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Scattering and absorption of light by aerosol particles: a research-based teaching approach

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Abstract: Knowledge of how aerosols interact with radiation is important due to its significance in the total radiation balance. Different approaches describe the scattering cross section of aerosols with light as a function of the aerosol particle size. We give the basic definition of extinction, scattering coefficient factors, complex refractive indices and, describe different approximations of light-aerosol particles interaction such as the Raleigh approximation, the Mie theory and the Rayleigh-Debye-Gans approximation. In this work we suggest a research-led teaching approach of the light interaction with aerosol particles. This work can be used as a teaching resource for environmental physics instructors to update the curriculum by including recent research results and to help students to understand them. Contextualizing theory for some practical applications, provides an effective strategy for developing an appropriate teaching material.

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1. Introduction

Student learning can be supported through a close association between teaching and research [1]. The research-based teaching methods (research-led, research-oriented, research-tutored, and research-informed) are approaches implemented during instructions to bring research knowledge in the classroom. Loraine and Fathima (2019) [1] argued that research-based teaching strategies adopted in science stimulate the development of knowledge and skills for students. Teaching methods that integrate the research outputs with theoretical knowledge have a direct significance on the quality of students' intellectual development. These context-based methods make the understanding of scientific concepts more relevant than traditional approaches that cover scientific ideas first before looking their applications [2, 3]. The literature for various research-based teaching in physics is extensive [4, 5, 6]. Such a research-oriented approaches led the students to learn about, to acquire and practice research skills. There are different ways that academics practice a course content underpinned by their research findings. The prominence of research-led teaching approach is on learning the research results rather than research procedures which are transmitted to the students through teaching [1].

Understanding the properties of aerosols is of great practical importance, due to their ability to affect not only visibility and global and regional climate change, but also our health and quality of life. During the interaction of light with matter, two main phenomena can be observed: scattering and absorption of light, depending on wavelength and optical characteristics of aerosols. The scattering and absorption processes determine the reduction of light intensity passing through particles. Many aerosol assessment techniques in the atmosphere are based on measuring the scattering of light by aerosol particles. The amount of scattered light depends not only on the wavelength of the light used and the scattering angle but also on the physical parameters of the particles, such as shape, size, and refractive index.

A research-led teaching sequence about the scattering and absorption of light by aerosol particles is proposed in this paper. The material presented in this paper can be used as course material in undergraduate and graduate programs of atmospheric physics and chemistry, environmental sciences and engineering, meteorology, and climate change.

2. Aerosol particle size

Fundamental knowledge about the properties of aerosol particles and the layers of the atmosphere where they are found is the first stage of understanding their interaction with light. Microscopic particles suspended in the air are diverse such as soil dust particles, fly ash and soot particles from burning fuels, energy production and industrial emissions particles, photochemically formed particles, biogenic, sea salt, sand and volcanoes particles [7]. All of these are examples of aerosol particles. They constitute an important element in the earth-atmosphere system that affects the radiation budget through scattering and absorption of solar radiation [8].

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Particle size is the dominant parameter that determines the interaction of aerosol particles with the atmosphere. Atmospheric aerosols lying in the range from 0.005 μm to 100 μm are classified in three main modes, which are the nucleus mode in the range $0.005 \leq d \leq 0.1\,\mu m$, the accumulation mode in the range $0.1 \leq d \leq 2\,\mu m$ and the coarse mode with size $d \geq 2\,\mu m$ [7]. The nucleus mode is the smallest of atmospheric aerosols, in terms of both particle size and mass concentration, but containing the largest number of particles. The nucleus mode is formed by photochemical reactions of gases in the atmosphere and high temperature combustion processes [7, 9]. Since the size of the atom is of the order of 10^{-4} μm, an aerosol particle in the nucleus mode is hundreds of times larger than an atom and contains many atoms or molecules. Particle size described by a simple linear dimension or physical diameter can be uniquely defined only for spherical particles. However, for irregular-shaped particles, a specific parameter must be clearly defined to include not only physical dimension but also information on the density and shape [10]. A well-known parameter called the equivalent diameter of irregularly shaped particles is defined as the diameter of a sphere that has the same value of physical property as that of the particle under consideration [7]. The equivalent diameter is determined by measuring a physical characteristic that is particle size dependent such as aerodynamic, inertial, diffusion, optical and electrical mobility [9, 11].

There are many aerosol size-measuring techniques based on these physical properties. The use of aerodynamic properties is widely accepted as more convenient [7, 11, 12] because these properties govern the mechanical processes affected by gravitational and inertial forces (transport, removal, deposition efficiency) and better describe the behaviour of particles into the air. Romain and Berg (2021) [13] argued that atmospheric aerosols are often best investigated via remote-sensing methods that employ a variety of light scattering techniques. LiDAR (Light Detection and Ranging) measure the aerosol cross-section area using direct backscatter method. The optical particle counters use the light-scattering phenomena described by Mie theory to calculate the spherical equivalent diameter of a particle [14]. Other methods use optical imaging for indirect measurement of the physical particle size based on analysing the photomicrographs of the silhouette or projection of the particle [15-17]. The inertial impactors classify particles into different sizes based on the particle behaviour in the fluid flow field [18].

Although air molecules are the main contributors on scattering and absorption from the atmosphere, aerosols influence is present to solar radiative forcing in direct way through aerosol-radiation interaction and in semi-direct way through aerosol-cloud interaction [19]. Aerosol particles scatter and absorb solar radiation at different wavelengths depending on their size. Solar radiation spectrum covers a broad range of wavelengths from 0.01 to 4 μm. About 99% of solar radiation entering the earth's atmosphere is in the ultraviolet-visible-infrared region (from 0.15 to 4 μm). The extreme ultraviolet radiation $\left(< 0.1\,\mu m\right)$ is absorbed by the atmospheric nitrogen above 100 km. Ultraviolet radiation $\left(0.1 - 0.32\,\mu m\right)$ is absorbed by the combination of oxygen and stratospheric ozone. Ultraviolet radiation larger than 0.32 μm, visible and infrared radiation reach the earth's troposphere where the aerosols - radiation interaction takes place [11].

3. Preliminary: Interaction of aerosols with radiation

In this section an explanation of how scattering and absorption of light take place when light interact with aerosols is presented. Aerosol light scattering redistributes the electromagnetic energy into different directions and aerosol light absorption transforms the electromagnetic energy into thermal energy. The resultant effect of scattering and absorption is known as extinction of light radiation (a measure of attenuation or removal of light from the beam).

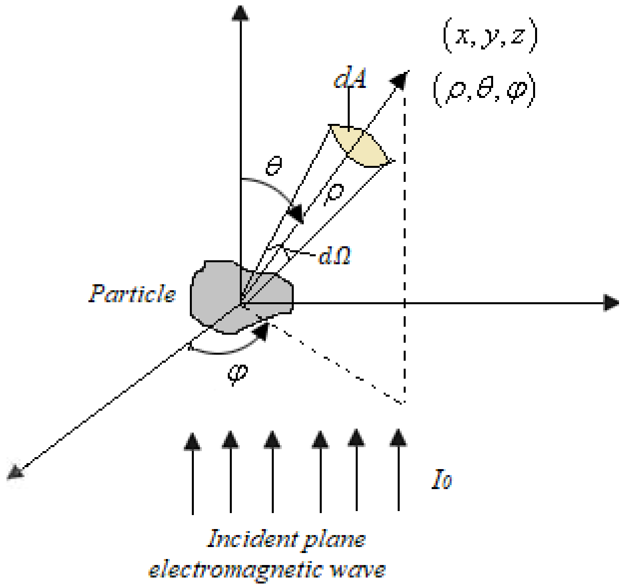

Figure 1. Geometry of electromagnetic wave scatters off a single particle.

If an electromagnetic plane wave is incident on a single particle of any shape and size (Figure 1), at a large distance compared to the size of the particle, the scattered energy appears as the energy of a spherical wave centered at the particle. The total energy extinguished from the plane wave is equal to the sum of the scattered energy and the absorbed energy [20]. The intensity of emitted light depends on the direction of emission given by θ and φ.

The proportionality of the light scattered intensity I by a particle at a distance *r* far from it, to the intensity of the incident radiation I_0 can be quantitatively described by the cross section, which represents the effective surface of the particle as seen by light [21]. The ratio of intensity I_0 of incident beam and intensity of scattered radiation I is known as differential cross section:

$$\frac{I}{I_0} = \frac{d\sigma}{d\Omega}.$$

The scattering cross-section σ_s is defined as:

$$\sigma_s = \int \frac{d\sigma}{d\Omega} d\Omega = \int_0^{2\pi} \int_0^{\pi} \frac{d\sigma}{d\Omega} \sin\theta d\theta d\varphi, \quad (1)$$

where $d\Omega$ is the infinitesimal solid angle surrounding a given direction in spherical coordinates. The differential cross section $\frac{d\sigma}{d\Omega}$ represent the probability that light radiation incident on the particle is scattered into a unit solid angle in the given direction:

$$\sigma_s = \frac{1}{I_0}\int_0^{2\pi}\int_0^{\pi} I \sin\theta d\theta d\varphi = \int_0^{2\pi}\int_0^{\pi} \frac{1}{(2\pi/\lambda)^2} F(\theta,\varphi,\lambda)\sin\theta d\theta d\varphi, \tag{2}$$

where $I = \frac{I_0}{(2\pi/\lambda)^2} F(\theta,\varphi,\lambda)$ and $F(\theta,\varphi,\lambda)$ is scattering function, a dimensionless parameter. The ratio $F(\theta,\varphi,\lambda)/(2\pi/\lambda)^2$ has surface dimension m^{-2}. The scattering function $F(\theta,\varphi,\lambda)$ depends on the wavelength of the incident radiation, size, shape, and optical properties of the particle, but not on distance r. In the case of spherical particles, it does not depend on θ either. A dimensionless parameter (x_p) can be used as a function of the physical particle size d_p and the wavelength λ:

$$x_p = \frac{\pi d_p}{\lambda}. \tag{3}$$

The scattering cross-section σ_s has the surface dimension (m^{-2}). In general, it is not the same with geometric cross-section of the particle silhouette: $\sigma_{geom} = \pi \frac{d_p^2}{4}$.
The absorption efficiency of a particle is defined as the ratio of scattering cross-section and geometric cross-section:

$$Q_s = \frac{\sigma_s}{\sigma_{geom}}, \tag{4}$$

or:

$$Q_s = \frac{\int_0^{2\pi}\int_0^{\pi} F(\theta,\varphi,\lambda)\sin\theta d\theta d\varphi}{(2\pi/\lambda)^2 \sigma_{geom}}. \tag{5}$$

In the same way, the absorption effectivity is defined as the part of the incident radiation absorbed by the unit of the geometric cross-sectional area of the particle:

$$Q_a = \frac{\sigma_a}{\sigma_{geom}}. \tag{6}$$

where σ_a is the absorbing cross-section.

Applying the energy conservation law, the absorbing cross-section σ_a and scattering cros-section σ_s gives total cross section σ_t :

$$\sigma_t = \sigma_a + \sigma_s. \tag{7}$$

For non-absorbing particles, the total cross section is equal to the scattering cross section: $\sigma_t = \sigma_s$.

A very detailed review given by Romain and Berg (2021) [13] is focused on the light interaction with aerosol particles. It describes how the characteristics of the electric field within a particle affect the external scattered intensity and extinction cross section. This review present different methods and findings, ranging from models to applications for assessing the cros ssections of aerosol particles.

4. Light - aerosol particle interaction

At this point it is important to dwell with different theories used to describe the scattering and extinction of light, depending on the size, refractive index of the scattered particles and incident wavelength [22, 23].

4.1 Rayleigh theory

An atmospheric layer consists of molecules and aerosol particles. Rayleigh's scattering theory describes the scattering and absorption of light by molecules of small size in comparison to the wavelength. The Raleigh scattering is expected in the atmospheric layers above 4000 m composed only of molecules, like nitrogen, oxygen, hydrogen [24]. The Rayleigh theory applies to particles with dimensions much smaller than the wavelength of the incident radiation, under conditions where the external field can be considered uniform [22]:

$$x_p \ll 1 \qquad \text{(first condition).} \tag{8}$$

This condition corresponds physically to the assumption that electric field must penetrate the particle in a time t, smaller than the period of the electromagnetic wave oscillations T, to avoid the effects of resonance, or setting up the standing waves. Then, the electric field that encounters the particle can be considered uniform at any moment. From the condition $t \ll T$ and knowing that $m = c/v,$ the second condition is given by expression:

$$|mx_p| \ll 1 \qquad \text{(second condition),} \tag{9}$$

where m is the complex refractive index, the ratio of velocity c of light in vacuum to velocity v of light in a given medium. According to the electromagnetic theory, the refractive index is one of the most important aerosol properties determining the amount of light scattered or absorbed. It can be mathematically described as $m = n + ik$ in complex notation. The real term n describes the refraction of light entering a material, while the imaginary term k or the extinction coefficient is related to the absorbing characteristics [25] of the material. The absorption coefficient α is a useful parameter in considering light propagation in the case of absorbing materials and it is expressed as:

$$\alpha = \frac{4\pi k}{\lambda}. \tag{10}$$

The average complex refractive index of aerosols can be extracted from the analysis of individual particles and it strongly depends on the values of real and imaginary part of particles. For dielectric particles (non-absorbing) refractive index is real $(k = 0)$. The real part of the average of refractive index of total aerosols is mainly influenced by the abundance of metal oxide particles, whereas the imaginary part is mainly determined from the volume fraction of soot aggregates [26]. Different techniques have been developed to measure complex refractive index from real time monitoring (AERONET and SKYNET) [27] to indirect calculation by using SEM/EDX analysis of aerosol particles [26, 28]. Chen et al found that fine and coarse n and k values over China ranged from 1.52 to 1.56 and from 0.002 to 0.006, respectively. Mico et al (2019) [28] found that real part of refractive index n for the urban atmosphere of Vlora city varies from 1.55 up to 1.60, while the imaginary part, k varies from 0.016 up to 0.032, with an average refractive index of $m = 1.57 - 0.02i$.
The scattering effectivity for spherical absorbing particles can be expressed by considering the complex index of refraction [21]:

$$Q_s = \frac{8}{3} x_p^4 \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 . \tag{11}$$

The absorbing effectivity is given by the expression:

$$Q_a = -4 x_p I_m \left\{ \frac{m^2 - 1}{m^2 + 2} \right\}, \tag{12}$$

where I_m stands for imaginary part of $\frac{m^2 - 1}{m^2 + 2}$.

The corresponding scattering and absorbing cross- sections are given by:

$$\sigma_s = \frac{2 x_p^6 \lambda^2}{3\pi} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 , \qquad \text{or} \qquad \sigma_s = \frac{2\pi^5 d_p^6}{3\lambda^4} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 . \tag{13}$$

$$\sigma_a = -\frac{\lambda^2 x_p^3}{\pi} I_m \left\{ \frac{m^2 - 1}{m^2 + 2} \right\}. \tag{14}$$

Eq. 13 affirms that scattering cross section is inversely proportional to the 4th power of wavelength. Applying it for air molecules (mostly N_2 and O_2) result in the answer why the sky is blue. Experimental values for the total Rayleigh-scattering cross section as a function of wavelength for the terrestrial atmosphere can be found in the literature [29, 30]. Sneep and Ubachs (2005) [24] have measured the Rayleigh scattering cross section in various gases by using the sensitive technique of cavity ring-down (CRD) absorption spectroscopy. A scattering cross section of 4066 x 10^{-27} cm^2 was reported for oxigen at 532.2 nm.

4.2 Scattering from many identical particles

In this section, a method of calculation of the scattering properties of an ensemble of identical particles is presented. The Rayleigh scattering is more effective at short wavelength. It can be applied to scattering from particles up to 10% of the light wavelength. Any fine particle with volume V can be divided into many small regions considered as identical individual scatterers radiating in phase. The resultant scattering cross section of the particle is due to coherent addition of individual scattering amplitudes [31]. As the number N of particles in the volume V is given by number density of individual scatterers, the scattering cross section is given by:

$$\sigma_s = \left(\sum_{i=1}^{n} \sqrt{(\sigma_s)_i} \right)^2 = n^2 (\sigma_s)_i = \left(\frac{\pi}{6} N \right)^2 d_p^6 (\sigma_s)_i . \tag{15}$$

Absorption is due to incoherent process that transforms electromagnetic theory into thermal energy. Hence, absorption cross section of the particle is simply the sum of absorption cross-section of individual scatterers:

$$\sigma_a = \left(\sum_{i=1}^{n} \sqrt{(\sigma_a)_i} \right)^2 = n^2 (\sigma_a)_i = \left(\frac{\pi}{6} N \right)^2 d_p^3 (\sigma_a)_i . \tag{16}$$

In the Rayleigh regime, light absorption is important for particles emitted during high temperature combustion processes, corresponding to the nucleus mode of aerosols.
When the size parameter is comparable to or larger than one $(x_p \geq 1)$, Rayleigh theory is no longer applicable and the phase of individual scatterers will change independently and randomly with time. Differing from scattering that is limited by the coherence, the absorption process for large particles is limited by the incomplete penetration of the particle by the light in a time smaller than the period of electromagnetic wave oscillations. Based on the Ryleigh theory, the scattering cross section of a spherical particle is expressed as:

$$\sigma_a = 24\pi^3 \left| \frac{m^2 - 1}{m^2 + 2} \right| \frac{V^2}{\lambda^4} , \tag{17}$$

where $V = \frac{1}{6} \pi d_p^3$ is volume of the spherical particle with diameter d_p.

4.3 Mie theory

Some general highlights of Mie theory are introduced in this section. Fine particles in the range from 0.1 to 1µm are the particles of most interest that affect the visibility of the atmosphere and human health. In this interval, the Rayleigh theory cannot be applied, because the electric field cannot be considered uniform over the entire volume of the particle [22].

The Mie theory is a rigorous approach which applies to the assumptions:

a. Particle is spherical;
b. Light is scattered by individual particles;
c. Particle is homogeneous and isotropic (a single complex refractive index $m = n - ik$ of the material of which particle is composed at a given wavelength).

This theory represents the analytical solution of Maxwell's equations for scattering by a homogenous spherical particles of radius *R* and complex refractive index m, applied for suitable boundary conditions in the regions inside and outside the spherical particle. It uses the difference between the refractive index of the particle and surrounding medium to obtain the intensity of the scattered light.

For a spherical particle with size parameter comparable to one $\left(x_p \approx 1\right)$, intensity of light scattered in direction θ is given by Mie theory in terms of angular intensity functions i_1 and i_2 [32]:

$$I_\theta = \frac{\lambda^2}{4\pi^2 r^2}\left(i_1 + i_2\right), \tag{18}$$

where r is the distance from the particle to the observation location. Intensity functions i_1 and i_2 are complex functions given by:

$$i_1 = \left|\sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)}\left[a_n \pi_n\left(\cos\theta\right) + b_n \tau_n\left(\cos\theta\right)\right]\right|^2,$$

and

$$i_2 = \left|\sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)}\left[a_n \tau_n\left(\cos\theta\right) + b_n \pi_n\left(\cos\theta\right)\right]\right|^2.$$

Where a_n and b_n are complex functions of the size parameter x_p and complex refractive index m while angular dependent functions π_n and τ_n are expressed in terms of Legendre polynomials. These functions represent the light intensity distribution of Mie scattering by a spherical particle at a specific wavelength. The calculation of complex functions a_n and b_n is important to get the intensity distribution and represents a current research direction [33].

For spherical particles of any size the calculation of the integral:

$$\int_0^{\pi} I_\theta 2\pi r^2 \sin\theta d\theta = \int_0^{\pi} \frac{\lambda^2}{4\pi^2 r^2}\left(i_1 + i_2\right) 2\pi r^2 \sin\theta d\theta$$
$$= \frac{\lambda^2}{2\pi}\pi \int_0 \left(i_1 + i_2\right)\sin\theta d\theta,$$

gives the twice of scattering cross section, expressed as:

$$\sigma_s = \frac{\lambda^2}{2\pi}\sum_{n=1}^{\infty}\left(\frac{a_n^2 + b_n^2}{2n+1}\right). \tag{19}$$

For absorbing particles, the total extinction cross-section (scattering and absorption) is given by:

$$\sigma_t = \frac{\lambda^2}{2\pi}\mathrm{Re}\left|\sum_{n=1}^{\infty}(-1)^n i\left(a_n + b_n\right)\right|. \tag{20}$$

Mie theory is applicable for $x_p \approx 1,$ as far as particles will be considered spherical [12]. Mie scattering is mostly responsible for the reduction of atmospheric visibility in urban areas.
Mie theory is widely used to calculate the radiative properties of a single aerosol particle, including scattering and absorption cross-sections and scattering intensity functions, assuming the particle is spherical. Different Mie-based measurement techniques that require knowledge of particle size and refractive index are used to derive particle properties. Teri et al (2022) [34] used an integrating nephelometers to measure the influence of particle size, refractive index, and shape on the determination of the particle scattering coefficient. Nephelometers measure a signal proportional to the scattering coefficient. They found that using the Mie theory for mineral-dust-like irregular shapes the effect of non-spherical shape seems to be compensated by the effect of the imaginary part of the refractive index. Based on the measurements of backscattered and extinction coefficients at several wavelengths derived from detected lidar remote signals, Muller et al. (1999) [35] proposed a method to retrieve physical particle properties such as effective radius, volume, surface-area, and number concentrations, as well as the mean complex refractive index.

Mie-based laser diffraction analysers are widely used to provide particle size measurements. In addition, the Mie theory turned out to be the main method to study the light scattering properties of tiny particles (bubbles) in the wake [36]. Chen (2022) [36] used the analysis of dynamic and static light scattering signals to estimate the physical parameters of the bubbles in the water, such as bubble velocity, bubble diameter, and bubble group distribution density.

Particles with size parameter much larger than one $\left(x_p \gg 1\right)$ can be conceptually treated as usual surfaces and geometrical and wave optics is used to describe the light dispersion characteristics. There are three different mechanisms that cause the light scattering:

a) Diffraction of light – change of direction of light propagation without striking the particle.

b) Light reflection - change of direction of light propagation during the interaction of photons with the surface atoms.

c) Refraction of light - change of direction of light propagation that penetrate the particle.
They are well-known phenomena with scientific basis explained and interpreted in a broad range of topics in optics course.

4.4 Rayleigh-Debye-Gans theory

Among the particles of great interest in the study of aerosols are soot particles, which appear as individual particles (primary particles or monomers) or their clusters (aggregates). Soot aggregates consist of many very fine particles called primary particles which can be considered spherical. Since primary particles are very small compared to the wavelength, the scattering of light by these particles can be rigorously described by Rayleigh theory. This theory is no longer applicable for soot aggregates that contain many primary particles and that can be up to several microns in size. The research on the absorption and scattering properties of soot aggregates has become increasingly important to quantify the contribution of soot to different thermal radiation transfer in flames and combustion systems. It has practical significance in many optically-based techniques for measurements of soot properties, such as primary particle diameter and aggregate size. Laser-induced incandescence techniques use the absorption cross section of soot aggregates to calculate the laser energy absorption rate and the thermal radiation intensity. The scattering properties can be used as the basis for soot morphology measurements by laser elastic scattering techniques [37].

Bohren and Huffman [22] have developed the theory known as the Rayleigh -Debye- Gans approximation (called RDG approximation), for polydisperse fractal aggregates. The Rayleigh - Debye- Gans theory, although known as an approximation, is comparable to rigorous theories and has found wide use in the study of light scattering by aggregates [38, 39]. In this model, it is assumed that primary particles in an aggregate have dimensions that are within the limits of Rayleigh $\left(x_p \prec 3\right)$ and interact independently with radiation, not considering multiple scattering. Hence, it is assumed that every primary particle is exposed equally to the radiation. This theory is used for particles with refractive indices such that $|1-m| \prec 1$.
To evaluate absorption and scattering of light by soot aggregates, the main parameters needed to be known are:

a) The shape of aggregate.
b) Characteristics of the material of which primary particles are composed (complex refractive index $m = n + ik$ and mass density ρ_p).
c) The size parameter x_p of primary particles.
d) The number N of primary particles in an aggregate.

The total absorption of an aggregate is simply the individual contribution of a primary particle multiplied by the number of particles that compose the aggregate [40]:

$$\sigma_a^{ag} = N\sigma_a^p, \tag{21}$$

where σ_a^{ag} is absorbing cross-section for aggregate and σ_a^p absorbing cross-section for primary particles.

The absorption cross section for an aggregate with primary particles in the Rayleigh regime is given by the expression [38, 41, 42]:

$$\sigma_a^{ag} = N\sigma_a^p = N\frac{\lambda^2 x_p^3}{\pi}E_m, \tag{22}$$

where E_m stands for imaginary part of $m^2 - 1/m^2 + 2$.

Considering the dependence not only on the wavelength λ, the parameter x_p, the complex refractive index m but also on the shape of the particles, the scattering cross section is given by:

$$\sigma_a^{ag} = N^2\sigma_s g\left(x_p\right) = N^2\left(\frac{2\lambda^2 x_p^6}{3\pi}F_m\right)\left[1+\left(\frac{4}{3}D_f R_g^2\right)\left(\frac{2\pi}{\lambda}\right)^2\right]^{-\frac{D_f}{2}}, \tag{23}$$

where $F_m = \left|m^2 - 1/m^2 + 2\right|^2$; $g\left(x_p\right)$ represents the shape factor of aggregate; D_f is the fractal dimension of aggregate and R_g a quantity called radius of gyration of the aggregate.

The functions $F(m)$ and $E(m)$ are defined for a single refractive index, for example $m = 1.5 - 0.47i$ [43].

The fractal dimension D_f is introduced by Mandelbrot and the fractal formalism was used in excellent papers for soot aggregates [40, 42, 44, 45]. They have shown that there exists a relationship between morphological characteristics of soot aggregates:

$$N = k_f\left(\frac{2R_g}{d_p}\right)^{D_f}, \tag{24}$$

where k_f is a proportional fractal constant (called prefactor of fractal aggregates).

The radius of gyration of aggregate R_g is defined as:

$$R_g = \sqrt{\frac{\sum_{i=1}^{N} m_i r_i^2}{m_{ag}}}, \tag{25}$$

where m_{ag} is total mass of the soot aggregate and m_i is the mass of individual particle whose center is at the distance r_i from the center of mass of the aggregate. R_g is an important parameter of the aggregate because it directly affects the scattering of light.

The value of the coefficients included in the RDG formalism can be obtained from morphology analyses of samples rich in soot particles by scanning electron microscope method. The evaluation of radius of gyration R_g and the number of primary particles N it is quite difficult to realize directly with the image of the aggregate, due to the large deviations and errors. To evaluate R_g and N some authors have developed an approximation method suggesting the use of relationships between these parameters and the characteristics of the projected image of the aggregate [42-45]. The relationship between the radius of gyration R_g and the maximum length L of the projected image of the aggregate can be used to find the radius of gyration. By using computer simulations Koylu et al. (1995) [46] have shown that the ratio $L/2R_g$ decreases as the number of primary particles N increases reaches a constant value at $N \succ 100$:

$$\frac{L}{(2R_g)} = 1.49, \tag{26}$$

with a standard deviation of 0.02. Samson [41] suggests that $L/(2R_g) = 1.78$ and Brasil [47] report the value $L/(2R_g) = 1.5.$ $L/(2R_g) = 1.5$.

Also, there exists a correlation between the number $N,$ projected area of two-dimensional image of aggregate A_a and mean area of primary particle A_p :

$$N = k_\alpha \left(\frac{A_a}{A_p} \right)^\alpha , \tag{27}$$

where α is an empirical constant of projected area and k_α is a proportionality factor. This relationship can be used to evaluate the number N of primary particles of aggregates. Koylu et al. (1995) [46] report the compatibility of the measured values with the values found by the computer simulations of the aggregates, respectively $k_\alpha = 1.16 \pm 0.18$ and $\alpha = 1.1 \pm 0.02$. The exact values of α and k_α depend on the parameter δ of the overlap of primary particles in the aggregate, which is difficult to calculate directly from the image. Oh and Sorensen [48] report the values: $k_\alpha = 1.17 \pm 0.02$ and $\alpha = 1.07 \pm 0.01$ for $\delta = 1$ (without overlapping) and $k_\alpha = 1.81 \pm 0.03$ and $\alpha = 1.19 \pm 0.01$ for overlapping $\delta = 2$.

After N and R_g are estimated, a logarithmic scale plot of the number N as a function of L/d_p or R_g/d_p is graphed. The slope of the line that best fits the data on the graph gives the fractal dimension and the value of k_f is found from the intersection of this line with $\log N$ axis.

Comparison of the results obtained from the application of the RDG approximation [45] with the results obtained from the application of the exact theory of electromagnetism for soot aggregates [39], gives a percentage deviation of 10%. The RDG approximation is a simplified theory that gives approximate estimates of scattering and absorption cross sections, with considerable inaccuracy caused from the calculation of the number and size of primary particles, fractal dimension and complex refractive index.

Liu and Snelling (2008) [37] evaluated the accuracy of the RDG approximation for the absorption and scattering properties of fractal aggregates and came to the conclusion that the RDG theory underestimates the aggregate absorption and total scattering cross section areas by approximately 10 %, depending on the aggregate size. They showed that with increasing the number of monomers N the total scattering cross sections increase sublinearly in good agreement with other studies (farias, sorensen).Through their research, Sorensen et al. (2018) [49] have raised the questions how well and under what conditions the Rayleigh-Debye-Gans (RDG) approximation describes scattering and absorption of light by fractal aggregates including soot. They found a weak functionality of the deviation versus the number of monomers in the aggregate N and the smaller size parameter shows smaller deviations from RDG theory. Also, they found that refractive index has strong impact on the degree of deviation from the internal multiple scattering effects (RDG limit), the real part of the refractive index caused positive deviations form RDG theory whereas the imaginary part caused negative deviations.

Conclusions

Different theories describe the scattering and absorption of light, depending on the size, shape, refractive index of the scattered particles and incident wavelength. Rayleigh theory describes the molecular scattering and absorption of light in air. The Rayleigh scattering and absorbing cross- sections are valid for particles that have dimensions much smaller than the wavelength of the incident radiation $\left(x_p \ll 1\right)$, regardless of the shape of the particles. The Mie theory of scattering is a rather complicated theory, which deals with the problem of scattering and absorption of a plane wave by a homogeneous sphere. The Mie Theory is applicable for spherical particles under condition $x_p \approx 1$. Raleygh –Debay- Gans approximation is applicable for aggregates with primary particles within the limits of Rayleigh and refraction index $|1-m| \prec 1$. The Rayleigh-Debye-Gans (RDG) approximation can be used to calculate the optical characteristics of soot particles.

Academics are concerned about the challenges involved in creating meaningful intersection of theoretical knowledge and research in the higher education. A research-led teaching approach in the context of the interaction of aerosol particles with electromagnetic radiation aerosol is suggested in the present work. The suggested approach aims to equip students with competences required to apply their theoretical knowledge across all areas of aerosol research and even more broadly. Course design that guide the students through sharing research knowledge with academics shapes the students' experience. Alignment of the instructor's expertise with teaching subject is the key to succeed the research-teaching connection.

This research -based approach offers a teaching material for developing content and applying that knowledge in research work within undergraduate and graduate programs of atmospheric physics/chemistry, environmental sciences and engineering, meteorology, and climate change.

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