white ones. Such details may perhaps be accounted for by physiology.

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[1] *Nature*, **164**, 999 (1949) and **165**, 146 (1950).
[2] *Mon. Not. Roy. Astro. Soc.*, **87**, 506 (1927). Strömgren, B., *Festskr. Nørlund*, 1945; etc.
[3] Minnaert and Houtgast, *Z. Astrophys.*, **10**, 86 (1935).

NONE of the correspondents writing on this subject appears to have taken into account the fact that, as viewed by most people, most of the stars do not scintillate when observed with the naked eye from a point within the tropics. This at any rate is my clear recollection after spending more than three years in the tropical zone.

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PROF. HARTRIDGE[1] may well inquire whether a subjective element contributes to the scintillation of stars, for there is more in twinkling than meets the eye. But tremulous images are not entirely due to the observer; they can be detected by the photographic plate. Schlesinger[2] discovered changes in atmospheric refraction which give rise to small oscillations of the telescopic image, with an amplitude of about 1″ and a period of about 1 min. Even zenith stars are affected[3], though to a less extent and with a shorter period. The effect on twinkling caused by these irregularities of refraction could perhaps be determined by visual and photographic measures made simultaneously.

On the other hand, Prof. Hartridge will derive support for his ideas from the motion of 'jumping stars' (the so-called *Sternschwanken*), into which, in some cases at least, a subjective element would seem to enter[4], especially when the eye is tired. As regards dispersion, stars near the horizon sometimes appear to be drawn out into short spectra; at smaller zenith distances the dispersion would not be appreciable.

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[1] *Nature*, **165**, 146 (1950).
[2] Schlesinger, F., *Mon. Not. Roy. Astro. Soc.*, **87**, 506 (1927).
[3] Barocas, V., and Withers, R. M. J., *Observatory*, **68**, 153 (1948).
[4] Weyer, G. D. E., *Astro. Nachricht.*, **119**, No. 2841 (1888).

THE observations of scintillation of stars reported by Gregory and by Morton[1] can be extended and confirmed by simple experiments. Using either field-glasses or a hand telescope, the image of a star such as Sirius can be made to move rapidly in circles over the retina. By controlling the shaking of the hands, the period of the movement and the size of the circles can be varied at will. The image of a star then appears as a circle of light, and the scintillation is seen as variation in the brightness and the colour of different parts of the circle.

If stellar scintillation were largely a retinal phenomenon, as suggested by Hartridge and Weale[2], the pattern on the circles would be expected to vary little with changes in the period of oscillation of the image, or the size of the circles traced out. If the effect is largely atmospheric, the rapidity of the brightness changes will not be affected by the movement, so that the appearance of the bright lines on the retina will change from lines of coloured dots to coloured streaks as the speed of movement of the image increases. This is found to be so. Scintillation is very obvious with bright stars like Sirius down to those in the Pleiades, even in a telescope giving a magnification of $\times$ 20. Planets show scarcely any trace of this effect.

Morton's observation of Sirius through misted glass can readily be repeated by defocusing, and the defocused image can be moved as before. Scintillation is still visible, and is clearly almost synchronous over the whole disk of the image. Although the 'boiling' effect mentioned by Gregory shows as an occasional flash in the width of the ribbon of light, flashes must cover hundreds of times the retinal area covered by the image of the star when in focus.

It would be interesting to know what effects could be observed with Prof. Hartridge's apparatus if his small bright light were viewed in a slightly agitated mirror.

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[1] *Nature*, **165**, 146 (1950).
[2] *Nature*, **164**, 999 (1949).

THERE are a few simple experiments, perhaps not widely known, which have a bearing upon the physical interpretation of this phenomenon.

We have at the Royal Observatory, Edinburgh, a 6-in. objective prism set up in combination with a 5-in. aperture *f*5 camera lens. The spectrum of Sirius on a 'scintillation' night appears as a narrow line of rainbow colours about $\frac{3}{8}$ in. in length. Viewed through a low-power lens, the light in any part of the spectrum appears to show little fluctuation. If the viewing lens is now given a rapid vibration of small amplitude in the direction at right angles to the plane of dispersion, so that the spectrum is broadened and separated out into its *time elements*, a most surprising effect is seen. Each of these elementary spectra has one or more broad regions of colour missing: some exhibit only red and violet, others green or blue, and so on. Moreover, each of these patterns is seen to be changing along the length of the spectrum with great rapidity and in an apparently haphazard fashion. When the lens stops vibrating the time elements become superposed and the eye integrates, by the persistence of vision, all these instantaneous patterns, so that we obtain once more what is the normal state of affairs, a steady continuous spectrum. It seems that this phenomenon was first reported by Respighi in 1872.

We must infer, therefore, that when we observe a scintillating star directly, either with the unaided eye or through a small telescope, the 'white' image which we see is, in fact, composed of a succession of colours changing at such a high frequency that the eye is unable to distinguish them separately. If this be correct, it follows that we should be able to observe these colour changes in the image of a star if only we could separate them out on a time base.

Now this can be done by very simple means. Take a pair of prismatic (or Galilean) binoculars, focus on Sirius, or any other 1st mag. star at low altitude. Then give by hand to one end of the instrument a rapid rotary motion, so that the star image appears to be drawn out around the circumference of a small circle, oval, or figure-of-eight. The observed effect is one of extreme beauty: the line of light is seen to be divided up into a splendid array of sparkling colours.

One part of the curve is red, another green, another purple, some are of mixed shades; indicating that the colour of the image (which is normally *time-integrated* by the eye, as in Newton's 'colour disk') is *differentiated* out into a constantly varying colour sequence. With a pair of light red filter-glasses placed in front of the eye-lenses, the star is seen to go right out about thirty times a second, the circle of light now being discontinuous and composed of red arcs separated by dark spaces. Frequency may be estimated roughly by comparison with a mains-run neon lamp placed in the same field of view. These colour changes decrease with increasing altitude, but on frosty nights when the 'seeing' is poor, they can be seen even in bright stars near the zenith. If we turn next to Saturn, which at the time of writing is readily observable at the same altitude as Sirius, we find that the colours are entirely absent—the 'time-base' ring of light is quite uniform both in colour (a pale yellow) and intensity.

It seems very desirable, from the astronomical point of view, that the physical characteristics of these colour variations in star images should be investigated in greater detail, especially in regard to their dependence upon meteorological conditions and upon telescope aperture. One method which suggests itself is to direct the converging beam through a narrow band-pass filter before it reaches the principal focus of the telescope and there to receive it in a multiplier photocell. If the main beam were interrupted at a suitable frequency and the cell output displayed on the time-base of a cathode-ray tube, the fluctuations of intensity could be measured in light of different colours.

Seeking a physical explanation for these effects, it seems clear that the foci for the various wavelengths must be oscillating rapidly in and out *along the line of sight*. This must arise from the interposition in the parallel beam of starlight of weak atmospheric 'lenses'—some effectively converging, some diverging—forming and dissolving at a frequency of perhaps thirty times a second. It seems likely that these air lenses are identical with the moving striæ which have been postulated by R. W. Wood and others to account for scintillation and 'shadow-bands'. Chromatic aberration will be inherent in such lenses and will bring different colours to separate foci. As the lenses 'bulge in and out' and change their power, these colour foci may be expected to oscillate backwards and forwards in the line of sight. Visible scintillations probably arise from occasional abnormally large oscillations of this type. Finally: Do 'monochromatic' stars, like Antares, appear to scintillate more noticeably than white ones, like Sirius?

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The following observation seems to show that any physiological component[1] in the twinkling of the brighter stars is negligible compared with the physical. If half of a 1 cm. × 2 cm. rectangular hole in a sheet of cardboard is covered with a prism deviating light through about 7°, its apex towards the middle of the hole, an observer about 50 cm. behind the hole can place himself so that he sees one star through both halves of the hole, light from the uncovered half passing straight to one eye, light from the covered half being deviated by the prism to the other eye. If now the observer (assumed emmetropic) puts on $-2D$ spectacles and converges his eyes to the hole, he sees two well-focused images which, if of a bright and twinkling star, can easily be seen to twinkle almost exactly synchronously.

This is what is to be expected on R. W. Wood's explanation of twinkling, if the bright and dim bands in which a star is at any instant illuminating the earth's surface are of a size greater than about 1 cm., the distance between the rays passing from the star to the eyes in my observation. That they are so can be observed directly: if the eye is placed at the image of a star in a large convex lens, these irregular bands of light and darkness can be seen flitting across the lens. They are about 2–10 cm. in width.

Any physiological explanation of synchronous twinkling in this observation would necessarily apply also if the images seen in the two halves of the hole were not of the same star but of different stars of the same magnitude. This alteration can be achieved by removing the prism and suitably adjusting the distance and position of the hole; and it is then seen that the twinkling of the two images is not synchronous.

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[1] Hartridge, H., *Nature*, 164, 999 (1949), and 165, 146 (1950).

Before replying to the above letters there is one point which seems to require elucidation, namely, the exact meaning of the word 'scintillation'. Mr. Weale and myself, following the lead of Prof. R. W. Wood, limit it to two alterations only, namely, brightness changes and colour changes, and this fact we tried to make clear in our first letter to *Nature*. But it is obvious from many personal letters which we have received that some other people use the word in a much broader sense, and include such things as the apparent oscillatory movements of a star image at right angles to the line of sight as seen through an astronomical telescope, or the changes of focus which are also sometimes observed. "Scintillations can be photographed" they write. Further inquiry shows that they are usually referring to these oscillatory movements, and changes of focus, but sometimes they are also referring to alterations of shape, size and total brightness.

I am very grateful to Prof. M. Minnaert for the two references which he has given in his letter. Previously the only one known to me was "Physical Optics", by Prof. R. W. Wood. Here are some comments on the points which Prof. Minnaert raises.

(1) The statement that the movements of star images are too small to be visible to the naked eye surprises me. While average star-image displacements usually have values of 3″, exceptional ones, I understand, may have values as large as 10″ or even 15″. If, then, two neighbouring stars are moving towards, or away from one another, their relative angular displacements of 20–30″ should be visible to the naked eye of an observer who has good visual acuity for detail. Thus if the entire sky were filled with stars undergoing such displacements, it would superficially resemble Brownian movement, as I suggested in my first letter.

(2) If I am under a misapprehension, as Prof. Minnaert suggests, when I expect the stars to make greater apparent movements in the direction of the wind, perhaps I may briefly state the reasons for that