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The dynamics of diffracted rays in foams

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A R T I C L E I N F O

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A B S T R A C T

We have studied some aspects of the optics of the light scattering in foams. This paper describes the difference between rays and diffracted rays from the point of view of geometrical theory of diffraction. We have represented some bifurcations of light rays using dynamical systems. Based on our observations of foams, we created a solid optical device. The interference patterns of light scattering in foams forming Airy fringes were explored observing the pattern named as the eye of Horus. In the cases we examine, these Airy fringes are associated with light scattering in curved surfaces, while the halo formation is related to the law of edge diffraction. We are proposing a Pohl interferometer using a three-sided bubble/Plateau border system.

1. Introduction

The sight of a halo in the sky hardly ever fails to evoke a sense of wonder. Similar patterns are seen in different contexts, for example, the parlaseric circle in light scattering in foams [1]. A possible connection between these halo patterns of the atmospheric optics and light scattering in soap films could be based in the concept of diffracted rays, introduced by the geometrical theory of diffraction [2,3]. From the point of view of this theory, the diffracted rays are produced by incident rays which hit edges, corners, or vertices of boundary surfaces, with the effects of ray splitting. Ray splitting is in fact a general phenomenon of wave propagation in optics at interfaces with sudden change in the refractive index, such as the Plateau border, which is the intersection of three thin films of soap bubbles. The pattern presented in Fig. 1 is a three-dimensional scattering of a laser beam hitting obliquely a Plateau border. The Plateau borders and ice crystals share this property, along with geometrical symmetry, and when these systems interact with light, halos and light spots can be formed, with the coexistence of light rays and light diffracted rays. However, it raises some questions: What are the conditions in which light behaves as a diffracted wave and a ray at same time? What is the difference between light rays and diffracted rays?

One possible way to answer these questions is doing experiments and comparing the observed effects with some patterns reported in the literature. For example, the physical phenomena explicitly associated with thin film interference colors have been observed since antiquity, in some Babylonians cuneiform texts [4,5] four millennia ago, and people have used optical elements to change the direction of propagation of light such as lenses, prisms, mirrors, beam splitters, filters, diffusers, polarizers, diffracting gratings, halo generators, systems in optofluidics, and so on. In the context of halo generators, some authors have reported the observation of patterns such as the Keller's cone in laser/razor blade

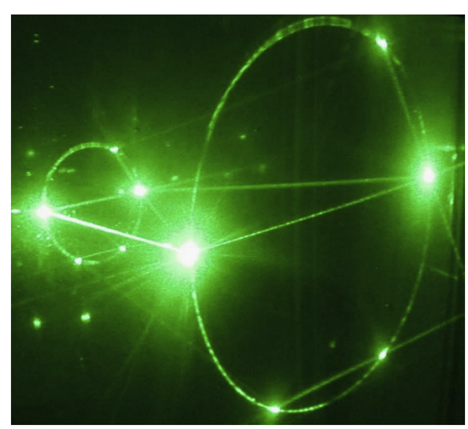

Fig. 1. Observing diffracted rays, in the image of the conic structure of the laser scattering in a Plateau border. This structure is inside a glass box filled with water. The small halo at left is where the light enters the back side of the box. Light travels through the box and it is scattered by the water. When light hits the next side of the box, we can see a larger halo. According to geometry, it is known that the cross section of a cone can be a circle, ellipse, parabola, or hyperbola, depending on the position and orientation of the observing plane. The conic scattering occurs when light hits obliquely needles, hairs or Plateau borders, and this type of light scattering is a signature of the existence of diffracted rays.

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demonstrations [6], or witnessed halos related to the geometrical theory of diffraction in a hotel room [7]. According to Keller [8], the geometrical theory of diffraction is an extension of geometrical optics, and it earned a remarkable success mainly for engineering problems, by applying Fermat's principle, and by observing that high-frequency diffraction is a local phenomenon, reducing the solution for the scattering of electromagnetic waves from complex objects, such antennas or airplanes, to the superposition of simple canonical problems, such as wave scattering in an edge and a vertex, or creeping waves in cylinders. This theory was improved with its uniform versions, and some authors claim that the concept of diffracted rays is closely related to Young's edge wave picture [9], and these ideas have been pursued in quantum chaos [10], acoustics, and elasticity [11].

The observation of such patterns is also important in ophthalmology, because halos are symptoms described by patients, for example, medical students are taught that patients developing glaucoma report seeing colored halos, or the existence of epithelial corneal edema caused by poorly fitted contact lenses [12], and even Isaac Newton wrote about the observation of white, dark, and colored circles, while pressing his own eyes [13]. The role of colored circles fit into many of Newton's interests, for example, he discovered the colorful patterns when a convex lens is placed on a flat glass plate, and light rays are reflected by the plate and by the lower surface of the lens. The two groups of reflected rays interfere with each other to produce Newton's rings [9].

The aim of this Letter is thus to explore some patterns obtained by light scattering in detergent films and to investigate some dynamical systems related to these patterns. In order to accomplish this goal, this paper examines some aspects of the geometrical theory of diffraction in elements of foams and suggests new kind of optical element based on foams, and presents new patterns observed when light is scattered in foams. In the next section we describe our experimental apparatus. After that we present some results of light scattering in a straight surface Plateau border in Section 3. In Section 4, we discuss some aspects of dynamical systems in the formation of the parlaseric circle, including maps and bifurcations. We present a new pattern observed in laser beam scattered in three-sided bubbles in Section 5, named the eye of Horus, with a possible application to interferometry, and we close this paper in Section 6 with our conclusions.

2. Experimental apparatus

For a light wave, a foam is a complex system of arbitrary shaped interfaces, at which light is reflected, refracted, and diffracted multiple times. Because of this, we focused our attention in three specific film shapes shown in Fig. 2(a): a liquid bridge with surface Plateau borders, the Plateau border, and in the three-sided bubble, known as the tetrahedron bubble. The liquid bridge is observed between two Plexiglas plates separated by 2.0 cm, with these plates forming a box. In order to increase the stability of liquid film, the Plexiglas box is sealed, preventing the liquid film from evaporating, as reported by some authors [14]. The liquid bridge is one of the most studied soap film system and it consists of two vertical surface Plateau borders connected by a single thin film. While the thickness of the thin film ranges from 0.1 μm to 10 μm, the curvature of the surface Plateau border depends on the liquid content of the foam and the wetting properties of the Plexiglas plates, so their thickness is about 0.5 mm. In our experiment, we have taken measurements after one hour of drainage. The second optical element has a little more complex structure, the Plateau border, and it is the place where three films meet, forming a small triangular tube connected to each plate by three surface Plateau borders, represented at the bottom of Fig. 2(a). The Plateau border is in the horizontal direction, orthogonal to the two

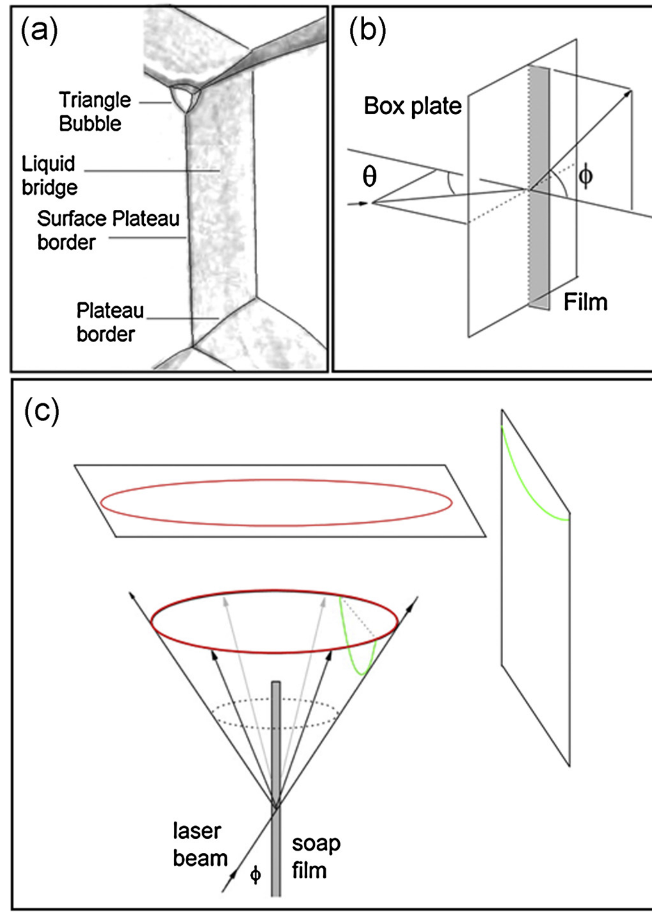

Fig. 2. Sketch of the foam for three types of geometry of the optical device used in our experiment: the liquid bridge, the Plateau border, and the tetrahedron bubble in (a). The liquid bridge is a detergent film. The Plateau border is the place where three detergent films meet. The tetrahedron bubble is related to the vertex structure, the place where four Plateau borders meet. The laser beam is directed on to each one of these devices to produce some patterns depending on the angle of incidence θ and ϕ. In (b), the angle θ denotes the inclination of a direction with respect to the horizontal plane, which is normal to the vertical plane of the liquid bridge, while the angle ϕ is the inclination of a direction with respect to the vertical plane. For example, if the Plateau border axis is in the same direction of the laser beam, these two angles are equal to zero. We have used two different positions for the screen, as it is shown in (c).

straight surface Plateau borders discussed in the previous case of the liquid bridge.

The tetrahedron bubble is shown at the top of Fig. 2(a), and it is the optical element constructed using a three-sided bubble, with Plateau borders, surface Plateau borders, and thin films forming a vertex structure. The vertex structure consists of six thin films forming a junction of four Plateau borders, a straight one, and three curved Plateau borders. The vertex is also known as Plateau border junction [15]. Due to the complexity of this structure, the tetrahedron bubble will be described in more detail in Section 5.

Based on our observations of foams, we have developed a solid optical device shown in Fig. 3. This device was produced by physically forming a groove in a polished acrylic glass disc, and the diagram of this device is shown in Fig. 3(a), and in the photograph of Fig. 3(b).

We have studied the effects of laser beams hitting the detergent films and the solid optical device at different angles. The direction of illumination is defined by the angles θ and ϕ in Fig. 2(b). The inclination in the same vertical plane of the liquid bridge is ϕ, and the angle in a horizontal orthogonal plane with the respect of the liquid bridge is θ. The light pattern is projected in the screen