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DIFFRACTION OF COHERENT LIGHT BY DIFFUSING SURFACES

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ABSTRACT

The rather unusual phenomena observed when diffusing surfaces are illuminated by coherent light have attracted considerable attention in the past few years. Recent work on the theory of these effects is briefly reviewed, and their principal features are examined. It is pointed out that similar effects were studied, and some of these conclusions were anticipated in earlier work by Professor Raman and his school.

CONSIDERABLE attention has centred in the past few years around the rather unusual phenomena observed when the beam from a continuous gas laser (such as a helium-neon laser) is scattered by a diffusing surface. The bright illuminated area then exhibits a remarkable granular appearance, not seen by ordinary light, and appears to scintillate or sparkle when there is relative motion of the surface and the observer[1,2]. The scale of the granularity increases when the viewing distance is increased, and also when the relative aperture of the viewing system (the pupil of the eye, or the iris diaphragm of a camera) is decreased. On the other hand, the general appearance of the granularity is essentially independent of the character of the surface and the viewing distance. A photographic film exposed directly to the radiation scattered by the surface records a random speckle pattern, as shown in Fig. 1.

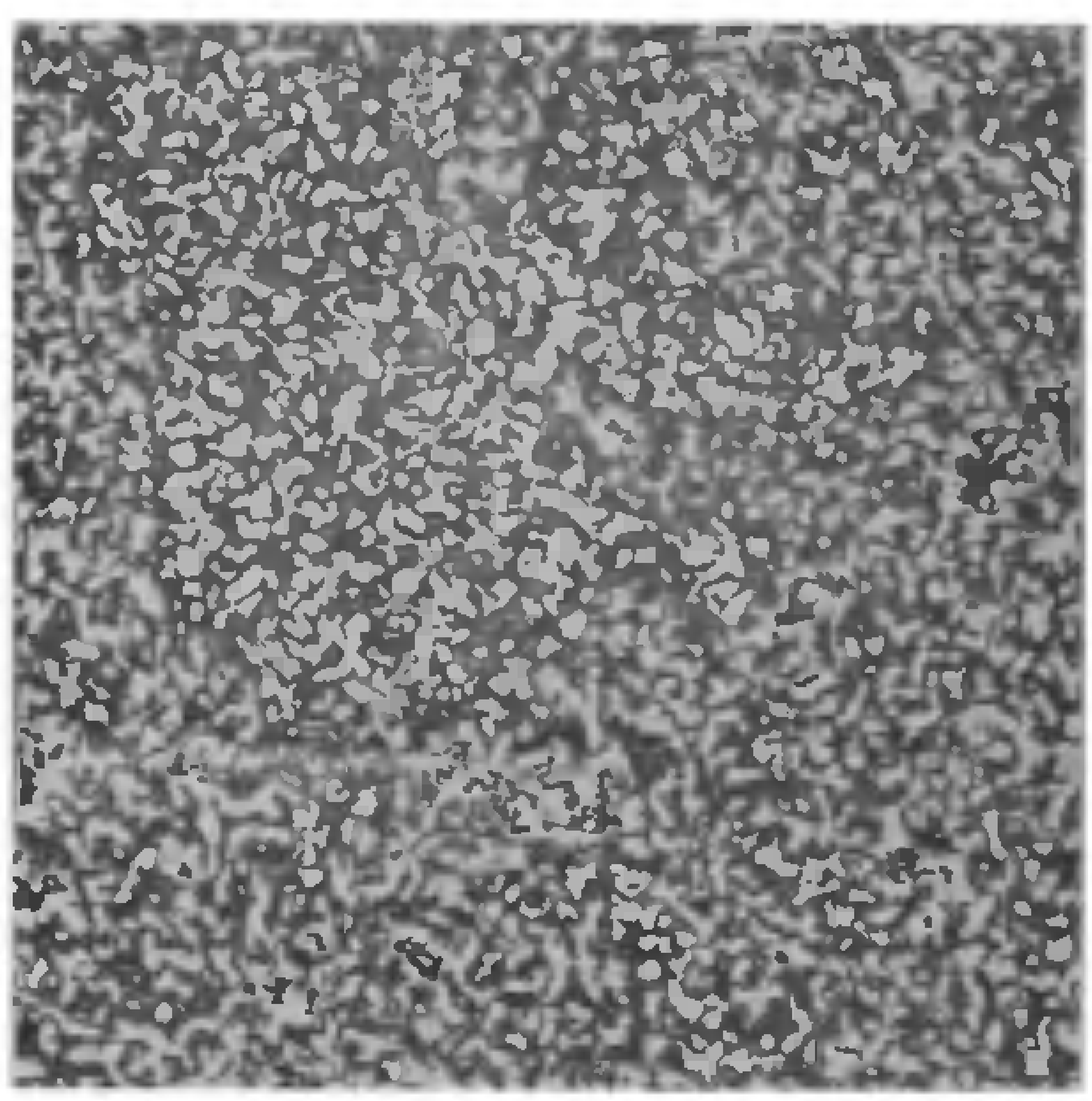


FIG. 1. Typical speckle pattern formed when a ground glass surface is illuminated by a coherent beam from a helium-neon laser.

The formation of such speckle patterns has been attributed to the high spatial coherence of the beam emitted by the laser. It can be explained on the hypothesis that coherent light reflected or transmitted by a diffusing surface produces a random, many-lobed, stationary pattern arising from the interference of the completely coherent diffracted beams from individual elements on the diffuser. Rapid movement of the diffuser results in variations in the appearance of the pattern which are too quick to be perceived by the eye, so that the pattern disappears. Similarly, with a diffuser consisting of a colloidal suspension, the Brownian movement of the individual scatterers causes rapid changes in the configuration of the interference pattern so that it can no longer be seen.

Since this phenomenon is essentially linked with the spatial coherence of the illuminating beam, such speckle patterns can be observed even with non-monochromatic sources, such as unfiltered sunlight, when the illuminating beam is, to some extent, diffraction limited[3]. (With such sources, due to the finite range of wavelengths present, the pattern exhibits beautiful, vividly coloured, radial streamers.) A recent analysis of the phenomenon of scintillation with projection screens has, in fact, shown that a major contribution is interference of the diffracted light which is directly related to the coherence properties of the projection optics[4].

The formation of laser speckle patterns was analysed in 1963 by Langmuir[5] and by Allen and Jones[6] who pointed out the similarity to the problem in radiophysics when a radio wave is reflected by a rough surface such as the ground. By considering the diffuser as a random array of coherent sources they showed that the power P received at any point in the pattern has a probability distribution proportional to $\exp(-P/P_0)$, where P_0 is the average power received, and that, therefore, large fluctuations in intensity could be expected in the pattern.

More detailed theoretical studies were made by Goldfischer[7] in 1965, and by Suzuki and Hioki[8] in 1966. Goldfischer's analysis was based on the assumption that the diffusing surface consists of an infinitely dense collection of scatterers, with random phases but uniform attenuation. Suzuki and Hioki, on the other hand, treated the diffusing surface as spatially continuous, in order to obtain a more generalized formulation and also because of certain problems which they considered inherent in Goldfischer's analysis.

More recently, this problem has been studied in detail by Crane[9], who also considered Goldfischer's model of a diffusing surface as unrealistic.

Following Crane's treatment, if we assume (*see* Fig. 2) that a coherent beam

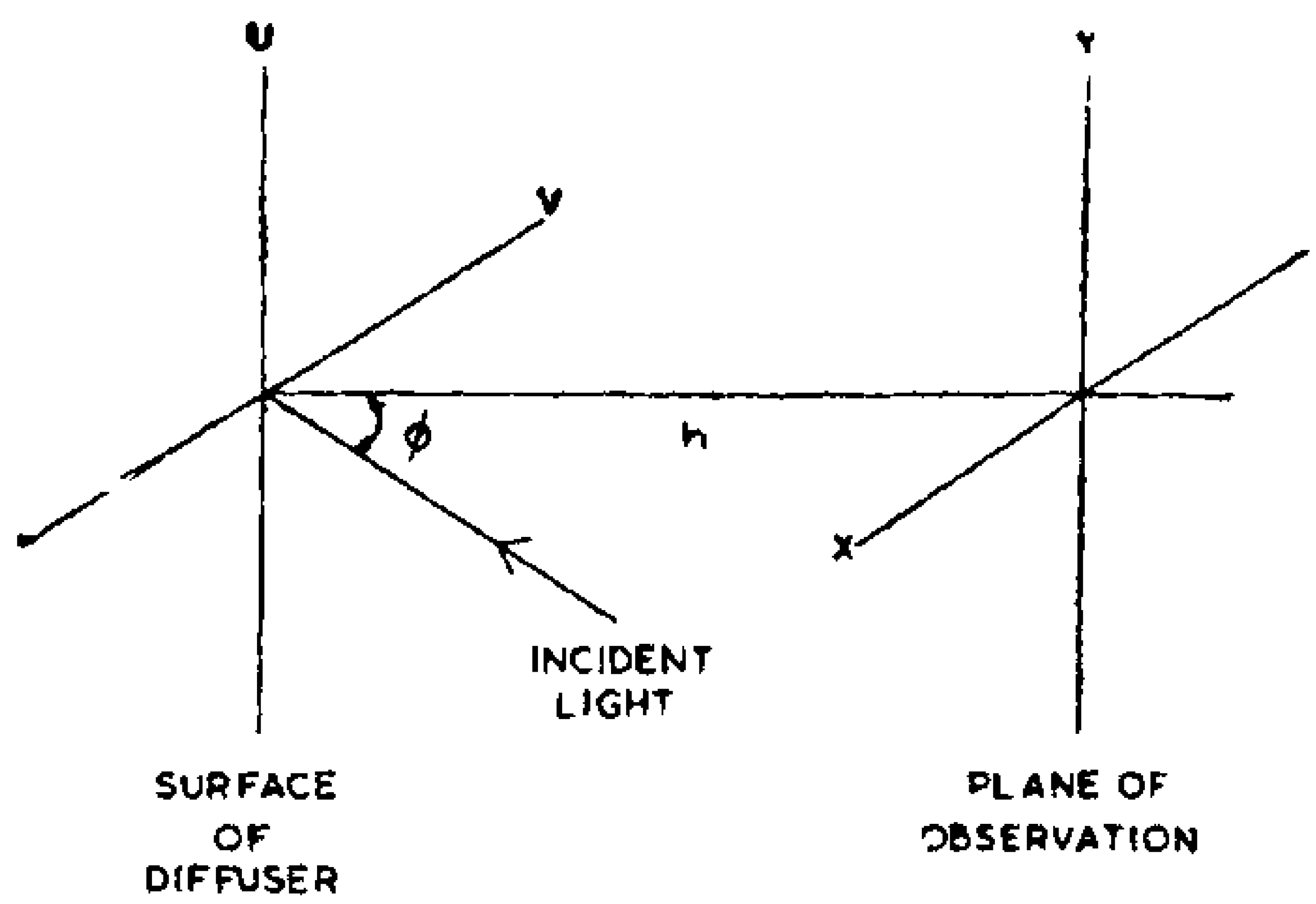


FIG. 2. Co-ordinate system for analysing the characteristics of coherent light diffracted by a diffusing surface.

of light is incident at an angle ϕ on a random reflecting surface, whose aperture is defined by the function $g(u, v)$, and whose deviation $W(u, v)$ from a plane at any point has a gaussian distribution, we find that $E[S(\omega, \Omega)]$ the average value of the power spectral density in the diffraction pattern formed in the plane of observation for spatial frequencies (ω, Ω) along the x and y directions, is given by the relation

$$E[S(\omega, \Omega)] = \exp. \left\{ -2 \left[\frac{2\pi}{\lambda}(1 + \cos\phi)\right]^2 \left[R_w(0, 0) - R_w\left(\frac{\lambda h \omega}{2\pi}, \frac{\lambda h \Omega}{2\pi}\right)\right]\right\}$$
$$\times \left| \int\int_{-\infty}^{\infty} g(u, v)\, g^*\left(u - \frac{\lambda h \omega}{2\pi}, v - \frac{\lambda h \Omega}{2\pi}\right) du dv \right. \quad (1)$$

where $R_w(\alpha, \beta)$ is the autocorrelation function of $W(u, v)$. The average value of the power spectral density is accordingly the product of a surface function and an aperture function. The aperture function is proportional to the square of the modulus of the self-convolution of the aperture, and determines the maximum spatial frequency which occurs in the pattern. On the other hand, the effect of the surface function, particularly for surfaces with a fine structure, is limited to low spatial frequencies in the pattern.

As distinct from the direct scattered field, the intensity fluctuations in the image of a diffusely reflecting object illuminated by a coherent beam have been studied by Enloe[10], Hopkins and Tiziani[11], and Dainty[12]. In this case, the variance of the intensity fluctuations is equal to the square of the mean intensity, while the spatial autocorrelation function and the power spectral density of the intensity fluctuations in the image are dependent upon the size of the aperture stop, which acts as a low pass filter. For simplicity, the entrance pupil can be considered as being illuminated by the primary diffraction pattern. This random illumination then appears in the exit pupil, so that the fluctuations in the image are obtained by considering the exit pupil again as a rough object.

The pronounced and irritating granularity due to speckle patterns is a major problem in holography[13]. They are also a source of noise in optical data processing. Early discussions of laser speckle have, in fact, been concerned mainly with ways to minimize its detrimental effects, and it is only relatively recently, that quite a few useful applications have been suggested.

One of the first and most obvious was in the detection of mode multiplicity in the output from high power gas lasers; in this case, any reduction in contrast of the speckle pattern provides a highly sensitive indication of additional transverse modes.

More recently, such patterns have been utilized by the author[14] as a random test pattern with a known spatial power spectrum in a very simple and rapid method for measuring the modulation transfer function of photographic materials.

Other applications have been concerned with studies of surface displacements, or the analysis of vibrating surfaces. One early technique was based on optical correlation of the speckle pattern recorded with the test specimen at rest, or in its initial position, with another recorded later[15]. Another simpler technique for vibrating surfaces involves only direct observation or photography of the surface, and is applicable for relatively large amplitudes[16]. The nodal areas appear covered with a stationary speckle pattern of maximum contrast, while in the oscillating parts the resultant tilt of the surface blurs out the bright and dark areas, resulting in a reduction in the contrast of the pattern. In this case, if the viewing system is focussed on a plane somewhere between the vibrating surface and the observer, the vibrating areas appear covered with speckles that are streaked in the direction of the gradient. In a variation of this technique[17], a speckle pattern is formed by a diffuser on the surface of the object under study. The oscillating parts of the object move through the stationary speckle pattern and appear as fuzzy spots, whereas the nodal areas are covered with sharp patterns. Such techniques have the obvious advantage that they are quick and simple and can be applied to tilted, vertical, and curved surfaces, which cannot be studied by classical methods.

In yet another technique called speckle interferometry, which is much more sensitive, the speckle pattern derived from light diffracted at the surface is made to interfere with a uniform reference beam of comparable brightness, or with a second speckle pattern[18,19]. Slow movements of any region of the surface result in alternations of brightness of the speckles in these areas. For more rapid movements the speckles become blurred in the moving areas, resulting in a decrease in the contrast of the speckles.

By measuring the correlation between two speckle interference patterns recorded at different times, changes of relative phase can also be detected[20]. This permits measurement of the normal component of displacement of the surface. In addition, by a simple modification of the system in which the surface is illuminated with two coherent beams at equal but opposite angles to the normal, the in-plane component of the displacement can also be measured.

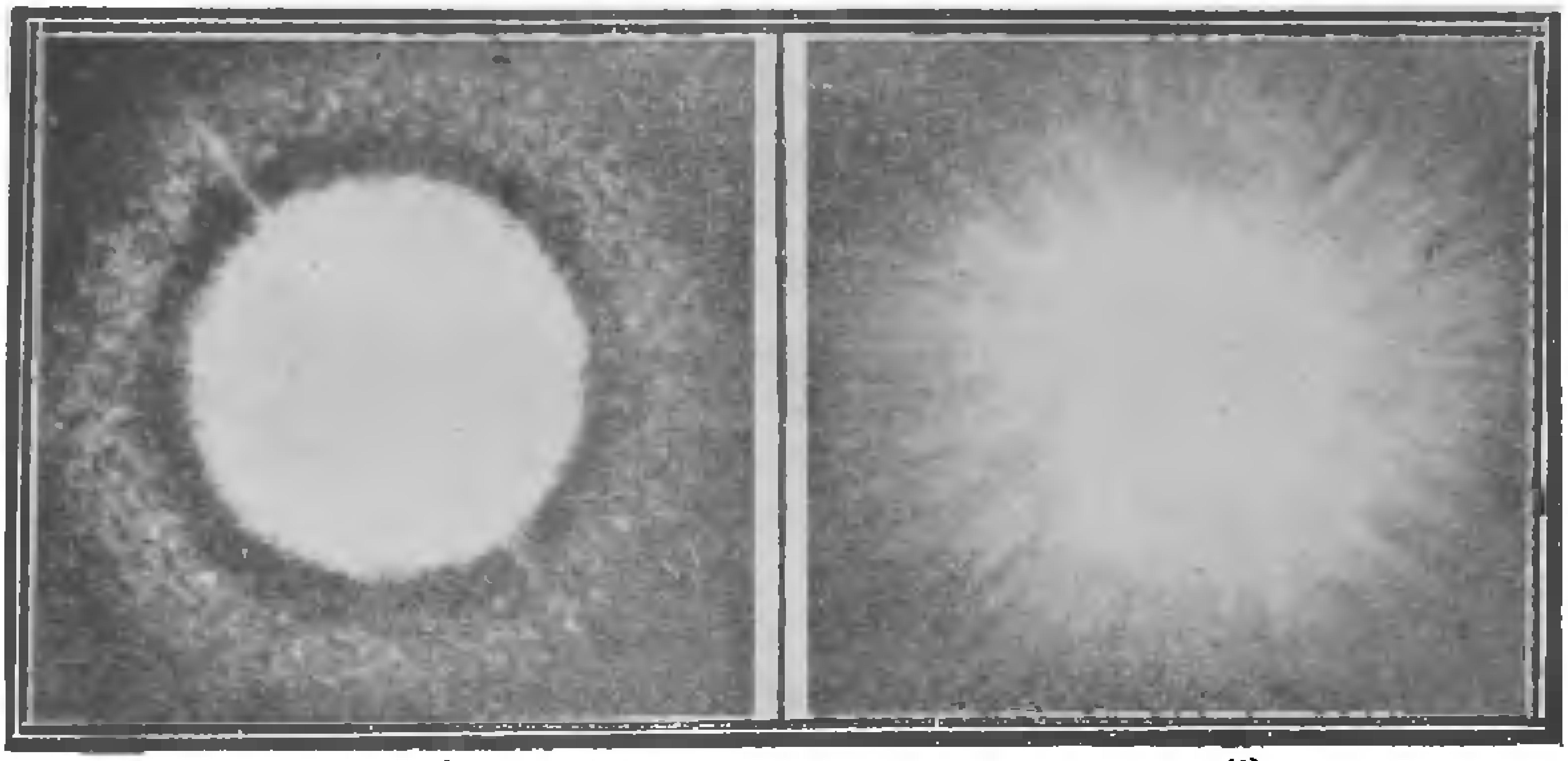
In view of the current wave of activity in this field, it is interesting to note that essentially the same phenomenon was studied by Professor Raman as far back as 1919[21]. It also seems rather unfortunate that no reference has been made to his contributions as well as those of his school in recent publications.

Professor Raman's interest appears to have been attracted, in the first instance, by earlier observations that when a very small and intensely luminous source of light is viewed directly against a dark background, it appears surrounded by a system of radiating streamers which seem to diverge directly from the source. This was wrongly attributed by Helmholtz earlier to diffraction at the irregular margin of the pupil of the eye. However, Professor Raman showed that this effect had a striking resemblance to the phenomena observed when a beam of light is diffracted by a large number of particles of uniform size distributed at random (*see* Fig. 3 *b*) and concluded that it was due to diffraction by particles contained in the structure of the eye. With a monochromatic source, instead of radial streamers, a circular halo showing bright and dark rings and exhibiting a finely mottled or granular appearance was seen around the source as shown in Fig. 3 *a*[22,23].

A quantitative theory of these fluctuations was worked out in 1934 by Ramachandran[24], in connection with a study of coronas. He pointed out that de Haas' earlier treatment[25] of the problem, in which the resultant intensity was considered as the superposition of interference fringes produced by each pair of particles, was inadequate, and that one must take into account the aggregate effect of *all* the particles. It is interesting that this paper anticipates several of the findings of recent studies.

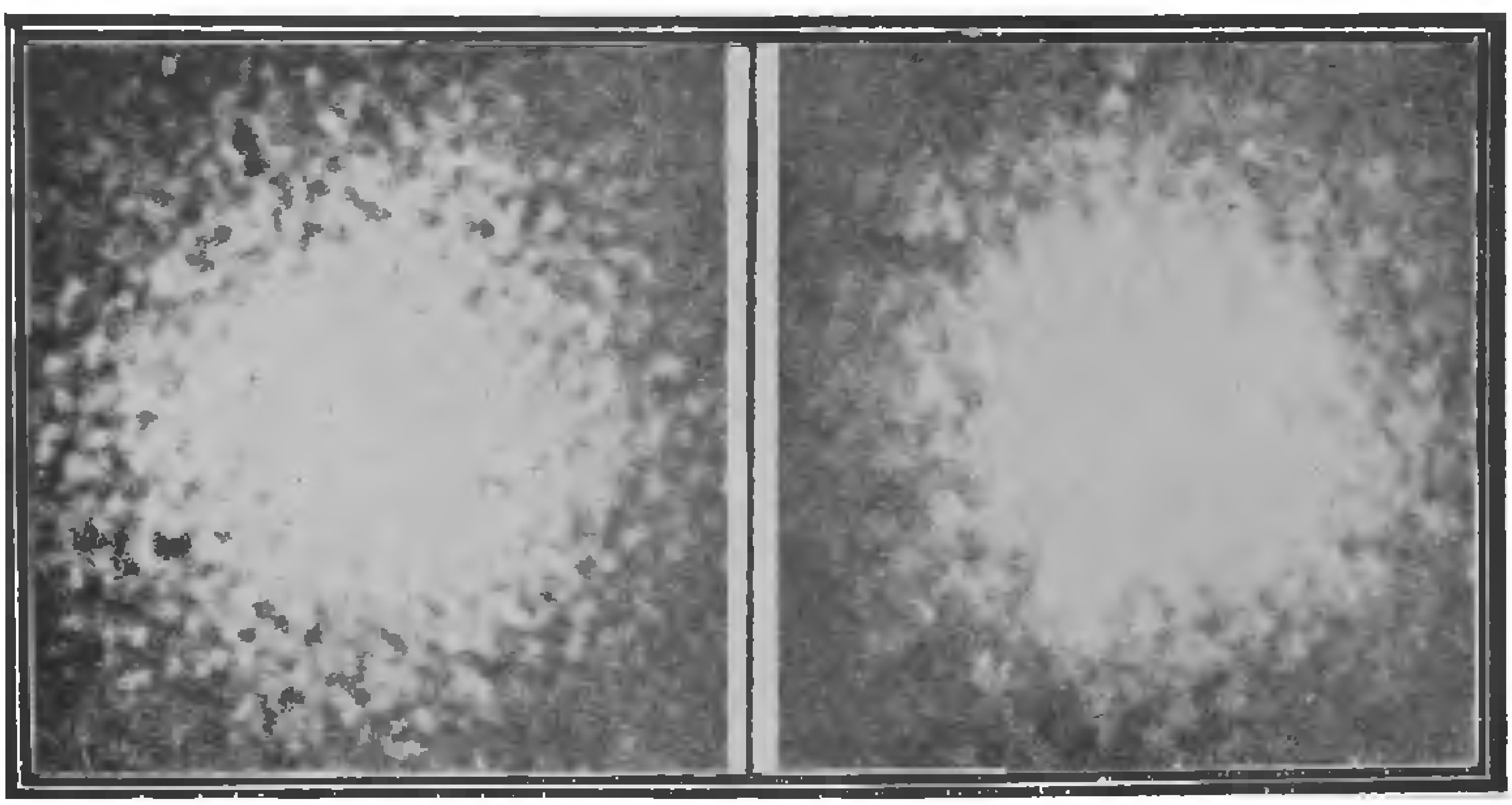
One of the most important conclusions, which was reached by applying Lord Rayleigh's expression for the distribution of intensity in the resultant due to n vibrations with random phases[26], was that the probability of occurrence of any intensity in the pattern (expressed as a fraction f of the average intensity) was a maximum for $f = o$ and decreased exponentially as f increased. This conclusion was also experimentally verified by classifying the spots in the successive rings of the corona according to their intensities.

that the angular width of the bright spots in the pattern was of the same order as that of an image of the source formed by a lens having an aperture equal to that of the diffusing screen, which is essentially the same conclusion arrived at recently by Hopkins and Tiziani[11]. This was also experimentally demonstra-



(*a*) (*b*)

FIG. 3. Halos formed by the diffraction of a coherent beam by randomly distributed particles (*a*) with monochromatic light, and (*b*) with white light.



(*a*) (*b*)

FIG. 4. Diffraction halo formed by randomly distributed particles when illuminated with light from (*a*) a circular source, (*b*) a triangular source.

The existence of an object-image relationship between the source and the spots in the pattern was also shown, leading to two results. The first was ted by varying the size and shape of the source and noting its effect on the appearance of the pattern. It was verified with a circular source, as well as with a triangular source, that all the bright spots in the field alter in the same way and have the same form as the source, and that the triangular spots appear inverted in the pattern as they would in the image formed by a converging lens (*see* Figs. 4*a* and 4*b*). The second was that any displacement of the diffuser resulted in a movement of the spots, exactly as if they were images formed by a lens at the same position—an effect also reported recently by Isenor[27].

Finally, it was shown that on increasing the aperture of the diffuser more spots must appear in the field of view corresponding to an extension of the spatial power spectrum to higher spatial frequencies, a conclusion also following from the recent, more detailed theoretical analyses of such patterns.

It is indeed a matter of gratification that this phenomenon, which attracted Professor Raman's attention half a century ago, and to whose elucidation his school made such substantial contributions, has once again become a subject of very live interest, and seems to offer much promise for the future.

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THE OPTICS OF HETEROGENEOUS MEDIA

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1. INTRODUCTION

I HAD occasion to read many of Prof. C. V. Raman's papers on the optics of heterogeneous media when I had to collaborate with Prof. G. N. Ramachandran in writing the monograph on Crystal Optics for Flugge's *Handbuch der Physik*. Recently I had to go deeper into many of these because of a rather interesting problem in materials science. When a composite or a polycrystalline aggregate is elastically deformed the question arises whether the strain-continuity condition is violated at the boundary between two phases or two grains? It seemed to us that the photoelastic measurements may be more effective in