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# Stars, nebulae and the physiology of vision

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On any clear dark night we see the sky studded with stars, a few very bright ones, many more not so bright, and a much larger number of faint ones. They appear to us as points of light standing out of a dark background and possessing no visible extension. Numerous as the stars thus visible to the unaided eye are, their number is but a fraction of the multitude of stars revealed to our eyes when we are aided by such a modest item of equipment as a pair of binoculars. The stars made visible by using more powerful instrumental aid are even vastly more numerous. The reason is evident, viz., that the stars which appear faint are far more numerous than those which are bright and the same situation extends without limit to fainter and still fainter stars. This may be illustrated by reference to the actual numbers determined and listed by the painstaking labours of astronomers in their published star-catalogues. The so-called bright stars whose visual magnitude is less than 6·5 are about 9,000 in number, those of magnitude less than 8·5 number a quarter of a million and those of magnitude less than 10·5 more than a million. The scale of visual magnitudes adopted by astronomers is defined by the rule that the ratio of the brightnesses of two stars whose magnitudes differ by 5 is 100.

We may here ask ourselves two questions. Why are we unable with our unaided vision to perceive stars in the sky whose visual magnitude is more than, say six? Why does it become possible to observe stars of higher magnitudes with telescopic aid? Answers to both of these questions are given if it be assumed that for the eye to perceive a star, the light-flux reaching its image on the retina should exceed a specifiable minimum. This light-flux may be taken as proportional to the area which admits the light entering the eye. For the unaided eye, this would be the area of its pupil and when there is optical aid, this would be the area of the objective of the telescope. On this basis, an increase of the diameter of the objective by a factor of ten would enable stars to be perceived whose magnitude is larger by 5.

We shall now proceed to evaluate the light-flux reaching us from stars of various magnitudes. The basis of the calculation is the known value of the energy received by us from the Sun and the known value of the Sun's luminosity relative to the light received from the stars. "The total output of the Sun between $\lambda 5480$ Å and $\lambda 5380$ Å is $5{\cdot}17 \times 10^{31}$ ergs $sec^{-1}$. The amount received per square cm at a distance from the Sun equal to the mean radius of the Earth's orbit or

$1{\cdot}496 \times 10^{13}$ cm, is $1{\cdot}838 \times 10^4$ ergs $cm^{-2}$ $sec^{-1}$. The Sun's International photo-visual magnitude is $-26{\cdot}84$ according to Kuiper. It therefore delivers to the Earth $10^{10{\cdot}736}$ times as much light as a star of zero magnitude—in every wavelength if the star has exactly the same spectral type as the Sun. Hence the amount received per square cm per second per 100 Å at $\lambda$5430 Å from a star of type dGo and of magnitude. $0^m$.ooIPv is $3{\cdot}37 \times 10^{-7}$ ergs; and the logarithm of the energy received from any star of this spectral type is $7{\cdot}53$—$4m_{vv}$." The above is quoted from the book on "The Outer Layers of a Star" by Woolley and Stubbs, Chapter XIII, page 274, where the corrections needed for stars of other spectral types are also listed.

In vision, we are chiefly concerned with the spectral region between 5000 and 6500 Å, as the luminous efficiency of radiation becomes rather small outside those limits. It is therefore sufficient to consider the energy appearing between these limits in the spectrum of a star in seeking to explain its visibility. In the spectral energy curves for a perfect radiator at 5740° K. which is the effective solar temperature, the wavelengths 5000 and 6500 Å are not far from the wavelength at which the radiation is a maximum. We shall therefore be justified in taking the flux of energy which determines the visibility of a star of the same spectral type as the Sun to be fifteen times the energy flux for a range of 100 Å quoted above. This may conveniently be expressed in terms of the quantum of energy corresponding to the wavelength 5600 Å which is that of maximum luminous efficiency. The number of light-quanta per second reaching the unaided eye from stars of various magnitudes has been thus calculated and shown in table 1, the area of the pupil of the eye being taken as 50 square.

We may now proceed to consider the significance of the figures listed in table 1 against the increasing orders of magnitude of the stars. If it be assumed that a single quantum of light if actually taken up by the visual receptors and passed on to the visual cortex could produce a detectable sensation, it is clearly necessary that the quanta should follow each other in rapid succession to enable the eye to perceive a star *steadily*. 30 quanta following each other in each second would probably suffice to produce a lasting impression. Actually, the table shows that a 6th magnitude star (which experience shows can just be perceived) has a light-flux

**Table 1.** Light-flux received by the eye

| Magnitude of star | Quanta per second | Magnitude of star | Quanta per second |
|---|---|---|---|
| $0^m$ | 7,10,000 | $6^m$ | 2,900 |
| $1^m$ | 2,90,000 | $7^{th}$ | 1,140 |
| $2^m$ | 1,14,000 | $8^m$ | 450 |
| $3^m$ | 45,000 | $9^{th}$ | 180 |
| $4^m$ | 18,000 | $10^{th}$ | 71 |
| $5^m$ | 7,100 | $11^{th}$ | 29 |

of 2,900 quanta per second, while stars of higher magnitude which have a smaller light-flux are not perceived at all. A reasonable explanation that can be offered for the facts is that the visual receptors take up or absorb only about 1% (averaged over the spectral range under consideration) of the light-quanta which reach them and transmit the impulses to the cerebral centres, while the rest go through unabsorbed to the pigment epithelium behind the retina. The number of quanta taken up and thus passed on would then just suffice in the case of a 6th magnitude star to enable us to see it steadily, while for stars of higher magnitude, it would be inadequate to produce such a result.

When we view the sky fixing our eyes on a particular star located on it, we have nevertheless no difficulty in recognising the presence of numerous other stars both far from and near to the one so regarded. The question then arises whether the brightness of any two stars as visually perceived in these circumstances depends to any noticeable extent on their positions relative to each other in the field of view and whether the visibility of any particular star depends markedly on its position in the field with respect to the point at which vision has been fixed. Both of these questions have an important bearing on the known variations in the anatomical structure of the retina as we pass from the fovea outwards. No answers can be given to these questions which are worthy of credence unless they are based on systematic observations and a careful comparison of our subjective impressions with the objective record furnished by photographic charts of the part of the sky under observation. If no effects of the kind indicated actually exist, it might reasonably be inferred that the visual process by which a point source of light is perceived does not vary sensibly in its nature over the area of the retina.

Other interesting questions arise which can only be answered by the results of specific investigations. It is familiar knowledge that when the night sky presents a background of continuous illumination, as for example, when the Moon is well above the horizon, the visibility of the fainter stars is seriously impaired. What is the precise origin of this effect, and how is the diminished visibility related quantitatively to the strength of the diffuse illumination of the sky? Then, again, is it possible to perceive quantum fluctuations in the visibility of faint stars? Here the difficulty presents itself of the fluctuations in brightness of stars due to the turbulence of the atmosphere which would also be present and interfere with the observations.

Having discussed the visibility of the stars of various magnitudes, we pass on to consider the highly interesting question of their colours. As seen by the unaided eye, a few of the very brightest stars show a hint of colour. But the vast majority of the stars appear to our unaided vision as mere specks of light of greater or less brightness and give no indication of the great differences in the spectral character of the light which they emit and the very large differences in the effective surface-temperatures inferred from these spectral characters and also from the luminosities as measured by photoelectric and photographic methods using colour filters to isolate different parts of the spectrum. The effective surface-temperatures range from 25000° K. for stars of the spectral class, BO, 5520° K. for those of spectral class G5, to 2710° K. for the spectral class M5. These enormous differences show up very clearly when the luminosities of the stars are determined using colour filters as stated above; the colour-index of a star is the difference between its magnitudes in two colours. It is frequently given as the blue *minus* the yellow or visual (B–V) magnitude. This difference may be as much as two whole magnitudes for a star belonging to the spectral class M.

We may, therefore, well ask ourself the question why our unaided vision fails to reveal the great differences in colour which might have been expected in the circumstances stated above. Here, a significant remark may be made, viz., that the colours of the fainter stars become distinctly more manifest when the stars are viewed through a telescope with an adequate aperture. Colour-differences between the two components of double stars also become noticeable with such aid and are indeed to be found indicated in the published catalogues of various observers. It is obvious from this that the magnitude of the light-flux reaching the retina from a star not only determines the visibility of the star and its brightness or luminosity, but also plays a highly important role in the perception of colour. We are indeed led to the inference that as the number of light-quanta received per second by the eye from a light-source progressively increases, the sensations of luminosity and of colour develop *pari passu* and become more pronounced. When the light-flux reaching the eye is small, we perceive a dim and characterless luminosity. As the light-flux increases, our perceptions develop into a bright and colourful sensation.

A great many years ago, the author visited the Mount Wilson Observatory near Pasadena and enjoyed the privilege of sitting at the eyepiece end of the 60-inch reflector one night and of the 100-inch reflector another night. Amongst the objects chosen for viewing through these telescopes were the famous Ring nebula in Lyra and the Great nebula in Orion well-known to all amateur astronomers. The writer was familiar with the appearance of these objects as seen through a 7-inch refractor available to him at Calcutta and was enormously impressed by what he saw of them through the great telescopes at Mount Wilson. The Ring nebula in Lyra exhibited flaming colours changing progressively from the external edge of the ring to its inner margin. The Great nebula in Orion which in smaller instruments appears as a shapeless patch of light without noticeable colour is seen with the sixty-inch as a blazing area of variegated colour determined by the light-emission of the gases of which it is composed. The impression left on the writer by these experiences was so vivid that it was recalled and a special reference made to it in a broadcast on "The Stellar Universe" given several years afterwards at Madras. This appears in a printed collection of the author's radio-talks on various aspects of science published by the Philosophical Library, Inc., of New York in the year 1951.

When we look at a star directly or when we view a star or a nebula through the eyepiece of a telescope, we make use of the region of the fovea in the retina. It follows that everything that has been stated above regarding the perception of light and colour refers to the functioning of our eyes in photopic vision, so termed by writers on physiological optics. It is a fact that our eyes are capable of functioning in very dim light and enable us, for example, to find our way through the countryside on a dark night when the landscape is lit only by starlight. This is scotopic or dim-light vision. But if, in the same circumstances, we look up and view a star which is a concentrated point-source of light, it is photopic and not scotopic vision that is functioning. That we are unable without optical aid to see stars of magnitude higher than six or to perceive the colour in any except the very brightest of stars are therefore characteristic features of photopic vision.

The real distinctions between photopic and scotopic vision are that scotopic vision does not function except when the eyes have been prepared for it by having been rested in the dark for an adequate period, and scotopic vision does not at all function in red light even after such a period of rest. It is often stated and generally believed that scotopic vision is achromatic while photopic vision alone is associated with the possibility of observing and recognising colour. Since, as we have seen, even in photopic vision, colour sensations become enfeebled at low levels of luminosity, likewise it is to be expected that they would be extremely weak at the very low levels of illumination at which scotopic vision functions. But that they are not wholly absent in scotopic vision even at such levels has already been noticed and remarked upon by the writer in an earlier publication (*Memoir No. 125 of the Raman Research Institute*, Vol. VIII, 1960, page 11).