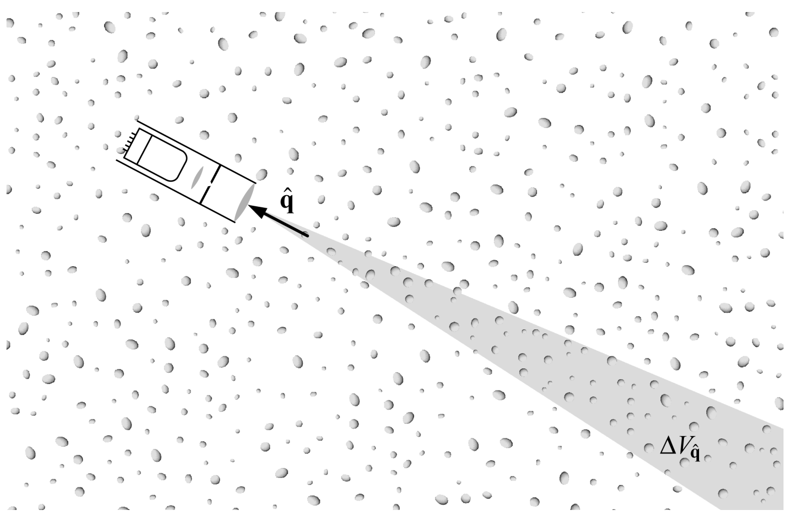

FIGURE 5. A WCR placed inside a random cloud of particles.

Both problems have been addressed by directly solving the Maxwell equations in [31, 36] based, in part, on the earlier work by Victor Twersky [37], Anatoli Borovoy [38], Yuri Barabanenkov [39], Leung Tsang [40], and other pioneers of the microphysical RTT. Let us, for example, consider what happens when a WCR is placed inside a cloud randomly populated by N sparsely distributed particles (Fig. 5). Assume for simplicity that the particles are separated widely enough to satisfy the conditions of applicability of the far-field Foldy–Lax equations (see Chapter 4 of Ref. [36]). Then the total instantaneous electric and magnetic fields at $\mathbf{r}$ in the absence of the detector can be expressed as superpositions of the respective incident and N scattered fields:

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}^{\text{inc}}(\mathbf{r},t) + \sum_{i=1}^{N} \mathbf{E}_i^{\text{sca}}(\mathbf{r},t), \qquad \mathbf{H}(\mathbf{r},t) = \mathbf{H}^{\text{inc}}(\mathbf{r},t) + \sum_{i=1}^{N} \mathbf{H}_i^{\text{sca}}(\mathbf{r},t), \tag{2}$$

where $\mathbf{E}^{\text{inc}}(\mathbf{r},t)$ and $\mathbf{H}^{\text{inc}}(\mathbf{r},t)$ represent the incident plane electromagnetic wave, while $\mathbf{E}_i^{\text{sca}}(\mathbf{r},t)$ and $\mathbf{H}_i^{\text{sca}}(\mathbf{r},t)$ describe an outgoing spherical wavelet centered at the origin of particle i. At a large distance from the particle this wavelet can be considered locally flat. Therefore, the WCR will select only those wavelets that come from the particles located within the "acceptance volume" $\Delta V_{\hat{\mathbf{q}}}$ of the instrument defined by its acceptance solid angle $\Delta \Omega_{\hat{\mathbf{q}}}$ (Fig. 5) and will integrate the corresponding composite Poynting vector over the objective lens. Assuming for simplicity that $\Delta \Omega_{\hat{\mathbf{q}}}$ does not subtend the propagation direction of the incident beam $\hat{\mathbf{n}}^{\mathrm{inc}}$, we conclude that the instantaneous value of the composite Poynting vector is given by $\sum_l \sum_m \mathbf{E}_l(\mathbf{r},t) \times \mathbf{H}_m(\mathbf{r},t)$, where the indices l and m number the particles positioned inside the acceptance volume $\Delta V_{\hat{\mathbf{q}}}$. Note that since $\Delta \Omega_{\hat{\mathbf{q}}}$ is assumed to be very small, each term in this sum is a vector directed essentially along the unit vector $\hat{\mathbf{q}}$ in Fig. 5. Averaging this reading over a sufficiently long time interval Δt yields the following average signal per unit area of the objective lens: $\langle \sum_l \sum_m \mathbf{E}_l(\mathbf{r},t) \times \mathbf{H}_m(\mathbf{r},t) \rangle$. This quantity can be computed analytically using the standard assumptions of the microphysical theory of radiative transfer [36] such as ergodicity of the random N-particle ensemble, the limit $N \to \infty$, the Twersky approximation, and the ladder approximation. The result of this computation [31] shows that the reading of the WCR in Fig. 5 per unit time is given by the product

$$S_o \Delta \Omega_{\hat{\mathbf{q}}} \tilde{I}(\mathbf{r}, \hat{\mathbf{q}}), \tag{3}$$

where S_o is the surface area of the objective lens and $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ is the first element of the four-element column $\tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}})$ satisfying the following integro-differential equation:

$$\hat{\mathbf{q}} \cdot \nabla \tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}}) = -n_0 \langle \mathbf{K}(\hat{\mathbf{q}}) \rangle_\xi \tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}}) + n_0 \int_{4\pi} \mathrm{d}\hat{\mathbf{q}}' \langle \mathbf{Z}(\hat{\mathbf{q}}, \hat{\mathbf{q}}') \rangle_\xi \tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}}'). \tag{4}$$

Here, $n_0 = N/V$ is the average number of particles per unit volume, V is the volume occupied by the cloud, $\langle \mathbf{K}(\hat{\mathbf{q}}) \rangle_\xi$ is the 4×4 single-particle extinction matrix averaged over all N particles, and $\langle \mathbf{Z}(\hat{\mathbf{q}}, \hat{\mathbf{q}}') \rangle$ is the 4×4 single-particle phase matrix, also averaged over all particles [36].

A companion result of the microphysical theory of radiative transfer allows one to compute the time-averaged Poynting vector at the observation point **r** by integrating the product $\hat{\mathbf{q}} \tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ over all directions $\hat{\mathbf{q}}$:

$$\langle \mathbf{S}(\mathbf{r}, t) \rangle = \int_{4\pi} \mathrm{d}\hat{\mathbf{q}}\, \hat{\mathbf{q}}\, \tilde{I}(\mathbf{r}, \hat{\mathbf{q}}). \tag{5}$$

Equations (3)–(5) are quite useful in practice. Firstly, Eq. (3) implies that if the underlying assumptions about the particulate medium are valid then the WCR shown in Fig. 5 measures the quantity $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ provided that the reading of the WCR is averaged over a sufficiently long period of time. Therefore, by sampling a sufficiently dense grid of incoming directions $\hat{\mathbf{q}}$, one can determine the local time-averaged Poynting vector according to Eq. (5) and thereby solve the radiation-budget problem experimentally by using Eq. (1). Secondly, the angular dependence of the measured function $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ can be analyzed by solving Eq. (4) for a representative range of physical models of the cloud and thereby retrieve valuable macro- and microphysical information about the particulate object. Furthermore, since the WCR selects only locally plane wavefronts propagating in directions very close to $\hat{\mathbf{q}}$, it is straightforward to convert the WCR into a directional photopolarimeter capable of measuring the entire column vector $\tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}})$. This measurement has been shown to contain additional implicit information about particle microphysics which can often be retrieved since solving Eq. (4) yields all four elements of $\tilde{\mathbf{I}}(\mathbf{r}, \hat{\mathbf{q}})$ at once (see, e.g., [41, 42]).

One might claim that Eq. (4) is the standard RTE postulated in the phenomenological RTT based on vague energy-conservation and directional-energy-propagation arguments. Furthermore, one might equate $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ with the phenomenological radiance and thereby attribute to it primordial physical significance as the quantity specifying the angular distribution of electromagnetic energy flow at the point **r** over all propagation directions $\hat{\mathbf{q}} \in 4\pi$.

The microphysical approach to radiative transfer shows that this interpretation of Eq. (4) and the quantity $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ is thoroughly incorrect [43]. The quantity $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ does enter the formula (5) for the time-averaged Poynting vector. However, we have already seen that even the Poynting vector cannot be legitimately claimed to specify the direction of the time-averaged electromagnetic energy flow, and so there is even less justification for ascribing any "directional energy" content to the specific intensity. The quantity $\tilde{I}(\mathbf{r}, \hat{\mathbf{q}})$ is nothing but a formal solution of the intermediate equation (4) and appears as a byproduct of the purely mathematical derivation of Eqs. (3) and (5) from the Maxwell equations.

In the words of Roy Glauber, "A photon is what a photodetector detects" [44]. Paraphrasing Glauber, we can say that the specific intensity is what a WCR measures, provided that the parameters of the particulate medium in question are consistent with the assumptions used in the derivation of Eqs. (3) and (4).

The RTE is derived from the Maxwell equations in the limit of infinitesimal packing density of the particulate medium, whereas in many cases of practical interest the packing density can be substantial [42, 45, 46]. It is therefore important to analyze the range of applicability of the RTE by comparing RTT computations with numerically exact computer solutions of the Maxwell equations. Given the practical importance of the phenomenon of weak localization (e.g., [42, 47] and references therein), the sensitivity of various manifestations of CB to packing density must also be examined. Significant progress in this direction has already been achieved [42, 48-53].

CONCLUSIONS

The RTE was introduced 125 years ago by Eugene von Lommel, while the heuristic concept of radiance was definitively formulated in 1906 by Max Planck. Subsequently, they were supplemented by the seemingly obvious concept of a directional radiometer. Since then, measurements with WCRs and calculations based on the RTE have been at the very heart of the disciplines of atmospheric radiation, remote sensing, astrophysics, heat energy transfer, and biomedical optics. Yet from the fundamental-physics perspective, both the discipline of DR and the RTT have been based on phenomenological notions many of which turned out to be profound misconceptions [27, 43, 54, 55]. It has been demonstrated that contrary to the widespread belief, a WCR does not, in general, measure the flow of electromagnetic energy along its axis, while the radiance cannot be interpreted as quantifying the amounts of electromagnetic energy transported simultaneously in various directions.

It is thus fundamentally important to understand why the phenomenological RTT and DR have often “worked” in the practical sense and determine the range of their applicability. The ultimate way to achieve this key objective is via the microphysical approach based directly on the Maxwell equations since it can clarify the physical nature of measurements with WCRs and the physical content of the RTE. This approach has finally been developed and has been used to demonstrate that the radiance has no fundamental physical meaning besides being a mathematical solution of an equation formally coinciding with the phenomenological RTE. Only under certain restricted conditions can it be used to compute the time-averaged local Poynting vector as well as be measured by a WCR. These firmly established facts make the combination of the RTE and a WCR useful in some well-defined applications and help “rescue” the majority of documented uses of the phenomenological RTT. However, outside the range of validity of the microphysical RTT the practical usefulness of measurements with WCRs remains uncertain. It is likely that in many cases the measurement with a WCR must be modeled with a more sophisticated tool than the RTE, which implies that the use of WCRs in quantifying the energy budget of the Earth’s climate system can be problematic and requires a detailed first-principle analysis.

In summary, there has been a paradigm-changing shift in the physical understanding of the discipline of directional photometry established phenomenologically 250 years ago by Bouguer and Lambert and of the RTE introduced 125 years ago by Lommel. From allegedly describing the “directional flow of radiant energy”, photometry has been reduced to making measurements with WCRs and modeling these measurements theoretically on the basis of fundamental physical theories. Paraphrasing the famous pronouncement by Willis Lamb, Jr. [56] that “there is no such thing as a photon”, we can conclude that there is no such thing as the specific intensity allegedly quantifying multidirectional flow of electromagnetic energy. What does exist is a potentially useful instrument called the WCR and the urgent need to understand its actual physical functionality in various practical situations.

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