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Astronomy. — *"The Structure of the Sun's Radiation".* By P. H. van Cittert. (Communicated by Prof. W. H. Julius).

(Communicated in the meeting of May 3, 1919).

It is known that the intensity of the light on the sun's disc very appreciably diminishes from the centre towards the limb, and that this takes place in a different degree for the different colours: regions near the limb[1] of the sun's disc are distinctly ruddy as compared with the centre.

By the aid of a spectral photometer Vogel[2] determined this distribution of intensity for six regions of wavelength in the visible part of the spectrum. The decrease of intensity towards the limb appeared to be greater for light of shorter wavelength than for light of longer wavelength; the diminution, however, does not take place quite regularly with the wavelength, but presents an anomaly in the neighbourhood of 5000 Å. the contrast of the limb to the centre is for this wavelength-region less than the contrasts for the other wavelength-regions would lead us to expect.

Vogel's observations were repeated by Abbot[3] in 1906 by the aid of a bolometer. Abbot determined the decrease of intensity for a great number of wavelength-regions in the infra-red and the visible spectrum. He also found a strongly pronounced wavelength-effect: the contrast towards the limb increased very greatly towards the violet. Also his observations presented an anomaly in the neighbourhood of 5000 Å, though less pronounced than that in Vogel's observations. In fig. 1 we have plotted as functions of the wavelength, what value the intensity has for places which are at a distance of 0.65, 0.825, and 0.95 of the radius of the sun's disc from the centre, when in the centre the intensity is put equal to 100 for all the colours. The data are borrowed from Abbot's tables. It is seen that the intensity rapidly decreases towards the limb, and this the more rapidly as the wavelength is smaller, but at the same time the fact

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[1] In the present paper, the phenomena at the limb itself and even in regions, more than e.g. $\frac{95}{100}$ of the radius of the disc removed from the centre, are left out of consideration.

[2] H. C. Vogel, Berl. Ber., 1877.

[3] C. G. Abbot. Ann. of the Obs. of the Smiths. Inst., **2**, 205, 1908; **3**, 153, 1913.

strikes us that in the region 6000—4000 Å this decrease of intensity presents an oscillation. It is noteworthy that the maximum of energy of the sun's radiation lies at the same place in the spectrum.

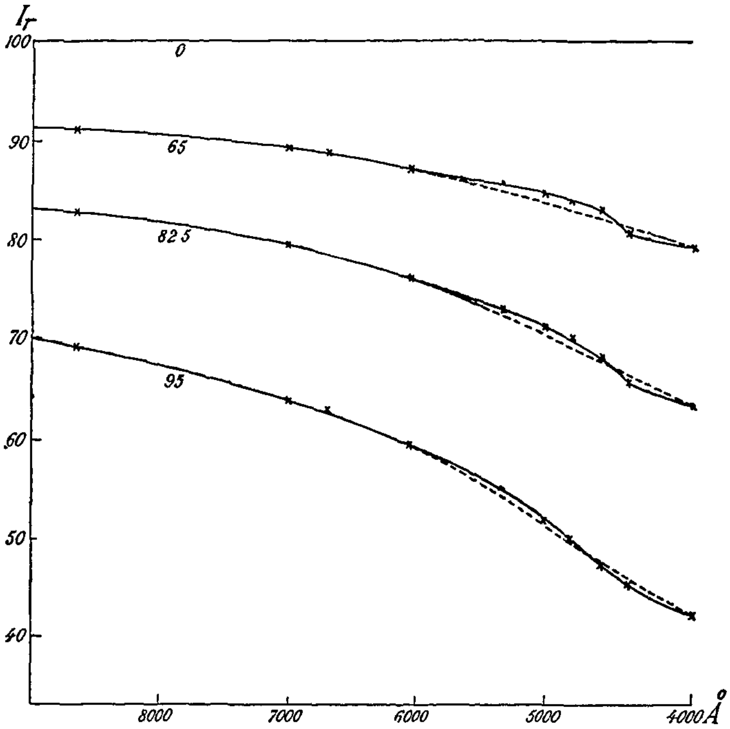

Fig. 1.

(Abbot's observations ranged from 21000 Å to 3800 Å; the part from 21000—9000 Å has, however, been omitted in the figure, because the curves do not present an irregular course there, but gradually approach the line $I_r = 100$ towards 21000 Å).

To account for this decrease of intensity towards the limb many investigators have considered the sun as a self-luminous uniformly radiating core, surrounded by a strongly absorbing atmosphere. Now the state in the sun's atmosphere must naturally be stationary on the average: the quantity of energy that the atmosphere absorbs, must be radiated again, even though it be in another form, and half must be radiated towards the outside. Now it has appeared convincingly from the observations of the annular eclipse of April 17th 1912 [1]) that of the total quantity of energy that the earth receives from the sun, at most one thousandth part can originate from the sun's atmosphere. It is, therefore, impossible that the absorption should be the chief cause of the diminution of intensity towards the limb.

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[1]) W. H. Julius. These Proc. 15, 1451.

Continuing the investigations of **Rayleigh**[1]), **Schuster**[2]), **King**[3]) and **Schwarzschild**[4]) on molecular scattering of light, **Spijkerboer**[5]) has treated the problem how the distribution of light on the sun's disc would be for the different colours, if exclusively molecular scattering in a non-absorbing and not self-luminous atmosphere were the cause through which the uniform radiation of a self-luminous solar core was modified. He arrived at a distribution of light which presents close resemblance to that observed by **Abbot**.

The influence of the diffusion (or molecular scattering) is determined by the product $H = s.t$, in which $t =$ the thickness of the dispersive layer and $s = \frac{32\pi^3(n-1)^2}{3N\lambda^4} =$ **Rayleigh**'s coefficient of scattering. When it is now assumed that t has the same value for light of different wavelengths, that the "core" lies, therefore, equally deep for all colours, the wavelength-effect is exclusively determined by the dependence of s on λ^4, because, when kinds of light in the neighbourhood of the proper-frequencies are left out of account, $(n-1)$ will vary very little along the spectrum. It appears, however, that the observed dependence of the wavelength is somewhat less great than theory would lead us to expect. This may be due to the fact that besides the *diffusion* another phenomenon appears, which has a similar influence on the distribution of light as diffusion, but which does not vary so much with the wavelength, e.g. scattering by *irregular refraction*, and possibly a very slight general *absorption*.

Now it is very probable that, particularly in the deeper layers of the sun's atmosphere, irregular refraction plays an appreciable part. The existence of a very irregular distribution of density in the solar gases can, indeed, not be doubted, the constant variations in the granulations and flocculi on the sun's disc point in any case to the existence of an intricate system of currents in that gas-mass, and these are not conceivable without differences of pressure and irregular density gradients accompanying them. The mean value of these gradients, which is small in the outmost layers of the sun, must at first increase as one gets deeper. At a certain depth the irregular density gradients must then on an average be of the same order of magnitude as e.g. the vertical gradient of our terrestrial atmosphere. A gas-mass of the dimensions of the solar atmosphere,

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1) **Rayleigh**, Phil. Mag., (5). **47**, 375, 1899.

2) **Schuster**, Astrophys. Journ., **21**, 1, 1905.

3) **King**, Phil. Trans. R.S., A (212), 375, 1912.

4) **Schwarzschild**, Berl. Ber., **47**. 1183, 1914.

5) J. **Spijkerboer**, Verstrooiing van licht en intensiteitsverdeeling over de zonneschijf. Proefschrift. Utrecht 1917. Arch. Néerl., (3 A), **5**, 1, 1918.

quite honeycombed with irregular gradients of such average magnitude, would, as JULIUS[1]) has demonstrated, refract, deflect and disperse the rays of light that penetrate there, so strongly to all sides, that the gas would present itself to a distant spectator as a turbid medium; the volume parts in which the density can be considered as constant, and hence the light as rectilinear, would be too small to be observed separately at such a distance. Since the degree of refractional scattering is determined by $(n-1)$, and accordingly varies comparatively slowly with λ, the co-operation of this kind of scattering with the molecular scattering will weaken the mean wavelength effect, peculiar to the latter.

Besides, the diminution of the intensity from the centre towards the limb will be greater than would be the case if only diffusion were the cause of this diminution. Irregular refraction, therefore, lessens the difference between the rates of darkening towards the limb shown by the different wavelengths, but at the same time strengthens the average contrast between limb and centre.

As another possible cause of the fact that the observed wavelength-effect is slighter than the theoretical, SPIJKERBOER suggests that the light of the longer wavelengths, as it gets less greatly weakened by diffusion, might come to us from deeper layers of the sun than the light of shorter wavelength. This supposition, evidently, excludes the older hypothesis that the sun would have to be conceived as a well-defined core surrounded by a sharply defined atmosphere. The idea that the various radiations originate at different levels is more in agreement with the conception of the sun as a glowing gas-mass, of which the density and the temperature gradually diminish towards the outside. Since the light of greater wavelengths is much less weakened than that of shorter wavelengths, it will come to us from deeper layers of the sun. The infra-red light will, accordingly, be relatively more weakened by molecular scattering than would be the case if it only came to us from equally deep layers as the violet light.

From what depth the light comes to us is, however, not only determined by the diffusion, but also by the irregular refraction. As this is little dependent on the wavelength, the differences in depth for the different colours will not be so great as in the case that only diffusion played a part. If, as is very probable, irregular refraction plays the principal part, especially in the lower layers, the difference in depth must be comparatively slight.

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[1]) W. H. JULIUS, These Proc. **16**, **264**, 1913.

Let us now consider the question how, seen from this point of view, the radiation emitted by the sun in a direction *w* (fig. 2) must be composed. The outer layers of the sun will emit very little energy; proceeding towards lower layers the quantity of emitted energy increases, at first slowly, then more rapidly, in consequence of the increase of temperature and density. Let us suppose *d e f* to be the layer outside which no appreciable quantity of energy is emitted. Let us first consider the radiation transmitted by the surface *d e f* in the direction *w*. We shall take the scattering in the atmosphere outside *d e f* later into account. From the region e_1 in the centre of the sun's disc *w* receives a comparatively slight quantity of radiation of comparatively low temperature, from e_2 a larger quantity of higher temperature, etc. At first the quantity of energy which *w* receives from the different depths, will increase; the deeper we get, however, the more will the emitted radiation be weakened by absorption, refractional scattering and diffusion. From e_p e.g. *w* will again receive less radiation than from e_2, but of higher temperature, from e_q very little, etc. Let us suppose that *w* does not receive an appreciable quantity of energy from layers lying deeper than *j*.

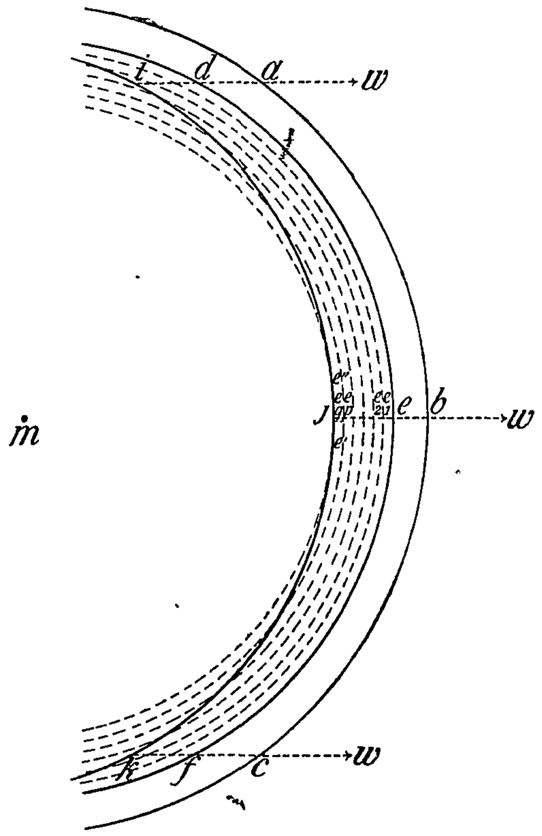

Fig. 2.

(It is noteworthy that *w* also receives radiation from *e* originating from regions *e'* and *e''* in the neighbourhood of the radius vector *j e*, which radiation has finally assumed the direction *e w* through diffusion and irregular refraction).

Let us now consider the energy curves of the radiations coming from those different regions, as functions of the wavelength. All of them will probably have the character of the curve of radiation of the absolutely black body: slow increase of the energy from the infra-red to a maximum, and then a comparatively rapid decrease on the violet side of the maximum. The loci of the maxima of the different curves are determined not only by the temperature of the corresponding radiations, but also by the relative importance of diffusion and refractional scattering. Since the light of shorter wavelengths is much more greatly weakened by diffusion than that of longer wavelength, the maximum will be displaced by the diffusion towards the side of the longer wavelengths; the irregular refraction, on the other hand, does not displace the maximum, because it is almost independent of the wavelength For the curves belonging to the radiation originating from deeper layers, the maximum would lie more to the *violet* than for the curves belonging to the outer layers, if the *temperature* were the only factor; more to the *red*, however, if exclusively the *diffusion* were efficient. The height of the maximum is determined by the temperature of the radiation, the density at the places of emission, and the weakening which the radiation has undergone by diffusion, irregular refraction, and absorption.

We may therefore conclude that from the centre of the sun's disc a quantity of energy is emitted in the direction *w* of which the energy curve, proceeding from the infra-red towards smaller wavelengths increases, at first slowly, then more rapidly to a flat maximum, and then runs very steeply down to the violet (fig. 3 I).

Not far from the limb of the disc, e.g. at *c* (fig. 2), we shall receive light from a longer path through the gases ($ek > bj$), but it will come from less deep layers. Hence at the limb radiation is received from *f* only from the regions round *kj* lying more outwardly. The quantity of energy that *w* receives from the limb of the disc is therefore for all colours smaller than that which *w* receives from the centre. Hence the energy curve of the limb of the sun will as a whole lie lower than that of the centre. *If the diminution of energy were the same for all the colours*, the composition of the light at the limb would be represented by a curve which had the same shape as that of the centre (fig. 3 II). Now it is directly to be seen that this cannot be the case, for the radiation at the limb will not present such a variety of temperature, irregular refraction,

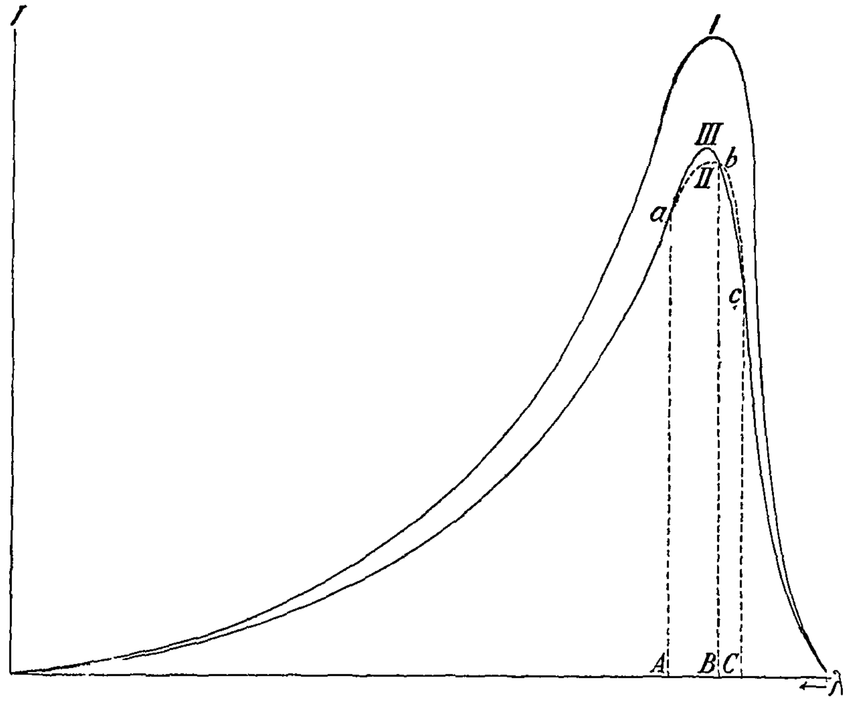

Fig. 3.

diffusion, etc. as that in the centre, because at the limb only radiation from a smaller number of layers contributes to the total radiation. The radiation at the limb will therefore have an energy curve with a maximum which is not so flat as that for the central radiation, and which, as we only receive radiation of lower temperature, lies somewhat more towards the side of the longer wavelengths (fig. 3 III).

When we now compare the curves fig. 3 I, II, and III, it appears that in the wavelength-region AB the limb radiation will have a relatively stronger, in BC a relatively slighter intensity than would be the case if the distribution of the energy were the same as in the centre.

When we now put the central radiation for all the wave-lengths $=100$, this is graphically represented by a straight line C parallel to the wavelength-axis (fig. 4). The limb radiation can then be represented by an almost straight line r, which runs about parallel to the wave-length-axis, but which exhibits an oscillation in the region ABC.

These radiations will be weakened by the diffusion and irregular refraction in the atmosphere outside def (fig. 2), light of the shortest wavelengths most. When again we put the resulting central

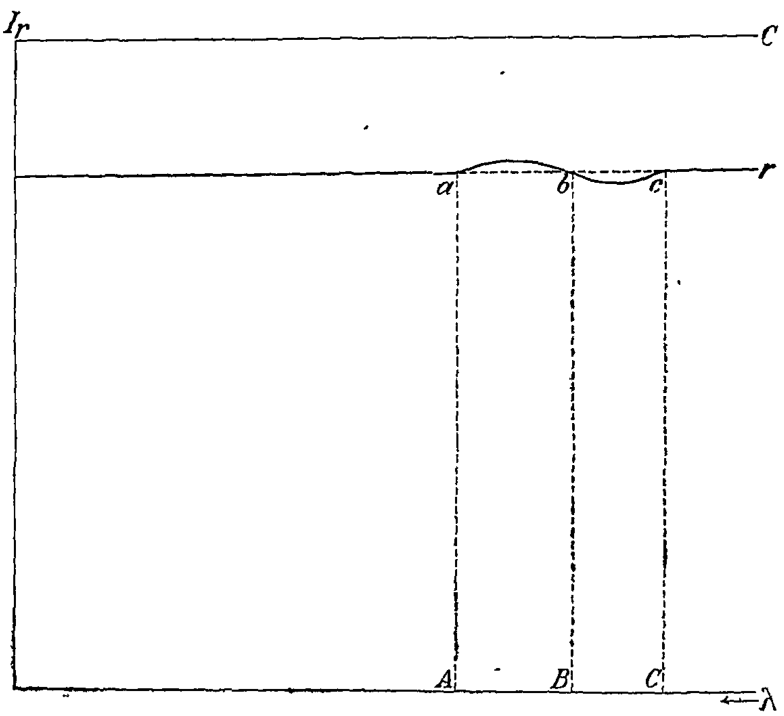

Fig. 4.

radiation for all = 100, the relative limb radiation will be represented by the line r in fig. 5. This radiation decreases therefore continu-

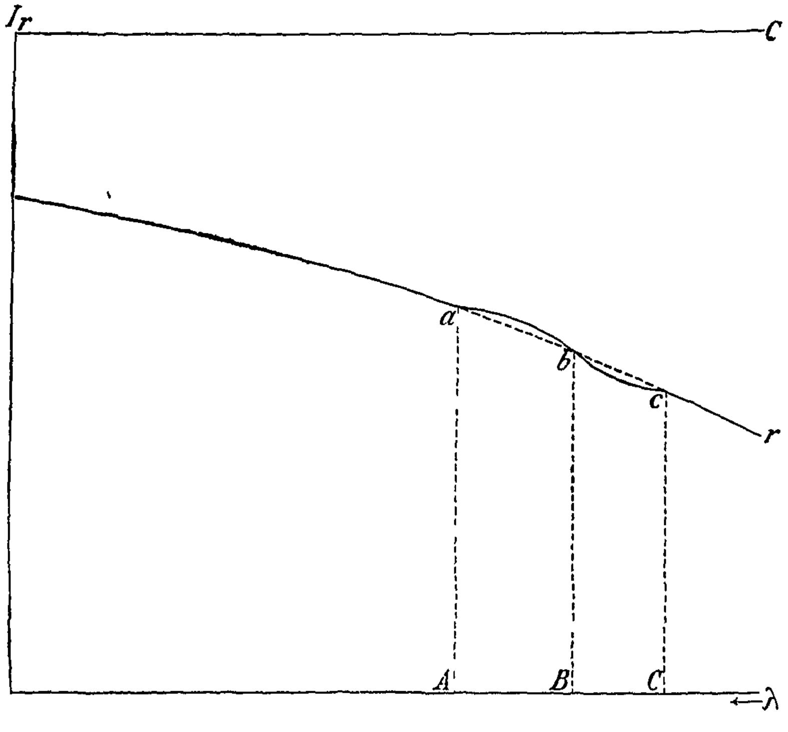

Fig. 5.

ously towards the violet, but presents the same oscillation in the region *ABC*.

Hence the relative distribution of intensity of the light on the sun's disc reckoned with respect to the centre, must present an anomaly in the neighbourhood of the maximum of energy. This anomaly bears entirely the same character and relates to the same region of the spectrum as the anomaly observed by ABBOT (c.f. fig. 5 with fig. 1; the part of the curve r outside C in fig. 5 has not been observed by ABBOT).

Summary. Starting only from the hypothesis that the sun may be conceived as a glowing gaseous body, in which the temperature and the density gradually decrease from the centre outward, and the outer layers of which consist of little luminous, little absorbing, but greatly diffusing and irregularly refracting gas-masses, we have derived an explanation of the anomaly, observed in the decrease of light of different wavelengths from the centre towards the limb of the solar disc.