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"On the Physical Constitution of the Sun and Stars"*. By G. Johnstone Stoney, M.A., F.R.S., F.R.A.S., Secretary to the Queen's University in Ireland. Received May 15, 1867.

Part I.—Of the Sun.

Section I.—*Introductory.*

1. The true surface of the sun is the outer boundary of his enormous atmosphere; but the principal escape of heat takes place from a concentric layer at a vast depth beneath the surface. Within this luminous film there is a dark body, glimpses of which are occasionally seen as the umbræ of spots.

2. The part of the atmosphere above the photosphere, which may be conveniently called the Outer Atmosphere, is eminently transparent to most of the rays which emanate from the shell of clouds, or from beneath them. But this is not the case in reference to others. The atmosphere absorbs rays of those refrangibilities which correspond to the dark rays visible in the solar spectrum, and multitudes of others of a like kind beyond the limits of the visible spectrum. The depth of the atmosphere is so enormous that we must conclude it to be many times more than sufficient to act as an opake screen in reference to the great majority

* Read June 20, 1867: see Abstract, vol. xvi. p. 25. A part of the second section of the MS. sent to the Royal Society has been published in the Phil. Mag. for Aug. 1868; and the substance of an Appendix suggesting observations to be made on the occasion of the Solar Eclipse of Aug. 1868, which also forms part of the MS., was published in the 'Monthly Notices' of the Astronomical Society for Dec. 1867, and reprinted in the Phil. Mag., vol. xxxiv. p. 502 (1867). The rest of the paper is printed here.

of such rays. That there are *dark* lines in the solar spectrum reveals to us the fact that the surface of the atmosphere is cooler than the luminous region beneath. But we may go further than this. Most gases are colourless; in other words, they do not scatter rays incident on them. Neither do they reflect light from their surface. It follows, then, from the laws which regulate the exchange of heat, that where such a gas is of sufficient thickness to be opake in reference to any particular ray, it will send forth the most intense ray of that particular refrangibility which it is possible for a body of the temperature of the gas to emit. Hence that there are lines in the solar spectrum of very different intensities is an evidence to us that the surfaces of the atmospheres from which they have their source are at different temperatures. It thus appears, upon a rough view, that the upper layers of the atmospheres of sodium, magnesium, and hydrogen are cooler than those of iron and calcium, and that these again are cooler than the upper layers of the atmospheres of nickel, cobalt, copper, and zinc. In this, then, we have evidence both that the atmospheres of the several gases extend to different heights, and that the temperature increases from the surface of the solar atmosphere downwards. Again, such facts as that some of the iron lines are less dark than others in their neighbourhood, that some of the copper lines are not noticeable, prove that even before descending sufficiently far to have passed through a stratum of these gases thick enough to be opake to these rays, we have already arrived at a sensibly higher temperature. This temperature, in the case of some of the lines of cobalt, copper, and zinc, appears to approach, if it does not pass beyond, the temperature of the luminous clouds.

3. Let us now direct our attention to the darker nucleus which lies within the photosphere. It is known that a body, when surrounded on all sides by an opaque envelope of others at its own temperature, will reflect some of the incident light, if its surface be in any degree polished, and if the body be not wholly transparent or wholly black. It will scatter others of the incident rays if either its surface or its substance be such as would not be wholly invisible if exposed to light brighter than that corresponding to its temperature. And, lastly, it will emit rays in virtue of its own temperature of such kinds and in such quantities that, along with those transmitted, reflected, and scattered, they will make up a total which is definite for each temperature. This is one of the established laws of the exchange of heat. It follows from this that a body thick enough to be opaque which emits much more feebly than others at a given temperature must reflect incident rays better, or scatter them more copiously. It cannot in an eminent degree do both. Unless the dark body of the sun is cooler than the photosphere it is therefore, at least in those places which are exposed to us as spots, either such that it scatters incident light abundantly, or it has a highly reflecting surface.

4 Before pursuing further our inquiry into the nature of the central body of the sun, it will be convenient to enter upon the discussion of the

phenomena of the luminous clouds; and it will avoid confusion in this part of our investigation to adopt provisionally the definite hypothesis that the central body of the sun is an opake ocean with a highly reflecting surface—such a surface as an untarnished white molten alloy would present. We shall run no risk of error in doing this if we afterwards carefully reexamine such parts of our inquiry into the phenomena of the clouds as would be affected by substituting for this hypothesis any other that is admissible.

5. [We shall also assume that the photosphere is not itself the origin of the heat which it disperses abroad, but draws it from the adjoining regions. No doubt if chemical action could be the source of solar heat, the photosphere might be its seat, and resemble the luminous part of a candle-flame. In this case the opaque regions within might be cooler than the photosphere, provided the photosphere were so translucent as to allow a sufficient radiation through it from the parts within to the open sky. But the photosphere to be thus translucent should of necessity be at a far higher temperature than an equally bright body with a perfectly radiating surface. And almost to this intense heat it would raise a great extent of the outer atmosphere, which, being eminently transparent, is but imperfectly fitted to moderate the heat it receives from contact with the photosphere. Hence we should expect to see conspicuous bright lines in the solar spectrum, which, however, we do not find. Moreover, the amount of the sun's radiation appears to be decisive against our attributing it to chemical action.—September 1868.]

6. Let us consider what would happen if the photosphere were away, and nothing but an atmosphere of fixed gases in contact with an intensely heated molten sphere. To simplify our conceptions, let us conceive the molten mass to have a core which is maintained at a constant temperature, to have a surface reflecting perfectly, and to be enveloped by an extensive atmosphere of one fixed gas, which, for further simplicity, we shall suppose gives a spectrum of invariable lines. The atmosphere is supposed to be extensive enough to render the change of temperature throughout it so gradual that there are no currents of convection. The under surface of this atmosphere would be raised by direct contact to the same temperature as the polished surface of the dark body within. The temperature would very slowly decrease in passing outwards from the core, first through the molten ocean, and then through the atmosphere, until that upper layer of the atmosphere was reached which alone can emit heat into space. Through the thickness of this outer stratum the temperature would rapidly fall, the whole escape of heat from the system taking place exclusively from it, in the form of undulations of the ether of those particular wave-lengths which the gas constituting the atmosphere can excite. Such is a picture of what would ultimately become the permanent state of such a system as we have imagined.

7. Let us now suppose the surface of the ocean to lose part of its reflecting-power, and to become such an imperfect mirror as is possible with the bodies we know to exist. The surface of the ocean will at once begin

moderately to radiate heat, most of which will escape into space. It will thus become a surface of minimum temperature, cooler than the depths of the ocean within, and also for a time than the adjoining parts of the atmosphere without—just as the surface of the ground becomes a surface of minimum temperature while dew is falling. This surface of minimum temperature will draw heat from the warmer bodies on both sides of it, and will thus tend to cool both the atmosphere above and the ocean beneath.

8. Let us next conceive a particle with a highly emitting surface, and of the same temperature as the surrounding medium, situated in the atmosphere a short distance above the ocean. Such a body, owing to its lavish radiation, would quickly fall in temperature far below the bodies around it. If, however, these latter can supply it with heat so fast as to prevent its reduced temperature sinking below the temperature of brilliant incandescence, it will continue a magnificent spectacle amid the comparative darkness around. Let us now suppose that we have in the neighbourhood of this particle a vapour such that it is gaseous at the ardent temperature of the surrounding medium, but that it is precipitated either as a smoke or mist by the coolness of the radiating particle; it will, the instant it is so precipitated, begin itself to radiate copiously, and so will tend to maintain the reduced temperature which is the condition of its continuing to blaze forth. The process is the inverse of what takes place in setting a flame alight, and is strictly analogous to it *. If the vapour be of great depth, the upper parts, when precipitated in luminous cloud, will protect the rest of the vapour from that free radiation towards the sky which is the necessary condition of the phenomenon. If the blaze had been first communicated to a part below the outer layer, it would at first form a cloud in that situation—the radiation from the upper side of this cloud would be least obstructed—the blaze would therefore tend to spread outwards, and would no doubt do so much more swiftly than the cloud could subside. The blaze would therefore soon fly to the upper † surface of the vapour, where alone it could establish itself permanently. Such, then, appear to be the luminous clouds.

9. Since the great escape of heat takes place from the photosphere, it must be cooler than the contiguous parts of the regions within or of the atmosphere without. And the lowest temperature to which either of these could possibly fall is evidently the reduced temperature of the clouds, a mi-

* It seems not improbable that as there are substances which will take fire spontaneously and, when they have done so, will maintain a temperature of ignition—a far higher temperature than they had before—so perhaps there may be vapours in the solar atmosphere capable of spontaneously forming a molecule of liquid or of solid at their own high temperature, which would have but a momentary existence were it not that its instantly beginning to radiate both renders its new state fixed and sets the whole neighbourhood ablaze.

† It will be shown further on, that a *trace* of the vapour which forms the clouds may, and probably does, extend far beyond them. But the clouds are at the boundary of the region in which there are *large* quantities of the vapour.

nimum which would only be possible under the condition that the luminous stratum was an absolute screen stopping every ray of heat coming from beyond it, and also reducing the entire of the intermingled atmosphere of fixed gases quite to its own low temperature. The former of these conditions, especially, seems improbable when we bear in mind that the film in which cloud can form must be so transparent as to admit of the abundant radiation towards the sky which we have found to be essential. We shall be able to treat this subject further on with more precision; but, in the meantime, we are clearly entitled provisionally to regard the film of clouds as colder than the regions on either side of it.

10. Let us now consider more attentively the thermal conditions of the photosphere and of the subjacent regions. In doing this it is necessary to distinguish that part of the condensed vapour from which there is so abundant a radiation outwards as would enable vapour in that region to pass into cloud, from such other parts of the condensed vapours as are too much screened from the sky to allow any more cloud to form. It will accordingly be convenient henceforth to restrict the word *cloud* to the former, and to use such words as *mist* or *rain* when we have occasion to speak of condensed vapour in a lower situation. Now, in the first place, if from any cause a part of the vapour fitted to produce luminous clouds rose above the general level and became detached, it would form a cloud, which by its own weight, and by the coolness it would impart to the fixed gases interspersed through it, would gradually settle down till it became merged in the general luminous stratum. This behaviour would be hastened by a sudden change of the density of the solar atmosphere, which, as we shall find hereafter, takes place at the boundary of the photosphere.

11. The clouds, though of a thickness small when compared with the enormous extent of the atmosphere of the sun, may nevertheless be of considerable depth; but they can in no place be of such a density and thickness as to be opaque, since no part of the stratum can come into existence from which there is not a sufficiently free radiation towards parts already cooled down or towards the open sky. This, then, will put a limit to the density of the clouds. If, from any cause, heat is supplied unequally to different parts of the stratum, the density of the clouds must be correspondingly unequal, inasmuch as, in the more heated regions, even the lowest part of the stratum, which is the worst-situated, must be sufficiently exposed to the sky to enable it, under these adverse circumstances, to maintain the low temperature which is essential to the formation of cloud. The clouds will accordingly be rarest where most heated. As, then, the clouds are translucent in all parts, and in some parts more so than in others, it becomes of importance to study the intensity of the heat and light which reach us from beyond them.

12. The clouds must either brood like a fog over the surface of the subjacent ocean, or they are separated from it by an interval. I will deal with the latter hypothesis first. Assuming, then, that there is such an in-

terval, we may suppose that the part of the atmosphere which occupies it is either nearly saturated with the vapour from which clouds are formed, or but sparingly supplied with it. If it be very moist, the clouds as they descend, either through convection or by subsidence, will pass into the form of mist, which will collect into a rain that will fall towards the ocean beneath. If, on the other hand, the interval between the clouds and ocean be far from being charged with vapour, the cloud as it descends will dissolve away among the hot and dry gases below, while the ascending currents, as they rise into the situation from which they can freely radiate, restore the same quantity of a thin gauze-like cloud. The possible alternatives, then, are, 1st, that the interval between the clouds and ocean is transparent, or, 2nd, that it is rendered in a considerable degree opake by mist and rain, or, 3rd, that the clouds reach to the ocean.

13. Let us examine these hypotheses, beginning with that of a clear atmosphere under the clouds. If there be such a transparent space, it is easy to see that the intensity of the rays which strike the under surface of the clouds is greater than that part of the solar radiation which emanates directly from the clouds; for a portion of the rays which flow downwards directly from the clouds will be reflected by the body of the sun beneath; another portion will be scattered at the same surface. These two portions will fall short of the entire quantity of rays in the first instance radiated downwards from the clouds. But as the body of the sun is hotter than the clouds, what is here wanting will, according to a known law regarding the exchange of heat, be more than made up by what the body of the sun will itself emit*. Thus we have already a quantity of heat radiated upwards against the clouds greater than that emitted by them downwards. But further, the clouds must scatter a part of the rays that strike their under surface. Some of the rays so scattered will be afterwards reflected or scattered by the body of the sun, and will augment still further the heat striking the under surface of the clouds over that which they radiated downwards. This excess will be great if the clouds be of a material that scatters light copiously; for in this case we shall not only have a large supply of rays that had been so scattered added to the stock, but also, if the clouds scatter incident rays abundantly, they will, in obedience to the laws of the exchange of heat, be at the same time such as will emit more feebly; and accordingly the brightness which shines upon them from the background will be relatively more conspicuous. But, however this may be, whether the excess be more or less, it

* In fact, if α be the proportion of incident rays reflected by the molten ocean, and β be the proportion scattered by it, and if A be the quantity of heat which would be emitted per square metre by the surface of a perfect radiator as hot as the molten ocean, then will the quantity emitted by the molten ocean be $(1-\alpha-\beta)$ A.

But B, the quantity sent down by the clouds which is incident on a square metre of the ocean, is less than A, since the clouds are at a lower temperature; and of this, $(\alpha+\beta)$ B is returned upwards. Adding, we find the whole quantity sent upwards to be $B+(1-\alpha-\beta)(A-B)$, which is greater than B.

at all events exists, if the space under the clouds be clear; and the clouds are in the position of a luminous and partially transparent body, with a still brighter body beyond. If the average condition of the nearer body, the screen of clouds, be such that it is in a considerable degree opaque, then will a small spot in it which is thinner and consequently more transparent than the neighbouring parts appear brighter than they; whereas, if the average condition of the nearer body allow rays to pass pretty freely through it, then will a thin spot appear but little brighter than the parts around, and the circumstances might even be such as to render it darker than them. We find both these appearances on the sun's disk. In the middle of the sun's disk we find it to be most luminous; and here the clouds would intercept least of the greater brightness beyond. In the marginal parts of the disk the spectator looks obliquely through the stratum of clouds, which is therefore more opaque to his view, so that, in approaching the edge of the disk, the less intense light emitted by the clouds would be progressively less and less fortified by the splendour within. The brightness of the disk would be accordingly shaded off towards the edge. At the same time thinner parts of the film, if not too extensive, would be seen conspicuously as faculæ near the edge of the disk, while towards the centre their brightness would be merged in the general illumination around.

14. But, further, as the shell of clouds is at a much lower temperature than the adjoining layer of the atmosphere beneath it, while it is subjected to but little less pressure, it is evident that there must be a violent motion of convection between the two, the chilled portions descending, while the hot vapours from below boil upwards. Cloud will form in the rising vapours, but it will be less dense than that of the parts more effectually cooled. The appearance will be very much like what we see when looking from above upon water in the act of boiling, the smooth tops of the columns of ascending water being represented on the sun by the brighter patches due to the thinness of that cloud which can maintain its existence in the hotter vapours, while the turmoil which is seen in the water between these columns corresponds to the darker interstitial spaces which give to the sun's surface a minutely granulated appearance (rice-grains, willow-leaves, &c.), and in which the cloud at times becomes so opaque that those flakes which by prolonged emission become the most dusky seem to show like black or, at least, very dark pores. This honeycombed structure of the stratum of clouds will modify the effect of obliquity in rendering the marginal parts of the sun's disk less bright than the centre. It will cause the effect to be perceived further from the border than it otherwise would be.

15. So far, then, the hypothesis of a clear space between the clouds and the ocean seems to square with the phenomena; but upon a further scrutiny we are forced to resign it as untenable. For, as has been explained, the light which has suffered but one reflection, or been but once scattered, by the body of the sun, falls short of that which emanates directly from the clouds, and the greater brightness of the background is

due to the additions made (1) by the rays emitted by the ocean in virtue of its higher temperature, and (2) by the light which has suffered more than one reflection or been more than once scattered at the surface of the ocean. Now the umbræ of spots exhibit to us the body of the sun so dark when compared with the luminous clouds, that the great brightness of the faculæ cannot be due to the light *emitted* by the ocean. It must therefore be due to the second cause, which, as we know, can only produce any considerable effect if the clouds are of such a nature that they scatter light abundantly. But, again, we know from the proximity in which the umbræ of spots have been seen to the edge of the disk, that the interval between the clouds and the ocean is trifling as compared with the superficial dimensions of many faculæ. Hence, if the illumination of the background be due to the second cause, to light reflected or scattered from the body of the sun, the parts under extensive thin portions of the clouds would be sensibly less illuminated, and would give rise to an appearance more like that of penumbræ than of faculæ. The hypothesis would therefore fail to account for *large* faculæ. Its rejection is also demanded by the appearance of the spectrum. For if the clouds had the property of scattering light in the degree which would account for the granulated aspect of the photosphere, they would in the same proportion emit light feebly; and the whole light reaching us, whether from or through them, would fall very perceptibly short of the maximum corresponding to their temperature. And as, on the other hand, a gas is a perfect emitter of the rays of which its spectrum consists, there could not fail to be conspicuous bright lines from those gases which extend only to the hotter strata of the solar atmosphere. Now it is certain that no such lines are *conspicuous*.

16. The same objections lie with still more force against the hypothesis that the clouds are in contact with a polished ocean. We may therefore summarily dismiss this hypothesis.

17. Let us then turn to the alternative of an interval with mist and rain. The mist beneath the clouds, as it is found in a hotter region, would emit more light, though the mist were no more dense than the cloud. But the mist is probably much more dense; and it is natural to suppose that it is dense enough to be opake, in which case, if it be formed of a material which is a good radiator, it will emit light of almost the maximum intensity which can be emitted by a body of its temperature. Indeed this effect would be produced if the mist and rain were in a quantity much less than that which would be opake, in consequence of the assistance rendered by the body of the sun beneath, and that without any hypothesis as to the state of the latter, except only that it is opake and at as high a temperature as the mist. Now as it is likely that the average quantity of mist and rain is much more than this, its density may undergo very considerable fluctuations without its ceasing to pour forth its full torrent of light and heat. Such, then, appears to be the brighter background which shines through the clouds. As in the last case, the currents of convection which

prevail generally over the sun produce the gradation of light fading towards the edge of the disk, and the *finely* granulated structure of his surface, with its little bright patches, its dusky intervals, and its dark pores. Where circumstances render the cloud thinner over any considerable extent while the rain continues, we have a facula which is visible (if it be not lost in the equal brightness of all around) when it is near the centre of the disk. Where such thin parts occur in numerous small patches, they produce that ordinary mottled appearance of the sun's surface which is visible in telescopes of moderate power. If the rain stop, we have penumbra. If the cloud also vanish, we have the umbra of a spot.

18. We have thus arrived at an hypothesis which in a very satisfactory manner agrees with several of the phenomena. Before, however, we trust ourselves to this or any other particular hypothesis, we must retrace our steps and go over the whole ground with care, retaining at each step all the alternatives which up to that point are possible, and reducing the number by eliminating from the list every hypothesis which we find to be inconsistent with any known fact.

19. Now, in the first place, the gradation of brightness from the margin to the centre of the sun's disk has usually been attributed to the action of an absorbing atmosphere telling with most effect upon the edges of the disk. But of course faculæ cannot be referred to any action of our earth; and it is incredible, therefore, that they exist only near the edge of the disk. Hence the cause of the gradation of light, whatever it is, must be such as will leave the faculæ of unimpaired lustre as they move from the centre to the edge of the disk, while it renders other parts more dusky. We may therefore discard the hypothesis that an absorbing atmosphere is the cause, since it would not act in this way. It is therefore due in some way to the nature of the photosphere itself.

The telescope informs us that the photosphere consists of two parts which may be distinguished:—a brighter part, seen in the centre of the disk, in the faculæ, in smaller bright patches, and in its purest form in the brighter specks of those parts of the surface which are granulated; and a dusky part, seen towards the margin of the disk and in the interstices between the bright specks of the granulation. Now, incandescent bodies radiate equally in all directions, and therefore, if the light of the sun emanated from a mere mathematical surface, the disk would not be brightest at the centre. Hence the photosphere is a stratum, not a surface. Again, the brighter parts cannot be at the top of this stratum, since in that case the margin of the sun's disk would be the brightest. Hence the bright and dusky parts are either intermingled, or the dusky parts form the outer layer; and if they are intermingled, the brighter parts must be the more transparent, to render this hypothesis consistent with the gradation of light we find on the disk.

Again, the observations show the whole granulated surface of the sun to be in a state of incessant change, although not by any means so impetuous

as the earlier observers supposed; hence at least the outer layer of the photosphere is mobile. It is accordingly either a gas, a liquid, or a cloud. The nature of its spectrum forbids our admitting it to be a layer of gas* of moderate depth; and if the layer of gas were so profound as to be opake, it would radiate the maximum amount of light belonging to its temperature at great depths, and so obliterate the mottled appearance which exists.

Again, an *opaque* liquid would be luminous only at its surface, which we have found to be inadmissible. Nor is an ocean of *transparent* liquid sufficient. Little light gets through 20 metres of sea-water, and probably a few hundred metres of the most transparent liquid would be practically opaque. This trifling depth therefore would render the incandescent ocean luminous to almost the full extent which is possible for a body of its temperature. Such an ocean, therefore, if tranquil at the surface, would reduce the whole sun's disk to an uninterrupted gradation † of brightness. If, to account for the granulation, we suppose the ocean to be every here and there fretted with storms, the foam, being endowed with the property of scattering light abundantly, would no doubt be a bad emitter, and would therefore form dusky spots; but these spots would be most conspicuous at the centre of the disk. We must therefore reject the hypothesis of a transparent ocean. The hypothesis of a cloud, then, is the only one which remains.

20. Of clouds, there are two well-marked varieties—clouds precipitated from a state of vapour, like the clouds in our atmosphere, and clouds of fixed solids or fixed liquids, such as smoke, a cloud of dust, the mud in turbid water, oil in an emulsion. The sun attracts with so much more force than the earth that everything on his surface presses down with a force twenty-eight times as great as that with which it would press downwards on the earth's surface. From this, and from the amazing extent of his outer atmosphere, it is natural to suppose that the pressure in its lower strata must be enormous. This must occasion the lower strata to be very dense, unless the effect of the pressure be counteracted by the terrific heat. On the other hand, the average density of the whole sun being only about one-fourth of that of the earth, the solids and liquids on his surface are probably much less dense than with us. If it should happen that the lower strata of the atmosphere were more dense than some of the solid or liquid substances on the sun, these latter would rise until they reached that part of the atmosphere which is of the same density as themselves, and would float there; and if in a state like dust, they would doubtless be maintained in violent agitation by currents of convection, those on the outside being most cooled by radiation and sinking, to be replaced by others from the

* [*i. e.* a layer of gas whose spectrum is interrupted. But if the luminous matter of candle-flames be gaseous, such a gas is not excluded by this consideration. A gas of this kind, however, would be in a considerable degree opaque, and behave on the sun like the cloud of dust which is disposed of in § 20.—September 1868.]

† The surface, if sufficiently undisturbed, would act as a mirror near the margin of the disk; and accordingly the light emitted by it would in proportion fall off.

hot regions beneath. The dust in the ascending currents would be the warmest, and therefore the brightest, and if the currents of convection were on a sufficiently extensive scale, we might expect as a result such a granulated appearance as the sun presents. But it would be one which would be incompatible with the gradation of brightness which extends from the centre to the margin of the sun's disk. The stratum in which these convection-currents exist could affect the light coming from beyond merely as a partial screen, since there would be no marked* difference in point of transparency between the ascending and the descending currents, so that the peculiar action which the honey-combed structure of the stratum would otherwise produce is not developed. There would accordingly be scarcely any diminution of brightness till quite close to the edge of the disk; and there it should fall off very rapidly. As these are not at all the appearances which present themselves, we must give up the hypothesis of a cloud of fixed solid or liquid matter. The hypothesis of clouds precipitated from vapour is therefore the only one not excluded; and we have found that it appears consistent with all the phenomena that have been yet discussed.

Section II.—*Collateral Inquiries.*

21. The only class of bodies about the molecular constitution of which we have any satisfactory † information is gases. These appear to consist

* [The increase of transparency of the heated portions would be due to the separation of the particles of dust caused by the expansion of the intermingled air. Now at these high temperatures an addition to the temperature produces an immense alteration in the quantity of heat and light radiated (see § 68). Hence the elevation of temperature cannot be great; and accordingly the volume of the air, which varies as the temperature measured from the absolute zero, is but little increased. Such a change would determine great currents of convection, but would not materially separate interspersed particles of dust.—September 1868.]

† The dynamical theory of the molecular constitution of gases, which, if I mistake not, may be ranked in point both of importance and probability along with the wave theory of light, does not appear to have yet met with that general attention and acceptance which it seems to deserve. It may not be out of place, therefore, to add to the numberless proofs which have been drawn from its interpreting the phenomena of gases, by many writers, but especially by Clausius, the following negative proof, which demonstrates that no statical theory, whether on the hypothesis of a continuous substance or of distinct particles, is *possible.*

A gas is susceptible of enormous dilatation and compression without an abrupt change in the laws upon which its pressure depends; hence, if it consist of particles at rest, the force which acts in any direction on any one, must be the result of forces emanating from many others, no one contributing more than a share which may be regarded as infinitesimal. Hence it is easy to see that if the density be changed, the pressure will vary as the square of the density; for the force in any direction on any one particle will increase as the number of the particles on that or the opposite side (according as the elementary forces are attractive or repulsive) near enough to act on it, *i. e.* will increase as the density; and the number of particles subjected to this augmented force which are found within each element of volume will also have increased in the same proportion. Hence the pressure per square millimetre across any surface within the gas will increase as the square of the density: and as this is a law which does not exist in

of molecules moving about actively and irregularly in all directions, the path of any one being for the most part rectilinear, or, in other words, most of its motion being executed at a sufficient distance from the neighbouring molecules to be beyond the reach of sensible influence from them. Every now and then, however, each molecule comes sufficiently near some other molecule to have its course bent, on which occasions it darts off in a new direction. Moreover many facts in physics and chemistry lead irresistibly to the conclusion that the molecules are resolvable into simpler elements; and the probability distinctly is that each in most gases is a highly complex system. When a body so constituted is enclosed, the molecules by flinging themselves against the walls of the containing vessel produce the pressure of the gas. If the enclosure be at the same temperature as the gas, they do so without gain or loss of *vis viva*. But if the wall be at a higher temperature, the activity of those molecules which strike it is increased, and *vice versâ*. The altered activity is shared with the rest of the gas by conduction and convection—or more slowly by conduction only, if the circumstances do not admit of convection; and so the temperature of the whole becomes changed.

22. When we compare different gases, we find that their molecules differ both in mass and in the motions that prevail *within* * them. That the internal motions differ is abundantly testified by the amazing variety in the grouping of the spectral lines to which the various gases give rise †. Again, the number of molecules per cubic millimetre is known to be the same in all perfect gases, when taken at the same temperature and pressure. Hence the masses of the molecules are in most simple gases proportional to what chemists have called their atomic weights; and in those instances in which this is not the case they stand in the same simple relation to these atomic weights as the densities of the gases nearly do. Thus the masses of the gaseous molecules of hydrogen, nitrogen, oxygen, chlorine, selenium, bromine, iodine, and tellurium bear to one another the ratios of the numbers 1, 14, 16, 35·5, 79·5, 80, 127, 129—which are the atomic weights of these substances, and nearly in the ratios of their vapour-densities. But to represent the mass of molecules of phosphorus on the same scale, we must double the number used as its atomic weight, and take 62 instead of

gases, it follows that no gas consists of distinct particles at rest. The same proof applies, by the principles of the differential calculus, to the hypothesis of a continuous and homogeneous substance. For this proof given more at large, see Proceedings of the Royal Irish Academy, vol. vii. (1858), p. 37.

* The molecular motions of a gas consist of two very distinct parts—the motions of the molecules among one another, and the motions in the interior of each molecule.

† [An inquiry into the numerical relations between the motions of gases and waves of light forms a collateral inquiry introduced here into the MS. of the present paper as sent to the Royal Society. It has, however, been separated and published independently in the Philosophical Magazine for August 1868, in order to shorten what is here printed as far as possible by confining the collateral inquiries to those which are indispensable.—September 1868.]

31, since its atomic vapour-volume is half that of the foregoing gases. Similarly in arsenic we must take 150 instead of 75; on the other hand, in cadmium and mercury we must halve the atomic weights, and take 56 and 100 instead of 112 and 200. In the case of sulphur, each molecule of its vapour has a mass represented on the same scale by the atomic weight of sulphur, viz. 32, if the vapour be observed at temperatures above 1000° Centigrade; but at some lower temperature it seems to contract to one-third of its former volume, since at 500° Centigrade, and under, it is found to be thus shrunk. The mass of each molecule has become three times what it had been before, and is therefore represented at low temperatures by 96.

23. Let us now consider what it is that puts a limit to the atmosphere. Let us first suppose that it consists of but one gas, and let us conceive a layer of this gas between two horizontal surfaces of indefinite extent, so close that the interval between them is small compared with the mean distance to which molecules dart between their collisions, but yet thick enough to have, at any moment, several molecules within it. Molecules are constantly flying in all directions across this thin stratum. Some of them come within the sphere of one another's attraction while within the layer, and therefore pass out of it with altered direction and speed. Let us call these the molecules emitted by the layer. If the same density and pressure prevail above and below the layer, the molecules which strike down into it will, on account of gravity, arrive with somewhat more speed on the average than those which rise into it. Hence those molecules which suffer collision within the stratum will not scatter equally in all directions, but will have a preponderating downward motion, so that of the molecules emitted by the stratum more will pass downwards than upwards. This state of things is unstable, and will not arrive at an equilibrium until either the density or the temperature is greater on the underside of the layer. If the density be greater, more molecules will fly into the stratum from beneath than from above; and if the temperature be greater the molecules will strike up into it, both more frequently and with greater speed. In the earth's atmosphere it is by a combination of both these that the equilibrium is maintained: both the temperature and the density decrease from the surface of the earth upwards.

24. We have hitherto taken into account only those molecules which, after a collision, have arrived at the stratum from the side on which the collision took place. But beside these there will be a certain number of molecules which, having passed through the stratum from beneath, fall back into it without having met with other molecules, either by reason of the nearly horizontal direction of their motion, or because of its low speed. The number of molecules that will thus fall back into the stratum will be a very inconsiderable proportion of the whole number passing through the stratum, so long as the temperature and density are at all like what they are at the surface of the earth. In the lower strata of the atmosphere, therefore, the law by which the temperature and density de-

crease will not be appreciably affected by molecules thus falling back. But in those regions where the atmosphere is both very cold and very attenuated, where accordingly the distance between the molecules is great and the speed with which they move feeble, the number of cases in which ascending molecules become descending without having encountered others will begin to be sensible. From this point upwards the density of the atmosphere will decrease by a much more rapid law, which will within a short space bring the atmosphere to an end.

Not, however, before the density has sunk immeasurably below what can be reached in our laboratories. If there be a unit-eighteen * of molecules in every cubic millimetre of the air about us, there will remain about a unit-fifteen in every cubic millimetre of the best vacuums of our air-pumps. The molecules are still closely packed, within about an eighth-metre of one another; *i. e.* there are about 60 of them in a row as long as a wave of orange light. This accounts for our atmosphere's spreading to the height at which meteors betray its presence, which is far beyond the height at which we can detect it by any ordinary means.

25. If an atmosphere consist of a mixture of gases (for example, of uncombined nitrogen and hydrogen), the boundary of each gas will be at a different height. Where the nitrogen is no longer able to maintain itself, the molecules of hydrogen, with a velocity $\sqrt{14}$ (or nearly 4) times as great, can still spread far beyond it. It is also to be observed that the nitrogen will reach a greater height in consequence of the presence of the hydrogen than it could alone, since an ascending molecule of nitrogen has more chance of escaping the fate of falling back without having encountered another molecule if there be molecules of hydrogen to be met with as well as molecules of nitrogen. In this way a substance of which there is but little in the atmosphere may ascend nearly to the full height to which it would rise if present in abundant quantity.

Thus the vapour of sodium, which, as we shall find, is present in the sun's atmosphere as a mere trace, seems nevertheless to reach nearly the full height assigned to it by the mass of its molecules, through the assistance afforded to it by the abundant atmosphere of hydrogen, which extends much further. In the same way the vapour of water is probably borne to the limits of the earth's atmosphere, although but a minor constituent; and the trace of carbonic acid which terrestrial air also contains, is probably supported to a height nearly as great as it would reach if present in much greater quantity. Where, then, as in the sun's atmosphere, the lightest constituent is abundant, all the other gases which enter into its composition, will range to heights which stand in the order of the masses of their molecules, whether they be present in large or in small quantities. And where, as in the earth's atmosphere, there is but a trace of the lightest

* See Phil. Mag. 1868, vol. xxxvi. p. 141. A unit-eighteen is a convenient name for the number expressed by 1 with eighteen 0s after it—that is, for a unit multiplied by 10^{18}. Similarly an eighth-metre is to be understood as a metre divided by 10^8.

constituent, viz. the vapour of water, it will form an exception to the rule, inasmuch as it will be unable to maintain its footing more than a little beyond the limits of the lightest of the abundant constituents, which in the case of the earth's atmosphere is nitrogen.

26. It becomes of importance, then, to arrange the constituents of the solar atmosphere in the order of the masses of the molecules, as this will be the order in which the surfaces of their successive atmospheres will succeed one another. A provisional attempt is made in the following table to arrange on this principle the better-known of the elementary substances, including all the bodies whose spectra have yet been compared with the spectrum of the sun, or with those of other celestial bodies. The position in the list of those substances whose names are printed in ordinary type has been ascertained by direct observations on the vapour-densities, and may be depended on; but all the rest, which are printed in italics, are placed on the provisional supposition that the masses of their molecules when in the state of vapour are proportional to their generally received atomic weights. It is probable that in some of these instances the mass is proportional to some simple multiple or submultiple of the atomic weight, and that the position in the list ought to be altered accordingly. We shall find grounds for concluding that this is the case with Barium, and that it ought to be placed in the list probably between zinc and selenium, perhaps between calcium and titanium, or between sulphur and chlorine.

Table I. Table of Elementary Substances arranged in the order of their Vapour-densities where these are known, and in the order of the Atomic weights where the Vapour-densities are not known.

Elements.	Observed vapour-density, that of air being the unit.	Observed vapour-density, that of hydrogen being the unit.	Presumed masses of the gaseous molecules, that of hydrogen being the unit.	Whether present in the sun's atmosphere or not.
Hydrogen	·0692	1	1 which is H	present.
Lithium	....	....	7 „ L	not.
Glucinum	....	....	9·3 „ G	
Boron	....	....	10·9 „ B	
Carbon	....	....	12 „ C	
Nitrogen.................	·9713	14·04	14 „ N	not.
Oxygen	1·1056	15·98	16 „ O	not.
Fluorine	....	....	19 „ F	
Sodium	....	....	23 „ Na	present.
Magnesium	....	....	24·3 „ Mg	present.
Aluminum	....	....	27·5 „ Al	doubtful.
Silicon	....	....	28 „ Si	doubtful.
Sulphur above 1000° C	2·23	32·23	32 „ S	
Chlorine.................	2·47	35·69	35·5 „ Cl	
Potassium	....	....	39·1 „ K	doubtful.
Calcium	....	....	40 „ Ca	present.
Titanium	....	....	50 „ Ti	

TABLE I. (*continued*).

Elements.	Observed vapour-density, that of air being the unit.	Observed vapour-density, that of hydrogen being the unit.	Presumed masses of the gaseous molecules, that of hydrogen being the unit.	Whether present in the sun's atmosphere or not.
Vanadium *	....	....	51·2 which is V	
Chromium	....	....	52·5 " Cr	present.
Manganese	....	....	55 " Mn	present.
Iron	....	....	56 " Fe	present.
Cadmium	3·94	56·94	56 " ½Cd	not.
Nickel	....	....	59 " Ni	present.
Cobalt	....	....	59 " Co	present.
Phosphorus	4·50	65·03	62 " 2P	
Copper	....	....	63·5 " Cu	present.
Yttrium	....	....	64·36 " Y	
Zinc	....	....	65 " Zn	present.
Selenium	5·68	80·46	79·5 " Se	
Bromine	5·54	80·06	80 " Br	
Rubidium	....	....	85·4 " Rb	not.
Strontium	....	....	87·5 " Sr	doubtful.
Zirconium	....	....	89·5 " Zr	
Cerium	....	....	92 " Ce	not.
Lanthanum	....	....	92 " La	not.
Sulphur under 500° C	6·617	95·62	96 " 3.S	
Didymium	....	....	96 " Di	not.
Molybdenum	....	....	96 " Mo	
Niobium	....	....	97 " Nb	
Mercury	6·976	100·81	100 " ½Hg	not.
Rhodium	....	....	104·2 " Ro	
Ruthenium	....	....	104·2 " Ru	not.
Palladium	....	....	106·5 " Pd	not.
Silver	....	....	108 " Ag	not.
Tin	....	....	118 " Sn	not.
Thorinum	....	....	119 " Th	
Uranium	....	....	120 " U	
Antimony	....	....	122 " Sb	not.
Iodine	8·716	125·95	127 " I	
Tellurium	8·913	128·80	129 " Te	
Cæsium	....	....	133 " Cs	
Barium	....	....	137 " Ba	present.
Tantalum	....	....	137·6 " Ta	
Arsenic	10·6	153·18	150 " 2.As	
Tungsten	....	....	184 " W	
Gold	....	....	196·6 " Au	not.
Iridium	....	....	197·2 " Ir	not.
Platinum	....	....	197·2 " Pt	not.
Osmium	....	....	199 " Os	
Thallium	....	....	204 " Tl	
Lead	....	....	207 " Pb	not.
Bismuth	....	....	210 " Bi	

* [The position of vanadium has been altered from that assigned to it in the MS. of this memoir, in accordance with Roscoe's recent investigations regarding this substance. If the vapour-density of vanadium be ever determined, it is presumable that its molecular mass will prove to be 2 V, *i. e.* 102·4, in analogy to those of phosphorus and arsenic, in which case its position in the Table will need to be altered again.—September 1868.]

Section III.—*Of the Outer Atmosphere of the Sun.*

27. Such, then, is the order in which we should expect to find that those of the elements which exist in the sun's atmosphere succeed one another,—the atmosphere of hydrogen far overlapping all the rest; then, at a profound depth, sodium and magnesium, reaching nearly to the same height, since the masses of their molecules are nearly equal; next, at a great distance further down, calcium; then, in a group reaching nearly to the same height, chromium, manganese, iron, nickel, and cobalt; then, within a moderate distance of these, copper and zinc; and lastly, after a vast interval, barium. These are all the elements as yet known to exist in the sun's atmosphere. Let us now compare with the observations this anticipation founded on the molecular constitution of the elements, bearing in mind that the order is likely to be in some few cases incorrect, owing to our having occasionally erred in assigning the foregoing masses to the vapour-molecules. To make this comparison most effectually, Table II., opposite to p. 32, of the intensities of the solar lines observed by Kirchhoff will be of use. In this Table the lines of each known constituent of the solar atmosphere are placed in the order in which they occur in the parts of the spectrum mapped by Kirchhoff, which extend between wave-lengths 43 and 77 eighth-metres, that is from the indigo about G to the extreme crimson beyond A*. Each spectral line is represented by a number,

* The reader should have by him Kirchhoff's maps of the solar spectrum in illustration of this paper. They have been published in a separate form by Messrs. M'Millan and Co. It will make a reference to these exquisite maps much easier, not only for the purposes of this memoir, but also for many other purposes, to mark with pencil-dots upon Kirchhoff's arbitrary scale each of the following positions of an absolute scale, founded upon Ångström's determinations of the wave-lengths of 70 lines (see Poggendorff's 'Annalen,' 1864, vol. iii., or Phil. Mag. 1865, vol. i.).

Positions upon Kirchhoff's scale of the principal points of a scale which expresses the lengths of the light-waves in air.

(N.B. Those positions which have a note of interrogation after them are doubtful, as they are too distant from rays measured by Angström to admit of a safe interpolation.)

Wave-lengths in eighth-metres, *i. e.* metres divided by 10^8.		Kirchhoff's arbitrary scale.	Wave-lengths in eighth-metres *i. e.* metres divided by 10^8.		Kirchhoff's arbitrary scale.
43	corresponds to	2873·1	44·30	,,	2651·5
43·10	,,	2855·0	45	,,	2553·2 ?
43·20	,,	2837·0	46	,,	2422·0 ?
43·30	,,	2819·0	47	,,	2292·5 ?
43·40	,,	2801·1	48	,,	2164·0 ?
43·50	,,	2783·4	48·50	,,	2099·8
43·60	,,	2766·0	48·60	,,	2086·7
43·70	,,	2748·8	48·70	,,	2073·7
43·80	,,	2732·0	48·80	,,	2060·8
43·90	,,	2715·7	48·90	,,	2047·9
44	,,	2699·6	49	,,	2035·2
44·10	,,	2683·7	49·10	,,	2022·6
44·20	,,	2667·6	49·20	,,	2010·2

1, 2, 3, 4, 5 or 6, which also indicates its strength in the solar spectrum, 6 meaning the darkest and 1 the faintest recorded by Kirchhoff.

28. The study of this Table is particularly instructive. It will be convenient to begin by studying the iron lines, since they are numerous, extend over a great range of the spectrum, and above all because there appear to be no bright lines in the iron spectrum to which dark lines in the solar spectrum do not correspond. This was invariably the case with those observed by Kirchhoff, who has mapped upwards of 70 of them

Table (*continued*).

Wave-lengths in eighth-metres, *i. e.* metres divided by 10^8.		Kirchhoff's arbitrary scale.	Wave-lengths in eighth-metres, *i. e.* metres divided by 10^8.		Kirchhoff's arbitrary scale.
49·30	corresponds to	1998·0	55	corresponds to	1309·0
49·40	„	1986·1	55·70	„	1248·4
49·50	„	1974·3	55·80	„	1240·2
49·60	„	1962·5	55·90	„	1232·0
49·70	„	1950·8	56	„	1223·8
50	„	1913·0 ?	56·10	„	1215.6
51	„	1762·0 ?	56·20	„	1207·4
51·60	„	1673·0	56·30	„	1199·3
51·70	„	1658·3	57	„	1144·0 ?
51·80	„	1644·3	58	„	1070·0 ?
51·90	„	1630·8	58·90	„	1009·7
52	„	1617·5	59	„	1003·0
52·10	„	1604·3	60	„	948·0 ?
52·20	„	1591·2	61	„	897·2
52·30	„	1578·3	61·10	„	891·9
52·40	„	1565·5	61·20	„	886·6
52·50	„	1552·8	61·30	„	881·3
52·60	„	1540·2	61·40	„	876·1
52·70	„	1527·9	61·50	„	870·9
52·80	„	1516·1	61·60	„	865·7
52·90	„	1504·8	61·70	„	860·6
53	„	1494·1	61·80	„	855·5
53·10	„	1483·8	61·90	„	850·5
53·20	„	1473·7	62	„	845·5
53·30	„	1464·0	63	„	800·0 ?
53·40	„	1454·4	64	„	758·5 ?
53·50	„	1445·6	65	„	719·1 ?
53·60	„	1436·1	66	„	682·3
53·70	„	1426·6	67	„	648·3 ?
53·80	„	1417·2	68	„	615·9 ?
53·90	„	1407·7	69	„	584·8
54	„	1398·3	70	„	555·8 ?
54·10	„	1389·0	71	„	528·4 ?
54·20	„	1379·7	72	„	502·4 ?
54·30	„	1370·5	73	„	477·7 ?
54·40	„	1361·2	74	„	453·8 ?
54·50	„	1352·1	75	„	430·3 ?
54·60	„	1343·3	76	„	406·9
54·70	„	1334·7	77	„	383·6 ?

The following Table contains the original determinations expressed in metrical measures on the supposition that a Paris inch=27·07 millimetres. The sign + is added where the omitted decimals lay between ·0016′ and ·005, and− where they lay between ·005

between G. and C. Kirchhoff used a Ruhmkorff's coil to produce the iron lines; but Ångstrom has lately compared the solar spectrum with

and 0083′: + is accordingly to be read plus one-third of a Xth-metre, and −, minus one-third of a Xth-metre. This goes to about the same amount of approximation as the numbers given by Ångström.

Wave-lengths of 68 *rays of the solar spectrum in VIIIth-metres, reduced from Ångström's determinations.*

Designation of ray.	Wave-lengths in eighth-metres.	Intervals between rays in tenth-metres.	Corresponding positions on Kirchhoff's arbitrary scale.	Darkness of ray, 6 being the darkest, and breadth of ray, G being very broad, according to Kirchhoff.	Remarks.
H_2	39·36	36−	....	....	Ca.
H_1	·72−	36−	....	....	Ca.
	40·07+	40+	....	....	Unknown; strong.
	·48−	18+	....	....	Fe; strong.
	·66	9	....	....	Fe; strong.
	·75	29−	....	....	Fe; strong.
h	41·04−	43+	....	....	H; very strong. Lately ascertained to be a fourth Hydrogen line.
	·47	82+	....	....	Double.
g	42·29+	24	....	....	Ca; double line.
	·53+	9+	....	....	Fe.
	·63−	12	....	....	Fe.
	·75−	36−	....	....	Fe.
G	43·10+	18−	2854.4	6	Fe.; winged.
	·28	15	2821·9	6	Fe; winged; broad.
	·43	43+	2796·2	6	H; winged; very broad.
	·86+	22	2721·2	6	Fe; winged; very broad.
	44·08+	10	2686·4	6 *f*	Fe; winged.
f	·18+	447	2670·0	6 *e*	Fe.
F	48·65+	10+	2080·0	6 *g*	H; winged.
	·76−	19+	2066·6	5 *c*; 5 *c*	Fe; double.
	·95	27+	2041·7	6 *b*; 6 c	Fe; double.
	49·22+		2007·2	6 *c*	Fe.
	·24+	2	2005·2	6 *d*	Fe; winged on one side.
c	·61	37−	1961·0	4	Fe; with wings of intensity 6.
b_3 {	51·72−	211+	1655·6	6 *e*	Fe; Mg; winged on one side.
	·73+	2−	1653·7	6 *b*	Fe; Ni; winged on one side.
b_2	·77	4−	1648·8	6 *f*	Mg; winged.
b_1	·88	11	1634·1	6 *g*	Mg; winged.
	·96+	8+	1622·8	5 *b*, 5 *c*	Fe; double like E.
	52·37	46−	1569·6	5 *c*	Fe.
	·70	28	1527·7	5 *c*	Fe; Co.
E_2	·73+	3+	1523·7	6 *c*	Fe } Interval between E_2 and E_1=1·07 Xth-metres.
E_1	·74+	1	1522·7	6 *c*	Fe, Ca.
	·87+	13	1508·6?	5 *b*	Fe.
	53·20	33−	1473·9	5 *b*	Fe.
	·28−	8−	1466·8	5 *c*	Fe.
	·32−	4	1463·0	5 *c*, 5 *c*	Fe; double line, closer than E.
	·44	12+	1451·8	5 *b*, 5 *c*	Fe; double line like E.

that given between iron electrodes from a battery of 50 cells, which gives a far greater number* of iron lines, and with this apparatus he has been able to observe the enormous number of 460 coincidences.

TABLE (*continued*).

Designation of ray.	Wave-lengths in eighth-metres.	Intervals between rays in tenth-metres.	Corresponding positions on Kirchhoff's arbitrary scale.	Darkness of ray, 6 being the darkest, and breadth of ray, G being very broad, according to Kirchhoff.	Remarks.
	53·69+	25+	1428·2	5 *b*	Fe.
	·71+	2	1425·4	5 *b*	Fe.
	·74+	3	1423·0	5 *b*	Fe.
	·76−	1+	1421·5	6 *c*	Fe.
	54·08+	33−	1390·9	5 *d*	Fe.
	·10−	1+	1389·4	6 *c*	Fe.
	·28+	19−	1372·6	5 *b*	Fe.
	·34−	5+	1367·0	6 *d*	Fe.
	·49+	16−	1352·7	5 *b*	Fe.
	·51	1+	1351·1	5 *b*	Fe.
	54·60−	9	1343·5	6 *c*	Fe.
	55·77−	117	1242·6	6 *c*	Fe.
	·91	14+	1231·3	5 *d*	Fe.
	·99	8	1224·7	5 *d*	Ca.
	56·03−	4−	1221·6	5 *d*	Ca.
	·07	4+	1217·8	5 *d*	Fe; Ca.
	·20	13	1207.3	5 *g*	Fe.
D_2	58·94+	274+	1006·8	6 *b*	Na } Interval between D_2 and D_1
D_1	59·00+	6	1002·8	6 *b*	Na } =6·03Xth-metres.
	61·05−	204+	894·9	2 *e*	Ca.
	·24−	19	884·9	4 *b*	Ca. Co.
	·39−	15	877·0	4 *c*	Fe.
	·43+	5−	874·3	4 *b*	Ba.
	·63+	20	863·9	5 *b*	Ca.
	·71	8−	860·2	3 *d*	Ca.
	·92−	21−	849·7	3 *c*	Fe.
a	62·59	67+	....	....	A strong line caused by the earth's atmosphere.
C	65·68	309	694·1	6 *c*	H; winged.
B	68·75	307	592·7	6 *c*	Winged on one side.
A	76·12	737	404·1	6	Winged.

In this list two of Ångström's rays have been omitted—those to which he assigns the wave-lengths 1903·4 and 1936·4 VIIIth-inches, which correspond to 51·53−, and 52·42 VIIIth-metres; since there are no conspicuous lines in the solar spectrum corresponding to them, and since, in the case of the latter at least, there is plainly some misprint. If we might conjecture that they ought to have been entered as 1900·4 and 1932·4 eighth-inches, they would correspond to 51·44+ and 52·31 eighth-metres, and belong to two strong iron rays.

* This appears at variance with the usual law that spectral lines increase in brightness with the temperature, inasmuch as the temperature of a Ruhmkorff's spark is probably very much higher than that from the battery of many cells. We are still too

29. The first thing that strikes the eye in the part of the table appropriated to the iron lines is a continuous gradation of intensity from the indigo to the red. The most refrangible iron lines mapped by Kirchhoff are those in the indigo, all of which he found of the deepest black, which he represents by the number 6. Then follow the lines in the blue, in which there appears to be a struggle between this intense blackness, and the darkest shade short of blackness recorded by Kirchhoff, and to which he assigns the number 5. In this part of the spectrum lines of the intensity 6 are still predominant. In the next region, the bluish-green, this struggle is continued, but now with a predominance of lines of the intensity 5. About the middle of the green we for the first time meet with an unexceptionable line of intensity 4, corresponding to the wave-length 53·87 VIIIth-metres. The last line of intensity 6 presents itself at wave-length 55·77, after which, in the yellow, orange, and red, the intensity of iron lines has for the most part sunk to 4 or 3.

30. Now the iron lines seen in the solar spectrum originate in the upper part of the iron atmosphere, each ray coming from a stratum of such a thickness that it is opake for that particular ray. This thickness differs from ray to ray, being greater for those rays which are caused by atomic motions of feeble intensity. Such rays therefore will in part originate from a greater depth in the solar atmosphere, and therefore from a region of greater heat. They will therefore be brighter, or in other words less con-

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little informed on these subjects to speculate with any confidence on the cause, and perhaps the following conjecture is the best that can yet be made.

The effect may perhaps be due to the brief duration of the sparks. The enormous temperature caused by each spark lasts for a very short time, and is not renewed until after the lapse of an interval long in comparison. The electricity, when it passes, probably produces its direct effect in accelerating and controlling the directions of the motions of translation of the molecules of the gas; and only indirectly, through the resulting violence of the molecular collisions, excites those more subtle atomic motions which give out the light. Those of the atomic motions therefore which are most influenced by each collision will be the first to reveal themselves, and the rest not until after very many collisions shall have taken place, so that before they have had time to culminate, the duration of the spark may be over: whereas when they have time fully to unfold themselves, as they can in a continuous current, they may attain in some cases a higher intensity, and consequently emit a greater brightness.

In support of this explanation, we have the fact that the lines seen with Ruhmkorff's coil have been observed to correspond to the most conspicuous lines in the solar spectrum. Now those atomic motions which are most developed by a few collisions will usually be those of which the periodic time is most subject to perturbation (see Phil. Mag. 1868, vol. xxxvi. p. 132). They will therefore in such cases give rise to *dilated* lines in the solar spectrum, and if the circumstances be such as to cause much of the breadth of the line to appear quite black, as for example in many of the iron lines, it will in consequence of its breadth appear much more intense. On the other hand it should be remembered as against our conjecture, that if the Ruhmkorff's sparks last as long as the measures Wheatstone made of the duration of the spark of a Leyden Jar, viz. four Vth-seconds, the number of collisions which take place during the continuance of a spark must be so great as to take away much from the probability of the explanation.

spicuous as dark rays. These same rays, since they are due to feeble atomic motions, will, in the iron spectrum produced by artificial means, appear the faintest. Now in all regions of the iron spectrum artificially produced, rays present themselves of every possible degree of intensity; whereas of those observed by Kirchhoff in the solar spectrum, the fluctuation of intensity in any one region of the spectrum seldom exceeds one degree of his numerical scale, and but once exceeds two degrees. This is conclusive evidence that iron is so very abundant in the solar atmosphere as to be opaque for the feeblest of these rays before a depth is reached which is very much hotter than the outer surface of the iron atmosphere. It also shows that the gradation of brightness in the iron lines from the more to the less refrangible parts of the spectrum is not due to the less refrangible lines coming from profound depths, and being on this account brighter. But the cause is sufficiently obvious. If a body of such a kind that it emits the maximum light corresponding to its temperature, be gradually heated, it will first begin to glow with scarlet, orange, yellow, and green rays; and according as its temperature rises its spectrum will expand in both directions towards the extreme red, and still more towards the violet. If, then, a body heated in a furnace be compared with one at a much higher temperature, the spectrum of the former will everywhere be fainter than that of the latter, but not equally so. It may have a considerable brightness in the red and orange rays, and show sensible light in the green, and at the same time appear in the comparison absolutely black at higher refrangibilities. And the same general appearance* would doubtless be found if the maximum spectrum of any one temperature were compared with the maximum spectrum of a higher temperature†. Now the upper layer of the iron atmosphere, from which comes all the light that reaches us in the iron lines of the sun's spectrum, is at a vastly lower temperature than the photosphere, but not so cool as to be of insensible brightness through the whole range of the spectrum. It begins to glow sensibly in the green, even in comparison with the intense light of the sun, and renders the iron lines of the green short of absolute blackness. And this effect goes on increasing until it reaches its climax in the orange and red.

31. As molecules of calcium vapour are of a mass less than that of iron molecules, in the ratio of 40 to 56, calcium vapour must reach a far cooler

* See § 52.

† It is natural to suppose that this steady increase of intensity with the temperature which pervades the whole range of the visible spectrum, should extend beyond it; and we are assured of it by the phenomena of calorescence. Dr. Tyndall succeeded in heating a body so as to be visible by the concentration upon it of rays beyond the red. This would have been impossible,—it would have been at variance with the principles of the exchange of heat, if the rays which were brought together were of an intensity that could be emitted by a non-luminous source. Hence the source from which they came (which was in fact a far hotter body whose luminous rays had been intercepted) was able to send forth invisible rays more intense than any non-luminous body could emit.

region of the solar atmosphere than iron. Nevertheless none* of the calcium lines observed by Kirchhoff appear to be as intense as many of the iron lines. This is no doubt due to calcium vapour being a much smaller constitueut of the sun's atmosphere than iron, just as oxygen is less abundant in our atmosphere than nitrogen, and carbonic acid much less abundant than either. Judging from the indigo and green calcium lines, which are all less intense than the iron lines in their neighbourhood, it would appear that some light reaches us from a hotter region than any light that reaches us from iron lines, and accordingly that calcium gas is so rare, and in consequence the stratum which can intercept and therefore is employed in emitting these rays is so thick that, though its upper surface soars far above the upper surface of the iron atmosphere, its under surface stretches further down than the under surface of the corresponding, and comparatively shallow, active stratum of iron gas. This appears to be the case too with most of the rest of the calcium lines observed by Kirchhoff; but the lines 55·99 and 56·03 in the yellowish-green, and the lines 61·63, 64·32, and 64·55 in the red, all of which are of intensity 5, are probably exceptions, and owe their strength to calcium gas being much more opake in reference to them, so that they are emitted by a stratum shallow enough to reach but little beyond the extreme verge of the iron atmosphere. These are some of the lines that give the calcium light, when seen undispersed, its beautiful purple colour. Calcium is no doubt very opake also in reference to the other lines of the same class, such as the lines H_1, H_2 and g, beyond the limit of Kirchhoff's maps. In taking a general review of the calcium spectrum, these lines should be left out of consideration as not being comparable with the rest; and if this be done, the remaining lines will exhibit the same gradation of intensity from the red to the blue which we found in the iron lines.

32. But in the immense extent of atmosphere which spreads upward from the surface of the calcium, in the vast elevation to the boundary of the atmospheres of magnesium and sodium, and in the far greater heights to which hydrogen alone can soar, the temperature has fallen too low to produce light visible in comparison with solar light in any part of the spectrum. And accordingly all the lines referable to magnesium, sodium, or hydrogen, in whatever part of the spectrum they may lie, are intensely black. But before proceeding to examine these lines in detail, it will be convenient to inquire into the state of the regions further down.

33. The sun's atmosphere is heated beneath by contact with the scorching body of the sun, and it would throughout its whole extent attain this

* The lines 48·83 and 52·74 of intensity 6, the latter of which is the less refrangible of the lines constituting the close double line E, are left out of account; as they are also iron lines, and no doubt owe their intensity to this circumstance. The line 56·07 of intensity 5, which is also a line common to the two spectra, is probably a stronger line on this account than it would be either as a calcium or as an iron line.

enormous temperature were it not for the escape of heat from it, which is perpetually going on. The first and principal escape of heat takes place from the photosphere, but it is also going on in the form of spectral lines, whether visible or beyond the range of refrangibility that the eye can see, from the upper layer of each gas that is successively left behind in ascending through the atmosphere. The last escape of heat is from the hydrogen lines. The stream of heat which passes per second through any spherical shell concentric with the sun into those parts of the atmosphere that lie outside it, is equal to what escapes per second from the latter into space. This stream therefore remains constant wherever an interval exists between the outer boundary of one gas and the bottom of that upper layer of the next which is thick enough to be opake for the faintest of its spectral lines; but throughout the depth of each such upper stratum the stream of heat is on the decrease.

34. We shall better understand what takes place by considering the agency by which the heat is carried outwards through the solar atmosphere. It is partly by conduction, but principally by what may be called internal radiation, to which are probably to be added in some situations convection and irregular motions such as would result from storms. By conduction I mean that conduction which is effected by the rectilinear motions of the molecules. It is the only conduction to which experimentalists have found it necessary to attend, since the quantities of transparent gas upon which they operate are not such as to be, in the cool state in which they have examined them, perceptibly opake to any of the incident rays. But when the gas is incandescent and present in enormous quantity, the chief transference of heat through it will be in consequence of what I have called internal radiation, which comes into play whenever the spectral rays emitted by one part of the gas are absorbed by the surrounding parts before they can reach the outer boundary and escape. If the gas be highly opake for any particular ray, which is in general the case of those rays that appear very bright in spectroscope experiments, it will travel but a short distance before it is effectually absorbed; but the rays which are faint in spectroscope experiments will wander further, and will contribute the most to the rapid carriage of the heat to great distances. It should also be borne in mind that if an extensive gas have a uniform temperature throughout, the rays which at profound depths are dashing about, are all of the maximum brightness corresponding to that temperature; but that if the temperature of the gas be shaded off in one direction, as it is in the solar atmosphere, the rays of internal radiation which are directed outwards at any particular spot are brighter than the maximum brightness corresponding to the temperature of that situation, since they come from warmer regions; and that those rays will be the brightest which in our experiments would be faint, since they come from the most remote, and, therefore, from the hottest of the parts from which any of the rays arrive.

35. It will not now appear strange that the region immediately outside

the photosphere should attain an enormous temperature. It is in contact with the luminous clouds, and would on this account alone be brought to as high a temperature as theirs; but, beside this, rays of every refrangibility are emitted from the hotter region beneath the clouds of an intensity corresponding to the far more consuming heat which there prevails. And if out of this terrific heat all the rays be selected which correspond to all the spectral lines of every gas in the solar atmosphere, they will constitute a body of heat, a small part of which is no doubt spent upon the gauze-like luminous clouds, or absorbed by the intermingled atmosphere, but the bulk of which is poured into the atmosphere overhead. On the other hand the only heat which escapes *outwards* from this upper atmosphere is the quantity, small in comparison, which is emitted by these same spectral rays at the reduced temperatures which correspond to the dusky lines visible in the solar spectrum, or to similar lines lying beyond the limits we can see*. All the rest of the heat received by the superincumbent atmosphere is returned by it downwards, and is the measure of the fervid temperature which its lowest stratum attains. Thus the atmosphere above the luminous clouds will begin by waxing in temperature, and continues to grow hotter through that interval to which the heat emitted from beneath can in any abundance directly penetrate. At the limit of this space there will be a surface of maximum temperature, after which the heat will very gradually fade off by reason of the conduction, convection, and internal radiation which feed the escape outwards from the upper layers of the successive atmospheres.

36. It is of importance to observe that if the boundary of any one of the gases that constitute the sun's atmosphere fall within the stratum which is hotter than the luminous clouds, or very close above it, that gas can only exist in a state of such utter attenuation within the stratum that we can scarce expect to detect any lines in the spectrum corresponding to it. The stratum in question rests upon the luminous clouds beneath, and its upper limit is to be defined as that situation in which the temperature has again fallen to the same point at which it stands in the shell of clouds. At all intermediate stations the temperature is higher, or, in other words, the motions of the molecules of the gases are more active. At the upper and under boundaries of the stratum they are equal; but the pressure, and consequently the density, is somewhat less at the upper station, or, in other words, the molecules of the gases constituting the atmosphere are there a little more separated. Now any gas which comes to an end within the stratum must be unable to maintain itself at the upper surface

* We should remember that much of the sun's heat lies in this direction; for the wave-lengths of almost all visible vibrations lie between 4 and 8 seventh-metres, and the invisible rays beyond the extreme lavender probably do not include waves much less in length than 2 seventh-metres, while the obscure heat-rays at the other end of the spectrum have been observed to extend, though with decreasing intensity, until the waves are 18 or 20 seventh-metres long, and probably reach much further.

of the layer, while in the stratum of luminous clouds it is able to hold its ground with equal molecular motions, solely because the molecules are there somewhat nearer together. It must therefore at the lower station be in a state of almost inconceivable rarefaction; and, from the laws of diffusion, its density at any higher point can nowhere go beyond this. It appears, therefore, almost in vain to expect to see bright lines in the solar spectrum. If, however, any such exist*, they will probably be most readily detected in light taken from near the margin of the sun's disk, where the brightness of the region behind the luminous clouds is cut off, and where the thickness of the stratum of attenuated gas which forms the bright lines is increased by the oblique position of the spectator.

37. This rarefaction (which would be carried to an extreme in the case of a gas, if any such exist, which extends into, but not beyond, the stratum that is hotter than the luminous clouds) will also affect in a very considerable degree those gases which do not spread far beyond it. Accordingly the fainter lines in the solar spectrum either arise from such low-lying gases in a state of great tenuity, in which case those lines only can be visible in reference to which these gases are most opake, which will therefore be the brightest of their artificial spectra; or they arise from constituents of the solar atmosphere which spread into the colder regions above, in which case they can only be those lines in reference to which these gases are highly transparent—such as are lines 50·48 and 53·52 of the Calcium spectrum, and the lines 49·21 and 51·81 of the Nickel spectrum. It may perhaps be found that faint lines of this latter class will be seen about equally distinctly in spectra formed of light taken from the centre of the sun's disk, and in spectra formed of light taken from near its margin. When the light is taken from the centre these lines have the advantage of a brighter background to set them off; when it is taken from the margin they have in their favour the greater depth of Calcium or of Nickel atmosphere which is looked through. But in the case of those faint lines of the other class which originate in the lower strata of the sun's

* I have several times thought I saw such a line, of wave-length 58·88, between the more refrangible of the lines D and the next line recorded in Kirchhoff's map to the left, almost in contact with this latter line. The appearance, however, may have arisen from the adjoining part of the spectrum having been subdued by lines not marked on Kirchhoff's map, and which a spectroscope of two equilateral flint-glass prisms could not sufficiently make out. I sometimes received the impression that there were such dim lines, but could not satisfy myself that they accounted for the bright line. Possibly there is also a bright line somewhere between the lines 1025·5 and 1027·7 of Kirchhoff's scale, and another in the right hand of the two parts into which the space between the lines D is divided by the Nickel line. Although it is on the whole improbable that the appearances are really due to bright lines, it would perhaps be worth repeating the observations under more favourable circumstances, of which the most important would be to admit only light from the margin of the sun's disk. If the suspected bright line between the lines D should prove real, it is perhaps occasioned by zinc. [For a continuation of this note, see the postscript, p. 57.]

atmosphere, the effect of obliquity will be very much greater; so that we may expect to find these rays most conspicuous in spectra of light from very near the edge of the disk. This appears to account for observations* lately made by Ångström.

38. Let us now consider the information given to us by the lines of the spectrum which are due to hydrogen, sodium, and magnesium. In the first place the sodium lines are narrow and sharply defined. In both respects they differ from the lines of hydrogen and magnesium, which are broad and winged, that is, shaded off on one or both sides into dusky bands less dark than themselves. Now at and up to the temperature of the flame of a spirit-lamp sodium vapour can give rise to such lines; but at the temperature of a Bunsen's burner the sodium lines have begun to expand and be ill defined. Hence we learn that in those upper regions of the sun's sodium atmosphere in which these lines originate, the temperature is lower than that of the flame of a Bunsen's burner. Nor need we be astonished that this or a much lower temperature can prevail so close to the fierce heat of the photosphere, when we take into account how effectually the outer parts of the sun's atmosphere are screened from the glare beneath by the stoppage in the intermediate regions of almost every ray that could act upon them.

39. The absence of wings to the lines D indicates† to us that there is not in the sun's atmosphere enough of sodium vapour of temperatures intermediate between the temperature of a Bunsen's burner and the temperature of the photosphere to be in a sensible degree opake to the wings of the rays which it emits. This both shows what a mere trace of sodium is diffused through the solar atmosphere, and also to what a vast height it rises as compared with the thickness of that part of the solar atmosphere which ranges in temperature between a temperature below that of a Bunsen's flame, and a temperature comparable with the intense heat of the photosphere. In fact, the atmosphere of sodium, owing to the small mass of its molecules, which is less than half the mass of molecules of iron, must spread to a vast distance beyond the iron atmosphere; and through this immense space the temperature appears to vary very slowly, and to be nowhere high.

40. The outward stream of heat which reaches the upper layer of the iron atmosphere for the most part escapes into space from that neighbourhood through the numberless lines of iron, calcium, chronium, manganese, and through the darker of the lines of nickel and cobalt, all of which

* See Comptes Rendus of October 15, 1866, or Philosophical Magazine of January 1867. It would be very desirable to have observations made upon spectra of light taken from different parts of the sun's disk, brought one over the other into the same field.

† [I remain unsatisfied with part of this discussion of the absence of sodium wings. There is something in the limitation of the wings of the rays of this and of some other gases, especially of hydrogen, of which I do not see the explanation.—September 1868.]

drain off heat from this region. No heat passes beyond, except the small quantity necessary to keep up the feeble escape from the lines of hydrogen, sodium, and magnesium, and others of the same class, such as B, A, &c., which are not only of a lower temperature, but are also few in number, if we may deem those that fall within the visible part of the spectrum a sufficient sample of the whole. Since, then, there is so much greater an escape of heat from the upper layer of the iron atmosphere than from the regions outside, there will exist a surface of minimum temperature near the limit of the iron, beyond which there will be first a very slight recovery and then a gradual fading off of the temperature. The observations of the sodium lines indicate that this surface of minimum temperature which lies near the outer boundary of the layer from which iron lines originate, cannot be as hot as the flame of a Bunsen's burner.

41. Within the iron atmosphere, on the other hand, there is a rapid stream of heat directed outwards to supply the outpourings from near the boundary of the iron atmosphere, as well as what is feebly dispersed by lines such as those of hydrogen, sodium, and magnesium. Still further down the stream becomes a torrent, as it has there to supply also the lavish expenditure of heat by the multitude of lines more faint than the iron lines, which are not only more numerous than lines of an intensity comparable with the iron lines, but also each one of which discharges into space a flood of heat proportioned to its exalted temperature, or, in other words, to its faintness as a line in the spectrum. All this leads us to conclude not only that the temperature increases very rapidly within the iron atmosphere, but that the rate of this increase becomes more and more precipitate as we descend. And this is in exact accordance with the intelligence brought to us by the sodium lines, which, from being wingless, indicate that the interval from the surface of the iron to the region where the temperature first becomes comparable with that of the photosphere, is both intensely hotter, and of trifling extent when compared with the vast expanse from the surface of the iron up to the surface of the sodium atmosphere.

42. Molecules of magnesium have very nearly the same mass as molecules of sodium. The two gases therefore rise to nearly the same height in the solar atmosphere. Nevertheless the lines in the spectrum due to magnesium present a very different aspect from those of sodium, into which we must now inquire. The lines of sodium are narrow and sharp; those of magnesium broad and fringed, the borders being of the intensity that Kirchhoff represents by the number 4. Now, the iron lines in their neighbourhood are of intensities 5 and 6, which shows that the upper layer of iron in which the iron lines take their rise may be distinguished into two strata, the outer of which produces in that part of the spectrum lines of intensity 6, while both together produce lines of intensity 5. To produce a line of intensity 4, a third stratum below the layer in which iron lines originate must be in action. Light reaches us from this third stratum in

the wings of the magnesium lines; and in fact the black part of the magnesium lines is due exclusively to the magnesium vapours between the top of the magnesium atmosphere and the plane of demarcation between the two strata into which we have distinguished the active layer of iron, while the wings are caused, at least in part, by the magnesium vapour which exists in the lower section of the active layer of iron and in the stratum which immediately adjoins it beneath. Thus the layer of magnesium which gives rise to the lines of the group *b* may conveniently be distinguished into two parts, the outer of which extends from the remote boundary of the magnesium atmosphere to the middle of the layer from which iron lines originate, and the second from this latter station through a hotter layer which lies further down. If magnesium vapour existed in the situation of this lower moiety only, the magnesium lines would be bands of their present breadth, but nowhere attaining the intensity 6: the superposition of the central black stripe is the work of the magnesium vapour in the vast outer section.

43. When we take into account how much higher a specific opacity sodium and magnesium vapour have than iron for the principal rays which they respectively emit, we are led to conclude that while magnesium vapour is abundant when compared with the attenuated vestige of sodium in the sun's atmosphere, it may be but sparingly present when compared with such a constituent as iron; and that this is so is established by the absence from the sun's spectrum of any lines corresponding to the rays of magnesium, in reference to which the specific opacity of magnesium is low, such as the magnesium lines 44·92 and 46·06.

44. We have found that there is but the merest trace of sodium in the sun's atmosphere, and that this trace mounts to an immense height above the iron. To render this possible there must be some abundant gas which extends as far as or beyond the sodium, in which it may diffuse itself, and so be borne to the full height corresponding to the small mass of its molecules. The gas which does it this service appears to be hydrogen, which, having a molecular mass only one twenty-third of that of sodium, must soar to an almost inconceivably greater height.

Hydrogen seems to be a very large constituent of the sun's atmosphere. There are three considerable rays in the spectrum of incandescent hydrogen, and a fourth faint one has been lately pointed out by Ångström. To these four rays, even to the faintest, there correspond intensely black lines in the solar spectrum. This indicates an abundance of hydrogen. The wave-lengths of the four lines are 41·04, the new hydrogen line, Ångström's *h*, in the violet; 43·43, in the indigo, which is the second of the six very conspicuous lines seen in the sun's spectrum on the less refrangible side of G; 48·65 in the blue, which is Fraunhofer's F; and 65·68 in the red, which is Fraunhofer's C. All these lines are winged: the black stripe in the more refrangible lines is very broad, and in the others it is of considerable width. These circumstances also indicate an abundance

of hydrogen. The temperature of the sun's atmosphere above the surface of the iron is too low to dilate hydrogen lines. The breadth, therefore, of the black part of the hydrogen lines must be due to the quantity of this element which is to be found in the interval between the outer boundary of the iron and that situation in which the temperature first becomes too high to appear black when projected against the brightness of the photosphere. This interval is small in the part of the spectrum where the line C occurs; at the line F it extends through a considerable part of the thickness of the layer that gives out iron lines; at the hydrogen line near G it extends quite through this layer; and in the situation of the fourth hydrogen line it extends much further down. But even in the least of these intervals there is enough of hydrogen to give a very sensible breadth to the line C. This quantity must be very considerable; as also must the quantity which can produce, in the hotter regions below, the fringes which border all the hydrogen lines. To recapitulate,—the width of the hydrogen lines, the wings that fringe them, the intense line in the sun's spectrum which corresponds to a faint hydrogen ray, and the height to which hydrogen can support traces of other gases, and more especially the vestige of sodium in the solar atmosphere, all testify to the abundance of this element.

45. The sodium lines D are an open channel through which heat is poured from a very hot region into that immense upper expanse of the sun's atmosphere which is tenanted by sodium, magnesium, and hydrogen alone. This is not the case with the magnesium lines of the group *b*, nor with the four hydrogen lines. These all stop heat before it has travelled to any great distance, by reason of the great abundance of hydrogen, and by reason of the specific opacity of magnesium for the rays *b*, and its quantity, which, though small, is immeasurably greater than the quantity of sodium. And on a different account, the same may be true of the faint rays of the spectra of sodium and magnesium. Two such magnesium rays were observed by Kirchhoff of wave-lengths 44·92 and 46·06; and Huggins has recorded three faint pairs of sodium lines, of wave-lengths 51·6, 56·9, and 61·6, and a nebulous band at 49·9. It is not yet fully ascertained whether there are lines in the solar spectrum answering to any of these rays. If there are such lines, they are faint. Now, if it shall prove that no such lines can be detected, it will indicate that heat from beneath of these wave-lengths passes without sensible diminution through the cool parts of the sun's atmosphere and therefore does not heat them; and if it be found that they give rise to faint lines, this faintness is to be attributed to but little of the heat despatched from hot regions being entangled in its passage outwards. Similarly the heat which is so transmitted through the *wings* of conspicuous lines crosses with little obstruction the colder regions above; since at the temperatures that there prevail few of the periodic times of the atomic orbits deviate sufficiently from those central periodic times which correspond to the middles of the lines.

46. But of whatever kind these or other vehicles for the conveyance of heat beyond the atmospheres of calcium and iron may be, it is certain that no sodium or magnesium rays can carry heat beyond the limits of the sodium atmosphere. It is also certain that the heat borne outwards is unable to maintain beyond the iron atmosphere a temperature as high as that of a Bunsen's burner, and that, after passing a situation but little outside the iron, the temperature falls off from this maximum. It must have sunk very low where the next considerable escape of heat takes place —at the boundaries of the atmospheres of magnesium and sodium. Accordingly, we must regard the hydrogen in that still higher dreary waste which is tenanted by hydrogen alone, as a feebly conducting body, of immense depth, warmed but moderately beneath, and exposed on the outside to a chilling radiation towards the open sky. Its outer strata must be intensely cold.

47. The case of a comet consisting of a gas * not found in the solar atmosphere is altogether different. As it approaches the sun it is exposed to the full unveiled glare of the photosphere, and absorbs the heat of those wave-lengths which correspond to the lines of its spectrum. However small a part of the incident heat this may be, it may make the comet nearly as hot as an opake body would become; since the comet can lose by radiation no heat except through these same spectral rays.

48. Having now examined in detail the lines of hydrogen, sodium, magnesium, calcium, and iron, we may treat in a more cursory manner the other elements that have been observed in the sun's atmosphere. Chromium, nickel, cobalt, copper, and zinc enter in small quantities into the

* If, indeed, a comet consist of gas, which, perhaps, we ought to deem highly improbable. The molecules of a gas pass most of their time beyond the reach of one another's molecular action, and, unless further confined by a sufficient force of gravity, would each pursue an independent orbit of its own. They would therefore tend gradually to extend like a stream of meteors along their common path; for the orbits being slightly different would have slightly different periodic times, which in the lapse of ages would operate in this way. It does not appear likely that the gravity of a body so large, and with so small a mass as a comet, could successfully withstand this tendency. But if the comet were kept together by a molecular cohesion, somewhat like a solid, there would be no such difficulty. Nor is it necessary to suppose that this solid, if such we are to call it, would retain this constitution when subjected to an intense gravity like the earth's: the hardest Archangel pitch flattens down under its own weight, and in time adapts itself to its containing vessel. The matter of comets may on our earth be gas.

And, again, it seems improbable that a comet can have been raised to the temperature of ignition at the distance from the sun that the earth is; yet this was the distance of Tempel's comet when its nucleus was seen by Mr. Huggins to emit a spectral ray. The only bodies we know to have the property of glowing at low temperatures are phosphorescent bodies; and we know from Becquerel's observations that the spectra of phosphorescent solids consist of bands, in some cases narrow.

The comæ of comets cannot be *transparent* gas, since transparent gas would not be conspicuous by reflected light. The phenomena of tails, too, suggest some entirely peculiar constitution.

composition of the sun's atmosphere. Probably nickel is the most abundant of them. Of the others no lines appear in the sun's spectrum, except those in reference to which they have a high specific opacity, in many cases higher than that which iron has for any of its rays. There are, therefore, but traces of them present; and the appearance of the lines agrees well with the situation in the sun's atmosphere assigned to them by the masses of their molecules: chromium, projecting quite through the iron atmosphere, produces a few lines of an intensity comparable with that of the iron lines in their neighbourhood; and the boundaries of cobalt, nickel, copper, and zinc, appear to lie within that upper layer of iron which sends forth iron lines.

49. The appearance of the zinc lines is not incompatible with this element's having the vapour-density usually supposed by chemists, viz., 32·5 instead of 65; but the evidence of the sun's spectrum, such as it is, for it is scanty, owing to the paucity of the lines, seems to lean against this hypothesis, unless a similar reduction is to be made in the case of all the other metals of the atmosphere. But whatever uncertainty may rest on this point, there is at least no doubt that barium cannot have a vapour-density anything like so high as 137. At most it cannot exceed half that number, which would barely raise the boundary of the barium atmosphere within the lower part of the layer from which iron lines proceed; and, if it were not for objections on chemical grounds, the strength of such lines as the barium lines 45·66, 49·37, and 61·43 would prompt us to suspect for the vapour of barium even a lower density. But the strength of these lines is probably due to the remarkably high specific opacity of the vapour of barium in reference to them. There is plainly only a small amount of barium in the sun's atmosphere.

50. It will readily be perceived that it is vain to look for the cause of any conspicuous line mapped by Kirchhoff, in any substance with a vapour-density more than 70 times that of hydrogen. This narrows very much the field in which to search for the origin of the darker of the lines enumerated in Table III., opposite, the table of unappropriated lines. Many of these, as, for example, three of the five lines of the group at 60·3, are probably due to manganese, and may be removed from this table, as soon as a list of the thirty manganese lines, lately identified by Ångström, shall have been published. Others of them are probably some of the 460 iron lines, produced by a continuous electrical current, or among the additional lines which may be produced under like circumstances in others of the elements which we have been heretofore examining. When all these are eliminated it does not seem likely that many conspicuous lines between G and B will remain to be traced to their source. Carbon is probably as devoid of volatility as it is infusible; or at all events the one probably bears some proportion to the extraordinary eminence of the other. If this be so, it cannot be a gas at the temperature of the situations from which *dark* lines come, or at least not in sufficient quantity to produce visible effect.

Table II.—Table of the Solar lines identified by Kirchhoff with

Colours................................... Indigo. Blue.
Standard rays .... G. f. F. c. b.
Wave-lengths in eighth-metres 43 44 45 46 47 48 49 50 51 52

Hydrogen 1	1 2 6 2 1	......	......	...	......	4 6 4	....	....	....
Sodium 23	....	......	......	...	......	....	....	....	....
Magnesium 24·3	....	0	......	0	......	....	....	....	4 4 6 6 6 4 4 4 (Fe)
Calcium 40	5 4 4 5	......	......	...	......	6 (Fe)	....	2	....
Chromium 52·5.........................	....	......	......	...	......	....	....	....	....
Manganese 55	....	......	......	...	....	....	....	....	....
Iron 56	4 3 2 6 6 6 4 3 3	3 6 6 3	......	...	......	6 5 5 6 6 6 (Ca)	6 6 6 5 4 6	5	6 6 5 6 6 6 5 5 (Mg)(Ni)
Nickel 59	....	......	......	2	6 3 4	3 3 3 3 2	4 1 3 4 4	5 4 3 3	2 3 3 3 5 4 4 6 1 (Fe)
Cobalt 59	....	......	5 6	...	1 3	3 2 4 1	....	....	....
Copper 63·5	....	......	......	5	......	....	....	....	4 3
Zinc 65	....	......	......	...	2 3	5	0 0	....	....
Barium 137	....	......	4 6	...	......	....	2 6	....	....

Table III.—Table of the numb

No. of rays of intensity 6	0	2	2	4	2	0	0	7	0
Ditto ditto 5	5	11	14	9	13	4	7	4	9
Ditto ditto 4	29	11	17	11	15	12	13	7	8
Ditto ditto 3	51	28	18	14	19	14	7	19	8
Ditto ditto 2	47	28	27	27	19	13	21	13	8
Ditto ditto 1	47	39	20	18	13	16	14	11	12

Wave-lengths in eighth-metres 43 44 45 46 47 48 49 50 51 52

* The numbers of Table III. had been counted before the integer wave-lengths were laid down upon Kir

hoff with rays in the spectra of gases; distinguishing the intensity of each, its position in the spectrum, and the substance to whi

	E. Green.						Greenish-yellow and Orange. D.			
–52	52–53	53–54	54–55	55–56	56–57	57–58	58–59	59–60	60–61	61–
....	....	....	....	....	......	...	......	...	......	....
....	....	....	....	....	......	...	6 6			
....	4 4 4 5 6 (Fe)	2	....	3 4 2 5	5 3 5 (Fe)	...	3 (Ni)	...	0	2 4 5 3 ((Co)
....	5 5 6	....	5							
....	The Mangan	ese spectrum is not given in Kir	chhoff's map.							
6 5 5)	5 5 5 6 6 6 5 (Co) (Ca)	5 5 5 5 5 5 5 5 5 6 4 4	5 5 6 4 4 5 6 5 5 5 6 4	4 6 4 5	5 5 4 (Ca)	3	......	3	4 3	4 3
4 6 1 (Fe)	....	....	4	....	......	...	3 2 (Ca)	...	......	2 2 0
....	0 0 2 5 1 2	1 2 1 4 0 0 0	0 0 3	....	......	...	......	...	0	4 0 (Ca)
	1 1	....	....	....	......	2				
....	....	....	....	....	......	...	0	...	0	0
....	....	....	1	1 3	......	2	0 2	0	0 0	1 4

he numbers of the other Solar rays recorded by Kirchhoff, distributed according to their intensities and situations*.

–52	52–53	53–54	54–55	55–56	56–57	57–58	58–59	59–60	60–61	61–
	0	0	0	1	0	0	0	0	0	0
	2	1	0	3	1	0	0	0	0	0
	4	5	3	0	1	1	0	0	4	1
	9	7	2	10	5	6	2	10	3	1
	14	10	2	16	18	13	6	14	5	11
	9	13	14	7	15	11	5	20	13	14

52 53 54 55 56 57 58 59 60 61

upon Kirchhoff's maps with the care that was afterwards taken. Accordingly in some cases a few of the rays entered in one column may more proper

ce to which it is attributed. [*To face* p. 32.

	Scarlet.				Crimson.											
	a.			C.			B.								A.
62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
....	...	...	....	I 6 I											
2 4 5 3 0 0 (Co)	0	...	5 3 5 2 2 2	...	...	2									
4 3	4	4	5 2												
2 2 0															
4 0 (Ca)															
0	...	1													
1 4	...	...	2												

62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
0	0	0	0	0	0	0	1	0	0	2	3	0	0	0	3
0	0	0	0	0	0	0	0	0	0	6	4	0	0	1	2
1	5	1	3	0	0	0	3	3	2	0	6	1	0	0	7
1	3	6	4	1	0	0	8	9	6	4	4	2	0	0	2
11	13	3	3	12	4	0	1	10	4	7	10	8	7	2	0
14	11	6	6	7	2	6	10	8	6	2	4	7	1	1	0

ıore properly belong to the column next before or next after it.

But it is very much to be wished that a comparison should be made of the spectra of boron, fluorine, sulphur, chlorine, titanium, and phosphorus, with the sun's spectrum, and especially of chlorine, if any weight is to be attached to the suspicion, founded on very insufficient grounds, that the solar lines 43·40—, 43·55—, 66·38, 66·50, 66·68, and 70·00, the group of three lines at 45·1, and several others, are to referred to this element.

51. The absence from the sun's atmosphere of such gases as nitrogen and oxygen, and of hydrogen from the atmospheres of some other stars, and the fact that while some active chemical agents lose, like sulphuric acid, their energy under such increasing temperatures as our laboratories can provide, others, like boracic acid, become practically more powerful, give a considerable amount of colour to the presumption that compound bodies exist in the sun. The masses of the molecules of these compound bodies will in most cases be too high to permit them, however volatile, to reach the cool parts of the sun's atmosphere, so as to reveal themselves in conspicuous solar lines. But the probability of their so appearing is very much greater in the class of ruddy stars, as we shall find in the sequel; and, perhaps it is not impossible that the line B of the solar spectrum, or some of the lines less refrangible than B, may result from some compound of low vapour-density, such as hydrochloric acid*. It is certainly very remarkable that neither B nor any line less refrangible has up to the present been identified with a ray of any simple substance.

52. Upon a general view of all the lines of the solar spectrum it appears that their intensity continuously diminishes from the violet end of the spectrum up to the line B. At this point, owing to the sudden introduction of an entirely new set of lines, their intensity abruptly and very much increases. These new lines either have a terrestrial origin or come from substances which stand high in the solar atmosphere. The lines, however, which originate further down, do not attain their minimum of intensity until they reach a point further to the right than B. This appears both from the progressive diminution of their intensity up to B, and from the total, or almost total, absence of lines further on, wherever a vacuity is left between the lines which we must attribute to a different origin, as at wave-lengths 71·1, 73·8, and in the wide spaces between the prominent lines from this situation up to the line A.

53. When this is considered in connexion with the cause to which the diminution of intensity is to be referred, it indicates that if two perfectly radiating bodies were gradually heated while the difference of their temperatures was kept constantly the same, the point of the spectrum at which the difference of their brightness is least would advance with increasing temperatures towards the red end of the spectrum. When the body of

* If there be chlorine in the sun's atmosphere, the presumption upon chemical grounds is very strong that there must be hydrochloric acid in the upper regions; and from its vapour density (18·25) the lines of hydrochloric acid would be black in whatever part of the spectrum they might occur.

lower temperature has but just begun to glow, we know that this situation of minimum difference of brightness is found in the orange; at temperatures approaching that of the photosphere it has removed at all events as far as the line A, that is nearly to the extreme verge of the visible spectrum, and it has, perhaps, advanced beyond it. This, as we shall find further on, explains how some solitary stars can attain a depth of colour that approaches crimson.

54. It appears from the analysis which has been made that none other of the gases in the solar atmosphere that extend as far as the stratum from which iron lines come, can compare in quantity with hydrogen and iron; and from what has been stated in § 36, we may be sure that there is no very abundant gas which comes to its limit in the hot regions that intervene between this stratum and the photosphere. Hydrogen and iron are accordingly the principal ingredients of the parts of the sun's atmosphere which extend beyond the photosphere.

Section IV.—*Of the Photosphere and the subjacent parts.*

55. In interpreting phenomena of solar spots we should never forget the disadvantages under which we attempt the enterprise. Our theory may be true, but it is incomparably more meagre than our knowledge of the causes of terrestrial weather. Our observations may be correct, but they give us only outside glimpses, and from such a distance that France or Spain would be specks too small to make out whether they are round or square. We must not imitate the peasant who saw from afar the smoke of a great city, and persuaded himself he had a very good idea of the kind of place a city is. If our explanations of the phenomena of terrestrial weather are dim and unsatisfying, we cannot reasonably ask from a theory of the corresponding phenomena of the sun, even though it were beyond a doubt the true theory, more than the first hazy and rude sketch of an interpretation.

56. Many fixed gases which are too heavy to extend at all, or in any abundance, through the stratum of minimum temperature, must wax in density very rapidly within it. Hence the density of the solar atmosphere becomes almost suddenly greater at the shell of luminous clouds. This may be the cause of an appearance not unfrequent in spots near the margin of the sun's disk, in which situation the further side of the umbra of a spot is often bordered by a bright crescent, giving to the umbra the appearance of a hole punched through a plate. This appears to be because there is, in these cases, in reality a depression of the dense strata at the umbra, shallow, perhaps, but yet with sides sufficiently inclined to enable light coming so obliquely as to suffer total reflection* against the flatter surface of the penumbra, to escape through it. A similar cause may, perhaps, and probably does, enable light to escape from patches of the penumbra when the surface of the penumbra is irregularly undulating in a sufficient degree.

* Such as that which produces Fata Morgana.

Local showers are in other cases the cause of brightness in the umbra and penumbra.

The sudden increase of density of the sun's atmosphere at the photosphere must serve to keep the luminous stratum in a nearly spherical form. The surfaces of the gases above the photosphere may be violently tossed about by the storms of the solar atmosphere, but the surface of the photosphere is never carried further than to the top of a facula or the bottom of the umbra of a spot.

57. The winds which affect the photosphere may be distinguished into two classes, those of the sun's outer atmosphere, and those of the regions within the photosphere. Both classes may coexist in different parts of the same storm. The former class sweeping through the open space above the photosphere, and through rarefied air, will often come from far, and as a general rule be the swiftest. Those below, moving in the dense part of the atmosphere, and perhaps within a confined space, can but seldom attain the same high velocity.

58. Both classes of wind tend to obliterate the cool film in which clouds usually exist, and to replace it by hotter air. But the hotter air substituted by winds from below, will be equally charged with moisture; while winds from above will tend to dilute with dry air both the cool film and the adjoining strata immediately under it. In both cases new and more transparent clouds will form; but in the former case the rain will not cease, and we have only facula; in the latter it may and often does,—in fact, whenever the film of clouds and the subjacent stratum with which it is mixed by convection, have been rendered sufficiently dry. When by prolonged convection this state of things is passing away, there will be a struggle between dry weather and wet, which we shall see in the patched appearance of the penumbra.

59. An umbra presents itself when the cloud, too, is removed, and the dusky body of the sun seen through the opening. It does not seem likely that this can take place so long as there is any of the moist stratum at a temperature below its boiling-point and exposed to radiation. If this view be correct, the umbra can only occur either when the depression caused by a rotatory storm, or by winds impinging from above, has obliterated the dense stratum and brought the air into contact with the ocean; or when, by the influx of hot air from above or the upheaving of the hot strata beneath, it has come to pass that throughout the whole of a vertical column there is no place where the vapour which forms cloud is at a temperature below its boiling-point. If this happen through the rise of subjacent strata, we should have an umbra without penumbra; and it does not seem impossible that the same appearance may sometimes present itself where a depression is caused by a wind impinging from above which has not exerted much horizontal friction against the surrounding parts of the photosphere.

60. It must often happen that a hot current sweeping over the surface of the penumbra dissolves away part of the cloud, diluting the vapour

with dry air up to the point of being but just unable to precipitate itself while exposed underneath to the heat of the penumbra. If a current so charged with vapour happen to cross the umbra, it will receive less heat from below, and some of the vapour in it will now be able by radiation to maintain itself as cloud. This cloud will be peculiarly circumstanced. It is formed from an isolated body of vapour, and once formed will continue in existence, since the hot currents which will rise at intervals through it when convection sets in, will consist of dry air unable to generate the cloud overhead, which would otherwise screen it from the open sky. It will accordingly often find itself under circumstances to become by reason of this prolonged existence progressively cooler; and as the temperature falls, more of the vapour is able to precipitate itself, until at length the cloud becomes so dense that rain sets in. The rain is probably caught and dissolved in the dry air below, long before it can reach the body of the sun; but if it last through a space of even a few thousand metres, it will give to the bridge of vapour the brightness of a facula. In other cases the vapour either carried into the umbra from around, or perhaps rising into it from a steaming ocean beneath, appears to form mere pellicles of cloud that mottle its deep shadow. When the storm is of the nature of a whirlwind, a current of dry outer air which has not lapped up moisture from the photosphere, usually seems also sucked in, and manifests its presence in the dark spot which Mr. Dawes has called the nucleus of the umbra.

61. It appears more reasonable to suppose that the phenomena which have hitherto been explained by the transference of ponderable matter over immense distances in incredibly short times, the filling up of gulfs, and the like, are phenomena of the rapid formation or dissolution of cloud, and lose much of their marvellous character. Terrestrial cloud may be seen to form within a very few minutes over the whole of the visible heavens, and often when there is no wind, or apparently advancing against the wind.

62. If there be a substance in the sun of low vapour-density, but not capable of existing in a state of vapour in the coolness of the height to which it would otherwise rise, and if this refractory substance is volatile at the temperature and pressure which exist lower down, it will behave in a very peculiar manner. In the lower strata of the sun's atmosphere it will exist as a vapour; and from this situation it will keep continually making its way upward in its effort to find its natural level. Before it reaches its destination, however, the gas incessantly streaming upward will as incessantly be precipitated. If the particles of the cloud so formed are heavier than the surrounding atmosphere, they will begin to subside. Not only so, but the chill caused by their radiation in their new solid or liquid state, will make the inverse flame spoken of in § 8 burn downwards, until it sinks to that level at which the upward supply of vapour, owing to its tendency to diffuse itself upwards, or caused by currents of convection, exactly balances the downward motion of the fiery cloud from subsi-

dence or the descending currents of convection. Here, then, if this substance be in sufficient abundance, we have all the conditions necessary for the sun's luminous clouds. And we are led almost irresistibly to conjecture that in carbon* we have such a substance. The mass of its molecules is very low, either six, or twelve, or twenty-four times the mass of a molecule of hydrogen. It appears to have just the requisite degree of fixedness; it shows no sign of volatility at any ordinary high temperature, but has been driven into vapour by one hundred elements of Bunsen's battery, each element consisting of six ordinary cells coupled side by side; that is at a temperature which may, quite consistently with everything we know, be that of the strata adjoining the sun's photosphere. There is enough of carbon in the sun to produce the luminous clouds, if carbon be as large a constituent of the sun as it is of the earth; and most of the carbon in the sun is probably uncombined, as carbon does not seem apt to form compounds likely to be abundant which can stand intense heat. It is, moreover, precipitated from its vapour as a black body with the most perfect power of emission of any known substance; and we are assured that the luminous clouds consist of some such material by the absence of bright lines from the solar spectrum. It would probably be impossible, in the present state of our knowledge, to put forward on behalf of any other substance, simple or compound, anything like the same claim to be deemed the material of which the luminous clouds consist. And I know of but one consideration to be set on the other side, viz. that if the luminous clouds be a smoke of carbon, and if the rain beneath is more properly to be described as a fall of soot, in flakes like snow, and if these flakes come to rest upon the surface of an ocean beneath, they must by their high radiating power render this surface eminently luminous, which we know from the phenomena of spots that it is not.

63. As, then, there are strong reasons for surmising that the luminous clouds consist of carbon, we are led to enquire what may exist to remove the one difficulty in which this hypothesis involves us. Now, in the first place, it would disappear if the heat in the space beneath the clouds melts the falling flakes, so that they reach the ocean like rain, and mix with the other liquids constituting it. And it would disappear if the heat and dryness of the space beneath the clouds enable it to evaporate the flakes ere they reach the ocean. And, finally, it would disappear if there be no such ocean, but only a continuation of the atmosphere becoming denser and hotter. It will be necessary to examine this last hypothesis with some care to see that it is compatible with the known phenomena of spots.

64. It is not likely that carbon is the only substance in the sun that

* In connexion with Dr. Frankland's discoveries respecting flame, it should not be forgotten that such solid particles as Davy supposed in flame are undoubtedly adequate to produce luminous effects, and possibly are a source of light in other cases as well as on the sun.

possesses the properties which are the conditions for the formation of cloud, although it is probable that carbon is, of such substances, that one which has by far the lowest vapour-density. It is, at all events, presumable that among such abundant elements as nitrogen, oxygen, silicium, and aluminium, or such of their compounds of low vapour-density as can exist in the sun, there may be some which, like carbon, are solid or liquid at the temperatures and pressures of the greatest heights to which they would, if gaseous, rise. And if the atmosphere of the sun extend to any great distance below the photosphere, there must be in the sun such a substance to account for the dusky background we see in the penumbræ and umbræ of spots. There must in this case be a second layer of clouds, formed not far beyond the photosphere, in the comparatively short space through which the temperature augments rapidly between the luminous clouds and the central parts of the sun. These clouds must, moreover, be of some transparent material to possess in a sufficient degree that property of scattering light which would render them as devoid of emissive power as we see them to be. For the same reason we must conclude that the sooty shower from above cannot reach them, as it would inevitably soil them, so as to deprive them of these essential qualities. We learn from this, that the point at which carbon boils must fall within the short interval between the two layers of clouds. This is not at all unlikely, inasmuch as the advance downwards of the inverse flame, of which mention has been so often made, would probably be arrested only by its close approach, either to the bottom of the atmosphere, or to the situation in which carbon boils, so as to be entirely dissipated in vapour. And the second layer of clouds would quickly follow, since its position depends on that taken up by the carbon clouds, as it must lie within the layer of *rapidly* varying temperature immediately under them. If this hypothesis, then, be the true account of what takes place on the sun, the penumbræ of spots are caused by our seeing the clouds beneath through a gauze-like film of carbon cloud which has ceased to send down rain; and the umbræ of spots are formed when a very shallow saucer-like depression of the photosphere has carried a part of its outer surface so far that it has reached the region in which carbon will boil. Here the filmy cloud of carbon, which nowhere else can entirely disappear, will be completely dissolved away.

65. In this branch of our enquiry we are often obliged to deal with hypothetical matter, and cannot in such cases look for conclusions which command our assent. We must be satisfied if we may hope that they will prove of use in guiding future investigations. Nevertheless, I am disposed to think that we should give the preference, as a provisional hypothesis, to the supposition of a layer of cloud lying under the photosphere, rather than to the only other alternative which seems in any considerable degree admissible, namely, a highly reflecting ocean. It is perhaps, on the whole, and in our present state of ignorance, encumbered with fewer difficulties.

Section V.—*Of Clouds in the Outer Atmosphere.*

66. But to return to what is more to be relied on, we may be sure that some small part of the carbon, or whatever else the luminous clouds mainly consist of, and similar traces of any other ingredients that enter in less quantities into their composition, must escape precipitation, and will diffuse themselves upwards, and the more freely as they come first to a region where they are raised to a higher temperature as well as subjected to less pressure. Through this hot stratum they will continue gaseous, but a short distance above it they will meet with a temperature low enough to condense them. Here, then, separated from the photosphere by the whole depth of the hot stratum, they will form a second film of luminous clouds, one, however, which is so attenuated as to be visible only during an eclipse, when it constitutes the lowest of the clouds that then present themselves. They may be traced in Dr. De La Rue's photographs of the eclipse of July 1860* as continuous arcs of cloud extending about 35° on either side of the points of first and last contact. Hence, and from the apparent magnitudes of the sun and moon on that occasion, we may conclude that this upper shell of clouds was at an apparent distance of about 11″ of space from the edge of the sun's disk, which corresponds to an absolute height above the photosphere of 8 metre-sixes, or $1\frac{1}{4}$ time the earth's radius †. And as the clouds of which we are now speaking are a little outside the hot stratum that lies immediately over the photosphere, we shall not be far wrong in concluding this stratum to be about as thick as the earth's radius is long. The clouds outside it probably form a nearly continuous shell round the sun. They are everywhere of extreme tenuity, but may nevertheless be very variable in density; and it is probably owing to this that the concave

* Philosophical Transactions for 1862, p. 333.

† A metre-six means a metre multiplied by 10^6.

Dr. De La Rue took two eye-sketches also of the eclipse, commencing the first about thirty seconds, according to his estimate, after the eclipse began. Now the arc of cloud about the point of first contact is represented on the first, and indeed on both drawings, and must have been at a greater height in the sun's atmosphere than I have assigned to it, to have been seen by Dr. De La Rue, unless we may suppose that he overestimated the interval of time which had elapsed by a few seconds. This, however, on an occasion of so much hurry, may perhaps have happened, and it seems difficult otherwise to reconcile the eye-draughts with the photographs. The data made use of to get out the result in the text are:—

		°	′	″
Length of arc of cloud visible five seconds after the moment of contact	=	70		
Sun's apparent semidiameter	=	0	15	45
Moon's apparent semidiameter	=	0	16	33

Sun's diameter = 13·7 metre-eights.

Earth's diameter = 12·7 metre-sixes.

Approach of the sun and moon's centres per minute of time = 25″ of space.

The allowance of 5 seconds from the moment of contact has been made, because the cloud seems to have taken about that time to impress itself upon the photographic plate.

sides of the two arcs shown in the photographs exhibit such a ruggedness that, as Dr. De La Rue has pointed out, it cannot be accounted for by the mountainous edge of the moon. In fact the film of cloud seems to be so excessively thin that even during an eclipse it can only be seen where it is presented very nearly edgewise at the extreme margin of its disk, or for a short distance inside it, a distance which varies with the local density of the film, and so gives rise to the appearance in question.

67. This second shell of clouds, as they consist of the same materials as the clouds of the photosphere, and are higher in the atmosphere, and therefore subjected to less pressure, will evidently not form until they can do so at a somewhat lower temperature. But the difference may be so slight that in their normal position these clouds lose more heat by radiation towards the sky than they receive by absorption from the photosphere, which would cause them to imitate, but with a languor proportional to their flimsiness, all the phenomena of convection, &c. which we have traced in the principal layer of clouds.

68. But this behaviour would be altogether changed if by any cause a part of the film were borne upwards into the cool regions above. At whatever part of the atmosphere a cloud may find itself, it will be exposed to the unmitigated glare of the photosphere, and will be raised by it to a temperature bordering upon that of the photosphere itself*. A cloud in this situation will therefore warm, instead of cooling, the air in which it is dispersed, and will tend to float violently upwards until it gets to a part of the atmosphere so rare, that the particles of condensed vapour tend to sink in it from their specific gravity as fast as they are carried upwards by the body of heated air entangled with them. This may be the cause of the columnar clouds with overhanging tops which have been observed during eclipses. As they spread out at the top and become diffused, they will not as effectually heat the intermingled air, and will therefore begin to subside. Between clouds that are carried so violently upwards and those that repose in the luminous shells, any intermediate descriptions may exist, and were perhaps the cause of the mountainous projections from the upper shell that have been seen, and of several of the detached clouds.

69. But besides the materials that enter into the composition of the

* If we could trust at high temperatures, which of course we cannot, Dulong and Petit's law for the velocity of cooling, viz.:—

$$v=k(a^t-a^{t'}),$$

where v is the fall of temperature per unit of time;

t, temperature of the particle in Centigrade degrees;

t', the temperature of the radiations to which it is supposed to be subjected on all sides;

k, a constant, depending on the nature of the particle and on the position we assume as the zero of our thermometric scale; and

$a=1{\cdot}0077$;

we should find that the temperature of a cloud exposed, on one side to the photosphere, and on the other to the sky, falls short of the temperature of the photosphere by little more than 90° Centigrade.

clouds of the photosphere, we must remember that there may exist other substances in the sun or in some other stars capable of giving rise to clouds. If there be materials of sufficiently low vapour-density, and in a sufficient degree more volatile than carbon, though not volatile enough to stand the cold of the height to which their vapour-density would otherwise lift them, they will be precipitated in cloud. Or gases in the solar atmosphere which are kept asunder by the temperatures of its lower strata, may be able to combine in the cooler regions above. If the new body be a solid or liquid, it will constitute a cloud. Even if it be gaseous, it will in general have other spectral lines than those of any lower-lying gas in the atmosphere, and will therefore be subjected to the direct radiations of the photosphere; it will accordingly become intensely heated, and in many respects behave like a cloud. Its density, too, will in most cases be greater than that of either of its constituents. And, finally, a gas which in the lower parts of the sun's atmosphere emits only rays of a spectrum of the second order, may in the upper regions find itself under circumstances to produce a spectrum of the first order. If this should happen, the gas in its new condition would be exposed to the full heat of the photosphere, and would conduct itself like a cloud.

70. From the exceeding transparency of the solar clouds, they are entirely without that abundance of internal reflections and refractions which are what give to a cloud of steam dense enough to be opake, or a sheet of paper, or a piece of white marble, their lustre when illuminated. It is accordingly by their inherent splendour given to them by their being made intensely hot by the photosphere, not by borrowed light, that they shine. A cloud of dark opake materials is therefore, *cæteris paribus*, the brightest. Those which Mr. De la Rue found impressed on the photographs, though not visible to the eye, must have been of substances transparent in regard to most visible vibrations, but opake for some of higher refrangibility.

71. It is very likely that there may be substances in the sun's atmosphere, or in those of some of the stars, which reach a height at which they are unable to remain in the state of gas by reason of the surrounding cold, or to assume permanently the form of cloud because of the heat of the photosphere to which they would thereupon immediately become exposed. In such cases there will be a struggle between the two conditions, the vapour continually condensing and redissolving until it has by this process imported much heat into its neighbourhood. Wherever such a state of things exists, it must inevitably have the effect of raising some of the isothermal surfaces above the position in the atmosphere they would otherwise occupy. Similar consequences would ensue if two gases became so cool that they could no longer continue uncombined, and were so heated through their new spectral lines the instant they united that the new substance was at once resolved back into its constituents; or where a gas reaches a situation too cold for its existence in the state in which it sends

out spectral rays of the second order, and no sooner changes its condition than it absorbs through its new spectral lines heat to such an extent that it must fall back again. Such struggles may be the prolific source of storms when they are local, and perhaps of an appreciable variation in the brightness of stars when they are on a great scale.

Section VI.—*Of the Distribution and Periodicity of the Spots.*

72. We may catch a glimpse from the foregoing investigations of what appears at least a possible explanation of several phenomena of the solar spots, which we do not seem yet in a position to refer to their causes with confidence, such phenomena as the local distribution of spots and their periodicity. If from any cause a portion of the lower strata of the outer atmosphere is thrown upwards, it will carry a part of the second stratum of clouds above its natural level. The intermingled air will dilate and tend to cool down as it ascends; but its temperature will be restored by the heat absorbed and communicated to it by the cloud carried with it. Its thus remaining hot will convert what was perhaps at first only a gentle upheaval into a violent upward current, which will, from the operation of causes familiar upon the earth's surface, occasion a cyclone in the lower strata of the outer atmosphere. The inner atmosphere (that is, the dense atmosphere from the surface of the photosphere downwards) cannot be readily drawn into the vortex, by reason of its great specific gravity; but it will be swept round and round by the violence of the hurricane above, and a kind of whirlpool will result which will depress the central parts into the penumbra and umbra of a spot and lift its borders into faculæ. The formation of this whirlpool will be greatly assisted if, as we shall presently see we have reason to suspect, there are preexisting currents in the inner atmosphere setting in opposite directions along the zones of spots.

73. If, then, we are right in attributing a large proportion of the spots to ascending currents in the outer atmosphere, we must next seek some cause which can determine the existence of such upward currents in two bands parallel to the equator. It is natural to look for this in some phenomenon analogous to our trade-winds; and, as Sir John Herschel has observed, such a phenomenon may arise if the ellipticity of the sun bring about an unequal escape of heat from his poles and from his equator. The elliptic strata of the atmosphere could be *in equilibrio* only on the supposition that they are of precisely the same density throughout: but this they cannot be; for as the outer atmosphere is an imperfectly conducting plate, heated on the one side by the photosphere, cooled on the other by radiation towards the sky, at the poles, where the plate is thinnest, its outer strata will be sensibly hotter than their average temperature over the whole sun, and their inner strata very slightly cooler; and at the equator, where the plate is thickest, its inner strata will be hotter than the average, and its outer strata cooler. Hence at the poles, where the temperature of the outer parts of the atmosphere is higher than the average, they will diffuse

themselves upwards and overflow; at the equator, where the temperature is less than the average, they will subside and tend to escape laterally at the bottom. Moreover, the lower strata being subjected at the equator to more pressure than the average, by reason of the coolness of the superincumbent strata, and to less pressure at the poles, will also contribute to produce an under-current in the outer atmosphere from the equator towards the poles. Hence if it were not that the rotation of the sun modifies the result, we should have a constant wind blowing steadily from the equator to the poles over the surface of the photosphere, and a counter-current in the upper regions of the atmosphere.

74. The effect upon the inner atmosphere is directly the reverse. Heat will escape from the photosphere very slightly more freely at the poles, less freely at the equator, than the average. The upper strata of the inner atmosphere will therefore be a little lighter at the equator, and will overflow towards the poles, tending to produce a feeble surface-current in the photosphere in the same direction as the wind which blows above it from the equator towards the poles.

75. But the sun's surface is all the time being carried round by his rotation from east to west. This will impart a strong westerly direction to the descending current where it reaches the photosphere at the equator*, and will further render it where it spreads out over the photosphere towards the poles, a south-east wind in the northern hemisphere, and a north-east wind in the southern. Thus these winds blow in such directions as to rotate more rapidly than the general body of the sun, and they therefore seek to raise themseves above the photosphere†. At the equator the

* [This first part of the effect of the sun's rotation was overlooked by the author when writing this paper. The omission has been supplied in the text above, and the reader is requested to correct the error in the abstract of the memoir (see Proceedings of the Royal Society for June, 1867) where a calm is spoken of as prevailing over the equatorial zone of the photosphere.—July 1868.]

† The similar centrifugal tendency in the current which overflows from the earth's equator would no doubt keep it throughout its whole course outside the polar current, were it not that being charged with moisture and cooling as it advances, some of its strata soon become so loaded with clouds, that they, and the clouds amongst which they are entangled, come to have between them so much higher a specific gravity that their downward tendency due to this cause overcomes the outward tendency of their superior rotatory motion. In the case of the sun, on the other hand, the clouds and the rotatory motion operate at first in the same direction upon the equatorial current, both tending to raise it; but after some elevation has been attained, they there, as on the earth, act in opposite directions, the motion of rotation tending to depress the current as soon as it gets above a height which must be moderate, when compared with the vast extent of the sun's atmosphere.

Furthermore, the earth's polar current coming from regions of slower motion has a tendency to descend, and when it gets down, a tendency to creep along the surface of the ground. Both the currents accordingly seem to contribute to that descent of both which takes place in the earth's temperate zones. But on the sun the ascent of both the currents over the zones of spots seems to be brought about by the tendency of the equatorial current to rise being more powerful than the tendency of the polar current to cling to the photosphere.

upward tendency expends itself in somewhat retarding the descending current, but a few degrees on either side, where this obstacle has become sufficiently feeble, it determines extensive upheavals of the lower strata

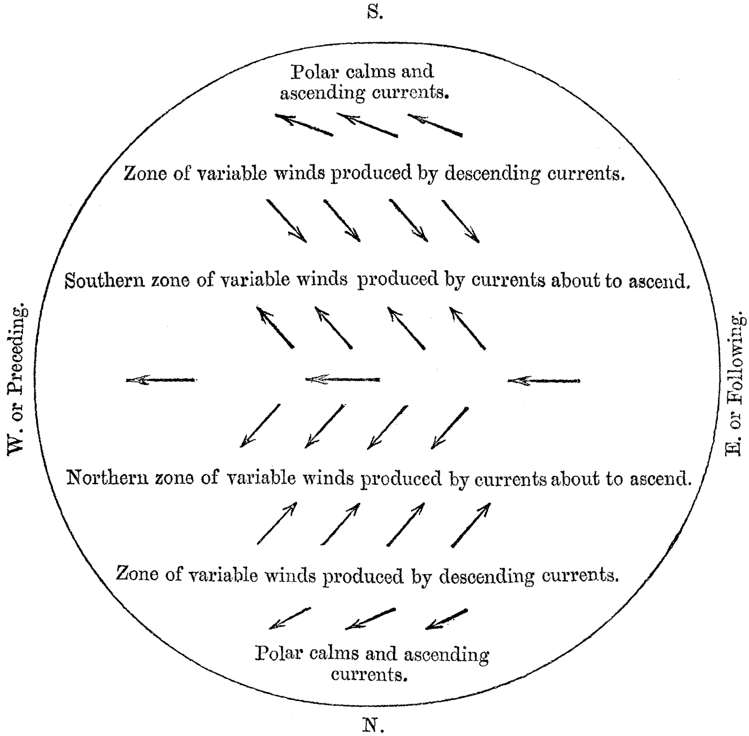

Diagram of the winds supposed to blow over the photosphere of the sun.

of the outer atmosphere, which, however gently they may begin, we have seen will terminate in a cyclone. Hence the two belts of spots on either side of the equator. In somewhat higher latitudes, the equatorial current having ascended, and, as it were, split the polar current into two sheets, has diverted one of them along the surface of the photosphere. In these regions, therefore, there is a constant wind blowing over the photosphere from the north-west in the northern hemisphere, and from the south-west in the southern. Accordingly, in the two zones of spots there are probably variable winds blowing over the photosphere, the polar and equatorial currents threading their way through each other, and both tending upwards, like the fingers of the two hands interlaced into one another. Meanwhile the equatorial current which had risen into the middle of the atmosphere over the zone of spots exchanges, in the northern hemisphere, its north-westerly direction, first for one due north, and then for one towards the north-east, as it ascends still higher.

But this temporary effect of its vertical motion will be lost, and it will again, when it ceases to ascend and advances only horizontally, direct its course to the north-west, until, in higher latitudes, the swifter rotation which its westward direction imparts to it no longer offers any sensible impediment to its sinking in the atmosphere *. And here it will be induced to do so by meeting in greater concentration the upper polar current, coming too from regions of slower rotatory motion, and therefore with a tendency to descend. Here, then, will end the space throughout which it has split the polar current into two sheets. It descends to the surface of the photosphere producing a zone of variable winds—in this case, however, caused by polar and equatorial currents which are both descending, and so unable to give rise to cyclones. Between this and the pole the equatorial current seems to be next the photosphere, and blows somewhat towards the pole, but chiefly from the east. There will be ascending currents about the poles; but they will breath upwards so gently, and over so great a space, that they are probably unequal to the task of heaving up the upper stratum of clouds in the vigorous way that leads to cyclones. Our conclusions may now be collected. The annexed diagram shows in one view the directions of the various trade-winds that seem to blow over the surface of the photosphere, and the prevailing character of the zones that separate them. The diagram is in the position in which the sun's disk is usually seen in a telescope.

76. We found that there is in the inner atmosphere a slight tendency to produce surface-currents from the equator towards the poles, owing to the greater escape of heat at the poles. But the influence of the winds in determining currents in the photosphere over which they sweep is probably so predominant, that both between and beyond the belts of spots they are able to determine the currents in the photosphere, those of middle latitudes being accordingly currents towards the east, whilst the equatorial and polar currents set in the opposite direction. Such currents would evidently conspire with the winds that blow over them to produce agitations in the photosphere. They would also contribute to that proper motion of the spots in longitude which has been observed.

77. We appear to be compelled to resort to some external cause to account for the periodicity of the spots. Among causes known to exist, that which seems to offer itself with most plausibility for our acceptance is a swarm of meteorites like those which visit us in November three times in a century, and those which visit us in other months every year†. To account for the periodicity of the spots, we must suppose the meteorites to describe their orbit in 11·11 years, the period of mutations of the spots. Hence

* Near the equator a swifter rotation tends to make a body fly outwards through the atmosphere; near the pole it tends to made the body retreat from the pole without much changing its level.

† [I find that Sir John Herschel in 1864 suggested such a swarm of meteorites operating in a different way, as a possible cause of this phenomenon. (See Quarterly Journal of Science, 1864, vol. i. p. 233.)—July 1868.]

the semiaxis major is 4·98 times that of the earth's orbit. The perihelion distance must be very small (say, 0·01) to admit of the swarm's grazing the sun's atmosphere at each perihelion passage. This would assign 9·95 to the aphelion distance, a quantity from which it cannot much deviate. Now the mean distance of Saturn is 9·54; so that we may safely conclude, if the explanation which is now offered is the correct one, that the meteorites in question were diverted into the solar system, by either Jupiter or Saturn, at no enormously remote period; just as the November meteors seem to have been brought in by the attraction of the planet Uranus in A.D. 126. At each perihelion passage some of the outlying members of the stream become entangled in the upper parts of the sun's atmosphere, dashing through it at a rate of about 414 kilometres per second *. The enormous friction they must undergo before they are brought to a state of relative rest will convert their immense *vis viva* into heat, which will be expended in raising the temperature of the upper strata of the part of the sun's atmosphere upon which they act. This part is of necessity more equatorial than polar, and is very much more equatorial than polar, except on the peculiar supposition, which we have no reason to select, that the plane in which the meteors move is very nearly perpendicular to the plane of the sun's equator. The heat imparted by the meteors to the sun's atmosphere therefore tends to diminish that defect of temperature in the upper parts at the equator which occasions the trade-winds of the sun. The influx of meteors, therefore, into the sun's atmosphere mitigates the violence of the trade-winds, and in this way enfeebles the cause of cyclones and of spots. Furthermore, except on the very improbable hypothesis that the axis-major of the orbit of the meteors lies exactly along the line of intersection of its plane with that of the sun's equator, the meteors must act more on one side of the equator than the other, and thus soften the trade-winds, and render the spots less frequent and extensive in one hemisphere than in the other. So that the hypothesis of a stream of meteors has the following points in its favour:—it is a *vera causa*; it accounts for two wholly distinct phenomena, the periodicity of the spots and their prevalence in one hemisphere more than in the other†; and it leads to such an aphelion dis-

* The velocity of the sun's equator is about 2 kilometres per second.

† [It also accounts for the approach of the zones of spots to the equator during the periods of minimum spot-frequency; inasmuch as when the current descending at the equator from great altitudes is enfeebled, the surface winds of middle latitudes, which have a tendency to cling to the photosphere, owing to their having a less rotation, will encroach further upon the equatorial current and will thus bring the junction between them, along which the spots lie, nearer to the equator.

If the decennial mutations of the spots be due to a current of meteors, this hypothesis ought to offer some indication of the cause of fluctuations of longer period, such as that of fifty-six years. This is perhaps to be sought in the great perturbation which the motion of the members of the stream must suffer from the attraction of Jupiter. This planet must act upon them with intense effect, since the planet and the meteors have nearly the same periodic time.—July 1868.]

tance of the orbit of meteors as assigns to them a position into which either Jupiter or Saturn could have brought them.

78. If these solar meteorites exist, they would seem to have had time to extend themselves round the greater part of their orbit, and leave the vacant space smaller at present than that which is occupied, so as to render the phenomenon depending upon their absence, viz. the *increase* in the number and size of spots, that which develops itself in the most marked manner. We may, then, perhaps presume that the epoch at which they came into the solar system was long before the year 126, though, cosmically speaking, a recent occurrence.

79. This appears the proper place to observe that the heat which is so lavishly dispersed by the sun cannot be kept up, as has sometimes been supposed, by the continual falling in of meteorites moving in orbits round him; since if that were so, the outer parts of the solar atmosphere would be kept intensely heated, which is contradicted by all the phenomena. In the next part of this memoir, which will treat of other stars, I will offer what appears to me a possible account of the proximate source of solar heat.

Part II. Of other Stars.

Section I.—*Of Solitary Stars.*

80. Observations with the spectroscope having apprised us of the presence in the sun and other stars of several of the elementary bodies with which we are familiar on the earth, we are bound to assume provisionally and until something offers to warrant a different belief, that those which are abundant on the earth and in the sun are abundant elsewhere also. Let us then consider how such differences as we must presume to exist between star and star would affect a body like the sun.

81. Star manifestly differs from star in mass; they probably also differ in temperature. Let us therefore inquire how a great change in the sun's mass or in his average temperature would operate. Strange to say, an increase of his temperature would produce many of the same effects as a diminution of his mass. This is because the dilatation of the sun's bulk, and the consequent removal of the outer parts of his atmosphere to a greater distance from the centre would lessen the force of gravity upon them. In either case, therefore, the effect upon the atmosphere would be the same as if the gases constituting it became specifically lighter. They would all be able to maintain their footing with feebler molecular motions. In other words, each gas would rise in the atmosphere until the distance between its outer layer exposed by radiation to the intense cold of the sky, and the inner layer heated by the photosphere, interposes a space of such thickness as will, in obedience to the laws of conduction, reduce the temperature on the outside to the lower minimum which the gas can now endure. Accordingly, the spectral lines of a star, either hotter or less massive than our

sun, should be all of them more intense than the corresponding lines of the sun's spectrum. Moreover, many substances which by reason of the large mass of their molecules are unable to stand in the sun the low temperature* of the clouds of the photosphere, and are therefore confined to the regions within, are able, on a star which attracts with less force or whose centre is far removed, to pass through this obstacle and show themselves in the atmosphere above. Finally, such stars will be ruddy. The sun himself is a somewhat ruddy star, as may be seen by a glance at Tables II. and III. Both ends of his spectrum are subdued by lines. The yellow, orange, and scarlet are nearly as bright as they came from the photosphere; the green is sensibly shaded over by lines; the blue suffers somewhat more; the indigo about G and the crimson beyond B, very much; and the violet from G to H to such an extent, that it is difficult to find a spot where the full light of the photosphere appears to penetrate. The chemical rays beyond the violet are progressively more and more enfeebled as their wave-lengths shorten; so much so, that the fluorescent spectrum from several artificial sources is longer, and from some much longer, than the sun's. A similar deficiency seems to exist at the other end in that prolongation of the solar spectrum beyond A, which Sir David Brewster has dimly seen and succeded in figuring. Now every encroachment upon the spectrum will be more marked when very dark lines become numerous, that is, in stars hotter, or of smaller mass; and if the lines themselves are pretty evenly distributed, it will subdue the different colours in proportion to their refrangibilities †. Ruddy stars, therefore, either have a less mass than our sun, or are more dilated by heat throughout the regions beneath the photosphere.

82. The consequences of the two other alternatives, of a star's mass being greater than the sun's, or of the temperature within the photosphere being less fierce, so that these regions are of less bulk, will be plain now. In such stars, some of the substances which range through the part of the sun's atmosphere above the photosphere are imprisoned within that luminous shell. Others of them, such as iron, calcium, and those of a like vapour-density, can only hold their ground while at a higher temperature, and would show faint though numerous lines in the spectrum. A few, such as sodium, magnesium, the substance that causes the line B (if this ray be of solar origin), and above all, hydrogen, would perhaps still continue dark. The lines of hydrogen, from its incomparably small vapour-density, would be so much the last to yield, that there is probably no star with gravity so intense as to produce any sensible impression upon them. And accordingly, in all very white stars which have been examined, these four lines stand out in extraordinay prominence.

83. It is now no longer a mystery why solitary stars are either white or of a red or yellow tinge. In all those cases in which the dilatation of the central parts by heat is so proportioned to the mass of the star as to render

* A variation of this temperature from star to star is another circumstance which must tell on the composition of the outer atmosphere.

† See § 52.

the force of gravity upon the outer atmosphere the same as it is upon the sun, the star will be equally white. The class of more brilliantly white stars with an almost violet gleam, such as Sirius and α Lyræ, are those with masses too great in proportion to their temperatures for this adjustment. And, on the other hand, those whose masses fall short of what the foregoing condition assigns, or, on the other side, whose temperatures are in excess, will, in proportion as they deviate from its fulfilment, have spectra more and more closed in upon that part in which the spectra of two incandescent bodies differ least in brightness when the luminous bodies are at nearly, but not quite, the same temperature—that is, upon the green, yellow, orange, and red rays, uniting into a tint which always inclines to either yellow, orange, scarlet, or crimson. The minute crimson stars which are met with here and there in the sky seem to be either very small stars, or stars enormously distended by heat. It is very desirable that the proper motion and parallax of these bodies should be inquired into when practicable, on the chance that some of them may be found to owe their colour to being very small, and therefore very close to us.

84. I need not say with what fidelity these many consequences of a change in the force of gravity in passing from star to star reproduce themselves in Mr. Huggins's observations. But before making the comparison, it will be well to consider rapidly what interfering causes may have to be taken into account.

85. We have hitherto spoken of the effects of the intensity of gravity in a star upon substances giving the same lines as we see in the sun. Our results are therefore subject to modification wherever the system of lines is itself changed. If, for example, the elements which give rise to the more prominent lines of the sun's spectrum are wanting in the stars, other lines, which perhaps are not, like those of the sun, pretty evenly spread over the whole spectrum, may take their place. If this should happen, some colours will be more absorbed by them than others; and this will tend to give to the star the complementary tint. In such cases the resultant effect will be mixed; the effect of the cause just mentioned being blended with that strengthening of the lines at the blue end of the spectrum which operates most when gravity on a star is weak. We shall presently find that this state of things, which would be improbable in solitary stars, may have been brought about in the case of the companions of some double stars. Or, again, elements which in the sun are free may in the stars be found only in a state of combination, and be either absent from the star's atmosphere or give rise in it to an entirely new set of lines. This* has perhaps been the

* Or the whole of the free hydrogen may have been thrown off into rings. If the star's rotation were such as to cast off the upper layer of hydrogen at his equator, and if the hydrogen could remain uncombined under these circumstances, fresh hydrogen diffusing upwards or flowing in from the poles would constantly fill the void; and each supply, as it arrived, would be in turn flirted off, until in the end the whole of the free hydrogen of the star would be in this way drained away. The explanation in the text is, however, on many accounts the more probable one.

fate of hydrogen in α Orionis, β Pegasi, and the other stars in which there are no lines corresponding to the solar lines C and F. If, however, the lines that are in this way withdrawn be as few as the lines of hydrogen, their absence will not sensibly affect the colour of the star. And finally, such conditions may prevail upon particular stars as will enable a spectrum of the first order to present itself,—that kind of spectrum in which the usual scattered lines of a spectrum of the second order are replaced by a multitude of fine closely ruled lines arranged in groups of regularly shaded bands, so as to give to the spectrum of the gas the appearance of a fluted pillar. The bands in the spectra of α Orionis, β Pegasi, and some others probably arise in this way, and perhaps from some compound of hydrogen*. The lines constituting such bands will be affected by differences of the force of gravity in the same way as other lines, and will therefore, if distributed with tolerable impartiality over the spectrum, cooperate with them in producing that tendency towards a ruddy hue which belongs to stars that exercise a feeble attraction at their surfaces. It may be noted that in none of the figures which Mr. Huggins has given of the spectra of solitary stars with shaded bands, do they seem crowded abnormally over the yellow, orange, and red, but rather the reverse.

86. We are now in a position to appreciate the significance of the phenomena which the spectral examination of stars has brought to light. We can easily see why in the class of bluish-white stars of which Sirius and α Lyræ are types, stars at whose surfaces the force of gravity is greater than on our sun, "the dark lines they present in great number are all, with one exception, very thin and faint, and too feeble to modify the original whiteness of the light," and why "the one exception consists of four very strong single lines, one line corresponding to Fraunhofer's C, one to F, and another near G"†. There can be little doubt that the multitude of faint lines will prove to be due almost exclusively to iron and the substances near it in vapour-density, such as calcium, chrómium, manganese, nickel, and cobalt, with of course sodium and magnesium. These, with the exception of sodium and magnesium, can produce only lines which are faint through the whole extent of the spectrum, since when attracted down with so much force as they are by the stars they cannot exist beyond regions of elevated temperature. And substances a little higher in vapour-density will be unable to endure even the chill of the photosphere, and therefore shrink within it. The violet and indigo rays being in these stars not subdued by lines in the same way as they are in the sun, gives to the whiteness of the stars a somewhat coloured tinge in eyes, like ours, accustomed to adjudge the sun's light to be white.

* If this surmise is well founded, the compound must be sought among the compounds of hydrogen of low vapour-density, such as marsh-gas (mass of molecules 8), ammonia 8·5, water 9, olefiant gas 14, methylamine 15·5, sulphuretted hydrogen 17, phosphuretted hydrogen 17, hydrochloric acid 18·25, &c.

† Huggins's Lecture before the British Association at Nottingham, published by Ladd.

87. On the other hand, Aldebaran is a good sample of a star which exerts less attraction at his surface than the sun, but which in other respects differs little from him. All the gases which cause solar lines can rise in the atmosphere of Aldebaran to colder heights than they can on the sun, and, as a consequence, they encroach more upon the violet end of his spectrum, and thus give to his light its rose-like tint. Another consequence is, that substances present themselves in the star's outer atmosphere with vapour-densities so high that the sun's superior attraction keeps them imprisoned within his photosphere. Mercury, mass of molecules 100; antimony, 122 (?); tellurium, 129; bismuth*, 210 (?).

88. All the foregoing appearances present themselves in α Orionis, which is therefore also a star on which the force of gravity is less than on the sun. They are found in α Orionis with the addition of a spectrum of the first order, one of whose bands has been observed to fluctuate in distinctness. We have reason to suspect, therefore, that the changes of brightness of this star, which is slightly variable, arise from some cause which alters periodically the temperature of the upper layer of that gas in its atmosphere from which the spectrum of the first order comes.

Section II.—*Of Multiple Systems*†.

89. Hitherto we have considered only the case of stars uninfluenced by one another. If, however, two stars should be brought by their proper motions very close, one of three things would happen. Either they would pass quite clear of one another, in which case they would recede to the same immensity of distance asunder from which they had come; or they would become so entangled with one another as to emerge from the frightful conflagration which would ensue as one star; or, thirdly, they would brush against one another, but not to the extent of preventing the stars from getting clear again. It is this last cause which we must now closely examine. After the stars disengage themselves they will be found moving in new orbits, which, if their motions before contact had been parabolic, will become elliptic. They will therefore return again and again, and at each perihelion passage will become engaged. If we take into account only the tangential resistance which the atmosphere of each presents to the motion of the other, we shall find‡ that the mean distance of the

* See Table I. p. 16.

† The following attempt to trace double stars, the solar system, and the amazing store of heat which we find in nature, to a proximate mechanical origin, is brought forward in the hope that it will prove of service in guiding inquiry, and in other ways; as an hypothesis always should, if not abused, which strikingly accords with many of the phenomena, and admits of being refuted or strengthened by future observations. I trust this will be accepted as a sufficient apology for offering to the scientific public what is as yet, of necessity, a speculation.

‡ These results appear from the following formulæ of elliptic motion:—

$$\frac{1}{a}=\frac{2}{r}-\frac{v^2}{\mu}, \qquad (1)$$

$$\frac{2}{\beta}-\frac{2}{r}=\frac{v^2}{\mu}\left(\frac{p^2}{\beta^2}-1\right),$$

stars would be reduced. If the resistance acted only at the apse of the orbit, the diminution of the mean distance would be effected by a shortening of the aphelion distance exclusively, the perihelion distance remaining unaltered. But since the resistance is not confined to this spot, but acts also for some space on either side of it, the perihelion distance will at each passage undergo a slight decrease, which would inevitably cause the stars in the end to fall into one another, if the tangential resistance were the only force disturbing the orbits. But there will be normal forces also. The resistance to which each star is subjected in passing through the atmosphere of the other is a force neither directed through its centre, nor parallel to the tangent of its orbit, since an atmosphere is not a thing of uniform density. Since these forces are not parallel to the tangents of the orbits, they will produce normal components, which will be directed outwards; and since they are not directed through the centres of the stars, they will cause the stars to rotate, and these motions of rotation, which will take place in the same direction in which the stars are revolving in their orbits, will in the subsequent perihelion passages cause each star to sweep the atmosphere that opposes it downwards towards the other star while bursting through it. It will accordingly itself suffer an equal reaction, which will be another force normal to its orbit and directed outwards. Such forces will lengthen the perihelion distance, while they leave the mean distance undisturbed*. Accordingly the combined

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where β is the perihelion distance, and the other letters have their usual significations.

A tangential resistance acting at any point of the orbit diminishes v, and therefore by equation (1) diminishes a, the mean distance.

To find its effect on β, the perihelion distance, transform the second equation by putting

$$\beta=p\,.\,(1-x); \qquad (2)$$

whence, neglecting the higher powers of x, since we only seek the effect of a resistance acting in the neighbourhood of the perihelion where x is small,

$$\frac{1}{p}-\frac{1}{r}=x\left(\frac{v^2}{\mu}-\frac{1}{p}\right). \qquad (3)$$

From equation (3) it appears that if v is diminished while p and r continue unchanged, x must increase, and therefore by equation (2) β, or the perihelion distance, is reduced.

* This appears from the foregoing equations by supposing p to receive an increment, while v and r remain unchanged. Equation (1) is not disturbed; in other words, the mean distance is unaffected. Equation (3) shows that x becomes less; and equation (2) that β, or the perihelion distance, is increased both by the increase of p and the diminution of x. The reverse effect upon β is produced by a decrease of p. Now p is increased by the normal forces from the time the stars touch up to the moment of the perihelion passage, and decreased during the second half of the transit. Accordingly β, the perihelion distance, is first increased and then diminished. If the stars behaved to one another like perfectly elastic bodies, these changes would be equal, and would cancel one another. But at each transit vis viva is converted into heat, in other words the stars do not behave like perfectly elastic bodies, and the mechanical forces elicited during the second half of the transit are feebler than those during the first. Hence there will on the whole be an increase of the perihelion distance.

effect of both forces will be at each revolution to shorten the ellipses in which the stars move, and at the same time to augment or reduce the perihelion distance, according as the effect of the normal or tangential component of the resistance preponderates. If the normal force carry the day, the stars will at successive passages gradually work themselves clear of one another, a result which may be very much promoted by the behaviour of the atmospheres.

90. If what I here venture to offer as a surmise with respect to the proximate cause of stellar heat and the origin of double stars, is what really took place, we must conclude the sky to be peopled with countless hosts of dark bodies so numerous, that those which have met with such collisions as to render them now visibly incandescent, must be in comparison few indeed. In the majority of those cases in which adequate collisions have taken place, the two stars must have emerged from the catastrophe, moulded into one, dilated by the conflagration to an enormous size*, and rotating. Occasionally, however, the circumstances of the collision must have favoured the disentanglement of the two stars from one another by a predominating influence in these cases of the normal force acting in the way that has been traced in the last paragraph. Wherever this happens, there is a prospect that a double star may form. The heat into which much of the previous *vis viva* of the two components has been converted will dilate both to an immense size, and thus enable the two stars gradually in successive perihelion passages to climb, as it were, to the great distance asunder, which we find in the few cases in which the final perihelion distance can be rudely estimated, a length comparable with the intervals between the more remote planets and the sun. While this is going on, the ellipticity of the orbits is at each revolution decreasing; but if the stars succeed in getting nearly clear of one another's atmospheres before the whole ellipticity is exhausted, the atmospheres will begin to shrink in the intervals between two perihelion passages more than they expand when the atmospheres get engaged, and will thus complete the separation of the two stars. When once this has taken place, a double star is permanently established.

91. It is a striking confirmation of this view to find that the astonishing phenomena witnessed last year† in T Coronæ were precisely what we should expect to arise towards the end of the process which has been described. The stars having been intensely heated by previous perihelion passages, and having begun to shrink, would, at ordinary times, present a spectrum subdued by an abundance of very dark lines; but immediately after one of the

* If any dependence is to be placed upon the records of Sirius's having formerly been a ruddy star, it would appear to argue that Sirius when he last met with a collision was heated only in the outskirts of his enormous mass: that these parts were so dilated as to render him a ruddy star, but that the store of heat laid up was so small that even within the little term of human history he has so cooled down as to have during it shrunk into an intensely white star.

† This was written in the spring of 1867.

last occasions upon which their atmospheres brush against one another, the outer constituent of their atmospheres, and the outer constituent alone, would be raised by the friction to brilliant incandescence, which would reveal itself by the temporary substitution of four intensely bright for four dark hydrogen lines in a spectrum which everywhere else continues to be filled with dark lines. And, moreover, these dark lines would for a while be rendered faint by the fierce heat radiated upon the outer parts of the atmosphere of each star by its companion*. It will be a matter of great interest to watch this star when sufficient time shall have elapsed to give a hope of seeing it double.

92. When a body of moderate dimensions enters the atmosphere of a great star, the resistance to which it is subjected will be very nearly the same per square metre over the whole of its front surface; but if it be of sufficient size to occupy a considerable height of the atmosphere through which it passes, it will be exposed to much more resistance beneath than above; and those conditions will have arisen which may terminate in a double star. The cases must be rare in which two stars that clash together happen to be of nearly equal mass. But when this does occur, the circumstances which are the *most* favourable to the formation of a double star have taken place. This seems to account for the very remarkable proportion of double stars which have nearly equal constituents. It would appear, too, that in this class we should expect to find those instances in which the perihelion distance is greatest, since it will be nearly the sum of the radii of the distended atmospheres of the two stars.

93. If two stars which are undergoing the process of formation into a double star, be of very unequal mass, the smaller one will be stripped at each perihelion passage of some of its atmosphere. All those parts which by the friction are brought into a state of rest relatively to the parts of the atmosphere of the larger star with which they come in contact, will, after the stars have been separated, settle down upon the larger star. They will, before the next perihelion passage, be replaced upon the smaller star by a fresh supply of the same gases diffusing upwards from beneath, and almost to the same height. When the stars come together again, this, in its turn, will be stripped off; and by a sufficient repetition of the process at successive perihelion passages several of the lighter constituents of the atmosphere of the smaller star will be transferred over to the larger. Upon the larger star this will not have any visible effect; the acquisition will

* γ Cassiopeiæ may perhaps be a similar system, in which the elliptic orbit has degraded either quite, or nearly into, a circular orbit, so as for the present to subject the outer layer of hydrogen to such a friction as keeps it constantly alight. If so, and if the stars are of materially unequal size, this must terminate, either by the atmosphere of the large star shrinking away from the companion, or by the companion's settling gradually down by a spiral motion through the atmosphere of its primary. If the latter be what is to occur, we shall have a splendid conflagration, the star first becoming intensely white, and afterwards deep red.

not even swell his bulk perceptibly *. But upon his satellite the consequences will be very remarkable. Hydrogen was the first gas to go; then, in order, sodium, magnesium, calcium, chromium, manganese, iron. If the process has gone far enough to distil away all of these gases in the free state, the spectrum of the companion has been robbed of the principal lines found in solitary stars, to be replaced by an entirely new system emanating from substances of higher vapour-density, which, to judge from the spectra of the few coloured double stars that Mr. Huggins has succeeded in examining, are crowded abnormally over the scarlet, orange, yellow, and part of the green, giving to the companions of double stars those blue, violet, or greenish tints which are met with nowhere else. If the process be continued still further, more gases will be swept away, and the photosphere laid nearly bare; as a consequence, the smaller star will appear white and nearly destitute of lines. This may have furnished that numerous class of double stars of which the companions are small and white.

94. No double star can come forth unless unequal pressure has acted so effectually on the smaller constituent as to communicate to it a swift motion of rotation. It is likely that cases may occur where the forces that accomplish this act with such inordinate strength that the cohesion of the smaller star is unable to withstand them, and there result two or more fragments spinning violently, and destined thenceforward to traverse slightly separate paths. This seems a not improbable account of such a multiple system as γ Andromedæ.

95. Upon the primary the consequences of the same violence would probably be entirely different. They would compel him to rotate at a great speed, perhaps so rapidly as to fling off his own equatorial parts†. These would form rings about him of the elliptic section which was investigated by Laplace; at least, they would assume this form if they consisted only of gas, or of gas with cloud dispersed through it which is constantly dissolving and reforming, so as to keep always in a state of minute division, —so long, in fact, as the gaseous pressure caused by any accidental conden-

* A moment's consideration will make this plain. In fact, if the quantities of all the gases in the earth's atmosphere were doubled, it would add only 3½ miles, or, more exactly, 5534 metres to its height. The result, after all disturbance had quieted down, would be the same as if a denser stratum of air of this trifling thickness were slipped in between the present atmosphere and the ground. To spectators from without, who would judge of our atmosphere chiefly as one which reaches upwards to a distance of about 200 kilometres (the height at which meteors begin to glow), the effect would be wholly insensible.

† This would be most likely to occur when the friction had acted chiefly on the superficial parts of the larger star, since under these circumstances a star might be enormously dilated without any considerable increase of its moment of gyration; so that, *cæteris paribus*, such a star would rotate swifter than one whose bulk was due to the equal expansion of all parts.

Sirius may have been an instance of such a star (see footnote, p. 53). We have perhaps some reason, judging from the existing areolar momentum of the parts of the solar system, to suspect that it was in a considerable degree the case of our sun also.

sation in one part of the ring tends to disperse the gas which had accumulated there and so restore the balance, with better effect than the slightly superior attraction of the condensed knot can disturb it. The gases first cast off will soon be replaced on the star by a fresh supply of the same kinds diffusing upwards from below, to be in turn flirted off into the rings, if the star have retained sufficient rotation. It would seem, then, that the rings must of necessity consist of exceedingly light materials. These rings will obviously move nearly in the same plane as the companion, or fragments of the companion, as the case may be.

96. Now, as has been explained above, when the circumstances are such as favour the formation of a double star, the perihelion distance of the relative orbit is, after every revolution, on the increase, and the eccentricity on the decrease. If the two stars manage to get clear of one another before the eccentricity is worn out*, the process is complete, and a double star has come into being. But it must often happen, and is especially likely † where the companion is small, or has broken up into a number of fragments, that after the perihelion distance has become very considerable, but before the stars are quite clear of one another, the orbit will have degraded into a circular one. If this happen to any fragment of which the distance is at the time less than the radius of the distended primary, the two bodies must fall together and become one. But if the perihelion distance had attained a sufficient magnitude to place the fragment in one of the rings surrounding the primary, it will there play a very important part. It will by its attraction collect this ring about itself, and thus become covered with an enormous atmosphere, encircled by which it will continue to spin vigorously in the direction in which it moves in its now nearly circular orbit. If this rotation should be rapid enough, the new planet will itself throw off rings; and if any of these should afterwards become concentrated into satellites ‡, they will, like our moon, keep the same face

* The following eccentricities of double stars have been determined with more or less probability.

Star.	Eccentricity.	Authority.
61 Cygni	nearly circular	
ζ Cancri	0·23	Mädler.
η Cor. B.	0·29	Mädler.
ξ Ursæ Majoris	0·41	Mädler.
ζ Herculis	0·43	Mädler.
p Ophiuchi	0·47	Sir J. Herschel.
ξ Bootis	0·59	Sir J. Herschel.
δ Cygni	0·61	Hind.
ω Leonis	0·64	Villarceaux.
Castor	0·76	Sir J. Herschel.
γ Virginis	0·88	Sir J. Herschel.

† Since tangential resistance, which is what shortens the ellipse, acts with much more effect upon a small body than upon a large one of the same density.

‡ Can chemistry have intervened on the satellites, and formed heavy products out of materials originally very rare? or may the density and want of atmosphere of these bodies

always turned towards their primary. All this seems in a very remarkable degree to be what we see about us in the solar system.

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be due to such a moderate change of temperature as, for instance, would convert the vapour of water into ice? It should be borne in mind that if the earth was at any time sufficiently hot, the ocean must have then formed an atmosphere of steam so vast, that it may perhaps have even reached to a ring which afterwards became the moon.

Possibly the giants of our system (Jupiter, Saturn, Uranus, and Neptune) owe their small density to their great mass, by reason of which they retain enough of their pristine heat to be still clothed in immense aqueous atmospheres.

If these surmises should prove to have any foundation, water was probably the material of rings thrown off originally by the sun, and is therefore not improbably an ingredient of the atmosphere of those dilated stars which do not exhibit hydrogen lines. (See footnote, p. 50.)

Postscript.

[(*Continuation of the note on* p. 26.) I have during the present summer often received the impression that I saw several other faint bright lines in other parts of the spectrum, of which the principal is a line which is coincident with or very close to Kirchhoff's copper line of wave-length 52·23. It should be borne in mind that if such bright lines exist, they are due to constituents of the solar atmosphere which are eminently transparent to these rays, either from being intrinsically so, or from the excessive tenuity of the gas. Hence the gas adds in these rays, but only adds a little, to whatever brightness may be transmitted through it from beyond. It behaves like a faintish flame of very high temperature placed between the eye and a more conspicuous but less hot coal. Hence, if the background be the spectrum of the umbra of a spot, the bright line should be a *faint* streak across it. On the only occasion on which I had an opportunity of examining the spectrum of a spot, one of the rays I suspect to be bright lines presented this appearance to my eye.

Mr. Lockyer and Mr. Huggins have observed that *some* dark lines appear broader in the spectrum of a spot than in the spectrum of ordinary solar light. This is no doubt because the wings of these lines lose brightness which had before shone through them from beyond, and the duskier parts of them in consequence become dark enough to add to the breadth of the central black stripe. Wings appear to be always (except in the anomalous case of the iron line 49·61, which demands a careful experimental scrutiny) fainter than the central band. This may arise in either of two ways, either, 1°, because the gas is so rare, or else the perturbations which occasion the wings so evanescent, that the wings are in a considerable degree transparent, and much light from the photosphere streams through them; or 2°, because though opaque they come from a region hot enough to render them less dark than the central stripe. It is in the case of wings of the former kind only that the appearance recorded by Messrs. Lockyer and Huggins will present itself. Lines of which the wings are quite opaque ought, on the other hand, to appear narrowest when seen in the spectrum of the umbra of a spot, since the brighter parts of the wings would be then undistinguishable from the faint background, which would therefore seem to encroach upon them.—September 1868.]

Table II.—Table of the Solar lines identified by Kirchhoff with rays in the spectra of gases; distinguishing the intensity of each, its position in the spectrum, and the substance to which it is attributed.

Wave-lengths in eighth-metres	43–44	44–45	45–46	46–47	47–48	48–49	49–50	50–51	51–52	52–53	53–54	54–55	55–56	56–57	57–58	58–59	59–60	60–61	61–62	62–63	63–64	64–65	65–66	66–67	67–68	68–69	69–70	70–71	71–72	72–73	73–74	74–75	75–76	76–77
Colours	Indigo.					Blue.					Green.				Greenish-yellow and Orange.					Scarlet.								Crimson.						
Standard rays	G.	f.				F.	c.		b.	E.						D.				a.			C.			B.								A.
Hydrogen 1	1 2 6 2 1	...	...	...	...	4 6 4	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1 6 1											
Sodium 23	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	6 6																		
Magnesium 24·3	...	0	...	0	...	...	...	...	4 4 6 6 6 4 4 4 (Fe)																									
Calcium 40	5 4 4 5	...	...	...	...	6 (Fe)	...	2	...	4 4 4 5 6 (Fe)	2	...	3 4 2 5	5 3 5 (Fe)	...	3 (Ni)	...	0	2 4 5 3 0 0 (Co)	0	...	5 3 5 2 2 2	...	...	2									
Chromium 52·5	...	...	...	...	...	...	...	...	...	5 5 6	...	5																						
Manganese 55	...	...	...	...	...	...	...	...	...	The Manganese spectrum is not given in Kirchhoff's map.																								
Iron 56	4 3 2 6 6 6 4 3 3	3 6 6 3	...	...	...	6 5 5 6 6 6 (Ca)	6 6 6 5 4 6	5	6 6 5 6 6 6 5 5 (Mg)(Ni)	5 5 5 6 6 6 5 (Co) (Ca)	5 5 5 5 5 5 5 5 5 5 6 4 4	5 5 6 4 4 5 6 5 5 5 6 4	4 6 4 5	5 5 4 (Ca)	3	...	3	4 3	4 3	4	4	5 2												
Nickel 59	...	...	...	2	6 3 4	3 3 3 3 2	4 1 3 4 4	5 4 3 3	2 3 3 3 5 4 4 6 1 (Fe)	...	...	4	...	...	...	3 2 (Ca)	...	...	2 2 0															
Cobalt 59	...	...	5 6	...	1 3	3 2 4 1	...	...	...	0 0 2 5 1 2	1 2 1 4 0 0 0	0 0 3	...	...	...	...	...	0	4 0 (Ca)															
Copper 63·5	...	...	...	5	...	...	...	...	4 3	1 1	...	...	...	...	2																			
Zinc 65	...	...	...	...	2 3	5	0 0	...	...	...	...	...	...	...	...	0	...	0	0	...	1													
Barium 137	...	...	4 6	...	...	...	2 6	...	...	...	...	1	1 3	...	2	0 2	0	0 0	1 4	...	...	2												

Table III.—Table of the numbers of the other Solar rays recorded by Kirchhoff, distributed according to their intensities and situations*.

Wave-lengths in eighth-metres	43–44	44–45	45–46	46–47	47–48	48–49	49–50	50–51	51–52	52–53	53–54	54–55	55–56	56–57	57–58	58–59	59–60	60–61	61–62	62–63	63–64	64–65	65–66	66–67	67–68	68–69	69–70	70–71	71–72	72–73	73–74	74–75	75–76	76–77
No. of rays of intensity 6	0	2	2	4	2	0	0	7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3	0	0	0	3
Ditto ditto 5	5	11	14	9	13	4	7	4	9	2	1	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4	0	0	1	2
Ditto ditto 4	29	11	17	11	15	12	13	7	8	4	5	3	0	1	1	0	0	4	1	5	1	3	0	0	0	3	3	2	0	6	1	0	0	7
Ditto ditto 3	51	28	18	14	19	14	7	19	8	9	7	2	10	5	6	2	10	3	1	3	6	4	1	0	0	8	9	6	4	4	2	0	0	2
Ditto ditto 2	47	28	27	27	19	13	21	13	8	14	10	2	16	18	13	6	14	5	11	13	3	3	12	4	0	1	10	4	7	10	8	7	2	0
Ditto ditto 1	47	39	20	18	13	16	14	11	12	9	13	14	7	15	11	5	20	13	14	11	6	6	7	2	6	10	8	6	2	4	7	1	1	0

* The numbers of Table III. had been counted before the integer wave-lengths were laid down upon Kirchhoff's maps with the care that was afterwards taken. Accordingly in some cases a few of the rays entered in one column may more properly belong to the column next before or next after it.