# THE CAUSE OF THE DARKNESS OF SUN-SPOTS.

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THE most generally received doctrine as to the constitution of the Sun is probably that in which the entire internal mass of that body is regarded as being in a gaseous condition; the temperature, below the photospheric layer, being above the critical point of all known substances. The low mean density is accounted for by supposing that the temperature increases rapidly with the depth below the surface, the expansive energy of the internal gaseous nucleus largely counteracting the enormous force of compression due to gravity.

It appears to be pretty generally admitted, too, by recent writers, that the photosphere is a surface of condensation; a region, exposed to the cold of space, where elements of high boiling point, such as those of the carbon group, are precipitating from the gaseous state and forming clouds of highly emissive solid or liquid particles.

I propose in this paper to discuss the question as to the cause of the relative darkness of Sun-spots on the basis of these fundamental ideas, and with special reference to the recent work of W. E. Wilson on the "Thermal Radiation of Sun-spots."

Most spot theories in vogue at the present time attribute the blackness of spots to masses of relatively cool vaporous material which absorbs the intense light of the underlying photosphere. Thus in Secchi's theory a spot is regarded as a kind of sink in the photosphere, into which the materials which have been erupted in the neighborhood are settling down again into the body of the Sun, forming a great cloud of cool absorbing vapors. Faye believes spots to be vortices set up by the relative drift of adjacent portions of the photosphere, the dark absorbing material accumulating in the vortex by reason of the indraught. Oppolzer likens a spot to a disturbed region in our atmosphere in which great contrasts of temperature arise; and he explains the obscurity in the same way as a result of increased absorption by relatively cool vapors.

Many other theories have been proposed in which absorption is regarded as the principal factor in causing the darkness, and the evidence afforded by the spectroscope seems always to have been taken as practically demonstrating the truth of this hypothesis.

But absorption as ordinarily understood is in many respects very difficult to reconcile with the common features of spot formation. The well-defined structure and abrupt transitions in passing from photosphere to penumbra, and from penumbra to umbra, points rather to the *absence* of the bright photospheric clouds from the spot, than to their suppression beneath a mass of absorbing material; and seems much more suggestive of an actual rent in the photospheric layer through which a less luminous region is revealed.

Quite recently in a paper on the "Level of Sun-spots,"[1] read before the British Astronomical Association, Mr. Maunder argues that absorption can have but little effect in causing the spot darkness, for whether the spot be regarded as a depression or an elevation compared with the photosphere, the obscuring effect of an absorbing layer would be vastly increased when near the Sun's limb as compared with its effect at the center of the disk, owing to the foreshortening; and the greater the area of the spot the more noticeable would this become, so that in many cases the entire spot would appear as black as the umbra when near the limb. As this is not the case at all, the conclusion is drawn that diminished radiation rather than increased absorption is mainly operative in a spot.

In the same paper Mr. Maunder suggests that a spot may be regarded as a region of high temperature in which the condensation of highly incandescent carbon does not take place to the same extent as in the photosphere, the diminished radiation being due to the relatively low emissive power of the gaseous contents of the spot; just as in an ordinary gas burner the pre-

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[1] *Jour. B. A. A.*, 7, No. 3.

cipitation of solid carbon produces a bright luminosity, whilst the purely gaseous portion of the flame glows but feebly.

This explanation of spot darkness certainly harmonizes very well with the observed structure of spots and with many of the attendant phenomena, such as the great brilliancy of the faculous bridges and the surrounding faculous region; the intensification of the H and K lines and frequently of the hydrogen lines over the entire spot region; all of which suggest that a spot is really a center of relatively high temperature.

Unfortunately it is open to a very serious objection when we consider the application of Kirchhoff's law to solar conditions. For suppose we liken a spot to a non-luminous Bunsen flame, or better, to a pure hydrogen flame burning in air, and a bright facula bridging the spot to a platinum wire held in the flame. The analogy would at first sight appear to be a very striking one, the hydrogen flame emitting a very feeble continuous spectrum and the glowing solid a very brilliant one, although no hotter than the flame. But yet according to Kirchhoff's law the feeble emissive power of the gas is exactly compensated by its feeble absorptive power, so that if we were to increase the thickness of the non-luminous flame indefinitely the brightness would increase, until finally, it would equal that of the glowing solid; even that of a theoretically "black" solid which has the highest emissive power. This condition would be reached when the radiating gas was of such thickness as to be entirely opaque to transmitted light.[1]

In the case of the Sun-spot, therefore, we should expect that the immense and practically unlimited depth of the interior gases would compensate for their relatively feeble radiating power, even if we took no account of the much higher temperature and high state of compression of the interior regions. There seems to be no escape from this difficulty, even if we imagine the interior of the Sun to be absolutely non-luminous, for then,

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[1] The cumulative effect of a great thickness of radiating gas can easily be shown with a row of Bunsen flames such as are used in tube furnaces. If these are observed "end on" the brightness is seen to increase in proportion to the number of flames, or very nearly so.

according to Kirchhoff, it will also be absolutely transparent, and the photosphere on the opposite side would be seen through the spot opening.

Again, if the internal gases are so compressed as to be practically opaque like solids, then they must radiate like solids, they cannot continue to accumulate the energy acquired by absorption indefinitely. Thus we seem driven back again to some modification of the absorption hypothesis, unless we find that the ordinary laws of heat exchange are not applicable under solar conditions.

The structural characteristics of spots might perhaps be explained on the absorption hypothesis by supposing that the cooled absorbing material was situated at a considerable depth, being partly overlaid and encroached upon by the photosphere, the spot opening being at the same time filled up with dark material; and it would be natural to suppose this absorbing material to be the same as that which everywhere covers the Sun, producing the absorption at the limb, and giving rise to the mottled appearance of the disk due to variations in level of the photospheric clouds in this smoke-like veil. Thus there would be no real distinction to be drawn between a well-developed spot and the minute pores and interspaces between the photospheric clouds. It will be shown later, however, that there is a very marked difference in the character of the spot darkening and the general shading at the limb. It is clear that if a spot is really an accumulation of absorbing vapors it must be cooler than the photosphere, whilst if on the other hand, it is an opening where the photospheric clouds have been evaporated, we must regard it as being as hot as or hotter than the surrounding region. Evidence in support of the absorption hypothesis has been frequently derived from the widened lines seen in spot spectra, which are supposed to indicate a lower temperature in the absorbing gases. But the widening is at the most very slight; a proportionally slight increase in the depth of the gases concerned will equally well account for it. Furthermore, only a very small proportion of the lines in the spectrum are widened or intensified; probably many others are weakened, or suppressed altogether even when they do not appear as *bright* lines. It has not, perhaps, been sufficiently realized that a large proportion of the light we are dealing with in the spectrum of a dark nucleus is not derived from the spot at all, but is simply photospheric light reflected from the sky; the contrast between the umbra and the sky illumination outside the limb being in many cases almost inappreciable. Thus the majority of the Fraunhofer lines in the umbral spectrum may be spurious lines; could we remove our atmosphere and wholly isolate the umbral light, it is quite possible that the spectrum would be found to be, in the main, an emission spectrum.

However this may be, the widened lines are evidently not a satisfactory criterion as to the relative temperature of spots and photosphere, and the slight extra amount of gaseous absorption implied by their presence can have practically no effect on the darkness of spots. This is obviously due to the general darkening, which is apparently continuous all along the visible spectrum, and may or may not be the result of absorption. The resolution of a portion of the spot band by Professor Young into innumerable closely crowded dark lines with occasional bright intervals,[1] would seem to point to absorption, but absorption by gaseous rather than solid or liquid matter.

In the opinion of the writer, no satisfactory explanation of spot darkness is likely to be arrived at until the spot band itself has received the closest investigation, both in the visible and invisible regions of the spectrum, particularly with regard to the relative intensity and character of the band and quite apart from the question of widened lines or bright lines, which can only give information as to the condition of the gases in the overlying reversing layer and chromosphere, and which taken all together can have but little influence on the general radiation of the spot.

### THE THERMAL VALUE OF THE SPOT RADIATION.

The measurements of total radiation from spots by Langley,

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[1] YOUNG, *The Sun*, 4th ed., p. 323.

using a bolometer, and recently by W. E. Wilson with a radiomicrometer, do not give any direct information as to the relative temperatures of photosphere and spots; the relative emissive powers being unknown. Indirectly, however, they would seem to afford a clew.

In the thermal measuring apparatus the blackened receiving surface may be supposed to absorb indiscriminately all the radiant energy falling upon it, whatever the wave-length, that is, the whole range of wave-lengths, including of course the visible rays. Thus the measurements sum up the energy in the entire spectrum, and show, as it were, the *average* darkness of the spot band when the whole spectrum is taken into account.

The results show that a spot is very much less dark measured thermally than visually. The spot band is, therefore, much darker in the visible region of the spectrum than it is in other regions; where, it would seem, it may even be *reversed.* This fact is the more striking, when we consider that in ordinary sunlight the rays which possess the maximum heating power are those about the middle of the visible spectrum, so that one would expect, *a priori*, to find a practical agreement between thermal and photometric estimates of the darkness.

Referring to Mr. Wilson's paper (*Monthly Notices*, Vol. LV, No. 8), the monthly mean values of the umbral radiation are found to vary from .35 to over .50; that of the photosphere at the center of the disk being 1.00. The photosphere radiation, however, rapidly diminishes from the center towards the limb where it becomes .45, whilst the spot radiation remains nearly constant in all positions on the disk. Thus the ratio between the radiation of the spot and that of the *neighboring* photosphere approaches unity as the spot nears the limb. The highest value of this ratio recorded by Mr. Wilson is .83, but both Langley and Frost have measured spots in which the thermal intensity even exceeded that of the surrounding photosphere.

With regard to the visible radiation of spots, it is quite obvious from ordinary telescopic observation that the umbra of a normal spot does not emit more than a very small fraction of the light of the photosphere, even of the neighboring photosphere, when the spot is near the limb. To make sure of this point the writer has roughly estimated the relative darkness of a spot by means of an Abney photometer, so arranged as to reduce the light of any portion of the photosphere by any known amount The results obtained show that the *penumbra* of an ordinary spot is not more than one-third or one-fourth as bright as the photosphere; whilst the umbra itself is probably in most cases less than one-twentieth.

The apparatus being incapable of measuring small fractions, this latter value is probably an upper limit, the intensity may have any value less than that ; many spots must indeed be at least a hundred times less bright than the neighboring photosphere at the limb, for in this position the dark umbra often presents the illusion of a piece cut out of the limb ; proving that no more light comes from the spot than from the sky outside. Perhaps the average spot nucleus is not however quite so dark as this, for during partial solar eclipses spots are said to appear lighter in tint than the black disk of the Moon.

But whatever may be the true photometric value of the spot darkness the discrepancy between thermal and visual estimates is evidently very marked, and it would be of great interest to determine in what region of the spot spectrum the extra energy is to be found, which is shown by the relatively high thermal value of the radiation. Does the spot band become less dark or even reversed, in the infra-red or in the ultra-violet ?

The question of the relative temperature of spots and photosphere must largely depend on the position in the spectrum of this region of maximum intensity. For suppose we admit that the whole of the Sun's interior below the photosphere behaves like an opaque solid as regards radiation. The emission spectrum will be a continuous one ; but the distribution of energy in the spectrum will not be uniform. The wave-length of the rays of greatest intensity will depend on the temperature, the wave-length decreasing with increase of temperature according to a well-established law of radiating solids. Now the temperature of the photosphere is such as to give, according to Langley, a maximum in the visible spectrum. But deep down in the interior the temperature must be enormously higher and the wave-length of maximum energy from that region must be shifted far into the ultra-violet.

If then in a spot we have a glimpse of the interior intensely hot regions below the photosphere we should expect to find the spot spectrum brighter (or less dark) in the ultra-violet. But if relatively cool absorbing vapors are the principal cause of spot darkness, then the maximum should be found in the infra-red; not a true emission maximum perhaps, but a part of the spectrum where the absorption has less influence than in the visible spectrum.

There is one point which would seem to be definitely settled by the thermal measures. It has been previously mentioned that the spot darkness and the general shading at the limb are different in character. This results from a comparison between the thermal and visual estimates of the darkening in the two cases. In the limb absorption the discordance between these measures is not greater than would be the case assuming it is due to a smoke-like layer which absorbs the blue rays more completely than the red and yellow, which in sunlight have the greater heating power, a feature too that is well brought out by Vogel's detailed measures made in different colors. But the spot darkness is evidently of a different character, the thermal intensity being extraordinarily high, and it is certainly not possible to explain it by assuming a greater thickness of the *same* absorbing material.

For supposing we reject Langley's and Frost's measures of abnormal spots giving a higher thermal intensity than the photosphere and consider Wilson's average result, namely .75 at .95 from the Sun's center, to be an overestimate. If a spot near the limb gave only .66 of the thermal effect of the surrounding photosphere, then, assuming the darkening of spot and limb to be only a question of degree, this would imply in the spot a 34 per cent. absorbing layer added to that which gives the general absorption. But a layer which absorbs 34 per cent. of general radiation (heat) will absorb 46 per cent of light[1] if it is of the same material which covers the photosphere, leaving .54 as the photometric value of the umbra compared with the adjacent photosphere, or about .25 compared with the center of the disk values which are evidently quite inadmissible, for large spots near the limb often appear as dark as the sky, their intrinsic light being only a minute fraction of that of the surrounding region.

A possible clue as to spot darkness has occurred to the writer which does not necessitate absorption and still does not violate the ordinary laws of heat exchange. The temperature gradient in the Sun is not known, but it is believed that the temperature near the surface must increase very rapidly with the depth According to Oppolzer this increase must be at least 6000° C for each second of arc (see *Astronomy and Astrophysics*, Oct. 1893 p. 739). A few thousand miles below the photosphere therefore the temperature must enormously transcend that of the Sun's visible surface. Is it possible that the radiation from this inconceivably hot interior region takes place in wave frequencies of a higher order altogether than that of the photosphere?— the visible radiations being relatively feeble.

This assumes that in a radiating body at high temperature the intensity of the longest waves tends to diminish with increase of temperature. That is, as the radiations of maximum energy move up the spectrum with increasing temperature, the actua as well as relative intensity in the lower region of the spectrum must be supposed to diminish.

In a general way the shifting of the maximum intensity towards the violet with increase of temperature may be said to be confirmed by star spectra. It is well known that the photographic magnitudes of many stars do not correspond with the visual magnitudes. Thus the first type stars are photographi

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[1] Compare the tables of absorption given by Wilson and Rambaut: "Th Absorption of Heat in the Solar Atmosphere" (*Proc. Royal Irish Acad.*, 3d serie Vol. II, No. 2), and Young, *The Sun*, 4th ed. p. 247.

cally brighter than solar stars of the same visual magnitude, that is the blue and violet in the spectrum of the hotter stars is relatively brighter than the yellow and red.

Whether the red rays are really less bright in the Sirian stars than would be the case if the temperature were reduced to that of the solar stars, it is not possible to say. Langley has found however, that very far down in the normal solar spectrum the intensity is very much less than might have been expected. He found it easier, in fact, to detect these long waves in the spectrum emitted by a copper vessel filled with boiling water, and even in the rays of the Moon when its surface has become slightly warmed by the Sun.[1]

It would seem not impossible therefore that in the radiation of a Sun-spot this relatively feeble part of the spectrum has crept up into the shorter visible wave-lengths, following the rays of greatest energy which have traveled far up into the ultra-violet. It is true that if this be the real explanation of spot darkness the total radiation of the umbra should greatly exceed that of the photosphere, whereas according to Wilson's measures it is never even equal to it. It is probable, however, that the bulk of the energy would be absorbed by the Earth's atmosphere, which is a far more efficient screen for the ultra-violet rays than for visible light. It would seem too, that some of the energy does not assume the form of heat on reaching the Earth, but is effective in producing those magnetic disturbances which are characteristic of large umbræ.

But as the writer has already pointed out, a little further research into the character of the spot band in the invisible reaches of the spectrum would doubtless throw much light on the question, even if it did not at once demolish the above somewhat speculative theory.

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[1] S. P. LANGLEY, "The Solar and Lunar Spectrum" *Mem. Nat. Acad. Sci.*, Vol. IV, Part. 1.