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Light transmission through dense packings of glass spheres

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Despite the great number of studies concerning the propagation of light through random media, the exact way it propagates through dense translucent granular systems is still an open problem. Here, we are interested in the transmission of light through disordered packings of glass spheres. We use monodisperse systems with different diameters and propagate intense ultraviolet light through them. By measuring the outcome of the light signal with a calibrated radiometer and by using radiochromic films to get the radiation pattern, we found two different modes of transport: one entirely diffusive and the other non-diffusive.

Keywords: Granular packings; light transmission; radiation transfer.

Aún cuando existen muchos estudios sobre la propagación de la luz a través de medios desordenados, la propagación de señales luminosas en medios densos granulados translúcidos es un problema abierto. En este trabajo estamos interesados en la transmisión de luz en columnas granulares desordenadas compuestas de esferas de vidrio. Para este fin usamos monodispersiones de diferentes tamaños y luz ultravioleta. Midiendo la luz que sale del medio granular mediante un sensor de luz UV y usando películas radiocrómicas, obtenemos el patrón de radiación. Se distinguen dos modos de propagación, uno difusivo y el otro no difusivo.

Descriptores: Medios granulares; transmisión de luz; transferencia de radiación.

PACS: 42.25.Dd; 78.35.+c; 81.05.Rm

1. Introduction

The study of how electrical currents, heat, or acoustic waves propagate through granular media is, at present, an important issue in science [1,5]. It has been established that granular materials exhibit unusual properties, different from solids and liquids [6]; thus, the comprehension of these transport phenomena could give useful insights into the way physical transport occurs in nature. For instance, sound propagates through granular media in odd ways, giving rise to an ambiguous determination of the sound velocity [4]. Also, since acoustic signals propagate within the granular medium predominantly along force chains, any change in the packing configuration produced by thermal expansion of a single grain may produce changes in the transmission. The knowledge gathered so far by these studies is used nowadays in robust techniques to study stress fields within granular media in general [5] or in the fields of solid mechanics and geophysics [7,8].

Given that in classical electrodynamics light is described as a wave, a question physicists would like to answer is the following: does light propagate through granular beds like a sound wave? The answer to this question requires a comprehensive understanding of how light propagates in a strongly inhomogeneous medium where a lot of scattering events take place. Since these events are independent and the particles randomly positioned, interference between different paths is smoothed out by the disorder. In this case, although light is a wave and therefore there is no stochastic force that may produce a random walk, the multiple scattering path can be described indeed as a random walk.

In the scientific literature one finds several works reporting on light propagation within granular media at the optical wavelength scale (see for instance Refs. 9 and 10), or through media with even smaller scatterer particles [11,12]. However, as far as we know, there are no studies aiming to understand the phenomenon of light transmission through packings made of larger grains. The purpose of this work is to investigate the propagation of light through a dense medium composed of millimetric glass spheres. We are interested in knowing how the transmission of light behaves as the diameter of the spheres changes.

2. Experimental procedure

The experimental setup used in this work is shown in Fig. 1. Monodispersed borosilicate glass spheres (PGC Scientifics) with diameters 5, 3, 2, 1, and 0.5 mm were used in the experiments. The spheres are gradually poured inside a test tube whose inner diameter was 4 cm. Since there was no shaking of the samples afterwards, the packing fraction was ~ 0.57, which corresponds to the random loose packing. The bottom of the tube was a microscope slide. Below the slide there was a UV sensor (connected to a RM-21 radiometer, Grobel) and between the slide and the sensor, a MD-55 radiochromic film (International Specialty Products) was placed to capture the scattering pattern. The film is originally nearly transparent and turn to blue progressively according to the UV radiation absorbed [14]. Radiochromic films are made of photo sensitive materials that polymerize with UV light, and this is the reason we do not use other types of sources such as IR.

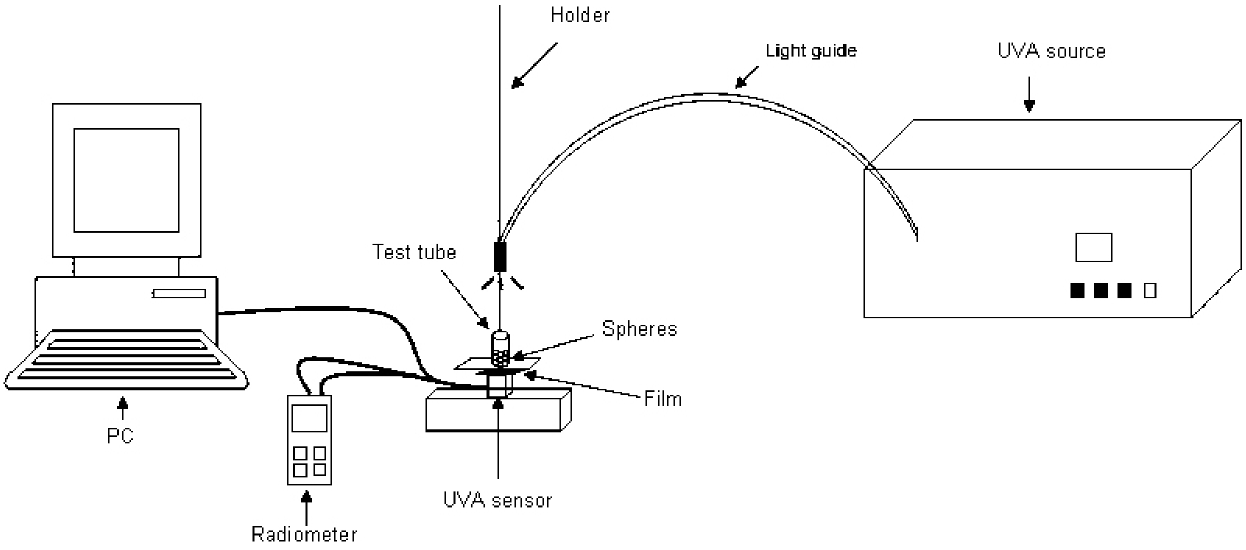

FIGURE 1. Experimental setup. A beam of intense light is shone onto the surface of a granular column whose height can be varied. The beam is brought from a light source to the granular sample by means of a water light guide. A UV sensor (connected to a radiometer) is placed at the bottom of the samples to measure the intensity of the transmitted light. Radiochromic films can be inserted between the sensor and the bottom of the granular container to capture the scattering pattern.

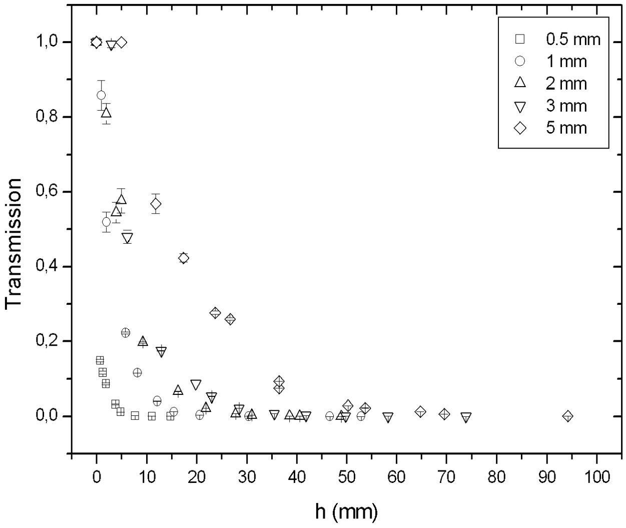

FIGURE 2. Light transmission as a function of the height of the granular column for different sphere diameters. We observe that the smaller the diameter of the grains, the faster the decay in the light signal.

The total height of the columns in every measurement varied depending on the sphere size (see Fig. 2). Indeed, as we changed the diameter of the spheres we always measured from maximum transmission to almost zero transmission. Therefore, different diameters gave different heights. The test tube was located 1 cm below a water light guide that conducts the signal from the UV source to the samples. The light source is an intense HP-120 UV point light that emits UV and visible radiation (300-600 nm). For every measurement an exposure time of 35 seconds was used. The experiments were carried out in a darkened room.

3. Results and discussion

Transmission curves, as a function of the column heights for five different diameters, are shown in Fig. 2. The effect the diameter of the glass spheres has on the propagation of light is clearly observed in the plots. As the diameter of the spheres increases, the decay of the signal is less and less pronounced, *i.e.*, the bed is more translucent. To see if some scaling is present, the height h is divided by the diameter of the spheres d. Figure 3 shows the light transmission values versus h/d. Interestingly, the first four plots (for diameters 5, 3, 2, and 1 mm) collapse. This means that what matters in the transmission is not the size of the particles, but the number of layers in the column. The transmission curve for the smallest diameter (0.5 mm), however, follows a different behavior: it decays faster than the others.

We would like to know which of the above light behaviors, if any, is diffusive. Normally, diffusion is related to gases or suspended particles in liquids, but not to light. Indeed, light is a wave, not a particle that bounces back and forth in a Brownian motion. Nevertheless, the random walk picture that explains a diffusive process is able to describe as well the transmission of light through random media [11]. Since successive scattering events of light inside a random translucent medium are independent, the distribution between two events can be considered Gaussian. As a consequence, the propagation is diffusive. Mathematically, if the energy density $\rho(r,t)$ is given by:

$$\rho(r,t) = \rho_0 \frac{1}{\sqrt{4\pi D t}} e^{-\frac{|r|^2}{4Dt}} \tag{1}$$

then light diffuses through an inhomogeneous medium following the Einstein relationship, *i.e.* $\langle r^2 \rangle = 2\rho_0 D t$, where

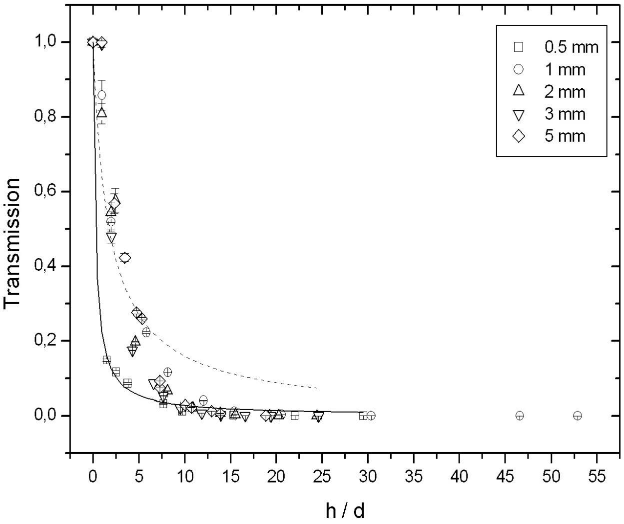

FIGURE 3. Transmission as a function of h/d. All the transmission curves, except the one corresponding to $d = 0.5$ mm, collapse reasonably well in one curve. The dotted line depicts a superdiffusive transmission (see the text). The solid line is the best fit of Eq. 2 to the transmission curve corresponding to $d = 0.5$ mm ($A = 3.46$ and $\alpha = 2 \pm 0.02$), indicating that this is the only case that is diffusive (see the text).

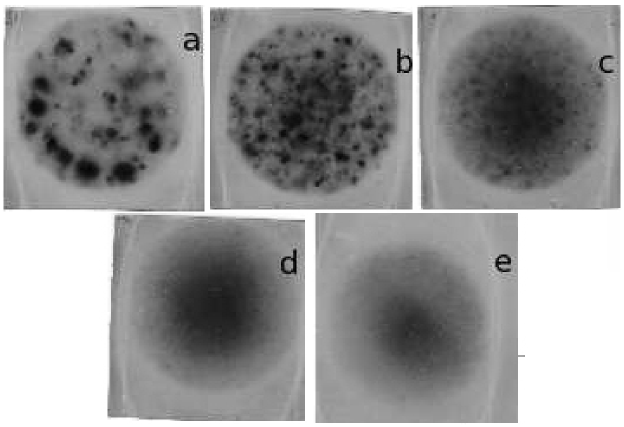

FIGURE 4. A sequence of radiochromic films after being radiated with light coming out from the granular samples. (a) corresponds to $d = 5$ mm, (b) to $d = 3$ mm, (c) to $d = 2$ mm, (d) to $d = 1$ mm, and (e) to $d = 0.5$ mm. It can be observed from these patterns that the scattering is diffusive only for the last case.

D is the diffusion coefficient. This expression can be extended to $\langle r^2 \rangle = 2\rho_0 D t^{\gamma}$ to describe subdiffusive ($\gamma < 1$) or superdiffusive ($\gamma > 1$) transmission processes.

Superdiffusion of light ($\gamma > 1$), linked to a special random walk called Lévy flight, has been observed recently by Barthelemy *et al.* [12] in a dielectric matrix with embedded particles and by D. Sharma *et al.* in a random amplifying medium [13]. A very simple way Barthelemy *et al.* used to evaluate how close a transmission process is from a diffusive regime, is by using Ohm's law decay. Ohm's equation reads:

$$T = \frac{1}{1 + AL^{\alpha/2}} \tag{2}$$

where $L = h/d$, A is a constant and α is related to γ in the following way: $\alpha = 3 - \gamma$ [12]. Therefore, $\alpha = 2$ means normal diffusion and $\alpha < 2$ superdiffusion.

We observe that the transmission data for $d = 0.5$ mm are well fitted by the above equation, giving $\alpha = 2 \pm 0.02$ (*i.e.* $\gamma = 1 \pm 0.02$) (see the solid line in Fig. 3). Accordingly, only for these spheres the light transmission is completely diffusive. For the other sizes, two behaviors are observed: light transmission seems to be superdiffusive for $h/d < 8$ and diffusive for $h/d > 8$. The dotted line in Fig. 3, corresponding to superdiffusion, has been obtained with $\alpha = 1.94 \pm 0.02$ (*i.e.* $\gamma = 1.06 \pm 0.02$) and $A = 0.56$.

Even if the transmission data decay slower than the diffusive line, and at small values of L are well fitted by the superdiffusive dotted line (Fig. 3), we must take care interpreting the results for the larger spheres. In order to say more about this behavior, we can spy on the way light transmits along the granular samples using radiochromic films. Such films change to a dark color when UV light impinges onto them. Therefore, put at the bottom of the samples, they would capture the scattering patterns. Figure 4 shows a sequence of these films obtained at a transmission of 0.2, *i.e.* at h/d values where the propagation seems to be superdiffusive. The patterns clearly depict the way light propagates through and exits from the samples. In order to develop some color, the beam was on during 35 seconds. Figures 4a to 4d indicate that light propagates non-diffusively but through a channeling-like way: *i.e.* light travels inside the glass spheres until it reaches the radiochromic film, leaving well defined discrete spots. This is a clear indication of the non-diffusivity found in Fig. 3, since a diffusive scattering would give a uniform shadow as in Fig. 4e. Whether these channeling-like processes are ballistic or not, requires further investigation.

Recently, two groups have reported the existence of photon channeling in aqueous foams [15,16]. Although different in nature, there are some similarities between foams and granular beds. An aqueous foam consists of gas bubbles separated by liquid films. When light propagates through the foam, it mainly does so through the liquid interface and it is scattered by the gas bubbles [15,16]. Therefore, even if this type of transmission looks like a Lévy flight, it is not superdiffusive in the sense described by the Einstein equation with $\gamma > 1$. Why? Because even if a Lévy flight is not diffusive, it is erratic, whereas the way light transmits through a foam, or through our granular samples, is guided (*i.e.*, not necessarily random).

Our experimental results show that light propagates through dense granular beds following a diffusive and non-diffusive transmission. Light travels diffusively through beds made of small grains but non-diffusively through beds with larger ones. However, our findings indicate that through sufficiently thicker samples, regardless of the size of the particles, light transmission seems to have a diffusive trend.

Acknowledgments

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