The Sun's Outer Atmosphere.[1]

By Prof. E. A. Milne, F.R.S.

Astronomers are accustomed to divide the outer regions of the sun into four parts: (1) the photospheric layers, (2) the reversing layer, (3) the chromosphere, (4) the corona. In this address I wish to deal particularly with the chromosphere, but before doing so I should like to dwell a little on certain aspects of this fourfold division. Meteorologists make a similar subdivision of the earth's atmosphere. We have the troposphere, the stratosphere, the conducting layers, the auroral layers, and so on. But meteorologists have at least one advantage over solar physicists—meteorologists know where the earth's atmosphere begins. It may leave off very indefinitely, but it certainly begins quite definitely—it begins at the solid and liquid crust of the earth. It is sharply bounded below. But on the sun, and indeed on any star, no such sharp base exists. Whether the sun is wholly gaseous, or whether with Dr. Jeans we suppose it to be ultimately in a liquid state in the far interior, we are at least certain that owing to the high surface temperature and the positive temperature gradient implied by the outflow of heat, the entire outer layers, down to a depth much greater than the furthest depth we can see, are in the gaseous state. We therefore have no datum line for the base of the solar atmosphere.

It is true that, as seen in the sky, the sun has a sharp edge. But we have to remember that at the sun's distance one second of arc corresponds to 700 km., and that a line of sight passing one second of arc inside the sun's limb traverses 64,000 km. of the solar sphere. Thus the sharpness is to some extent illusory. We can, however, assert that above the level corresponding to the 'sharp edge' the gases are practically transparent as regards their continuous spectrum, whilst below this level they are practically opaque. If we knew the intrinsic opacity (per unit mass) of the solar material, we could calculate the pressure at which the transition from practical transparency to practical opacity takes place, for a line of sight nearly tangent to the sun. Assuming that general opacity arises from the ejection of photo electrons, the various unknowns may be estimated. We find that the opacity of a column of given length varies as the square of the pressure, and hence falls off rapidly outwards. It appears that practical transparency along a tangential line of sight occurs at a pressure of about 10^{-6} atmospheres. When we view the sun's surface normally, at the centre of the sun's disc, we see to a deeper level. Calculation shows that all but one per cent. of the light originates at depths where the pressure does not exceed 10^{-3} atmospheres. This change of pressure, 10^{-6} atmospheres to 10^{-3} atmospheres, appears to take place in a range of depth of some 50 km. These limits serve to define the 'photospheric layers'—the layers within which originates the light of the continuous spectrum sent to us by the sun.

Superimposed on the sun's continuous spectrum is an absorption line spectrum. Some of these lines show in their fine structure reversals, but we may ignore these and state that for the undisturbed solar disc we have, broadly speaking, a spectrum composed entirely of absorption lines. We are not compelled to assume that the layers producing these lines are entirely exterior to the photospheric layers. Theory shows that, provided the temperature decreases outwards, an absorption spectrum will be shown if the gas has a general coefficient of absorption and superimposed on this certain selective absorption coefficients associated with particular wave-lengths. Thus if the general coefficient of absorption remained definitely constant at all levels up to the sun's boundary, we should still have a Fraunhofer spectrum. Actually, if we accept the photoelectric origin of the general absorption, the general absorption coefficient per unit mass decreases with the pressure, and thus as we pass outwards the general absorption coefficient becomes practically zero whilst the selective absorption coefficients are still large. There is therefore a region effectively transparent except in the lines themselves. Nevertheless, within the photospheric range of pressures already mentioned, selective line absorption will also be occurring. The term 'reversing layer' is used to denote in a general way those layers which contribute to the Fraunhofer spectrum, but we now see that there is no precise delimitation between the reversing layer and the photospheric layers. The two shade into one another. The photospheric layers are also giving rise to line absorption, though this absorption will be weak; in other words, the residual intensities of the lines produced in this region will not be much below the intensity of the continuous background. The upper reversing layer, transparent except in the lines, will give rise to stronger lines, that is, lines with smaller residual intensities.

As evidence for this we have that the stellar sequence of spectra indicates a pressure of the order of 10^{-4} atmospheres for the layer in which absorption lines of excited atoms originate, but a pressure of the order of 10^{-7} atmospheres for the layer in which absorption lines of normal atoms originate. The former pressure lies inside our photospheric range of pressure, the latter pressure lies outside it.

In the upper reversing layer a new feature begins to present itself—the selective effect of radiation pressure near a wave-length of selective absorption. Now it must be supposed that selective absorption is occurring to some extent at all depths throughout the sun; in the far interior, the X-ray levels of the atoms will be giving rise to selective absorption. We may, therefore, pause for a moment to inquire how it is that selective radiation pressure only arises on the fringe of the sun. The pressure of radiation at any particular wave-length is

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[1] Discourse delivered at the Royal Institution on Friday, Mar. 9.

proportional to two factors. One is the net outward stream of radiation—the difference between the inward and outward streams; the other is the selective absorption coefficient in that wave-length—the degree of obstruction offered. But the selective absorption has itself an influence on the net stream. Where the selective obstruction is high, neither an inward nor an outward beam can go very far without being absorbed, and consequently the average distance (from a given atom) from which either an inward or outward beam originates is very small. When the state is one of 'local thermodynamic equilibrium,' as can be shown to hold provided the density is not too low, this has the effect of making the inward and outward beams very nearly equal at a wave-length of strong selective absorption. They originate from places so close to one another, both in space and in temperature, that they are only slightly unequal. They accordingly very nearly cut one another out. Thus in the product (selective absorption coefficient) × (net stream) the effect of the large selective absorption coefficient is neutralised by the small net stream, and we get no appreciable effect of selective radiation pressure; the radiation pressure is the same at a wave-length of selective absorption as at a wave-length where there is no selective absorption.

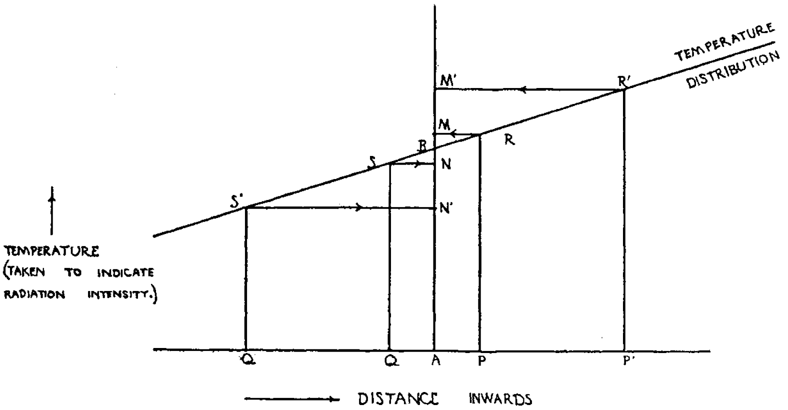

FIG. 1.—Diagram to illustrate the absence of selective radiation pressure in local thermodynamic equilibrium in interior. AM and AN represent the outward and inward fluxes at A in ν-radiation, AM′ and AN′ the outward and inward fluxes at A in ν'-radiation, where $k_\nu > k_{\nu'}$ (k=absorption coefficient). These fluxes originate at the mean positions P, Q, P′, Q′ respectively, where AP < AP′ because $k_\nu > k_{\nu'}$. The following relations hold:

i. Large absorption coefficient k_ν.
Net flux at $A \propto AM - AN = MN \propto PQ \propto 1/k_\nu$.

ii. Small absorption coefficient $k_{\nu'}$.
Net flux at $A \propto AM' - AN' = M'N' \propto P'Q' \propto 1/k_{\nu'}$.

Hence ($k_\nu \times$ net flux in ν-radiation) = ($k\nu' \times$ net flux in ν'-radiation), or radiation pressure due to ν-radiation = radiation pressure due to ν'-radiation.

Thus no selective effect in the interior.

Let us now see what happens near the boundary of the star, assuming local thermodynamic equilibrium holds up to the boundary. Near the outer confines of the star the inward stream is small, and there is little to neutralise the outward stream. The net stream is almost equal to the outward stream, and a big selective absorption coefficient will give rise to a big selective radiation pressure.

We can look at the matter at a slightly different angle. At the outside of the star, the big selective absorption coefficient, combined with such outward stream as exists, gives rise to a big selective radiation pressure, even though the big selective coefficient has itself cut down the outward stream to a value below the photospheric value. As we go inwards, an inward stream is generated by the back radiation from the atoms traversed, and this soon nearly balances the outward stream, giving a small net stream in the interior.

At all depths selective absorption cuts down the intensity of each stream. The difference between the interior and the surface is that in the interior the two streams are cut down to nearly the same amount and balance one another, whilst at the surface the outward stream, though cut down, is unbalanced.

The consequence of this is that in the upper reversing layer the gases are pushed outwards by selective radiation pressure, and so the layer is less compressed than the lower reversing layer and photospheric layer beneath. It is not easy to make an exact calculation, but it appears roughly that for calcium atoms the pressure decreases from 10^{-5} atmospheres to some very small pressure in a range of about 100 km. This estimate is not to be pressed—it may perhaps be an under-estimate. But we shall not go far wrong in attributing a thickness of the order of some hundreds of kilometres to the upper reversing layer.

In this region, in a steady state, the atoms are maintained in equilibrium under gravity, the gradient of gas pressure and selective radiation pressure. As we go outwards selective radiation pressure steadily increases in importance. The question arises, what happens at the upper boundary of this layer? Actually, it cannot have a definite upper boundary, but we will suppose we are endeavouring to trace the pressure upwards by the same principles as govern the equilibrium of the earth's atmosphere, selective radiation pressure only being added. Two possibilities arise: either selective radiation pressure, though increasing, remains steadily less than gravity, or it attains a value greater than gravity. It may do the former for some kinds of atoms, the latter for other kinds of atoms. In the former case nothing particular happens; the atoms of this particular kind simply thin out moderately rapidly. In the latter case, we arrive at a contradiction. When radiation pressure exceeds gravity, equilibrium is no longer possible unless the gradient of gas pressure becomes reversed. As it is difficult to see how the gas pressure could ever begin to decrease again once it began to increase—and it must ultimately

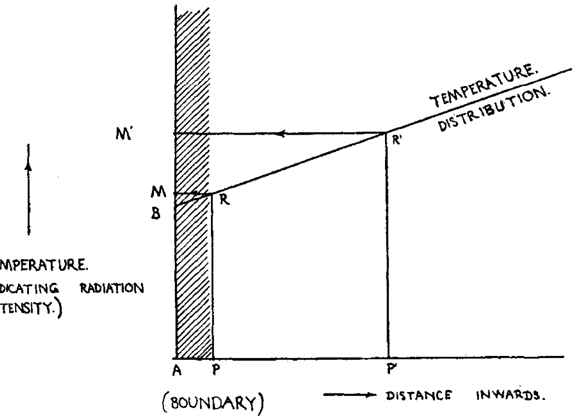

FIG. 2.—Diagram to illustrate existence of selective radiation pressure at boundary (chromosphere absent). AM and AN represent the emergent fluxes at the boundary in ν and ν'-radiation ($k_\nu > k_{\nu'}$). They originate at depths P and P′ respectively, and so correspond to temperatures PR and P′R′. Since k_ν is large, P is practically at A, and the emergent flux in ν-radiation corresponds closely to the boundary temperature AB. The following relations hold:

i. Large absorption coefficient k_ν.
Net flux $\propto AM = AB + BM = AB + c/k_\nu$.
ii. Small absorption coefficient $k_{\nu'}$.
Net flux $\propto AM' = AB + BM' = AB + c/k_{\nu'}$.
ν – Radiation pressure $\propto k_\nu AM = k_\nu AB + c$.
ν' – Radiation pressure $\propto k_{\nu'} AM' = k_{\nu'} AB + c$.
Hence $k_\nu > k_{\nu'}$ implies ν-radiation pressure $>\nu'$-radiation pressure.

decrease because the sun's atmosphere is finite—we reject this possibility. But if equilibrium is no longer possible, since we have assumed equilibrium all the time, something must be wrong with our assumptions. We could only now keep the atoms in equilibrium if we assumed some kind of hypothetical net which caged the atoms down. Let us suppose that the atoms are, in fact, kept in equilibrium by a net of this kind, and that then the net is suddenly removed. What will happen?

The atoms, being acted on by a radiation pressure exceeding gravity, will be ejected from the layers below. An outer atmosphere will come into being. But the ejection of atoms will not proceed indefinitely. As this new outer atmosphere becomes thicker and thicker its back radiation will begin to be appreciable; it must be constantly returning to the layers below some fraction of the radiation incident on it. The back radiation will exert a downward pressure, which will go on increasing with increasing thickness of the outer atmosphere until finally its back pressure is equal to the pressure exerted by our hypothetical net. After that no more atoms will be ejected, and the outer atmosphere will be permanent, and will exist in a state of equilibrium.

In the case of the sun we identify this outer atmosphere with the chromosphere, observed at times of total solar eclipse and spectroscopically at other times. About a century ago, Canning called a New World into existence to redress the balance of the Old. For millions of years the sun has been calling a new atmosphere into existence to redress the balance of the old.

(*To be continued.*)

Obituary.

DR. CHARLES H. GILBERT.

IN the passing of Dr. Charles Gilbert, America has lost one of her most trusted fishery authorities and a zoologist of wide reputation. He had retired from his professorial duties at Stanford University, California, some three years ago, and was devoting his whole energies to the working out of salmon problems on the Pacific coast, and specially in Alaska, where the most productive salmon fisheries of the world now exist, when a sharp attack of bronchitis terminated his career.

A native of the State of Illinois, Dr. Gilbert early came under the spell of that famous ichthyologist, David Starr Jordan, and in a short time was his most prominent pupil and then his associate in various expeditions. Ere long, papers were appearing on the fishes of southern California and the Pacific Islands over their joint names. When the Stanford University was created in 1891, Jordan became the principal and Gilbert the professor of zoology. At the age of sixty-five he retired, after occupying the chair for thirty-four years. His published work during this long period, as shown in Dr. Bashford Dean's "Bibliography of Fishes," was almost exclusively on systematic ichthyology. He described many new species—in one paper 32, and in another 25—in a search of American waters. He studied the fishes of Panama when de Lesseps was engaged upon his unsuccessful effort to construct the canal, and he also wrote on the fishes of the inhospitable Galapagos Islands, and of Hawaii and Japan.

It was in 1880 that Dr. Gilbert first became associated with the U.S. Fisheries Commission, and from that time forward much of his work had practical application to fishery problems on the Pacific Coast. The interests of the salmon began to claim him from the year 1912, and it may be said without much fear of contradiction that his best and most useful work was carried on in the elucidation of the great runs of salmon in British Columbia and Alaska, and that in this branch of investigation he became the leading authority. Salmon research in Scotland had already revealed not only the importance of marking fish, but also the great value of salmon scale study, and Gilbert was the first in America to appreciate the insight into the life history of fishes which this branch of study can yield.

The runs of salmon in the famous Fraser River, which since the days of the Hudson's Bay Company had been regarded as inexhaustible, had begun to decline in a rather alarming manner, and a great fall of rock into the Hell's Gate cañon during the making of the Canadian Northern Railroad had blocked the river and wiped out the 'big run' which occurred every fourth year. The extensive