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The scintillation of the stars

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1. Introduction

The stars in the sky appear to us as mere specks of light having no visible extension. But they exhibit a remarkable feature, viz., a noticeable fluctuation in their observed luminosity. The brightest stars also exhibit flashes of colour when they are located not too high up in the sky. This "twinkling" of the stars is a familiar phenomenon. Its real nature becomes clearer when by the aid of some simple optical device, e.g., a mirror or a lens moved in appropriate fashion, the observer views the image of the star drawn out into a continuous circle of light. This method of observation reveals large and rapid fluctuations of brightness along the track of the moving image of the star. Striking changes in colour are also noticeable in the case of the brighter stars as thus examined. Observation of such stars through a prism which draws out their images into a spectrum of colours further reveals some highly interesting effects.

We are clearly concerned here with an atmospheric phenomenon. In other words, the scintillation arises as a consequence of the passage of the light from a star through the air before it reaches our eyes. But it is by no means easy to understand how such a tenuous medium as the atmosphere could give rise to the observed fluctuations of intensity. It is thus evident that scientific problems of great interest are presented to us by the observed effects. Astronomers are naturally interested in the scintillation of stars by reason of its relationship to the unsatisfactory atmospheric conditions which often interfere with their professional activities. An important aspect of the subject is the location in the atmosphere of the regions in which the disturbed conditions exist giving rise to the observed scintillation. This brings the subject into close relationship with the science of meteorology. Finally, we are concerned with the problem in optical theory of determining how the propagation of the light of a star is modified by its passage through the disturbed layers and gives rise to what is actually observed.

The present communication is not a review article and it is not proposed to survey the published literature or to discuss in detail any particular aspect of the subject. The purpose of the author is to set out a general view of the field as it presents itself to him and in doing so to indicate the basis on which he feels it is possible to reach a clearer understanding of the observed phenomena.

2. The thermodynamics of the atmosphere

The light from a star has to traverse the entire atmosphere before it reaches the eye of the observer. The path traversed is the full height of the atmosphere if the star be at the zenith and increases progressively to several times that value as the star goes down in the sky and approaches the horizon. It follows that no attempt to explain the scintillation of stars can claim acceptance which does not take into consideration the actual condition of the atmosphere of the earth at all levels and their influence on the propagation of the light before it reaches the observer.

In the year 1899, the French meteorologist Teisserenc De Bort announced the discovery made by him of the existence of what he called the "Isothermal Layer of the Atmosphere" in its higher levels. The great importance of this finding was appreciated by meteorologists and it is now recognised that the lower part of the atmosphere known as the troposphere and the upper part known as the stratosphere exhibit different structures and play different roles in the thermodynamics of the air. Meteorologists have also given a special name, viz., tropopause, to the layer of transition between the troposphere and the stratosphere. The basic difference between the troposphere and the stratosphere is that the former normally exhibits a progressive fall of temperature with height, whereas the latter can be considered as isothermal, at least in the regions not exceeding some 20 km in height above the surface of the earth. Beyond this height, the density of the atmosphere becomes a small fraction of its value at sea-level.

The question naturally arises how this division of the atmosphere into two parts with a different thermal behaviour arises. The answer may be found in the processes by which the atmosphere periodically gains and loses heat. It is in the troposphere that the energy received as radiation from the sun and absorbed by the surface of the earth is carried upwards into the air as heat by convective processes. The upper limit of the troposphere may, therefore, be taken to be the level at which these convective processes cease to function. In the stratosphere, on the other hand, we are chiefly concerned with the circulation of the atmosphere on a global scale brought about by the unequal heating of the earth's surface in low and in high latitudes.

The explanation of the division of the atmosphere into two parts indicated above receives support from the actual facts of the case. In the first place, it is found that the rate of fall of temperature with the height—termed by the meteorologists as the lapse-rate—has approximately the same mean value at all heights in the troposphere and in all latitudes, viz., 6° C per kilometre. On the other hand, the height of the troposphere is found to depend very markedly on the latitude, being about 16 km at the equator, about 11 km in middle latitudes and dropping to about 6 km at the poles. Further, it has been established by regular soundings of the upper air that there are day-to-day and seasonal variations in the height of the tropopause, these being particularly marked in the middle latitudes. Indeed it is there found sometimes difficult to locate any well-marked discontinuity between the normal rate of temperature decrease occurring in the troposphere and the approximately isothermal distribution of the stratosphere. It is clear from these findings that the conditions in the layer of transition between the stratosphere and the troposphere are of a dynamic nature and far from being static.

3. The optics of the atmosphere

The atmosphere of the earth is a stratified medium in the sense that the refractive index of the air falls off progressively with the height above sea-level in proportion to the diminishing density, but less quickly than the atmospheric pressure owing to the fall in temperature. The figures in table 1 illustrate this for the wavelength λ 5896 and the standard USA atmosphere. They justify the remark made in the introduction that the atmosphere is a tenuous medium, which, indeed, is very much in the nature of an understatement with reference to its higher levels.

Table 1. Refractive index of dry air

Height (Km)	Pressure (mb)	Temperature (°C)	Refractive index
0	1013	+15	1·0002765
5	540	−17	1·0001658
10	264	−50	1·0000931
15	120	−56	1·0000435
20	55	−56	1·0000199

Accepting the proposition that the scintilation of the stars is a consequence of local variations in the refractive index of the atmosphere, we have to ask ourselves and answer the following questions. How do these variations arise? What is the numerical magnitude of the variations? What is the measure of their extension in space? In what region or regions of the atmosphere do they appear? Finally, are they actually capable of producing the observed effects? We proceed to deal with these questions *seriatim*.

The refractive index of air is determined by its composition and by its pressure and temperature. The content of water-vapour included in it is, in the lower levels of the atmosphere, the variable part of the composition. For the sake of simplicity, we shall, in what follows, not consider the variations of composition explicitly. For a standard atmosphere, the pressure and the temperature are known as functions of the height above sea-level. In dealing with possible variations from these standard values, a certain measure of simplification is introduced by the well known principle that any volume-element of air, whether it is in a state of rest or of motion, automatically takes up the pressure of its surroundings. Hence, the difference in the refractive indices of the element and its surroundings is determined by their respective absolute temperatures. It follows from this, that local variations of *temperature* play a specially important role in our present problem.

With these guiding principles in mind, we shall proceed to deal with the other questions raised above. The plane waves of light from a star have to travel through three distinct regions before they reach an observer. (1) The stratosphere, (2) the transition layer between the stratosphere and the troposphere, and (3) the troposphere. We may consider these in order.

As shown by the figures in table 1, the refractive index of the air in the stratosphere falls to very low values. Further, this region of the atmosphere may, at least as a first approximation, be considered as isothermal. We are, therefore, justified in assuming that the stratosphere does not play any role in the phenomena of scintillation, though naturally it would contribute sensibly to the refraction and dispersion of the light reaching the earth from stars at a low altitude above the horizon.

As has already been remarked, the region of transition between the stratosphere and the troposphere is one of dynamic change in which air-masses differing in thermal behaviour are continually altering their locations. Hence, this is a region which, *prima facie*, should be capable of giving rise to the phenomenon of scintillation. We shall return to this later and meanwhile turn to the case of the troposphere.

Meteorologists usually subdivide the troposphere into three parts, the lower, the middle and the upper troposphere respectively, and have recognized that each of these divisions has its own special features. The lower troposphere is that most affected by heat transfer between the surface of the earth and the air and it is, therefore, the region of which the structure shows the largest variations due to the periodic heating and cooling of the ground. It is in this part of the troposphere also that the so-called temperature inversions make their appearance in certain circumstances. The middle and upper troposphere, on the other hand, are practically uninfluenced by the diurnal temperature variations and exhibit the normal rate of temperature decrease with height. While they do exhibit seasonal variations in temperature, these variations are brought about by relatively slow processes. Whether in these circumstances, the troposphere can play any role in the production of scintillations may well be questioned. We shall presently proceed to discuss this matter.

4. The origin of the scintillations

It is clear that the methods and ideas of geometrical optics cannot possibly lead us to any acceptable explanation of the phenomena of scintillation. Indeed, one might go further and say that they are entirely out of place in any problem concerning the propagation of light in a medium of variable refractive index. This becomes evident when, adopting the language of wave-optics, we remark that a change of refractive index means an alteration in the rate of change of the phase of the waves as they advance through the medium and hence there arises the possibility of large changes of intensity being produced by interference when overlapping occurs of waves which have traversed slightly different paths in the medium. Considerations of this kind are wholly foreign to the concepts on which geometrical optics is based. On the other hand, they play an essential and highly successful role in explaining the observed phenomena in diverse cases investigated at various times by the present author and his collaborators. We may here mention particularly the phenomena observed when light waves traverse a transparent medium carrying ultrasonic waves.

The foregoing remarks indicate in a general way the lines on which an explanation could be sought of the phenomena of the scintillation of stars. Somewhere on the path of many kilometres which the light from a star has to travel, the wave-fronts pass through a disturbed region in traversing which retardations of phase are suffered which are unequal over the area of the wave-front, while the amplitudes remain unaltered. During the further propagation of the waves, the phase-changes transform themselves into amplitude-changes; in other words, the effect of the unequal retardations of phase higher up in the atmosphere manifest themselves as unequal intensities when the waves reach ground level.

In thus applying the ideas of wave-optics to determine the effect of the passage of light through an atmosphere of varying refractive index, a very great simplification is possible by reason of two characteristic features in the problem, viz., that the refractive index of the medium itself differs but little from unity, and that, further, any possible variations of it would be themselves a small fraction of the difference between the index and unity. From this, it follows that if the waves traverse in succession, two regions in one of which the index is higher and in the other it is lower than the average index of the medium, the phase-changes produced by them would cancel out partly or wholly depending on their actual values. In other words, a medium in a turbulent state and in which the refractive index exhibits random fluctuations would behave in much the same way as one which is quite uniform and has the same average index everywhere. Only in those cases where the phase-changes produced are so large and so distributed that they do not cancel out completely would the waves emerge from the disturbed region exhibiting any observable consequences of their passage through it.

From the figures given in table 1, we may readily deduce the difference in optical path resulting from the passage of light through a column of air one metre thick which is at the same pressure as its surroundings but differs in temperature by 1° C. The results of these calculations are shown in table 2.

Table 2. Phase-change in wavelengths

Height (Km)	Pressure (mb)	Temperature (°C)	Phase-change per metre per degree
0	1013	+ 15	1·69λ
5	540	− 17	1·02λ
10	264	− 50	0·7λ
15	120	− 56	0·34λ
20	55	− 56	0·15λ

5. Location of the disturbed regions

The lowest part of the troposphere lying within the first 5 km above the surface of the earth is the region in which the convective processes set up by alternate heating and cooling of the ground during day and night respectively are most evident. One might be inclined to infer from this that the same region of the atmosphere would be principally responsible for the scintillations of the stars perceived by an observer at ground level. Against this presumption can be urged the following considerations. Actually, we are concerned with the condition of the atmosphere at night time and not during the day. The upwelling of the overheated air from the ground would have reached and passed its maximum before nightfall and the violent changes of temperature consequent thereon would to a large extent have been smoothed out by the adiabatic expansion of the rising air and the cooling resulting therefrom, as also by the mixing up of the masses of air at different temperatures by the process of eddy diffusion. There would, no doubt, be left over some residual differences of temperature, but the individual volume-elements exhibiting such differences might be expected to be of very moderate dimensions. As already explained, the phase-changes suffered by the wave-fronts of the light in passing through these layers of air would be more or less completely cancelled out by a process of averaging. Temperature inversions, if any are present, would not alter this situation, so long as the surfaces of equal average temperature and the surfaces of equal pressure everywhere run parallel to each other, hence also to the surfaces of equal average refractive index.

Similar considerations would apply and even more cogently in the case of the middle and upper parts of the troposphere. The existence of regular stratifications of temperature parallel to the stratifications of pressure in those regions makes it highly improbable that phase-changes of the nature and magnitude necessary for giving rise to scintillations could be produced by the passage of the light waves through those layers.

Thus, we are led by a process of exclusion to conclude that, at least ordinarily, the disturbed region which is responsible for the scintillations perceived by an observer at ground level lies high up in the atmosphere being in fact the region of transition between the stratosphere and the troposphere. It has already been remarked that this region is essentially dynamic in its origins. Unless the transition between the troposphere and the stratosphere is a sharply-defined geometric plane—and such a situation cannot reasonably be expected to exist or persist—a wave-front passing through it would suffer phase-changes varying from point to point over its area. The figures exhibited in table 2 show that at that level, a transition layer only one metre thick and varying only by 1° C over its area would produce phase-changes of the order of half a wavelength. This would suffice to produce large and readily observable changes of intensity over the area of the wave-front when it has travelled over a sufficiently long path below the tropopause.

It is, however, necessary to remark that disturbed regions of other kinds may also appear in other circumstances and give rise to noteworthy optical effects. Meteorologists are familiar with the idea that a boundary or relatively narrow transition zone must exist between opposing wind currents or contrasting air-masses, and they refer to such boundaries as *fronts*. They are formed when two air-masses meet which differ in temperature and in density. The conditions existing at these boundaries or transition zones would evidently be favourable for large variations of phase to manifest themselves when they are traversed by the waves of light.

6. The character of the scintillations

The ideas set forth above when developed in detail lead us to a clear understanding of the entire ensemble of phenomena related to the observed scintillation of the stars. The wave-fronts which emerge from the disturbed regions of the atmosphere and exhibit localised phase-changes may be analysed into groups of plane wave-trains travelling in directions inclined at various angles to the original direction of propagation. The amplitudes of these wave-trains and their inclinations are determined by the magnitude of the phase-changes in the original wave-front and the areas over which they appear. As a consequence, the telescopic image of a star would be spread out over a finite range of angles. The light reaching down to the earth would also exhibit a pattern of interferences due to the overlapping of these wave-trains. The maxima and minima of intensity in this pattern would be the closer together, the larger the angles are between the interfering wave-fronts.

Since the region in the atmosphere at which the optical disturbances originate is at a high level, the interference pattern observed at the surface of the earth would necessarily exhibit a movement parallel to the surface as a result of the rotation of the earth about its axis. The intensity of the light reaching the observer would fluctuate as the interference pattern moves over his eyes. These fluctuations would be the more rapid, the closer together the maxima and minima are in the interference pattern. As has already been remarked, their spacing is determined by the magnitude of the disturbance to regular wave-propagation produced by the atmospheric conditions. A relationship thus emerges between the rapidity of the observed scintillations and the effect of atmospheric conditions on the telescopic appearance of the star.

Colour effects can arise in two different ways. Since the scintillations owe their origin to interference, colour may be expected to manifest itself by reason of the wavelength differences in the spectrum. Effects thus arising would however be inconspicuous unless the interferences are of low order. Colour effects of a different nature are also possible. The light from a star suffers refraction and dispersion in traversing the atmosphere of the earth. The deviations thus arising increase with the zenith distance of the star. The dispersion is however quite small unless the zenith distance exceeds 45° of arc. When the dispersion exceeds a few seconds of arc, the interference patterns for the different parts of the spectrum would cease to coincide at any given instant, but would become identical or nearly so at successive instants determined by the zenith distance of the star and the rotation of the earth. Very striking colour effects would then be observable, especially in the case of the brighter stars.

Summary

The scintillation of stars is explained as an interference effect which arises in the following manner. Plane waves of light from a star when passing through a disturbed region high up in the atmosphere suffer phase-changes but no changes of amplitude in their wave-fronts. At lower levels, the phase-changes are transformed into amplitude changes, in other words, interference patterns are formed. These patterns move over the surface of the earth by reason of its rotation about the polar axis. The fluctuations of intensity passing over the eye of the observer are perceived by him as scintillations. It is shown that in this way, the entire ensemble of phenomena related to the scintillation of stars receives a satisfactory explanation. Reasons are given for identifying the region in the atmosphere ordinarily responsible for the observed scintillations at ground level to be the tropopause, in other words, the region of transition between the stratosphere and the troposphere.